OCS Study MMS 2007-042

VARIATION IN THE ABUNDANCE OF ARCTIC CISCO IN THE COLVILLE RIVER: ANALYSIS OF EXISTING DATA AND LOCAL KNOWLEDGE

VOLUME I: FINAL REPORT

November 2007

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Allison Zusi-Cobb, Will Lentz, Matt Macander, and Becky Baird (all of ABR, Inc.) also contributed to this study.

EXECUTIVE SUMMARY

Arctic cisco (*qaaktaq*; *Coregonus autumnalis*) are important to the culture of Iñupiat people on the North Slope, and the subsistence fishery on the Colville delta provides a major food source for the residents of Nuiqsut. The goal of this study was to evaluate existing scientific data and local knowledge from subsistence fishers to increase our understanding of annual variability in the abundance and subsistence harvest rates of Arctic cisco in the Colville River. This study included five main tasks: (1) assemble all literature and data relevant to Arctic cisco, including and biotic and abiotic factors that potentially could be affecting their abundance and availability to the subsistence fishery; (2) convene and work closely with a Panel of Experts from the subsistence fishing community to obtain local knowledge for incorporation into the analytical work and to gain consensus, when possible, between the scientists and fishers on the results, interpretations, and recommendations resulting from the analytical work; (3) exploration of the relationships among biotic and abiotic variables and identify testable hypotheses; (4) test a series of *a priori* hypotheses, hypotheses identified during preliminary analyses, and hypotheses developed from input provided by the Panel and Experts; and (5) perform sensitivity analyses to determine the importance and influence of the variables evaluated and to help identify data gaps and future research priorities.

An improved understanding of the causes of this observed variability is needed by the Minerals Management Service (MMS) to support environmental risk assessments, Environmental Impact Statements for potential oil and gas leasing, and for other decision documents in the Beaufort Sea Planning Area.

LIFE HISTORY OF ARCTIC CISCO

The current understanding of the life history of this fish suggests that most or all Arctic cisco in the Beaufort Sea originate from adults spawning in the Mackenzie River in Canada. In the spring, juvenile (i.e., young-of-the-year) Arctic cisco are carried downriver into ice-free waters of the coastal Beaufort Sea and then are transported westward towards Alaska by currents. If easterly winds prevail during the summer, juveniles can be carried as far west as Prudhoe Bay and the Colville River region where they take up winter residence. Although juveniles may overwinter in the Sagavanirktok delta, most juveniles and subadults (< age 7) are believed to overwinter in the brackish waters of the Colville River, which is the only river in Alaska known to support significant numbers of Arctic cisco. In summer, subadult Arctic cisco swim into Beaufort Sea coastal waters to feed. They remain in the Colville River region until the beginning of sexual maturity at about age seven. These sexually mature fish then migrate back to the Mackenzie River for fall spawning. Arctic cisco continue to spawn every other year or so and likely remain in the Mackenzie region for the rest of their lives, with life expectancy being 19 years or more.

PANEL OF EXPERTS

With help from Kuukpik Subsistence Oversight Panel, Inc. (KSOPI), the scientific team sought to engage Nuiqsut residents who were experienced and knowledgeable about Arctic cisco and also were willing to attend workshops and meetings with scientists. Ten residents were selected to be on a Panel of Local Experts, and their primary roles, as outlined by MMS, were to identify sources of information, including traditional knowledge, that would help the scientific team understand the observed annual changes in Arctic cisco abundance and to evaluate (validate) the findings of the scientific team.

Four meetings were held with the Panel of Experts during the course of the project, with meeting content closely paralleling progress on the analytical work. Hence, the first two panel meetings focused on local knowledge and trying to determine if testable hypotheses could be developed from local knowledge. Subsequent meetings focused on presenting analytical results to the panel and getting their input on how to interpret those results.

The Panel of Experts provided valuable input to the scientific team, including (1) Arctic cisco life history information; (2) among-year changes in the size, weight, texture, color, and taste of the fish; (3) among-year changes in the distribution and abundance of fish available for harvest; (4) anthropogenic and natural factors thought to either positively or negatively affect the quality, distribution, and abundance of the fish; and (5) critical reviews of the results and conclusions of the scientific findings. The panel thought the collaboration was successful because it increased their understanding of the scientific research that has been conducted on *qaaktaq,* and because it gave them a forum for expressing their knowledge of the fishery and the factors they think are influencing harvest rates. Beyond that, they appreciated being integral team members who had input and influence on the analytical work and the interpretations of the results of that work. We did have some difficulty arranging meetings and getting consistent attendance from all panel members. However, our overall assessment of the collaboration between the scientists and the local experts was that it was successful, primarily because we were able to build a relationship of trust, which in turn facilitated effective information transfer.

ANALYTICAL RESULTS

We tested a number of hypotheses to assess the effects of environmental and human influences on Arctic cisco population dynamics. Specifically, we identified factors that have the strongest apparent effect on Arctic cisco recruitment, survival, abundance, or condition in the Colville River. The following general *a priori* null hypotheses were identified:

- Changes in oceanographic or hydrographic processes do not significantly affect the recruitment, survival, or abundances of Arctic cisco in the Colville River at any stage in their life history.
- Ecological processes and other species do not significantly affect recruitment, survival, or abundance of Arctic cisco in the Colville River.
- Human activities related to oil development or fishing do not significantly affect the recruitment, survival, or abundance of Arctic cisco in the Colville River.

These general hypotheses were refined into a set of testable hypotheses relating to specific environmental or human influences and to specific life-history stages.

Recruitment of Age-0 Juveniles

Our analyses demonstrated that ~ 80% of the variation in recruitment of juvenile Arctic cisco to the Prudhoe Bay region is determined by the strength of easterly winds during summer (July 1 – August 31). These results are consistent with previous studies and are evidence that much of the annual variation in juvenile recruitment into Alaskan waters can be accounted for by natural factors.

The lack of any recruitment to Prudhoe Bay when summer winds are westerly on average implies that the migration of young-of-year Arctic cisco is largely passive, which again is consistent with previous studies. The fact that some recruits arrive at Prudhoe Bay even when winds conditions are not favorable, however, suggests that active behavior may contribute to the juvenile fishes westward migration. For example, by moving inshore or staying in low-flow water layers, young Arctic cisco may be able to avoid eastward transport during periods of westerly winds.

Sufficient recruitment of young-of-year Arctic cisco to Prudhoe Bay is required to replenish the Colville River population and maintain the fishery at current levels over the long term. Recruitment anomalies (difference between observed recruitment and predicted recruitment based on the strength of easterly winds) have decreased substantially since at least the mid-1980s). Recruitment was much lower than expected in 2001, 2004, and 2005 and was essentially zero in 2002 and 2003. Low recruitment in the latter years was expected based on the prevalence of westerly winds in those years. Because of the low recruitment in recent years, catch rates of Arctic cisco in the Colville River are expected to be very low from at least 2007 to 2009.

Our observation that juvenile recruitment anomalies are positively correlated with the Arctic Oscillation (AO) index, suggests that the decreasing trend in recruitment may be related to changes in Beaufort Sea circulation as mediated by the AO. Recruitment anomalies have different means for positive and negative values of the Arctic Oscillation, with above-average recruitment when the AO is in its positive state. This may in part explain the high recruitment observed after the 1988/1989 shift in the AO from its negative to its positive phase. The underlying mechanism is not clear but may be related to large-scale changes in Beaufort Sea circulation associated with the AO. Other factors that we were unable to explore but that may affect recruitment include reduced production or survival in the Mackenzie River or reduced survival during westward transport.

We found no evidence that the amount of seismic activity or the number of drilling operations during a given year in the eastern Beaufort Sea (east of the Sagavanirktok River) was related to recruitment success in the same year. It should be noted, however, that this type of retrospective analysis does not account for the degree of spatial and temporal overlap between the industrial activity and the fish because the analyses are conducted at a regional scale. Accordingly, these analyses can only yield inferential conclusions, at best. More definitive conclusions on the effects of offshore seismic and drilling activity could only be derived from studies that were designed to measure the responses of fish to measured intensities and frequencies of disturbance.

Survival from Age-0 to Age-5

We detected few significant relationships between any of the environmental variables examined and the survival of age-0 at Prudhoe Bay to age-5 Arctic cisco in the Colville fishery. Survival appeared to be slightly lower in warmer years (i.e., summers with warmer air temperatures), but the relationship was weak and was heavily influenced by a few outlier years. Similarly, we found no significant relationships between survival of age-0 to age-5 fish and any of the indicators of human activity, including the Endicott Causeway, which has been and continues to be a source of concern for the subsistence community. Although average survival anomalies decreased after the construction of the Endicott causeway and decreased again after breaching, the differences were not statistically significant. Furthermore, a decrease in survival after breaching is counterintuitive because breaching should facilitate fish movements along the coast. The Panel of Experts did say that they thought the causeways were responsible for increased siltation west of the causeways and that this had affected seal distribution. They recommended that we explore whether this siltation also affected Arctic cisco, but we were unable to obtain data on siltation and examine this issue. The causeways and other development features that occur in nearshore waters are not under the purview of MMS, which manages offshore waters, but it was important to examine the full range of factors potentially affecting this anadromous species.

Survival from age-5 to age-7

We detected a significant negative relationship between our summer climate index (reflecting temperature, ice conditions, and discharge) for the central Beaufort Sea shelf and the survival of subadults, as determined by data from the Colville fishery. This result suggests that survival is reduced during summers with above-average temperatures and discharge rates and below average ice concentrations.

At the behest of the Panel of Experts, we also examined whether industrial activity on the Colville delta influenced Arctic cisco. We found that there was a period of low survival of age 5–7 Arctic cisco from 1997 to 2001 that coincided with the period of most intense development activities in the Colville delta and the larger Colville region. Over all years examined, however, the relationship was not statistically significant and was strongly affected by the large 1985 recruitment anomaly. Catch rates in the Colville fishery also declined after this period of intense activity (see below). Onshore developments like those occurring on the Colville delta are not within the purview of MMS, who manages offshore waters, but it was important to examine the full range of factors potentially affecting this anadromous species.

It also is important to note that our measures of human activity were retrospective and did not include any direct measurements of noise, vibration, or habitat alteration. Nor were our disturbance indices robust for assessing the magnitude of individual disturbance events or precise in terms of spatial and temporal concordance with important life history events for the fish. Hence, no cause and effect can be inferred from these analyses.

Colville River: Catch Rates in the Fishery

Catch rates in the Colville fishery were related to recruitment levels measured at Prudhoe Bay 5–7 years earlier ($R^2 = 0.49$). Although recruitment is largely mediated by summer wind, as described above, only ~24% of the variation in annual harvest of Arctic cisco can be predicted based on the wind/recruitment relationship.

The unusually low catch rate in 2001 could not be accounted for by specific events (such as oil spills or other short-term development activities) or any unique combination of environmental or development indicators. The low catch rate in 2001 was unprecedented in that it was not only the lowest catch on record, but also because the anomaly (i.e., variation not explained by wind) was greater that year than before or after (1969–2005). Hence, 2001 was not only a very bad year for the fishery, but it also was an unusual year for either other environmental factors besides wind or anthropogenic factors. Accordingly, we attempted to analyze what specifically happened in that year, but did not come up with any explanation.

Local catch rates in the Colville River varied substantially with the salt content in the river, with significantly higher average annual catch rates being associated with higher average salinity in the river. Our analyses confirmed results reported by previous studies. Average salinities in the river have fluctuated over time but do not show any long-term trend. A number of factors mediate salinity levels in the river but there are too few data available to analyze the proximate causes of these trends.

We examined the effects of causeways in the nearshore environment, where Arctic cisco migrate and feed during summer, on catch rates of Arctic cisco in the Colville fishery and did not detect any significant changes in average catch rates after the either construction of causeways (West Dock or Endicott) or after breaching. Onshore development activities may have influenced catch rates, however, as average catch rates of Arctic cisco in the Colville fishery declined following several years with relatively intense development activity in the Colville delta (drilling, construction, and ice roads).

Size and growth of Arctic Cisco

Based on patterns in size-at-age and summer winds and on our knowledge of coastal oceanography, it appears that the small size of Arctic cisco caught in the Colville fishery in 2002 and 2003 was caused by reduced prey availability resulting from a lack of upwelling of deep, nutrient-rich waters onto the shelf due to unusual westerly winds during summer 2002 and 2003.

Fishing

We found no evidence that high catches or high rates of fishing effort tended to be followed by reduced recruitment of young fish. Therefore, harvest rates experienced by Arctic cisco over the last 20 years do not seem to have negatively impacted the number of new recruits to the western Beaufort Sea.

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1. INTRODUCTION

Arctic cisco (*Coregonus autumnalis*), or *qaaktaq* as they are referred to in Iñupiaq, are an important subsistence resource to Alaska's North Slope residents, particularly the Iñupiat village of Nuiqsut. Nuiqsut is situated on the Colville River delta (hereafter Colville delta) in the central Beaufort Sea region (Figure 1). Between 1985 and 2003, the under-ice subsistence fishery yielded an average of 8,743 kg (19,200 lbs) of Arctic cisco annually (Moulton and Seavey 2003). From 1967 until recently, a commercial fishery for Arctic cisco was operated by the Helmericks family on the main channel of the Colville River. In 1993, the year with the highest combined harvest from these two fisheries, ~78,254 fish (31,340 kg) were taken on the Colville delta (Moulton and Seavey 2003). In contrast, only 5,859 fish (2,799 kg) were harvested in 2001, which was the lowest harvest on record. This substantial annual variability in harvest rates and a perceived overall downward trend in the fishery in recent years, coupled with increased development by the oil and gas industry within the range of the Arctic cisco, have raised concerns among subsistence users and agency regulators (MMS 2003). In 2003, the Minerals Management Service (MMS) convened a workshop in Nuiqsut to review the issue of *qaaktaq* variability, both from the perspective of the subsistence community and scientists who have conducted research on this species (MBC Applied Environmental Sciences 2004). One of the recommendations of that workshop was to review existing data from the full range of studies that have been conducted and also to document and incorporate traditional ecological knowledge (i.e., local knowledge) from subsistence users. This study was developed by MMS as a direct response to those recommendations.

GOALS AND OBJECTIVES

The goal of this study was to evaluate existing scientific data and local knowledge from subsistence fishers to increase our understanding of annual variability in the abundance and subsistence harvest rates of Arctic cisco in the Colville River. The information is needed by MMS to support environmental risk assessments, Environmental Impact Statements for potential oil and gas leasing, and for other post-leasing decisions documents in the Beaufort Sea Planning Area. The specific objectives for this study were to:

- gather existing biotic and abiotic multidisciplinary data relevant to Arctic cisco abundance in the Colville River;
- explore data patterns and identify biologically important relationships in the data;
- conduct sensitivity analyses of all relevant variables;
- quantify and synthesize the relative importance of natural factors and human activities on the variability of Arctic cisco populations in the Colville River; and
- identify any data gaps and determine priorities for acquisition of new data.

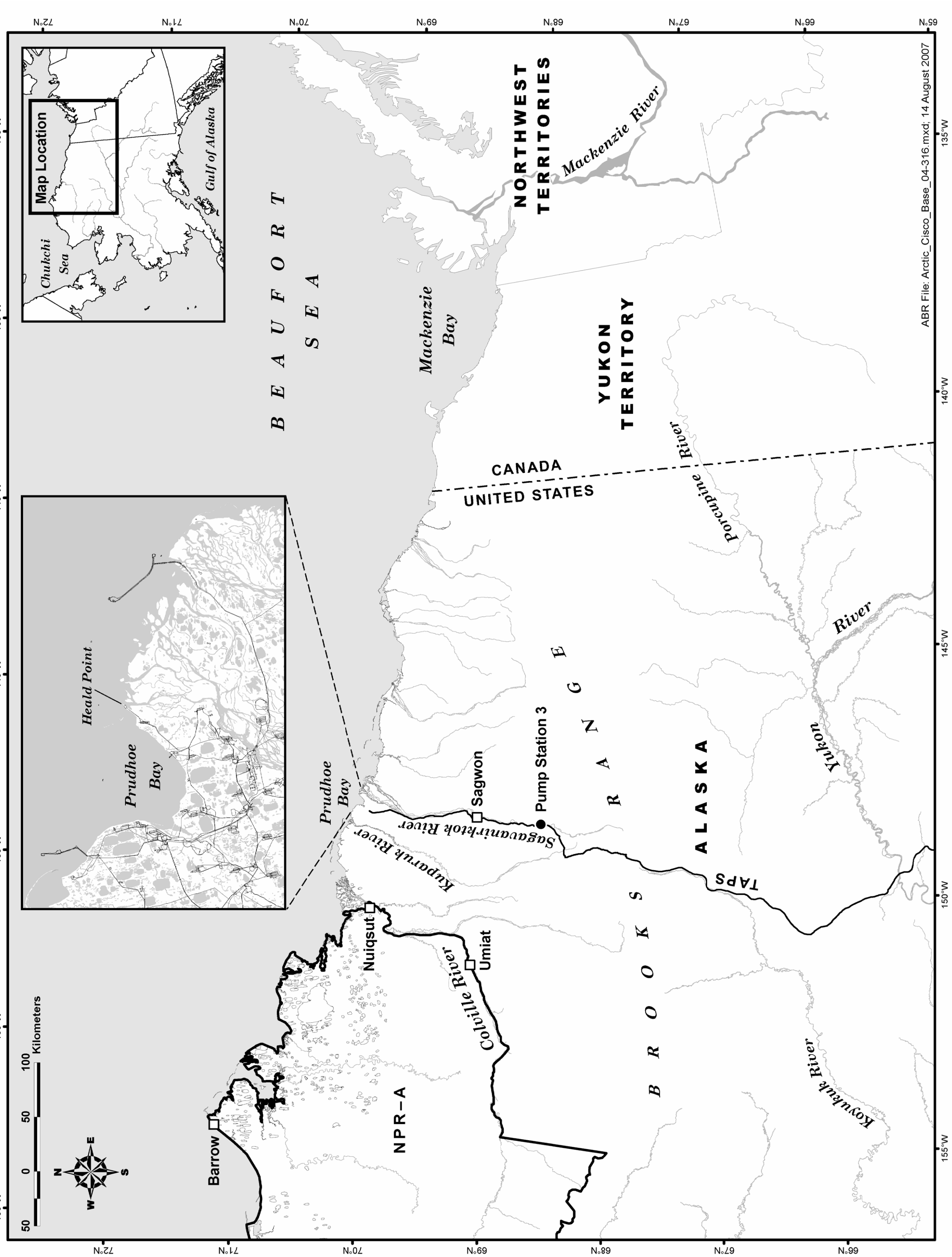


Figure 1. Central Beaufort Sea region in the United States and Canada.

Local knowledge was gathered by establishing a Panel of Experts comprised of Nuiqsut residents with knowledge of the subsistence fishery. The role of the panel, in addition to providing local knowledge, was to work directly with the scientific team to achieve the project objectives and to provide MMS with an independent report of their assessment the value of the expert panel as a method for integrating local and traditional knowledge into the scientific study. The overarching role of the panel was described by MMS as "Validating Interpretations"; hence, panel members were kept abreast of all of the analytical work and were given frequent opportunities to help develop additional hypotheses based on local knowledge or alternative interpretation of the scientific data.

This report is organized by the individual tasks as defined by MMS:

Data Collection

Validating Interpretations

Data Exploration

Hypothesis Testing

Sensitivity Analysis

Summary, Conclusions, and Recommendations

The flow of work among tasks and between the scientific team and the Panel of Experts is depicted in Figure 2. An unstated goal of this project was to develop improved methods in Alaska for integrating western science and traditional ecological knowledge.

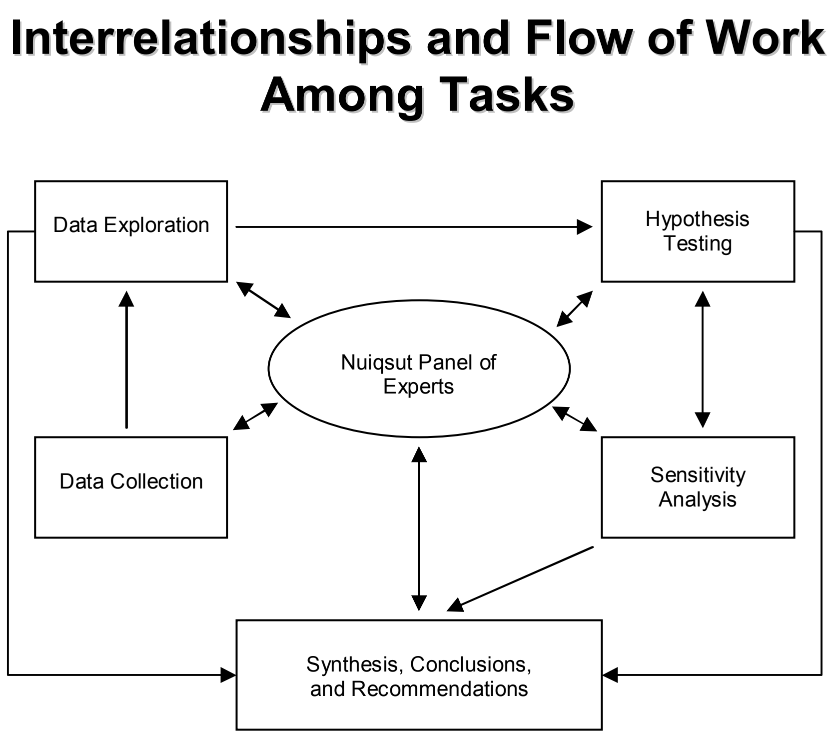


Figure 2. An overview of tasks, flow of work, and interrelationships between the scientific team and the Panel of Local Experts from Nuiqsut for assessing variation in the abundance of Arctic cisco on the Colville delta, Alaska.

BACKGROUND

LIFE HISTORY

Arctic cisco is an anadromous (also sometimes described as amphidromous) species of fish in the Arctic Ocean that hatches and rears its young in freshwater systems. After hatch, the young are flushed to coastal waters during spring floods (Strange 1985; Table 1). Arctic cisco spend most of their lives foraging in nearshore coastal waters in summer and in the delta regions of large rivers systems in winter. Upon reaching maturity, they return to their natal streams to spawn (Colonell and Gallaway 1997). After spawning, they return to delta waters for overwintering (Bond and Erickson 1997).

Arctic cisco epitomize the widely varied, complex and unique life histories of many coregonid species in the Arctic. The remote location, harsh weather, and complex lake and river systems have, until recently, limited basic research in the Canadian and Alaskan Arctic (Ford and Bedford 1987). Beginning in the 1970s, numerous research efforts were undertaken in coastal areas in the central Beaufort Sea region as a direct result of concerns over oil development in the Prudhoe Bay area (Doxey 1977, Bendock 1979, Gallaway et al. 1983, Bond and Erickson 1997 Craig 1984, Craig et al. 1985, Gallaway and Fechhelm 2000). Chief among observations made in these studies was that Arctic cisco found in the Beaufort Sea and its river drainages in Alaska probably originate from the Mackenzie River System in Canada (Figure 1) (Gallaway et al. 1983). Until that time it had been assumed that Arctic cisco in the Colville River were of local spawning stock (Alt and Kogl 1973, Craig and Mann 1974).

Subsequent studies have confirmed that the majority of Arctic cisco found in the Beaufort Sea region originate in the Mackenzie River in Canada (Bond and Erickson 1987, Cannon et al. 1987, Bickham et al. 1989, Moulton 1989, Reub et al. 1991, Gallaway et al. 1989, Fechhelm and Griffiths 1990, Colonell and Gallaway 1997). After hatch, young-of-the-year Arctic cisco are carried downriver into ice-free waters adjacent to the Mackenzie delta. Depending on prevailing winds, a portion of these young fish are transported via currents along the Beaufort Sea coast. If easterly winds are sufficient, juvenile Arctic cisco can be carried as far west as the Colville River (Fechhelm and Fissel 1988, Moulton 1989, Fechhelm and Griffiths 1990, Schmidt et al. 1991, Colonell and Gallaway 1997). Overall recruitment strength of Arctic cisco also has been correlated with the percentage of easterly winds in the Beaufort Sea region (Fechhelm and Fissel 1988). This wind- and ocean-current-driven recruitment process largely determines the age structure of Arctic cisco in Alaska (Gallaway and Fechhelm 2000). That is, if no recruitment of young-of-the-year Arctic cisco occurs in the Colville–Sagavanirktok region, then there will be no subsequent recruitment to the region of that age class in subsequent summers (Fechhelm and Griffiths 1990).

Arctic cisco display a high tolerance for brackish waters and spend summers feeding in higher salinity nearshore waters, sometimes embarking on extensive coastal migrations (Bond and Erickson 1989, Gallaway et al. 1989). Arctic cisco over winter in deep fresh and brackish water pools of river deltas (Bond 1982, Craig et al. 1985, Schmidt et al. 1989), and the rivers and deltas of the Colville and Sagavanirktok region appear to be the only drainages west of the Mackenzie delta capable of supporting over-wintering populations (Schmidt et al. 1989, Moulton and George 2000). Arctic cisco in the Sagavanirktok River generally disappear by age three (Moulton and George 2000), presumably finding their way farther west to the Colville delta.

Table 1. Arctic cisco life history in Canadian and Alaskan nearshore marine waters and in large river systems that drain into the Beaufort Sea.

Age (years)	Season	Event
0	Spring	Newly hatched young-of-year (YOY) Arctic cisco are flushed downstream from spawning/hatching tributaries of the Mackenzie River into ice-free coastal waters. Known spawning tributaries include the Peel, Liard, and Arctic Red rivers.
	Summer	Depending on the strength and persistence of easterly winds, an unknown portion of YOY passively migrate westward in nearshore coastal currents in the Beaufort Sea. In years with easterly winds on average, fish are transported as far west as Prudhoe Bay or beyond.
	Fall	Some unknown portion of YOY cisco (as well as ages 1–2) remain in the Prudhoe Bay / Sagavanirktok River area, while others move to overwintering habitat in the Colville River.
	Winter	YOY remain under ice in brackish riverine waters until spring thaw. Distribution is poorly known.
1–7	Spring/Summer	Juveniles and subadults move out into the marine environment to feed in nearshore habitat in Beaufort Sea.
	Fall	Most juveniles and subadults move up the Colville River and its tributaries to overwintering habitat.
	Winter	Juveniles and subadults remain under ice in brackish habitat until spring thaw. Distribution is poorly known.
4–8	Fall	Subadults are available to the under-ice subsistence and commercial fisheries in the Colville River.
7–8	Spring/Summer	Onset of sexual maturity occurs. Adults migrate back to the Mackenzie River and its tributaries to spawn.
8–19	Fall	Post spawning and non-spawning adults overwinter in the Mackenzie River and its tributaries. In subsequent years, repeat spawning is thought to occur.
	Winter	Adults are believed to overwinter in brackish riverine waters until spring thaw.
	Spring/Summer	Adults move out into the marine environment to feed in nearshore habitat in Beaufort Sea.

Subadult Arctic cisco feed in deltas and nearshore marine waters in summer months (Moulton et al. 1986) and continue to return to their rearing rivers (primarily the Colville River in Alaska) for over-wintering (Craig 1984). Females mature at around 7–8 years of age, whereas males are thought to mature at age 6–7 (Craig and Halderson 1981, Bond and Erickson 1985). Once achieving maturity, they migrate during summer to their birth rivers within the Mackenzie system to spawn in the fall (Gallaway et al. 1983, Bond and Erickson 1987, Moulton 1989, Bickham et al. 1989). Once they make the initial spawning migration to the Mackenzie, they do not return to the rearing streams and are thought to remain in the Mackenzie region where they continue to spawn in subsequent years (Bond and Erickson 1997). As a result of this departure by mature individuals, very few fish of eight years or older are found in the Colville River (Craig and Halderson 1981, Gallaway et al. 1983, Dillinger 1989). The maximum age of Arctic cisco is thought to be somewhere between 10–14 years, but examples of longer lived individuals have been noted (Craig 1989).

Arctic cisco appear to be generalists in their feeding habits (Strange 1985). Adults feed on a variety of available prey including small crustaceans and fishes during summer months (McPhail and Lindsey 1970). Stomach samples from Arctic cisco in nearshore coastal waters showed a predominance of crustaceans (Craig and Mann 1974). In the Mackenzie River, it is believed that little or no feeding takes place during spawning (Hatfield et al. 1972, Stein et al. 1973, Percy 1975). Bond (1982) suggested that winter feeding was opportunistic and included prey items such as polychaetes. Schmidt et al. (1989) found evidence of a number of prey items in over-wintering fish in the Colville delta, with amphipods making up the largest proportion of diet. During this same time period in the Sagavanirktok delta, Schmidt et al. (1989) found little evidence of winter feeding.

In summary, Arctic cisco originate in the Mackenzie River system and then spend the first 6–8 years of their lives in the western Beaufort Sea and the Colville delta. Winters are spent in the Colville River followed by summer feeding forays into the coastal Beaufort Sea. The center of their summer distribution is believed to extend between the Colville River and Prudhoe Bay. Therefore, conditions in these marine areas are likely to affect the survival of juvenile and subadult Arctic cisco.

STATUS OF THE SUBSISTENCE FISHERY ON THE COLVILLE RIVER

The *qaaktaq* (Arctic cisco) fishery is tremendously important to the diet and culture of the residents of Nuiqsut. The fishery occurs primarily during October and November when gill nets are set under the ice on the Colville River and its tributaries (Figure 3) to harvest over-wintering *qaaktaq* (George and Kovalsky 1986). *Qaaktaq* represent a high percentage of the local diet and are sold, bartered, or given away to family and friends within the community, including Barrow. *Qaaktaq* are eaten raw-frozen, boiled, dried, baked, aged, or smoked.

In the late 1970s, the Arctic cisco population in the Colville region began to show declines (Gallaway et al. 1983). At the same time, and in conjunction with increasing oil and gas development, a number of studies were initiated to study fish in the central Beaufort region (Bendock 1979, Doxey 1977, Craig and Halderson 1981, Craig and Griffiths 1981). Craig and Halderson (1981) found an 86% decline in population of over-wintering Arctic cisco in the Colville delta between 1976 and 1979.

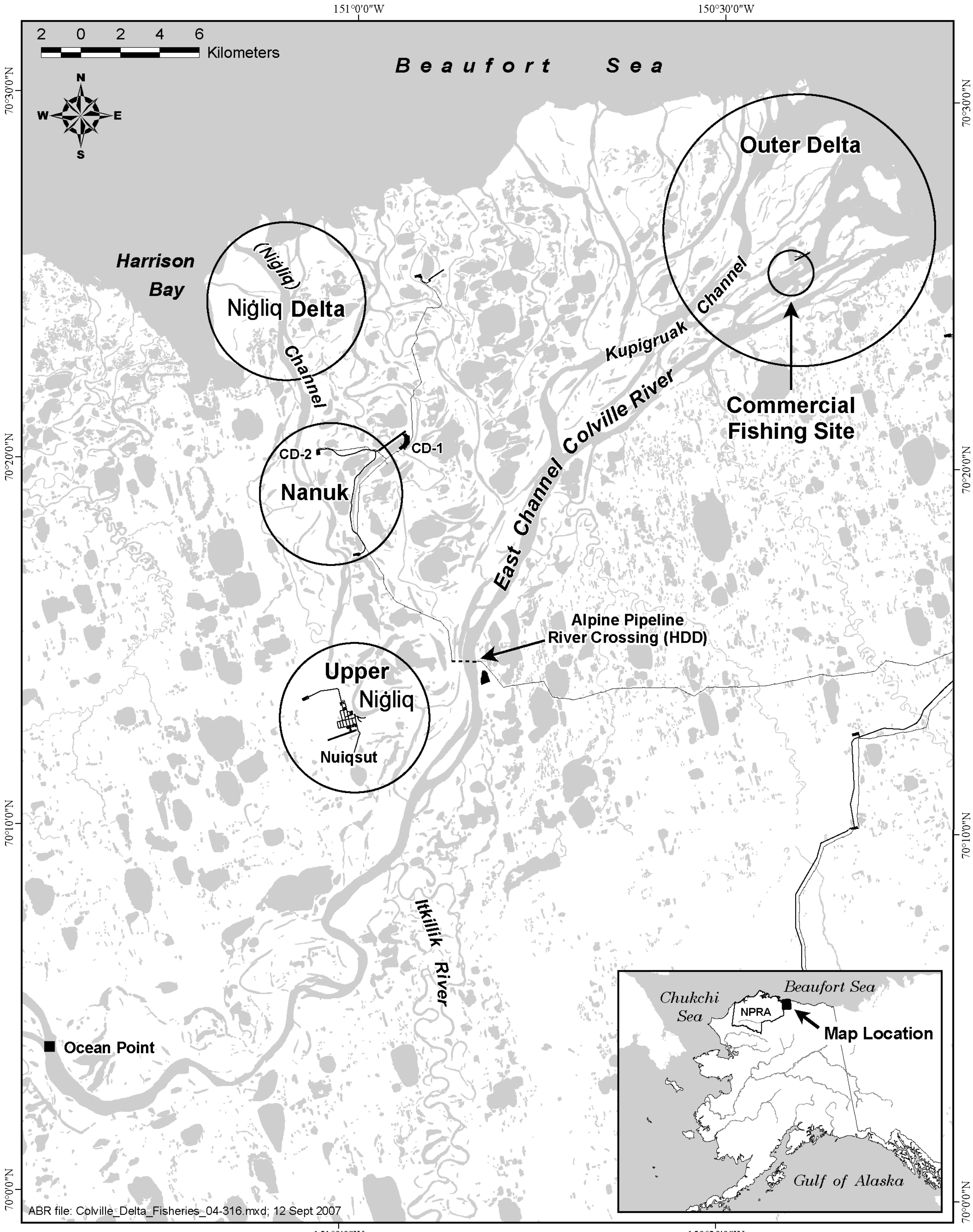


Figure 3. Colville delta and major subsistence and commercial areas used for harvesting Arctic cisco (after Moulton and Seavey 2003).

It has long been speculated that offshore causeways in the Beaufort Sea could hamper recruitment of Arctic cisco to the Colville River by obstructing the nearshore passive transport of juveniles westward from the Mackenzie River to over-wintering areas like the Colville delta. Another concern was that these causeways were blocking eastward feeding migrations by adults from the Colville River (USACE 1980, 1984). Oil companies acted by creating breaches in the causeways to allow passage of nearshore currents. While breaches in the causeways apparently have allowed for passage of Arctic cisco, there are concerns that currents in the area of these causeways are affected in such a way as to influence local temperature and salinity regimes (Fechhelm et al. 2001). This change could in turn affect the presence and foraging behavior of Arctic cisco in those waters (Griffiths et al. 1992, Jarvela and Thorsteinson 1997).

Other theories concerning the decline of this Arctic cisco population centered on increased fishing pressure as a result of the resettlement of the village of Nuiqsut in the 1970s (Gallaway et al. 1983). Monitoring of the subsistence catch of *qaaktaq* on the Colville River has been ongoing since 1984, when the North Slope Borough investigated these stocks (George and Kovalsky 1986). A year later, the oil industry began funding a monitoring program for the subsistence fishery on the Colville River, and this program has been conducted annually with village participation every year except 1999 (see Moulton et al. 2006). Although fishing effort (net days) in the subsistence fishery has increased over the past 20 years, harvest rates have decreased substantially in recent years (Moulton and Seavey 2003). Subsistence catches in 2001 and 2002 were the lowest on record and, as noted above, this decrease was a major impetus for developing this study. Although the catches recorded in 2003–2005 were substantially higher than in 2001 and 2002, predictions are for declining harvests in 2007–2010 (Moulton et al. 2006).

2. DATA COLLECTION

Data collection for this project primarily involved the review of multidisciplinary literature (Appendix A) and data from scientific studies (Table 2) relevant to Arctic cisco abundance in the Colville River. In addition to information derived from studies, we also collected traditional knowledge from residents of Nuiqsut (see Chapter 3) and information on human activities (primarily oil and gas exploration and development) in the region that might influence Arctic cisco. All of the studies, their associated databases, and other knowledge sources were assessed in terms of their value and appropriateness for the analytical tasks associated with this project. The sources of information that were deemed useful (Table 3) were incorporated into a Microsoft Access relational database and described in a Data Manual (Appendix B).

The initial search for suitable data to synthesize and analyze for this project located 42 databases, with 20 databases containing Arctic cisco data. The other databases provided data on climate and meteorological parameters (13 databases), sea ice (4), river hydrology (4), oceanography (4), and stream hydrology (1). The list of databases then was used to acquire suitable data to include in analyses and to construct data indices for inclusion in data exploration and hypothesis testing. Bibliographic references on Arctic cisco were compiled from a variety of sources, including the existing Arctic cisco bibliography (provided by MMS), a cisco bibliography provided by Larry Moulton (MJM Research, Inc.), the North Slope Studies bibliography (Gilders et al. 2000), existing ProCite® databases on arctic wildlife maintained at ABR, and searches of current literature through ABR's Current Contents® subscription. All the bibliographic references were compiled into a ProCite® database to which keywords were added to aid in database searches. The MMS Arctic Cisco ProCite® bibliography contained 419 references as of October 2007 and is presented in Appendix A.

FISHERIES DATA

The fisheries data used for data exploration and hypothesis testing are summarized below. Metadata for each of these studies and additional information on data quality (e.g., missing data), are explained in the data manual for this project (Appendix B). Relevant background and methodology are discussed for several of these studies because of their importance to database and subsequent analyses conducted for this study.

COLVILLE RIVER DELTA

The subsistence fishery in Nuiqsut on the Colville River delta has been monitored annually since 1985, except 1999 (Moulton et al. 2006), with funding provided by the oil and gas industry (ConocoPhillips Alaska, Inc., and its predecessors). Because the results of these studies are integral to nearly all of the analyses conducted for this study, the methodology used to monitor the fishery and calculate important metrics (e.g., catch per unit effort (CPUE) are reiterated here (also see Moulton et al. 2006).

The commercial and subsistence fisheries are concentrated in the major channels of the Colville River from the Itkillik River downstream to Harrison Bay (Figures 1 and 3). Primary fishing areas for Nuiqsut subsistence fishery include three areas in the Niġliq Channel: (1) the Upper Niġliq Channel near Nuiqsut, (2) the Nanuk area of the Niġliq Channel, and (3) the Niġliq delta (Figure 3). Additional fishing by Nuiqsut residents is near the mouth of the Kupigruak Channel. The commercial fishery is conducted near the mouth of the main channel.

Table 2. Potential data sources that were reviewed for the MMS Arctic cisco project.

Study	**Topic**	**Contractor**
ANWR	Fish	USFWS
Arctic Gas	Fish	Aquatic Environments Limited
Beaufort Sea	Fish	MMS
Beaufort Sea	Ice	ARCTEC Engineering
Beaufort Sea	Ice	Sea Ice Consultants
Beaufort Sea	Ice	Oceanographic Services Inc.
Beaufort Sea	Ice	Polar Expeditions
Beaufort Sea	Ice (broken ice periods)	Vaudrey & Associates
Beaufort Sea	Ice (Freezeup/breakup)	Vaudrey & Associates
Beaufort Sea	Ice (Reindeer Island)	Oceanographic Services Inc.
Beaufort Sea	winter/summer 1979	Woodward-Clyde Consultants
Beaufort Sea Drilling	Oceanography/Effluent	Northern Technical Services
Beaufort Sea Drilling	Oceanography/Effluent	Northern Technical Services
Beaufort Sea Drilling (offshore)	Impacts	MMS
Beaufort/Chukchi Sea	Ice (Freezeup/breakup)	Vaudrey & Associates
Colville River	Fish	Entrix (w/ Moulton)
Colville River	Fish	MJM Research
Colville River	Fish	ES&E (Moulton)
Colville River	Fish	Hunter/ESSE (w/ Moulton)
Colville River	Hydrology	Michael Baker Jr. Inc
Eileen West End	Fish	LGL
Eileen West End	Hydrology	LGL
Endicott	Fish	LGL
Endicott	Fish	Envirosphere
Endicott	Fish	Woodward-Clyde Consultants
Endicott	Fish	Dames & Moore
Endicott	Fish	UAF / Envirosphere
Endicott	Fish	LGL/ Hunter/ESE Environmental Svs/ W.J. Gazey Research
Endicott	Fish	MJM Research

Table 2. Continued.

Study	Topic	Contractor
Endicott	Hydrology	Dames & Moore/SAIC
Endicott	Hydrology	SAIC
Endicott	Hydrology (NPDES)	Kinnetic Laboratories
Endicott	Hydrology (NPDES)	NORTEC
Endicott	Ice Breakup/Freezeup	SAIC
Endicott	Modeling	SAIC
Endicott	NPDES	ENSR
Endicott	Oceanography	Sunbury Research Center
Endicott	Oceanography	LGL & Northern Technical Svs
Endicott	Oceanography	Ken Dunton (U of Texas)
Endicott	Oceanography	Envirosphere
Kalubik Creek	Fish	MJM Research
Kuparuk Field	Hydrology (breakup)	PND
Kuparuk Field	Fish	Woodward-Clyde Consultants
Kuparuk Field	Fish	MJM Research
Kuparuk River Waterflood	Marine Life	Dames & Moore
Kuparuk River Waterflood		Dames & Moore / Kinnetic Labs
Kuparuk Waterflood	NPDES/Oceanography	Kinnetic Laboratories
Lisburne	Oceanography	Woodward-Clyde Consultants
Lisburne	Oceanography	Battelle Pacific Northwest Laboratories
Lisburne	Offshore EA	Dames & Moore
Mackenzie/Yukon rivers	Hydrology	Univ. British Columbia
Mikkelsen Bay	Fish	LGL / Woodward-Clyde
Mikkelsen Bay	Oceanography	LGL / Woodward-Clyde
Niakuk Causeway	Oceanography	ES&E (Colonell)
Northstar	Fish	LGL
Northstar	Water/Sediment	Montgomery Watson
North Slope oilfields - seismic, drilling	Impacts	ADNR

Table 2. Continued.

Study	Topic	Contractor
North Slope oilfields - ice roads	Impacts	LCMF and Lounsbury
Northwest Gas	Fish	LGL
Oliktok Point	Fish	Woodward-Clyde Consultants
Oliktok Point	Oceanography	UAF (Weingartner)
Point Thomson	Fish	LGL
Prudhoe Bay Causeway Breaches	Fish	LGL
Prudhoe Bay Dock	Coastal Process/Marine Benthos	Woodward-Clyde Consultants
Prudhoe Bay Dock	Oceanography	Woodward-Clyde Consultants
Prudhoe Bay Seawater Treatment Plant	NPDES/Oceanography	Kinnetic Laboratories (via CH2M Hill)
Prudhoe Bay Waterflood	Fish	Biosonics, Inc.
Prudhoe Bay Waterflood	Fish	Woodward-Clyde Consultants
Prudhoe Bay Waterflood	Fish	Dames & Moore
Prudhoe Bay Waterflood	Fish	Envirosphere (w/ Moulton)
Prudhoe Bay Waterflood	Fish	Entrix, LGL, Woodward-Clyde (w/ Moulton)
Prudhoe Bay Waterflood	Fish	Fisheries Research Institute
Prudhoe Bay Waterflood	Fish	LGL & Woodward-Clyde
Prudhoe Bay Waterflood	Marine Life	Dames & Moore
Prudhoe Bay Waterflood	Oceanography	Kinnetic Laboratories
Prudhoe Bay Waterflood	Oceanography (benthos)	IMS (Feder)
Prudhoe Bay Waterflood	Water/Sediment	Entrix
Sag River	Fish	Woodward-Clyde Consultants
Sag River	Fish	Northern Technical Services
TAPS	Fish	Aquatic Environments Limited
West Dock Breach	Oceanography(bathy)	Coastal Frontiers Corp (CFC)
West Dock Causeway	Fish	LGL / ESE
West Dock Causeway	Oceanography	LGL, ES&E
Yukon Fish & Causeways	Fish	LGL Ltd & Arctic Sciences Ltd

Table 3. Descriptions of data sources used to compile the multidisciplinary database (Microsoft Access) for this study (see Appendix B for detailed descriptions of the Access database tables).

Table Name	Data_Abstract	Data_Location	Data_Type	Data_Source
TBL_ANWR_Catch	USFWS catch, length, weight, and mark recapture data for various ANWR location fyke nets 1988–1991	ANWR	Fishery	Tevis Underwood, F&WS
TBL_ANWR_CPUE	USFWS CPUE data for various ANWR location fyke nets 1988–1991 (location and effort data also in tables)	ANWR	Fishery	Tevis Underwood, F&WS
LU_ANWR_Species	Species, name, and associated species code from ANWR studies.	ANWR	Species	Tevis Underwood, F&WS
LU_ANWR_Locs	Location and effort of sampling location sites during the ANWR studies.	ANWR	Location	Tevis Underwood, F&WS
TBL_Colville_Age	The age frequency of Arctic cisco caught in 76-mm mesh in the Colville fishery from 1976–1978 and 1984–2002	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
TBL_Colville_Annual_CPUE_CV	The annual catch and effort totals for Arctic cisco caught in the Colville delta commercial fishery from 1967 to 2002 (effort in net-days of 46 m net)	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
TBL_Colville_CPUE	Catch and effort data for each net check in the Nuiqsut fishery	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
TBL_Colville _Daily_CPUE_CV	Daily catch, number of 76mm nets, and effort, of ARCS and LSCS caught by in the commercial (Helmericks) fishery 1967–2002	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
TBL_Colville _Effort	The effort and location data for each Nuiqsut fisher identified as participating in the fall fishery from 1986 to 2004.	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
TBL_Colville _Length	Lengths of Arctic cisco caught in the Nuiqsut fishery	Colville River delta	Arctic Cisco	Larry Moulton MJM Research
LU_Colville _Locs	Locations for the main fishing areas used by the subsistence fishery	Colville River delta	Location	Larry Moulton MJM Research
TBL_Colville_RKM	Location of river kilometers markers (RKM) along the	Colville River delta	Location	Larry Moulton MJM Research
TBL_Colville_Salinity	Salinity measurements on the Niġliq Channel taken in conjunction with fishing activity on the channel.	Colville River delta	Water	Larry Moulton MJM Research

Table 3. Continued.

Table Name	Data_Abstract	Data_Location	Data_Type	Data_Source
TBL_Dev_Beaufort	Information on timing, location, and type of oil exploration and development activities and ice roads built in support of industrial activities	North Slope coastal and offshore	Impact	Alaska DNR, Div. of Oil and Gas web pages. MMS Alaska OCS region offshore and drilling web site. CPAI Exploration environmental coordinators, pers. comm
TBL_Env_Arctic_Oscillation	Arctic Oscillation Index from NCEP reanalysis data	>20°N	Weather	National Weather Service Climate Prediction Center
TBL_Env_Bering_Transport	Water Transport (Sv) through the Bering Strait from wind forcing, based on Roach et al. 1995	Bering Strait	Oceanographic	Unaami Data Collection
TBL_Env_Colville_River_Breakup	Summary of Breakup Data obtained at the head of the Colville River delta, 1962–2004	Colville River delta	Water	Michael Baker, Jr., Inc., Alpine 2004 Spring Breakup and Hydrological Assessment Table 3-15
TBL_Env_Daily_River_Discharge	Daily mean streamflow data from the Kuparuk River, Sagavanirktok River, and the Colville River	North Slope, Alaska	Water	USGS National Water Information System
LU_Env_DailyDischarge_Locs	USGS river discharge locations.	North Slope, Alaska	Location	USGS National Water Information System
LU_Env_Discharge_Locs	Site information for TBL_ENV_River_Discharge.	Various Rivers	Location	R-ArcticNet
LU_Env_NCEP_Locs	Locations for NCEP daily winds.	70-72.5°N, 130–160°W	Location	NOAA-CIRES Climate Diagnostics Center
TBL_Env_NCEP_Daily_Winds	Model-based daily wind speeds at the surface in E-W (uwnd) and N-S (vwnd) at selected locations, Gridded data on a 2.5 degree grid with centers of grid points at 70°N and from 130–150° W	70°N, 130-150°W	Weather	NOAA-CIRES Climate Diagnostics Center, Boulder, CO NCEP/NCAR Reanalysis Project
LU_Env_OI_Locs	Location information for Optimum Interpolation SST and ice data.	1 x 1 degree grid	Location	Climate Modeling Branch W/NP24, NCEP/NWS/NOAA
TBL_Env_OI_SST_Ice	Monthly Optimum Interpolation (OI) version 2 Sea Surface Temperatures (SSTs) of Reynolds et al (2002) and mean ice concentrations for various 1x1 degree regions, Jan 1982–July 2005	1 x 1 degree grid	Weather	Climate Modeling Branch W/NP24, NCEP/NWS/NOAA
LU_Env_Reynolds_Locs	Site information for monthly Reynolds reconstructed SSTs	2.5 x 2.5 degree grid	Location	NCDC/NESDIS/NOAA
TBL_Env_Reynolds_SST	Monthly Reynolds reconstructed SSTs on 2 x 2 degree grid for several Beaufort Sea locations, Jan 1900-Nov 2003	2.5 x 2.5 degree grid	Weather	NCDC/NESDIS/NOAA

Table 3. Continued.

Table Name	Data_Abstract	Data_Location	Data_Type	Data_Source
TBL_Env_River_Discharge	River discharge volumes for Alaskan and Yukon rivers, taken from R-Arctic Net.	Various Rivers	Water	R-ArcticNet, Environment Canada for Canadian data
TBL_Peel_River	Sampling of Peel River spawning population, differences in mesh size, sampling location, etc	Peel River	Arctic Cisco	Jennifer Walker-Larsen
LU_Peel_River_Locs	Approximate sampling locations for Arctic cisco data for Peel River study.	Peel River	Location	Jennifer Walker-Larsen
TBL_PB_Body_Composition	Body composition of Arctic Cisco caught at Prudhoe Bay	Prudhoe Bay, Alaska	Arctic Cisco	LGL Alaska Research Associates Inc.
TBL_PB_Catch	Annual catch by species, year, and station (species totals only in 1998) at Prudhoe Bay	Prudhoe Bay, Alaska	Fishery	LGL Alaska Research Associates Inc.
TBL_PB_CPUE	Daily catch per unit effort by cohort at Prudhoe Bay	Prudhoe Bay, Alaska	Arctic Cisco	LGL Alaska Research Associates Inc.
TBL_PB_Effort	Effort (in days) used for CPUE calculations for Prudhoe Bay data	Prudhoe Bay, Alaska	Arctic Cisco	LGL Alaska Research Associates Inc.
LU_PB_Locs	Station information for linking to other LGL data (by station)	Prudhoe Bay, Alaska	Location	LGL Alaska Research Associates Inc.
LU_PB_Species	List of species, common names, scientific names, Inupiaq names and fish type for linking to other files (by common names)	Prudhoe Bay, Alaska	Species	LGL Alaska Research Associates Inc.
TBL_PB_Temp_Salinity	Temperature and salinity data for Prudhoe Bay from LGL Reports	Prudhoe Bay, Alaska	Water	LGL Alaska Research Associates Inc.
TBL_Weather_Barrow_Hourly	Hourly wind, temperature and precipitation data for Barrow, AK 1973–2004	Barrow, Alaska	Weather	NOAA Climatic Monitoring and Diagnostic Laboratory
TBL_Weather_Barrow_Monthly	Barrow monthly mean, min, and max temperature and precipitation	Northern Alaska	Weather	Western Regional Climate Center
TBL_Weather_Deadhorse_Daily	Daily weather data for Deadhorse AK 70°12'N / 148°29'W	Deadhorse, AK	Weather	NOAA National Data Center
LU_Weather_Locs	Locations of weather data sites.	Various	Location	Various
TBL_Weather_Mackenzie	Monthly weather summaries for the Mackenzie River from Environment Canada	Mackenzie River	Weather	Environment Canada
TBL_Weather_Nuiqsut_Daily	Daily weather data from unmanned NOAA weather station in Nuiqsut, AK	Nuiqsut, Alaska	Weather	NOAA
TBL_Weather_Nuiqsut_Hourly	Hourly Weather data from unmanned NOAA weather station in Nuiqsut, AK	Nuiqsut, Alaska	Weather	NOAA

During the annual monitoring of the subsistence fishery, village catches were sampled daily by Moulton and his colleagues (1985–2005) for species composition, number of fish caught, and fork length to the nearest mm. Fish were examined for tags, fin clips, and dye marks applied by other fish studies in the region. Whenever catch data were collected, set duration, net length, net depth (e.g., the width of the net) and mesh size data also were recorded so that catch per unit effort (CPUE) could be calculated for the net set. Effort was calculated in net days by using start and end dates for each net. Effort data were adjusted for various net lengths and set durations by standardizing net length to 18 m and set duration to 24 h. Nets used in the village fishery normally range from 18 to 30 m in length. Salinity measurements were taken every other day with an YSI 30 temperature/salinity meter at standard locations in three monitoring areas on the Niġliq Channel. Salinity was measured from a vertical profile of the water column at 0.5 m increments.

CPUE in each subsistence fishing area (Figure 3) was estimated by obtaining catch and effort data by mesh size from the fishers. For each mesh size in each fishing area, total observed catch was divided by total observed effort to provide the CPUE estimate. Catch rates for each mesh size by area were then multiplied by total effort estimated for each mesh size/area combination, and estimated catches were summed to provide estimates of total catch. In the village fishery, 76-mm (3 inch) mesh, multifilament nets were the preferred gear. Catch rate indices used for comparisons among areas and years and evaluation of changes in length distributions were based on 76-mm (3 inch) mesh.

Otoliths were obtained from Arctic cisco caught in 76-mm (3 inch) mesh in the commercial fishery to estimate age distribution of the harvest. Otoliths also were obtained from Arctic cisco caught in the subsistence fishery in the Niġliq Channel in 2004. Otoliths were analyzed using the break and burn technique, where the otolith is broken across the transverse axis, held over a flame until the edge begins to discolor, and placed in isopropyl alcohol to be viewed with a dissecting microscope at 30 power. Annuli appear as narrow dark rings between the wider, lighter annual growth bands.

Records of catch and effort have been maintained for the Colville delta commercial fishery since 1967 (summarized in Gallaway et al. 1983, 1989). Effort data were recorded as the beginning and end date of each net set. Catch data are recorded as catch by species for each net whenever nets were checked. Most effort has been with 76-mm monofilament nets, although 83-mm and 89-mm nets also are used to harvest larger fish. Usually the nets are checked daily or every other day, although longer sets are sometimes made. From 1967 to 1986, the fishery records were maintained by Mr. Jim Helmericks. In 1987, a second fishery operation was initiated by Mr. Harmon (Bud) Helmericks. Data from 1987 to 1991 contain estimates of the effort and catch for both operations. In 1992, the fishery reverted to a single operation. These data were converted to catch rates (CPUE) by dividing total season harvest by total effort expended.

PRUDHOE BAY AND ENDICOTT

Fisheries studies have been conducted in the Prudhoe Bay area since the late 1970s as part of several oil development projects in that region, particularly the Prudhoe Bay Waterflood and the Endicott Development projects. The Prudhoe Bay Waterflood studies evaluated the effects on the marine and terrestrial environment of the waterflood pipeline, the seawater plant, and the supporting causeway constructed on the western side of Prudhoe Bay in 1981 (Figure 1). This project provides water to the oilfields for reinjection down wells to enhance oil production. The causeway was extensively studied to determine its effects on the nearshore hydrology, oceanography, and fish populations. The causeway was breached in 1996 to improve hydrologic conditions in the nearshore environment. Fisheries data collected during the Prudhoe Bay Waterflood project were acquired and some were included in analyses for this study (Table 3).

The Endicott Development Project is located off the Sagavanirktok River delta at the eastern side of Prudhoe Bay (Figure 1). The development includes two artificial drilling islands in the Beaufort Sea that are connected to the mainland by a gravel causeway. The causeway currently has three breaches; one breach was part of the initial construction in 1986, a second was added in 1987, and a third was added in 1996. Fisheries studies supported by BP Exploration (Alaska), Inc. and its predecessors were conducted before and during construction, and post-construction monitoring has continued through 2007 (see Fechhelm et al. 2006 for an overview of these studies). Data from these studies were gleaned from hard-copy reports (Table 3) and are included in analyses for this study.

ARCTIC NATIONAL WILDLIFE REFUGE AND CANADA

In the Arctic National Wildlife Refuge (ANWR), fish populations (including Arctic cisco) have been evaluated since 1988 in the nearshore waters (sampling via fyke nets) by Tevis Underwood (USFWS). Data from this fisheries study were incorporated into the database used for the Arctic cisco analyses. Some additional data on Arctic cisco were obtained from a fisheries study at the Peel River, Northwest Territories, Canada (see VanGerwen-Toyne and Walker-Larsen 2004).

ENVIRONMENTAL AND WEATHER DATA

Environmental and weather data were acquired from various sources and added to the Access database. Environmental data acquired for this project contained information on large-scale environmental variables that may influence life-history parameters of Arctic cisco (Table 3; Appendix B). Many of these datasets are based on modeling of variables over large spatial extents. The environmental data incorporated into the database includes information on sea surface temperatures, sea ice cover, modeled wind speed and direction, ocean transport, the Arctic oscillation, and river breakup and discharge.

Weather data were acquired for Nuiqsut, Barrow, and Deadhorse in Alaska, and Tuktoyaktuk and Inuvik along the Mackenzie River in Canada (Table 3). Although weather data of varying quality are available for a number of locations in northern Alaska and the Yukon, these selected datasets covered the longest time span and represented the available weather data most relevant to the life-history characteristics of Arctic cisco .

HUMAN ACTIVITIES DATA

Human activities associated with oil and gas development in the nearshore and offshore Beaufort Sea and the Colville delta have the potential to affect Arctic cisco during critical life-history stages. These life-history stages (the relevant human disturbance) include: (1) the migration of juveniles (e.g., offshore seismic activity), (2) feeding and growth of juveniles and subadults in the nearshore areas (e.g., offshore drilling activities), and (3) over-wintering in the Colville delta (e.g., channel crossings by ice bridges, drilling). To evaluate human disturbance levels, we compiled a comprehensive database of activities related to oil and gas development in the Beaufort Sea and the Colville delta. The greatest volume of information was obtained by accessing online websites of the Mineral Management Service (MMS), and the State of Alaska Department of Natural Resources Division of Oil and Gas (websites are listed in the Data Manual [Appendix B: p.B-13]). Data were downloaded from these sites and incorporated into Excel spreadsheets; relevant components were then extracted either for inclusion directly into data analyses or to construct indices. All activities (e.g., drilling, construction) that took place directly on the Alaska Beaufort Sea shoreline, and in nearshore and offshore locations were incorporated in the database files. Information on the timing and location of ice roads and other associated construction activities on, and in the vicinity of, the Colville delta were provided by CPAI. These sources include most of the activities that occurred in the areas of interest, although the dates (in some cases, years) of the activity were not always available. Additional information also was gathered from an extensive compilation of human activities in the Alaskan Beaufort Sea prepared for MMS (Wainwright 2002).

Human activities were summarized by area and season. The broad geographic divisions consisted of three coastal sections (Figure 4):

- East—from the Canadian border to, and including, the Sagavanirktok River delta
- Central—between the Sagavanirktok River delta (Heald Point) and Oliktok Point (east of the Colville delta)
- West—between Oliktok Point and Cape Halkett (encompassing the Colville delta).

These sections were chosen to examine potential effects of development on Arctic cisco during the westward migration of juveniles from the Mackenzie River to Prudhoe Bay in the open water season, during the summer feeding season in the western Beaufort Sea (West and Central regions combined), and during the over-wintering season in the Colville delta.

ACCESS DATABASE AND DATA MANUAL

The Microsoft Access relational database prepared for this project incorporates all sources of data identified as pertinent to data exploration and hypothesis testing (Table 3). The Data Manual (Appendix B) for the Access database describes data structures, data formats, tabular structures and variables, and sufficient detail for new users to both use the existing data files and to add data as needed.

The Access database is comprised of existing biotic and abiotic multidisciplinary data relevant to Arctic cisco abundance in the Colville River. The database included data from fisheries research conducted on the Colville delta, in the Arctic National Wildlife Refuge (ANWR), in Prudhoe Bay, and in the Peel River, Canada, as well as oilfield-related development activities, oceanographic, hydrographic, and weather data. Currently, the Access database has 33 data tables that include these data types (Table 3). Original data were collected from the various sources and reorganized into formats suitable for entry into an Access database and, whenever possible, similar tables were combined into a single larger data table. When location or species information was repeated multiple times in different places in the database, it was incorporated into a lookup table that was linked to the species or location code in the original data table. The Access database currently has 12 lookup tables.

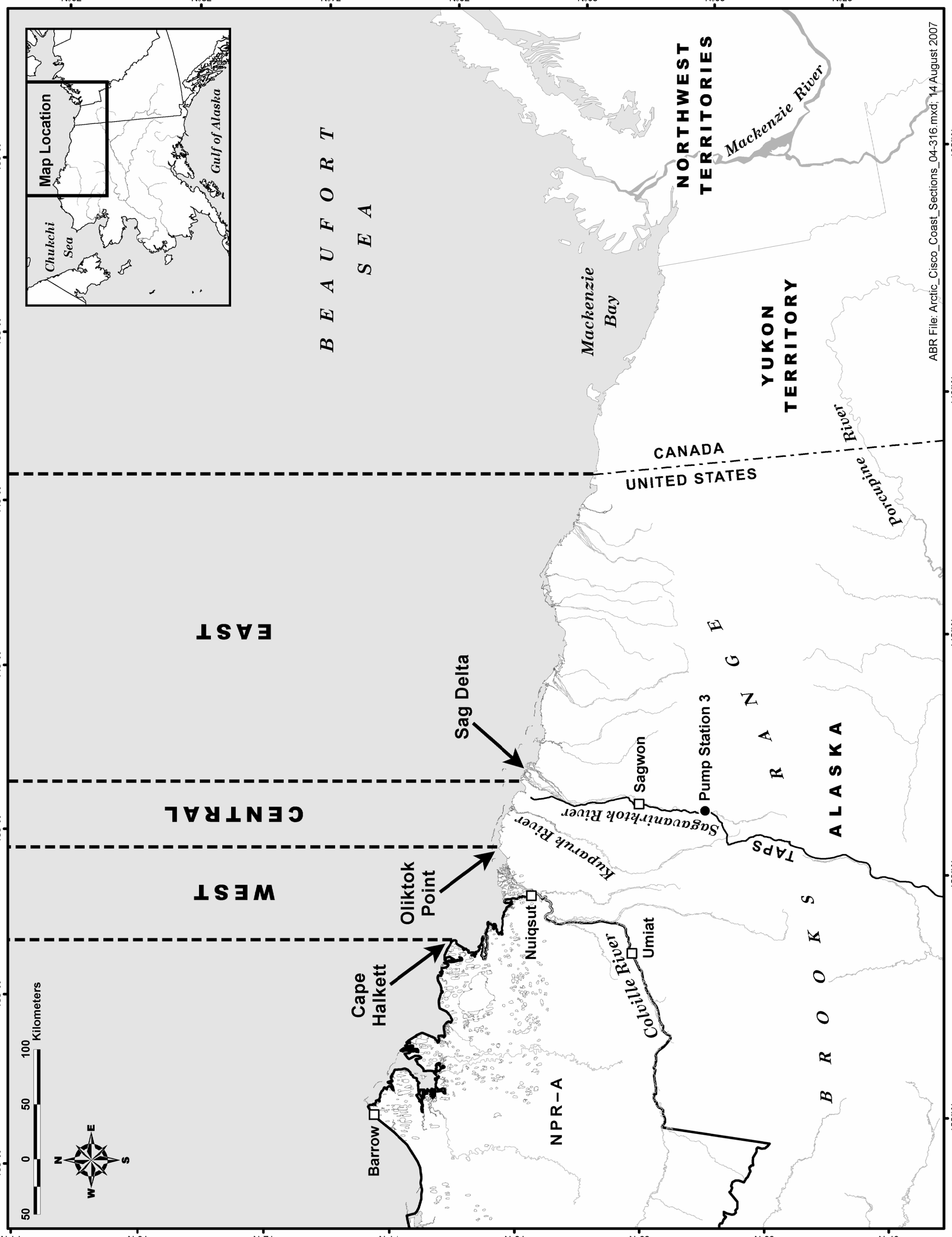


Figure 4. Central Beaufort Sea region depicting geographic boundaries used to classify offshore oil and gas exploration and development activity.

The Access database contains raw data used in the analyses of Arctic cisco in the Colville delta. A number of biotic and abiotic indices were developed based on these data and, in most cases, these indices and not the raw data were used in the analyses (see Chapter 4–Data Exploration).

The Data Manual (Appendix B) describes the seven themes used in the Access database, which were based on the different fisheries research projects (ANWR, Colville, Prudhoe Bay, and Peel River) or different types of data (Development, Environmental, and Weather):

- ANWR—Fisheries data collected during research conducted by the U.S. Fish and Wildlife (USFWS) in the Arctic National Wildlife Refuge (ANWR) conducted during 1988–1991.
- Colville—Fisheries data collected during ongoing research conducted by MJM Research on the Colville delta, Alaska. This includes Arctic Cisco catch by subsistence and commercial fisheries.
- Development—A summary of human activities related to oil development between the Canadian Border and Cape Halkett that may affect Arctic cisco.
- Environmental—Environmental data from various sources, including oceanographic and hydrographic data.
- Peel River—Fisheries data collected during research conducted on the Peel River, Canada, 1998–2002.
- Prudhoe Bay—Fisheries data collected during research conducted by LGL Research in Prudhoe Bay, Alaska.
- Weather—Various weather-related data sets. Including temperature and wind data from Deadhorse, Barrow, Nuiqsut, and the Mackenzie River.

The Data Manual includes detailed metadata about each table including the data source, locations, time period, relevant citations, and an assessment of any relevant data quality issues. The manual also includes descriptions of each data field included in the table. The relationship diagrams and data dictionary provided in the manual describe relationships among different tables within a theme (Appendix B).

3. VALIDATING INTERPRETATIONS—THE PANEL OF EXPERTS

INTRODUCTION

An important component of this project was the integration of scientific findings (western science) with traditional ecological knowledge (TEK). Understanding the appropriate approach to this integration required a conceptual understanding of both perspectives, and it also required an effective operational plan to facilitate communication, exchange ideas at the appropriate technical level, and, most importantly, to move the dialogue and action plans forward in the context of project objectives. A challenging aspect of the project was for the study team to work closely with the residents of Nuiqsut to seek validation of the interpretations advanced by the scientific team. It was not a viable strategy for the scientific team to simply show up in Nuiqsut and expect residents and village leaders to attend meetings and actively participate in accomplishing project objectives they had little familiarity with or stake in. Instead, the study team sought to formally include the community in the project and to create ownership in this project for Nuiqsut. Toward this goal, the Kuukpik Subsistence Oversight Panel, Inc. (KSOPI) was invited to be part of the study team. KSOPI was formed in the early 1990s in response to community concerns about the effects of Alpine Oil Development on subsistence resources. The panel is tasked with reviewing research being conducted near the community and frequently interacts with scientists. KSOPI agreed to join the study team and to help implement and sustain a successful dialogue between the scientists and the community throughout the study.

METHODS

IDENTIFICATION AND SELECTION OF PANEL PARTICIPANTS

The method of integrating the community into the project and validating the scientific interpretations was to choose a local panel of Nuiqsut experts (hereafter Panel of Experts) who were (1) especially experienced and knowledgeable about Arctic cisco (*qaaktaq*), who were (2) willing to work together and with scientists to explore the reasons for variability in *qaaktaq* abundance, and who were (3) able to attend the periodic workshops and meetings while the scientists were in the community. Toward this goal, social network methods were used to identify knowledgeable panel members and to ensure credibility and objectivity.

In overview, the study team used the social network method to identify knowledgeable and experienced subsistence persons, went to those persons and asked them to identify other knowledgeable persons, and worked to repeat this process until no new potential participants were named by peers. After identifying the larger list of potential *qaaktaq* experts, the method called for the study team, including KSOPI, to review the list, analyze the frequency of nominations, discuss the most highly recommended and knowledgeable persons, and to select 5 to 10 persons to serve on the Panel of Experts. Participants would be asked to join the panel only after the study team explained the project and the participants' roles on the panel.

Nomination Interviews

The cultural expert on the study team (Stephen R. Braund & Associates) began the nomination or referral interviews with the seven members of the KSOPI board plus the Executive Director. These persons mostly were experienced members of the subsistence community and represented a reasonable starting point for the interviews. The main objective of these interviews was to seek names of people with knowledge of the *qaaktaq* fishery. The following was conveyed to each person:

> We are working with KSOPI on an MMS-sponsored study with the objectives of gathering information from the residents of Nuiqsut of what factors are influencing Arctic cisco populations and to use this information and existing data from studies conducted on the Colville delta, near Prudhoe Bay, and at the McKenzie River to develop new theories on Arctic cisco that are supported by both traditional knowledge and western science. What makes this study unique is that the scientists are going to be guided by a Panel of Experts from Nuiqsut. The panel will be asked to interpret the results of the scientist's findings and to offer their own theories on what factors may be affecting Arctic cisco and harvest levels. We need your help in selecting local people to serve on this panel. Who are the most knowledgeable Arctic cisco harvesters in Nuiqsut who could serve on a Panel of Experts to work with scientists to explore the reasons for the changes in abundance of Arctic cisco?

This text was not recited verbatim because the interviews were more informal, but these points were covered in each discussion and explanation of the project. In addition, the study team member conducting these informal interviews indicated that the information and names provided by each person would be treated as confidential, and that the names of persons nominated would not be included in this report (except the selected panel members). In addition, the names of the persons that the interviewees nominated would not be attributed to them in any subsequent report. The study team explained they would use the nominations to measure frequencies of how many times persons were named as a part of the effort to select a knowledgeable, participatory, and locally chosen panel. Finally, the study team conveyed to participants that only aggregated information would be reported. During the nomination interviews, KSOPI members of the study team provided assistance by translating for residents when needed.

The study team interviewed seven of the eight KSOPI board members; one member was unavailable. Next, the study team systematically attempted to interview all of the persons identified by those seven persons, and continued this process until no new potential participants were named by peers. A total of 35 persons were interviewed and/or nominated. Of those, the study team interviewed 25 persons. The 10 (of 35) persons not interviewed included 4 persons who were out of town, 3 persons who declined to participate (including not participating on the panel if chosen), 1 person with a death in the family, and 2 persons the team was unable to locate.

Panel Selection

Thirty-four persons were nominated and received from 1 to 20 nominations (Table 4). A 35th person provided nominations, but did not receive any nominations. MMS recommended forming a panel of 5 to 10 members; hence the study team sought to enlist 7 to 8 panel members from the first 15 persons on the list. As a final step in the selection process, KSOPI study team members reviewed the list of 34 nominees and the number of nominations each received (see "Person Code" and "Number of Nominations" columns in Table 4). The criteria for selection KSOPI study team members used in their review included not only the frequency of nominations, but also the availability, willingness to participate, and time constraints of each of the nominees.

Table 4. Number of nominations and final committee members for the Kuukpik Subsistence Oversight Panel, Inc. (KSOPI).

	List of Persons (by code) and number of nominations		List of persons KSOPI indicated had agreed to be on the panel
	Person Code	Number of Nominations	
1	JJ	20	JJ
2	O	9	
3	U	9	U
4	BB	9	
5	S	8	S
6	F	7	F
7	P	7	P
8	D	6	
9	R	6	
10	H	5	
11	K	5	K
12	X	5	
13	Z	5	
14	HH	5	HH
15	N	4	
16	V	4	
17	CC	4	
18	I	3	
19	Q	3	
20	A	2	A
21	B	2	
22	C	2	C
23	E	2	
24	G	2	
25	J	2	
26	M	2	
27	T	2	
28	L	1	
29	W	1	
30	Y	1	
31	AA	1	AA
32	EE	1	
33	FF	1	
34	GG	1	
35	DD	0	

KSOPI, located in Nuiqsut and comprised of Nuiqsut subsistence experts, was in a position to knowledgeably apply these criteria. KSOPI study team members provided a list of 10 persons for the panel, including 7 names from the first 14 persons and 3 names from the remainder of the list. Hence, KSOPI suggested 10 panel members, including 7 from the top 15 nominations as instructed and 3 who had only one to two nominations.

Reviewing the three persons with fewer nominations suggested by KSOPI revealed that two of these persons were important and respected elders in Nuiqsut. The third person was a member of an active subsistence family in Nuiqsut. Although this person was lower on the list than some other nominees who were not selected, he/she was a member of the same family as the #13 nomination (with the same nomination frequency as #10).

In subsequent discussions, the study team considered the size of the panel (7 or 8 persons versus 10) and concluded that enlisting 10 members had several benefits. First, an important part of the project was to involve the local community and be respectful of their views. Because the local KSOPI study team members had recommended 10 panel members, it was appropriate to respect that recommendation. Furthermore, gaining local participation was a major challenge and goal for the project. Having the maximum 10 members enhanced local participation in the project and ensured greater minimum participation at meetings. The selection of a larger initial group resulted in a greater pool of members to attend meetings and, indeed, at least five panel members were in attendance at each of the four panel meetings.

The study team conducted a social network analysis in order to determine who among the nominees would be good candidates for participation on the Panel of Experts. The study team enlisted a social network specialist to prepare graphical representations of the social network process (Figures 5 and 6).

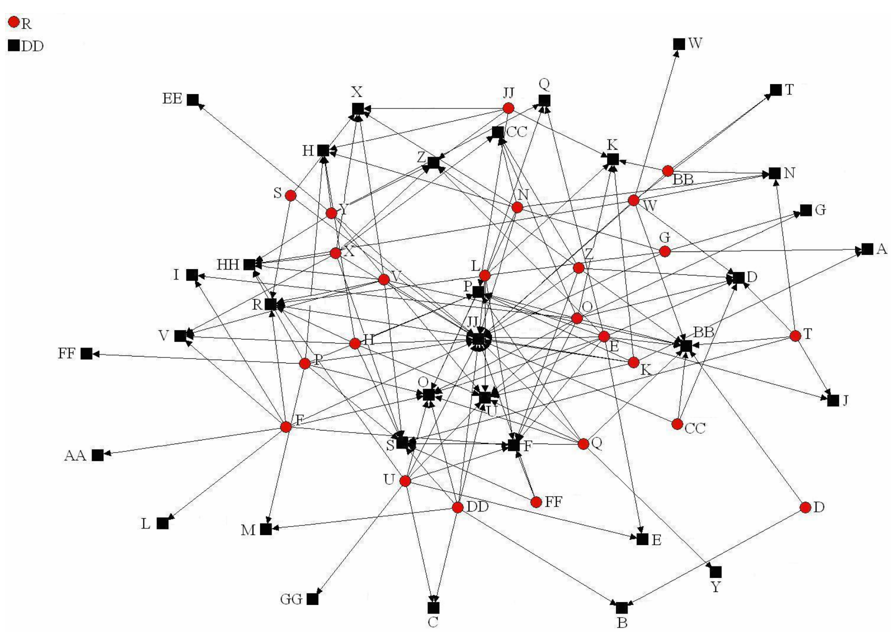


Figure 5. Social network analysis for panel selection. Nominators are depicted by circles and nominees are depicted by squares. Stephen R. Braund & Associates, 2006.

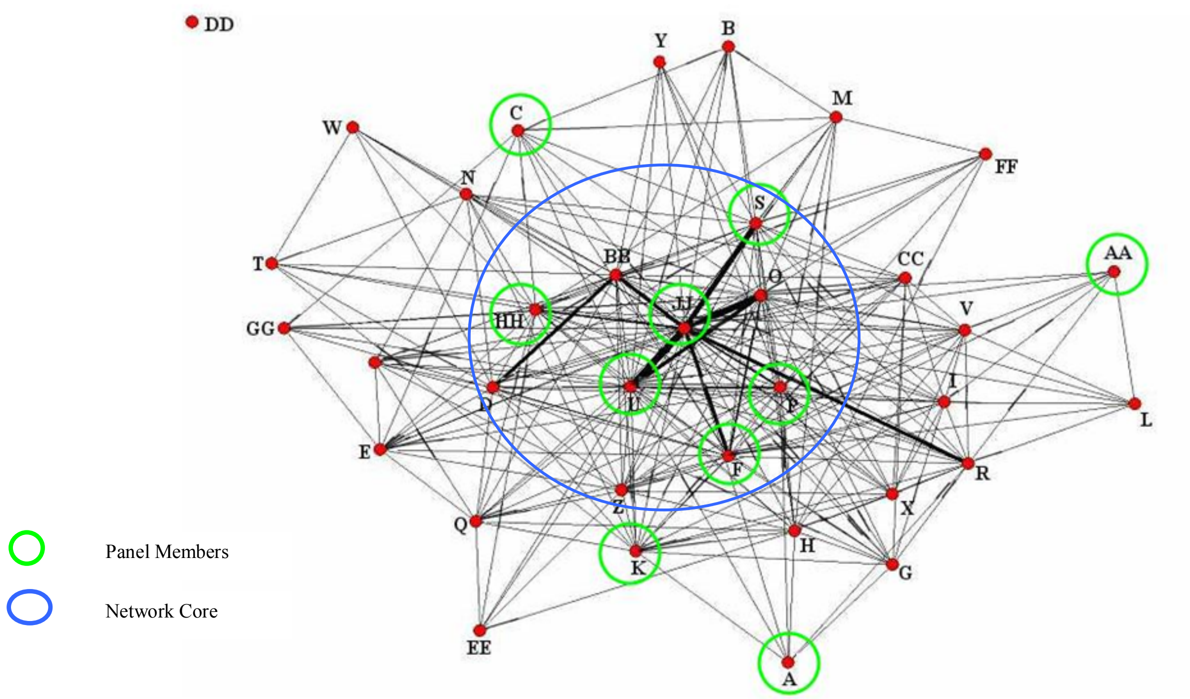


Figure 6. Affiliations among nominees based on nominators with line size a function of the number of co-occurrences (the thicker the line the stronger the affiliation). Selected panel members are depicted by the green circles (note: criteria other than this analysis were used to select panel members). Stephen R. Braund & Associates 2006.

Figure 5 shows the 25 nominators (circles), the 34 nominees (squares), and the multiple nominations for various persons and who made the nominations. Figure 6 depicts the affiliations among the nominees vis-à-vis the nominators, with line size a function of the number of co-occurrences (e.g., the thicker the line the stronger the affiliation). In this case, "affiliation" refers to nominees' relationships based on the number of common nominators between two nominees (e.g., B nominated both T and J, so a line exists between T and J). The figure shows linkages between nominees who have mutual nominators (this is their "affiliation"); the higher the number of common nominators between two individuals, the thicker the line. In other words, the graph shows the structure of relationships among nominations received based on the nominators. People in the middle of the graph were good candidates for inclusion on the panel because they are in the "core" of the social network. These individuals are in the "core" because they have strong affiliations with others in the network. These affiliations, as discussed above, are based on the number of mutual nominators among nominees. The purpose of a social network analysis is to identify not only individuals with high frequencies of nominations, but to identify how people in the core are connected within the social network, based on who they nominate and who nominates them. This ensures that not only highly nominated individuals in a single branch of the network are selected, but that a broad spectrum of the social network is represented. Thus, individuals who are good candidates for the panel might include “R” because that person is connected to both the core and to individuals on the periphery. Clearly, “JJ” also is very important, as are the people with whom he/she has a strong affiliation.

Figure 6 also shows the panel members depicted with a circle. Both Table 4 and Figure 6 show that the panel members reasonably represented people who were most nominated and those who were in the core of the network. In some cases, persons with a high number of nominations, as well as being in the core of the figures, were not included in the panel due to other considerations.

Identifying who is knowledgeable was only a part of the process of selecting the panel. It also was necessary to have people on the committee who were amenable to serving on the committee, who had the time to participate, who were willing to contribute, who were able to express their knowledge in the panel/workshop setting, and who would work well with other panel members. The first criterion related to whether they were qualified. The second set of criteria addressed whether potential panel members had the characteristics required to be a successful panel member. KSOPI study team members were in a position to consider these other characteristics.

As can be seen in Figure 6, the panel included 6 of 10 (60%) core nominees plus additional persons who were included for other reasons, including elders, those who may work best together, those who will participate and contribute in the panel discussions, and other community considerations. KSOPI had information on the persons most frequently nominated and most central in the core, and they took into account all of these other considerations necessary to have the appropriate, qualified people who would successfully serve on the panel.

After analysis of the social-networking data and consideration of recommendations and advice from KSOPI, the following residents were selected to be on the Panel of Experts:

1. Joeb Woods, Sr.
2. Dora Nukapigak
3. Gordon Matumeak
4. Gordon Brown
5. Robert Lampe, Sr.
6. Bernice Kaigelak
7. Sam Tukle
8. Archie Ahkiviana
9. Marjorie Ahnupkana
10. Frank Oyagak, Jr.

DEVELOPMENT OF THE INDEPENDENT PANEL REPORT

MMS stipulated that the Panel of Experts should produce an independent report that would include a summary of activities, recommendations provided to the scientific team, a discussion of where they felt their input was most valuable, and an overview of strengths and weaknesses of the process. To facilitate the preparation of this report, the study team distributed a "Summary Report of Technical Findings" and a "*Qaaktaq* Results Summary & Questionnaire" (Appendix C) to each attending panel member at the final panel meeting in Nuiqsut in February 2007. The results of the questionnaire were then used to prepare the panel's independent report. Leonard Lampe Sr. of Nuiqsut was retained to take the lead in drafting the panel's report. Mr. Lampe met with study team members several times between April 27 and May 1.

During the first meeting, Mr. Lampe reviewed the meeting minutes from each of the panel meetings (Appendix D) and the "Summary Report of Technical Findings" report and "*Qaaktaq* Results Summary & Questionnaire" that were prepared by the study team for the February 2007 meeting. Panel members completed the questionnaire at the February 2007 meeting. Study team members then provided Mr. Lampe with a basic outline for the Panel of Experts Report. Mr. Lampe provided content both verbally, with study team members taking notes, and in written form.

During the second meeting, study team members worked with Mr. Lampe to organize the report and to ensure that individual panel members' views were incorporated, including the results from the "*Qaaktaq* Results Summary & Questionnaire" (Appendix C). The text that Mr. Lampe provided was organized under topic headings and edited.

Mr. Lampe reviewed the draft report during the third meeting and made further recommendations about the organization and content of the report. The study team produced and printed multiple copies of the final version of the report at this time and gave them to Mr. Lampe for distribution among the panel members.

To ensure that all panel members received a copy of the panel report for their review and comment, study team members mailed each panel member a copy of the report. A self-addressed postage paid envelope was included for panel members to provide any written comments and/or edits on the report. Panel members also were invited to call with any comments. No responses were received from panel members regarding the panel report.

RESULTS

One public meeting and four panel meetings were held in Nuiqsut between March 2005 and February 2007. The purpose of each meeting and a summary of the proceedings are presented below. The descriptions and quotes provided under the meeting summaries were derived from notes taken by Stephen Braund during each of the four panel meetings. KSOPI also maintained separate meeting minutes for several of the meetings (Appendix D).

Attendance at panel meetings by panel members is depicted in Table 5. Panel member P, the fifth most nominated individual on the Panel of Experts with seven nominations, was the only member to attend all four meetings. Those members who attended three of the four meetings were JJ (20 nominations), U (9 nominations), S (8 nominations), F (7 nominations), and C (2 nominations). Table 5 indicates that those with higher numbers of nominations had higher participation rates. However, panel member C, who had only two nominations, attended three of the four meetings. This panel member was among the three members identified by KSOPI outside of the top 15 nominees and is a respected elder in the community.

Table 5. Meeting attendance by the Panel of Experts.

	Attended Meeting (Y/N)			
Panel Member	Panel Meeting No.1	Panel Meeting No. 2	Panel Meeting No.3	Panel Meeting No.4
JJ	Y	N	Y	Y
U	Y	N	Y	Y
S	Y	Y	Y	N
F	Y	Y	N	Y
P	Y	Y	Y	Y
K	Y	N	N	N
HH	Y	Y	N	N
A	Y	Y	N	N
C	Y	Y	Y	N
AA	N	N	N	Y
Total in Attendance:	9	6	5	5

PUBLIC MEETING AND PANEL SELECTION (22–25 MARCH 2005)

Steve Murphy (ABR, Inc.) and Stephen Braund (SRB&A) traveled to Nuiqsut to (1) meet with KSOPI team members, (2) conduct a meeting with the community to introduce the project and the concept and role of the Panel of Experts, and (3) to initiate the social networking process so that the panel could be selected. The meetings with KSOPI went well but the community meeting was poorly attended because of harsh weather (high winds) and the observances due to the death of an elder. At the community meeting, Steve Murphy presented an overview of the project and Stephen Braund described the panel selection process. Stephen Braund stayed in Nuiqsut for two additional days to acquire nominations necessary to conduct the analysis used to select panel members. There was a paid translator present for this meeting who translated as needed.

PANEL MEETING NO. 1 (27–28 JUNE 2005)

Steve Murphy, Stephen Braund, and Larry Moulton (MJM Research) met with the Panel of Experts in Nuiqsut on 27–28 June 2005. Nine panel members were present: Joeb Woods, Sr.; Dora Nukapigak; Gordon Matumeak; Gordon Brown; Robert Lampe, Sr.; Bernice Kaigelak; Sam Tukle; Archie Ahkiviana; and Marjorie Ahnupkana (Table 5). There was a paid translator present for this meeting who translated as needed.

The objectives of the first meeting of the Panel of Experts were to (1) introduce the project and describe the anticipated role of the panel, (2) review the proceedings of the *qaaktaq* workshop held in Nuiqsut in November 2003, (3) to solicit input from the panel on their theories on what natural and anthropogenic factors influence the distribution and abundance of *qaaktaq*, and (4) to acquire any data or records that the subsistence fishers might have that would help the scientists' analyses. The following questions were asked of the panel:

1. What are the reasons for *qaaktaq* changes in abundance?
2. What causes decreases in the number of *qaaktaq*?
3. What causes increases?
4. What are the sources of data to explain these changes?

To facilitate the discussion, Stephen Braund listed the factors potentially impacting *qaaktaq* identified by scientists and/or Iñupiat experts at the 2003 meeting. Panel members were asked whether they agreed with the factors identified in 2003 and whether they had any data or records that support their theories.

The following is a distillation of their responses. In addition to identifying agents of change, the panel also offered opinions on the nature of the effects, which go well beyond changes in abundance. All of the effects listed below are not independent (e.g., energetic stress and condition of the fish likely are related), but this list represents what was offered by the panel.

- Fewer fish available to subsistence fishery.
- Reduced size and/or weight of fish.
- Changes in distribution of fish in the Colville River.
- Changes in quality of fish (taste, texture, color).
- Deformed fish.
- Food chain effects (i.e., changes in prey availability and prey types).
- Energetic stress (e.g., cost of navigating obstructions).

Panel members discussed changes and variability in *qaaktaq*, particularly in their abundance, size, quality, and distribution. Regarding *qaaktaq* abundance, participants discussed yearly variations and several pointed out especially low harvest years. In 1999, for example, panel members indicated that they caught few fish; one observed that this was the first year after horizontal drilling under the main Colville River channel began. They also identified various other factors that they perceived to have an effect on *qaaktaq* numbers; these are discussed in further detail below, under "Potential Human Influences" and "Potential Natural Influences."

Panel members also commented that there have been changes in the size, health, and quality of *qaaktaq*. Several mentioned that the fish have been "skinnier," with one observing, "They are skinny now; not as fat." While discussing their skinnier appearance, one individual described a possible link to energetic stress caused by obstructions, saying, "They could be affected by energy spent. Maybe they get here and get through the causeways, but it requires energy and they have less fat." Two panel members also observed that access to food may have declined:

> Food for *qaaktaq* is less. They used to have shrimp in their stomach in the past; now it is like they are eating mud.

> There are little fish that are good for *qaaktaq* that discharge out of the Colville River– ice bridges are blocking them in.

Some panel members also reported changes in the taste and appearance of *qaaktaq*. One elder, who was not a panel member but attended the meeting, provided this observation:

> In the 1970s [the] fish were healthy and you could cook all of those fish and [the] taste was good most the time; now, the fish has changed, the taste has changed; even the fresh fish they catch today tastes like it has been in the freezer for a long time, freezer burn.

In addition to changes in *qaaktaq* abundance and physical changes in *qaaktaq*, panel members discussed changes in their distribution in the Colville River and along the shoreline. One panel member stated, "Wherever there is salt, there is *qaaktaq*." He went on to observe that he had once noticed salinity in the Colville River as far as Ocean Point, but not since 1964. Another meeting attendee indicated that warmer temperatures increase the amount of salinity in the Colville River, increasing the availability of *qaaktaq*:

> When the weather is warm, [there is an] overflow from ocean, in July. It changes the fish coming in. [I saw that] in [the] last few years. When the overflow from saltwater is coming in (from a west and southwest wind), it coincides with warm spell of the weather.

Panel members also discussed the decline in *qaaktaq* along the coastal shoreline. Several suggested that the development of the saltwater treatment plant at Oliktok may have caused this change in distribution.

In some cases, panel members clearly stated what he or she thought was both the cause and the effect. In other instances, the causes and effects were discussed separately. One objective of the next meeting was to try to revisit the cause-effect linkages with the panel. This was essential for formulating testable hypotheses.

With respect to causes or influences, it is important to note that the region that the panel discussed was mainly from Oliktok Point (just east of the Colville delta) to Fish Creek (just west of the Colville delta). Consequently, when they discussed the effects of wind direction, for example, they were referring to local winds that influence currents and salinity in the Colville River, and not the wind/juvenile migration issue for the Beaufort Sea. The study team prompted discussions of causeways, which panel members regard as obstructions, but unless prompted, panel members mainly talked about more local developments, such as the saltwater treatment plant (STP) at Oliktok Point, as being problematic. Panel members also frequently made comments about negative influences on the fishery resulting from construction of Drill Site Alpine 2 near the Niġliq channel and the Colville River pipeline crossing or HDD (Horizontal Directional Drilling), which is located upstream of Nuiqsut. Hence, while the study team's purview was to investigate all potential agents of change throughout the range of *qaaktaq*, the perspective of the panel was much more local. It also was striking how often panel members mentioned contaminants from a myriad of sources.

Potential Anthropogenic Influences:

- Obstructions

  – Causeways (specific dates available)
  – Ice bridges (specific dates available)
  – Noise
  – Drilling at Alpine (specific dates available)
  – Offshore drilling (specific dates available)
  – Offshore pipeline construction (specific dates available)
  – Offshore seismic, U.S. and Canadian (specific dates available)

- Vibration

  – Drilling at Alpine (specific dates available)
  – Offshore drilling (specific dates available)
  – Offshore pipeline construction (specific dates available)
  – Offshore seismic, U.S. and Canadian (specific dates available)
  – Horizontal Directional Drilling for Colville River pipeline crossing

- Contaminants

  – Drilling mud from HDD (specific dates available)
  – Drilling mud from Endicott (specific dates available)
  – Abandoned drums (specific dates not available)
  – Abandoned drill sites (specific dates not available)
  – From melting ice bridges and roads
  – Debris falling in river from upstream sites (e.g., Umiat runway, Itkillik)

- Over harvest by fishing

  – Colville River delta (CRD) commercial fishery
  – CRD subsistence fishery
  – McKenzie River subsistence fishery

- Upstream gravel extraction

Panel members discussed perceived human influences on *qaaktaq* abundance, health, quality, and distribution. These influences fell under the following categories: obstructions, vibration, contaminants, over harvesting, and upstream gravel extraction.

While discussing possible obstructions, a number of panel members expressed the belief that causeways have affected *qaaktaq* size, health, abundance, and access to food. One individual observed:

> Before industry came, they [*qaaktaq*] were always healthy: size was larger, the amount of fat was higher. After the causeway, they are smaller, unhealthy, their food is unhealthy; they are eating something different. In the past, they had shrimp in the stomachs, when they were caught before the causeways were built.

Ice bridges were another potential obstruction discussed by panel members. Some thought that the ice roads were blocking *qaaktaq* from winter feeding grounds due to the ice roads being grounded to the bottom of the river:

> Maybe [the change in quality] is related to the ice road. Maybe it's blocking wintering fish feeding grounds, blocking the freedom of movement for wintering fish; they are blocked from the ice road near Spy Island [a barrier island east of the Colville delta; Figure 1]. Most [of the ice road] is grounded.

Panel members also agreed that the offshore or undersea pipelines affect *qaaktaq*; one observed that the pipelines "generate heat" and wondered if changes in water temperature may affect the food chain.

Noise and vibration from industrial activities, including offshore drilling and seismic testing, was also perceived as influencing *qaaktaq* abundance or distribution. One panel member commented, "Drill rigs: our two lowest seasons was when all of that noise was going on over there; I only got two sacks." Another said, "It seems like every time after construction, the number of *qaaktaq* decreases due to noise and vibration from drilling." Panel members likened the effect of seismic testing on fish to seismic testing during the fall whaling season, indicating that the bowhead whales travel farther offshore when these activities take place. One person reported a change in the size of *qaaktaq* due to seismic testing since the late 1960s.

In addition to changes caused by physical obstructions, panel members discussed potential influences caused by contaminants from drilling muds, abandoned drums, drilling rigs, melting ice roads and bridges, and debris falling into the river from upstream sites. One panel member reported seeing oil in his fishing hole several years ago, saying, "I kept seeing oil, a rainbow color, in my [fishing] hole. I only saw that that one year, two to three years ago." Several panel members expressed concern that clean-up crews "take shortcuts" and do not properly reclaim sites once they have been abandoned. Others pointed out specific instances where they observed potential contamination of river or ocean water:

> Contaminants and drums were found in the rivers near the runway. A lot went in our rivers; that could be one factor to review.
>
> The first cat train in the 1940s, from Barrow to Oliktok, they did not open drums with a bung wrench but with an axe; they pumped what they needed and just left them in the river or lake. That was how they worked when they first came here.

> A lot of metal was dumped at the shoreline of Oliktok; there are contaminants at Oliktok. I wonder if they removed that yet.
>
> There are abandoned drums at Anaktuvuk River and Chandler River (still full).

Panel members commented on the possibility that *qaaktaq* are being over harvested by commercial fishing operations or subsistence users. Several agreed that a local commercial fishing operation could have an affect on the numbers of fish available for subsistence harvests. One person observed, “The perceived low abundance may be [that] they [*qaaktaq*] were intercepted [by commercial fishing nets] before they got to our nets.”). Another reported that local residents have had to move their nets to other channels to harvest adequately sized fish.

Panel members generally disagreed that subsistence fishing could influence *qaaktaq* numbers and argued that local subsistence users “only catch what [they] need.”

Potential Natural Influences

During the June 2005 meeting, panel members and attendees also discussed potential natural influences on *qaaktaq* abundance, health, quality, and distribution, and the following topics were discussed.

- River channel changes due to sedimentation and erosion
- Salinity
- Wind
- Slush in the river

Several people commented that changes in the river channels caused by erosion and sedimentation may influence *qaaktaq*, and they observed that erosion has increased over the years. In particular, panel members discussed certain areas where water levels have dropped and thereby have affected *qaaktaq* distribution and harvest locations. One individual said,

> Maybe *qaaktaq* depended on working both rivers; now that it is shallow and we cannot get there with boats, maybe the fish are using the Colville more and there are less fish on our side as we do most of our fishing on Niġliq Channel.

Another individual observed that the islands are also changing and suggested that this may affect the “funneling” of *qaaktaq* through the island openings.

As discussed earlier, panel members indicated that *qaaktaq* are found along the Colville River only as far as there is salinity in the water. They discussed wind and current conditions that affect salinity in the river and agreed that a west wind increases salinity. One individual said that the “west wind blows and pushes water in [from the ocean], and saline increases.” One elder, who was not a member of the panel but was in attendance at the meeting, commented that it has not always been this way. She observed,

> In older days, with a west wind [we] hardly caught any fish, but today we catch most fish [in a west wind]. In the past, the west wind used to push fish out, whereas today, we depend on the west wind to push the fish in.

Another natural influence discussed by panel members was that of the presence of slush in the Colville River. Participants indicated that slushy ice is pushed toward the mouth of the river during a west wind, blocking the *qaaktaq*. One panel member described,

> When it snows before it freezes, it causes slush to block the mouth of the river; we move [our] nets; the current pushes the slush toward mouth, the mouth is shallow; it leaves snow at the mouth of river when the wind comes from the west.

Another person commented that "slush means a 'delay' for catching *qaaktaq*."

PANEL MEETING NO. 2 (NOVEMBER 2005)

Steve Murphy, Stephen Braund, Franz Mueter (Sigma Plus, Statistical Services), Larry Moulton, and Kate Wedemeyer (MMS) met with the Panel of Experts on 8–9 November 2005. This meeting was the second with the panel, and the main objectives of the meeting were to (1) review and confirm accuracy of the study team's interpretation of comments and information supplied by the panel at the first meeting, (2) review results of analyses to date, and (3) redirect the analyses based on additional input from the panel. KSOPI members of the study team, in addition to members of the Panel of Experts, helped translate for panel members as needed during this and subsequent meetings.

Panel members in attendance included: Gordon Matumeak; Gordon Brown; Robert Lampe, Sr.; Archie Ahkiviana; and Marjorie Ahnupkana (Table 5). Leonard Lampe, Sr., of Nuiqsut also attended the meeting.

Franz Mueter provided an overview to the Panel on the preliminary analytical results, with an emphasis on environmental and fisheries data. Preliminary results from an analysis of causeway effects also were presented.

Based on feedback from the panel, several new hypotheses regarding human impacts on *qaaktaq* migration, growth, and survival were identified. Panel members identified the following additional human activities that could affect *qaaktaq* abundance and distribution:

- Construction of causeways changing sediment patterns.
- Construction of causeways creating more turbid water and affecting animal distribution.
- Pumping streams and lake water for ice roads changing fish habitat.

One panel member expressed that there have been changes in the nearshore environment west of the causeways in Prudhoe Bay. He/she hypothesized that the causeways had caused changes in deposition patterns, and that shallower and more turbid water had changed the distribution of seals and, perhaps, *qaaktaq*.

Meeting participants (panel members and other local residents attending) also discussed the possibility that pumping water out of streams and rivers for ice roads and bridges has an effect on *qaaktaq* habitat by changing water levels and temperatures. One individual said,

> What about pumping millions of gallons of water out of streams that cisco depend on for oxygen and habitat? If [there is] no oxygen or a place to spawn, that is different from what they know; they will not go there anymore. When you extract thousands of gallons of water, it changes the temperature of those streams or lakes.

A panel member added that companies are "over pumping the lakes, taking more than what they should."

Other topics that were mentioned during the June 2005 meeting were discussed in further detail during November. One meeting attendee, for example, commented on the potential influences of ice bridges on *qaaktaq* abundance and quality. He commented that the ice bridges go "to the bottom of the river and form a wall" and wondered if that could affect water temperature and flow in the Colville River. Panel members and meeting attendees also discussed the possibility of ice roads blocking *qaaktaq* and altering their distribution within the Colville and Niġliq channels.

Panel members also responded to some of the preliminary results presented by Franz Mueter. In particular, participants discussed the findings related to the influences of causeways on *qaaktaq*. Preliminary results showed no relationship between the causeways and *qaaktaq* abundance. Panel members suggested that while the effects of the causeways may not be immediate, there still may have been long-term effects on the *qaaktaq* from the construction of the causeways.

One panel member also emphasized that he would like to see studies on the effects of saltwater treatment plants on *qaaktaq*.

PANEL MEETING NO. 3 (OCTOBER 2006)

Steve Murphy, Stephen Braund, Franz Mueter, and John Seigle (ABR, Inc.) met with the Panel of Experts on 19–20 October 2006. This meeting was the third with the Panel, and the main objective of the meeting was to review results of analyses to date, with an emphasis on the analysis of anthropogenic factors that might be influencing *qaaktaq* distribution, abundance, or quality.

Panel members in attendance included: Joeb Woods, Sr.; Dora Nukapigak; Gordon Matumeak; Robert Lampe, Sr.; and Marjorie Ahnupkana (Table 5). The study team also had a separate meeting with Leonard Lampe, Sr., after the panel meeting to discuss the panel report to MMS.

During the meeting, panel members again expressed their disagreement with findings over the effects of causeways on *qaaktaq*, and one individual commented that the elders still believed the causeway to have an effect on the availability of *qaaktaq* to Nuiqsut residents. One said,

> At the last meetings with the elders, they did note that when the causeways at Endicott and West Dock were put in, it affected their fishing, the village's fishing and Niġliq [Channel] fishing.

Panel members also brought up the issue of saltwater treatment plants, with one individual saying, "Any studies on salt water treatment? There are 2.5 million gallons of water pumped out of the ocean—something is going on."

Other topics of discussion during the third panel meeting included the effects of salinity on catch rates, seismic testing and drilling noises, and ice bridges. Regarding salinity and *qaaktaq* availability, one panel member observed that west winds cause currents that increase salinity in the Colville River. She indicated that, last year, fishermen kept track of salinity at their fishing sites; these residents observed that there was less salinity in areas where the water was warmer.

A substantial portion of the meeting was spent talking about the potential effects of seismic and drilling activities on *qaaktaq* and the need for further studies. One elder panel member described his experiences observing these effects on a nearby lake, saying, "Oil companies turn on seismic and fish always go away. When they turn it off, the fish come back." He later went on to describe a similar occurrence near the Kuparuk River:

> At Kuparuk with [friend], when they did a study on lake with seismic vibration, the fish went away. Some actually died from that. It was an experiment they did.

Another panel member expressed the need to obtain specific data about the dates of drilling and seismic activities by oil companies, and compare this data with catch rates. She said,

> Go to Conoco, get the days they drilled, and overlap that with catch rates. The days where they drill and the days they do not drill. Can you get those data from the past? Tell us how intense your drilling is every day and where it occurs and we want that compared to our daily fish catch.

She added that when she and other community residents are fishing for *qaaktaq* during October, they can hear vibrations on the river caused by oil company drilling operations.

Panel members also discussed with the attending scientists the need for additional studies regarding the effects of ice bridges on *qaaktaq*. One panel member recalled recent studies conducted near Colville Crossing [located on the Colville River south of Nuiqsut], and suggested that these data be acquired for use in this study. An elder explained that when the ice bridges become grounded, "the ice will start seeping on the sides."

Attending scientists asked the panel members what they had observed during the most recent fishing season, and what net sizes they were using. One elder reported that the fish were skinnier than usual. In discussing the low catch rates reported in 2001, several panel members remembered that there had been high amounts of slushy ice that year. One observed, "We had a blockage with a lot of slush. It kept [the] water from coming in."

PANEL MEETING NO. 4 (FEBRUARY 2007)

Steve Murphy and Stephen Braund met with the Panel of Experts on 31 January and 1 February 2007. Panel members in attendance included: Joeb Woods, Sr., Dora Nukapigak, Gordon Brown, Robert Lampe, Sr., and Frank Oyagak, Jr (Table 5). The main objectives of this meeting were (1) to present the panel a synoptic report of the analytical findings and interpretations (Appendix C); (2) to solicit input from the panel regarding whether they understood the findings, whether they thought the findings and interpretations were valid, and whether they thought the engagement of the panel and meetings with the scientists were successful; and (3) to facilitate the production of the panel's report to MMS. During the meeting, panel members responded to the report findings, asked for clarification of some of the findings, and reviewed some of their observations about *qaaktaq* changes, including elders' comments on changes in *qaaktaq* quality.

Meeting attendees discussed the need to involve Canadian scientists and Native groups in gathering data on *qaaktaq* in the Mackenzie River delta. One panel member said, "It would have been nice for them to have been there [at an earlier panel meeting], to make them understand this information is very vital on both sides." Another individual present at the meeting wondered, "What are their survival rates when *qaaktaq* get back to Canada?"

Researchers brought up the existence of recruitment anomalies in their data, and panel members discussed a number of possible explanations. Several people agreed that further studies are needed regarding the effects of contaminants from drilling muds and other sources on *qaaktaq*. They also discussed the need for studies regarding changes in *qaaktaq* feeding. One panel member observed,

> It could also be the food they eat. What comes out of the Colville where the *qaaktaq* feed? I think they eat food that comes out of the Colville. We have lakes that are connected to the Colville that bring food for the fish. I have never heard anyone doing tests on water being discharged form the Colville. They come here; it has to be [for] food coming out of our drainage.
>
> Another recalled hearing about changes in the food chain from the elders, saying,
>
> An elder told me that the food that was there is no longer around. They do not see the food chain that they used to see back then. Elders do not see the kind of food that [*qaaktaq*] used to eat.

An elder panel member discussed changes in the quality of the fish, and agreed that some of these changes may come from changes in the food chain and in river vegetation.

Panel members also discussed the report outcome with the attending scientists and how the information obtained through research and during panel meetings could be used in the future. In particular, several panel members expressed concern that the findings of the report would be used to benefit oil companies in the future. One individual said, "I know you have a lot of good information. Who will this benefit: us or the oil companies, so they can put drill rigs in the ocean? Will we still get fish? Is this giving MMS more ideas to do more offshore [drilling]?"

The need to gather new data, such as data on contaminants, rather than relying on old data also was a topic of discussion at the final panel meeting. Panel members emphasized the need to use the hypotheses identified during the panel meetings to design future studies and to continue providing local input into these studies.

Regarding how well the incorporation of local knowledge and scientific findings worked, panel members in attendance at the final meeting indicated that they were pleased with the process. One individual indicated that it was "a good way to get our opinions across." Another said, "It was a good way for us to learn of the science this way." Several panel members also reported being satisfied that some of the scientific findings supported their own beliefs regarding the effects of development on *qaaktaq* numbers.

PANEL-RELATED REPORTS

The scientists, KSOPI, and the Panel of Experts prepared separate reports reflecting on the panel process. KSPOI and the panel were responsible for writing an independent report to MMS on the Panel of Experts' evaluation of the panel process ("Panel of Experts' Report"; Appendix E). The scientific team also wrote a report evaluating the panel process from their perspective ("Contractor's Report on the Panel Process"; Appendix F).

Panel Report

The "Panel of Experts' Report" (Appendix E) identified the strengths and weaknesses of the panel process from the perspective of the subsistence fishing community. Panel-identified strengths included (1) confirmation of local traditional knowledge by scientific findings, (2) the positive contribution of scientific findings to panel members' understanding of *qaaktaq*, (3) having multiple meetings that included summaries of previous meetings, and (4) panel member compensation. Weaknesses included poor communication between meetings and the lack of new data on which to develop study findings. In some cases, panel members believed that the research findings would have been more useful if new data had been collected for the purposes of the study.

The Panel of Experts' report recommended increasing communication between the scientists and panel members between meetings. In the panel's view, this would be best addressed by providing email accounts to panel members and involving them in email communications. The panel also suggested that study team members meet with panel members independently to document their answers to the final questionnaire, increase public education about the project by distributing flyers and pamphlets, and provide panel members with related traditional knowledge and subsistence-use documents for review prior to the meetings. In the future, panel members would like to see further research implemented to address their unanswered questions about *qaaktaq*.

Contractor's Report

The study team prepared a report on the strengths and weaknesses of the panel process (Contractor's Report on the Panel Process; Appendix F). The report identified a number of positive aspects of working with the Panel of Experts. Overall study objectives were met because the scientific team was able to use the input from panel members, in the form of traditional knowledge, firsthand observations, and feedback, to develop new hypotheses and research directions. For example, the panel's observations regarding the appearance of "skinny fish" during 2002 and 2003 led to further analysis by the scientists, who found a relationship between fish quality and environmental factors. Other positive aspects of the panel process included holding multiple meetings over the life of the project, building trust with local residents, and incorporating panel members' input into research design and the final report. The involvement of KSOPI as a member of the study team was instrumental in gaining acceptance into the community to conduct this project. Drawbacks of the panel process primarily involved problems with scheduling meetings when both panel members and scientists would be available, inconsistent attendance among panel members, and the requirement for written elements from the panel and KSOPI when residents were more comfortable with verbal communication. The following is a summary of the strengths and weakness of the panel process as identified by the scientists.

Strengths

- Having a local community organization be a part of the study team.
- Visiting the community multiple times during the project and developing an ongoing relationship with the panel members.
- Working with community residents on a continuing basis.

- Listening to the community residents/panel members.
- Incorporating community suggestions into the study plan.
- Working on a subsistence resource and issue that is important to the community.
- Paying panel members for their participation.
- Paying KSOPI for their participation.
- Conducting meetings and maintaining an ongoing dialogue between scientists and local knowledgeable subsistence harvesters.
- Reviewing study findings with community panel participants.

Weaknesses:

- Having a local person keep the meeting minutes.
- Getting a copy of locally kept meeting minutes.
- Requiring an independent panel report. Writing reports and keeping minutes are not necessarily strengths in small Alaskan communities.
- Conducting a retrospective study trying to answer community questions for which there were not adequate data.
- Scheduling meetings in Nuiqsut where people are busy with jobs, subsistence activities, and an ongoing dialogue with industry.
- Getting an invoice from KSOPI.

Contractors' recommendations for improving the panel process included providing more material to panel members between meetings, increasing communication among panel members and scientists between meetings, improving methods for obtaining written minutes and reports from panel members and local organizations, and determining the author of the independent panel report early in the study process.

DISCUSSION

Overall, the scientific team, panel members, and KSOPI thought the collaboration between the scientists and the local experts was successful. Everyone involved thought they gained new insights that would not have been realized under the traditional model of the scientists going about their business and then, at best, making their reports available to the village. The process truly was based on mutual respect and on being inclusive, and these are fundamental elements for this type of collaboration. Clearly, the residents in Nuiqsut want to be treated as important stakeholders who possess a great deal of critical information. This process was effective at demonstrating to the panel and, hopefully, the entire community that MMS perceives an important and knowledgeable constituent who needs to be consulted and compensated for their input into resource development decisions. See Appendices E and F for more in-depth analysis and discussion of the panel process.

4. DATA EXPLORATION

INDICATORS OF BIOLOGICAL AND ENVIRONMENTAL VARIABILITY

INDICATOR DEVELOPMENT

To examine environmental, biological, and human influences on Arctic cisco populations, we developed a variety of indices or indicators that are meant to best summarize the potential factors that are hypothesized to affect Arctic cisco recruitment or abundance. We consider it critical to develop these indicators independently and prior to the analysis of biological variability in Arctic cisco to reduce the risk of finding false relationships resulting from random variability in the data. The development of meaningful indicators is, to some extent, limited by the availability of appropriate data. We distinguish four types of indices that are relevant to the goals of the project:

- Environmental indices reflecting natural impacts on Arctic cisco throughout their life history, such as meteorological and oceanographic conditions in the nearshore environment (air and water temperature, salinity, nutrients, wind, currents), hydrographic conditions in the Colville River, and large-scale climate indicators.
- Indices reflecting human impacts on Arctic cisco, such as fishing, oil development (physical structures, contaminants), and other coastal development.
- Biological indices for Arctic cisco, including data-based or model-based indices of abundance and condition. These indices will be the dependent variables in most of the statistical models described below to meet the main goal of describing and explaining variability in the Colville River Arctic cisco population.
- Other biological indices that reflect potential effects on Arctic cisco, such as the abundance of other fish species that may compete with or prey on Arctic cisco.

Many of these indicators are expressed as anomalies. Anomalies reflect the difference between an indicator value and some “normal” value. The normal value may be defined as the long-term mean over some defined time period or may be the “expected” value based on some model or assumed relationship. For example, recruitment anomalies are defined as the difference between observed recruitment of age-0 Arctic cisco to Prudhoe Bay and the expected number of recruits estimated from a relationship between wind speed and recruitment. In addition, indicators may be standardized for the purposes of comparison or for statistical analyses. Standardization generally was achieved by subtracting the long-term mean over all years of data and dividing by the standard deviation. Therefore, values of -1 and 1 are one standard deviation below and above the mean, respectively, and 68% of the values are expected to fall between -1 and 1 if the variable is approximately normally distributed.

Time-series of the above indices will form the basis of much of the statistical analyses. The following sections describe the rationale for various indicators and show time series of the underlying data and of the final indicators used in subsequent analyses. A short name for each indicator used in the analyses, along with a brief description and the actual values of each indicator are provided in Appendix G.

DATA DISTRIBUTIONS AND OUTLIERS

We examined the distribution of each indicator variable prior to correlation analyses and modeling. When appropriate and if possible, indicator variables were transformed to meet distributional assumptions of statistical analyses. Each series also was examined for outliers. If distributional assumptions could not be met or outliers were present, robust statistical methods were used or analyses were repeated with and without the outlier(s) removed. Transformations of a variable and the handling of non-normal distributions and outliers are described in the individual sections where the variables are first used in an analysis.

ENVIRONMENTAL INDICATORS FOR THE MACKENZIE RIVER REGION

The Colville River population of Arctic cisco is believed to originate from the Mackenzie River, where the only known spawning grounds are located. It is believed that most or all maturing fish from the Colville River region return to the Mackenzie River to spawn. Therefore, effects on the spawning population and on the survival of eggs and larvae in the Mackenzie River may affect year-class strength and condition of Arctic cisco in the Colville River region. Four sources of environmental variability in the Mackenzie River region were examined and quantified for analysis. These data include river discharge, air temperatures (summer and winter), early summer sea-surface temperatures in the coastal Beaufort Sea off the Mackenzie delta, and spring ice concentrations in the same region.

RIVER DISCHARGE

Rationale: We obtained river discharge rates because they may affect spawning, the survival of fry, and the downstream migration of juveniles in the Mackenzie River. Such effects have been documented in many other systems and for many anadromous species. For example:

- Egg-to-fry survival is correlated with winter discharge rates in Atlantic salmon (*Salmo salar*) (Chadwick 1982).
- The survival of eggs and larvae of Atlantic salmon in six rivers of Newfoundland and New Brunswick is positively correlated with winter discharge rates (Gibson and Myers 1988).
- Survival of fall Chinook salmon (*Oncorhynchus tshawytscha*) in the Snake River decreases with decreasing discharge (Smith et al. 2003).
- Downstream migration of salmon fry (*Oncorhynchus tshawytscha*) in the lower Waitaki River, New Zealand, is enhanced by fluctuating discharge rates, provided discharge exceeded a threshold (Irvine 1986).
- Downstream migration of juvenile Atlantic salmon in the Girnock Burn in Aberdeenshire, Scotland, is elevated during periods with increased flow (Youngson et al. 1983).
- Growth and survival of young-of-the-year gulf menhaden (*Brevoortia patronus)* in Fourleague Bay, Louisiana, USA, are strongly correlated with river discharge into the bay (Deegan 1990).

- Discharge can affect timing of migrations (Jonsson et al. 1991), for example yearly maximum outdrift of larval cisco (*Coregonus albula*) from the Gudbrandsdalslaegen River, Norway, is positively correlated with the rate of increase in water discharge (Naesje et al. 1986).
- The arrival timing of Pacific salmon in the Columbia River is positively correlated with river discharge (earlier arrival in years with low discharge) (Keefer et al. 2004), and may affect subsequent spawning success.

Data: To examine the potential effects of Mackenzie River discharge rates on Arctic cisco, we developed annual discharge indices for several seasons separately. Monthly discharge rates for the Mackenzie River are available for at least two stations at Norman Wells and the Arctic Red River, a tributary of the Mackenzie River, through R-Arctic net (http://www.r-arcticnet.sr.unh.edu/v3.0/). Discharge rates vary on a seasonal and interannual basis with almost identical patterns at Norman Wells (Figure 7) and at Arctic Red River (Figure 8). Because of the similar patterns, we combined (summed) monthly discharge values from the two stations, which had similar mean discharge values, for 1973–2003.

Indicators: We developed three indices of discharge for the Mackenzie River system to capture variability in spring, summer, and winter discharge rates. Seasonal variability in discharge is characterized by low discharge values in the winter and early spring, rapidly increasing discharge in May, and peak discharges in June or July. After July, discharge gradually decreases almost linearly until November or December. One unusual outlier occurred in December 1996 at Norman Wells, which had unusually high discharge during that month. Arctic Red River discharge also was elevated during December 1996 (although not to the same extent), suggesting that the high value is not an erroneous measurement.

- May discharge (Dis.Mack.May[1]): This index is assumed to reflect spring conditions because early snow melt is likely to be associated with high discharges in May (Figure 9).
- Summer discharge (Dis.Mack.sum): Seasonal patterns suggest that average discharges from June through August should provide a good indicator of peak summer discharge (Figure 10). Depending on the timing of outmigration of juvenile cisco, either the early discharge rates (May) or summer discharge rates, or both, may be important for the timing of outmigration of juvenile Arctic cisco. Summer and fall discharge rates also may affect the timing of spawning migrations, which occur from mid-July through mid-August (Dillinger et al. 1992).
- Winter discharge (Dis.Mack.win): An annual index of winter discharge rates as measured at Norman Wells and the Arctic Red River was computed by summing total discharge between December of the previous year and April of each year (Figure 11). Winter discharge rates could affect the survival of eggs and fry in upstream spawning areas (e.g., Gibson and Myers 1988).

[1] Indicator names are given for each indicator examined and refer to names in Appendix G. These names were used as variable names in statistical analyses and summary output.

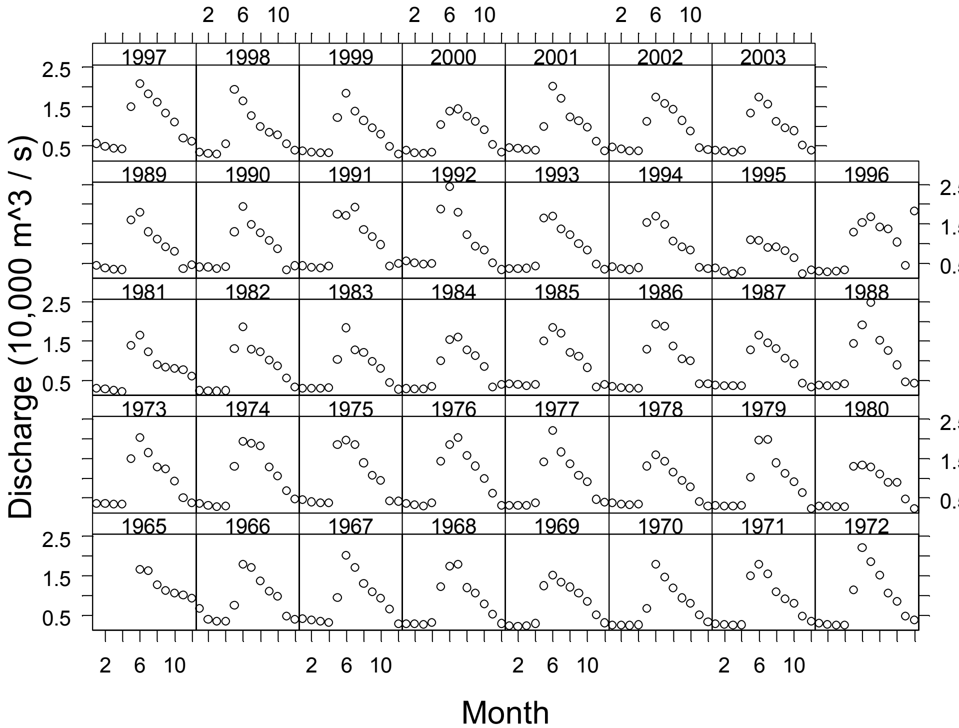


Figure 7. River monthly discharge values at Norman Wells, 1965–2003.

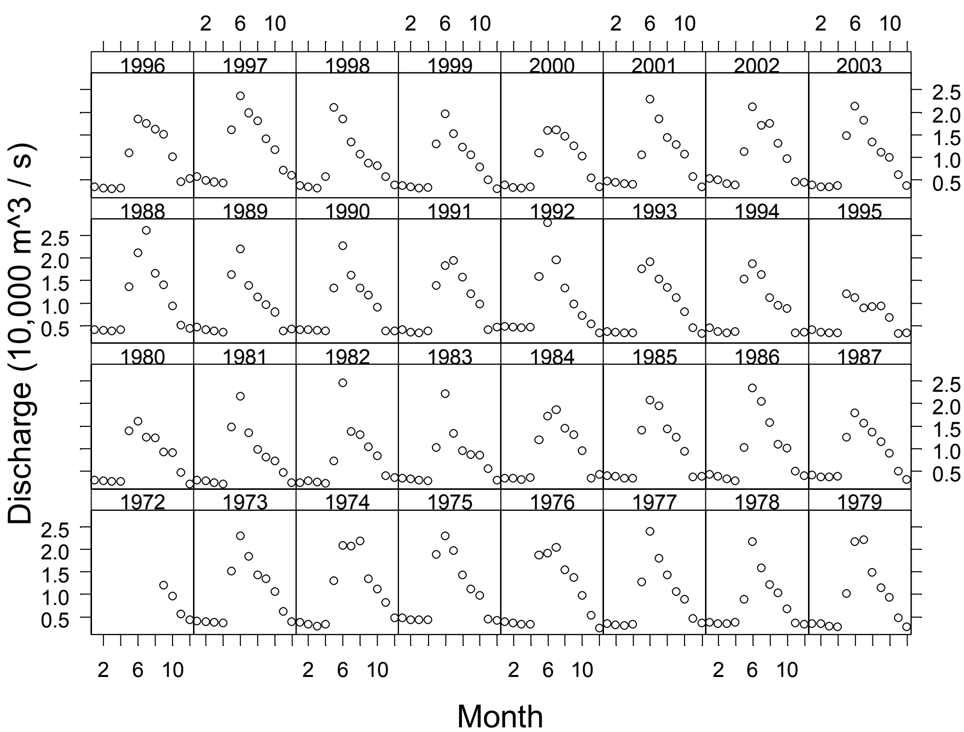


Figure 8. Mackenzie River monthly discharge values at Arctic Red River, September, 1972–2003.

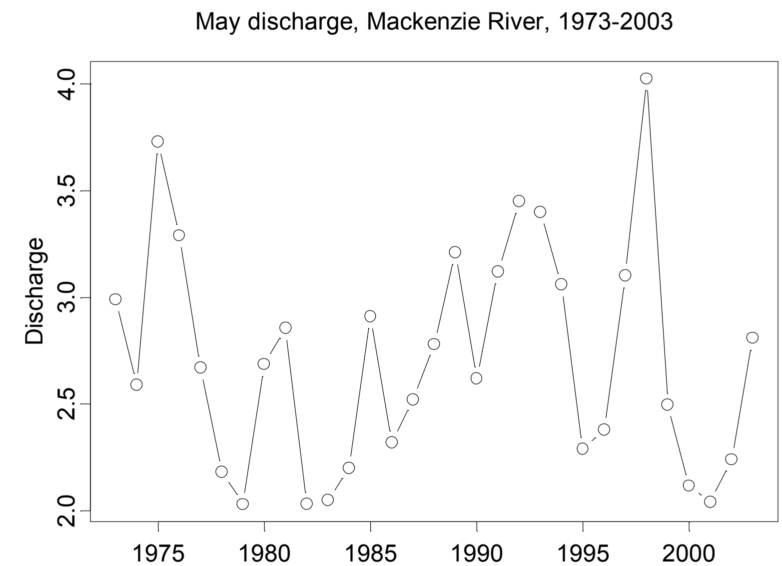


Figure 9. Mackenzie River discharge for the month of May, 1973–2003.

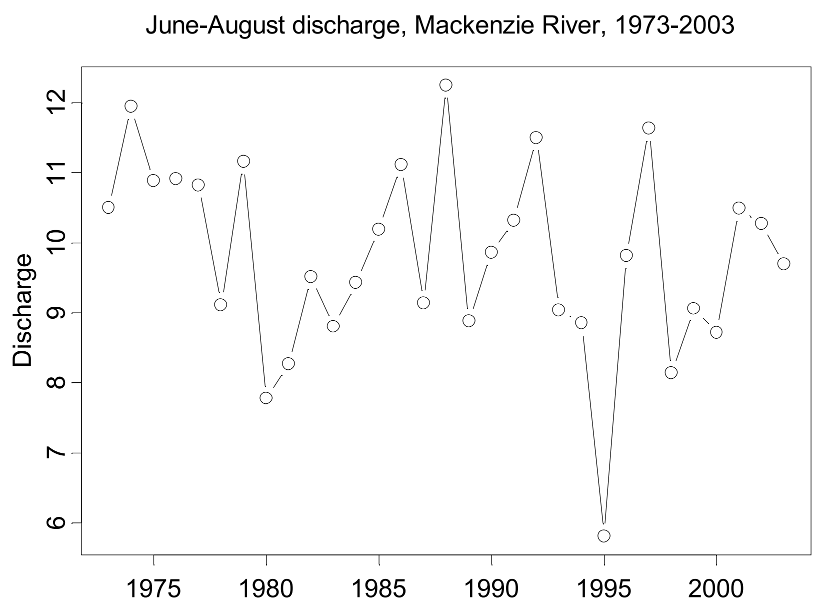


Figure 10. Mackenzie River discharge summed over June–August period by year, 1973–2003.

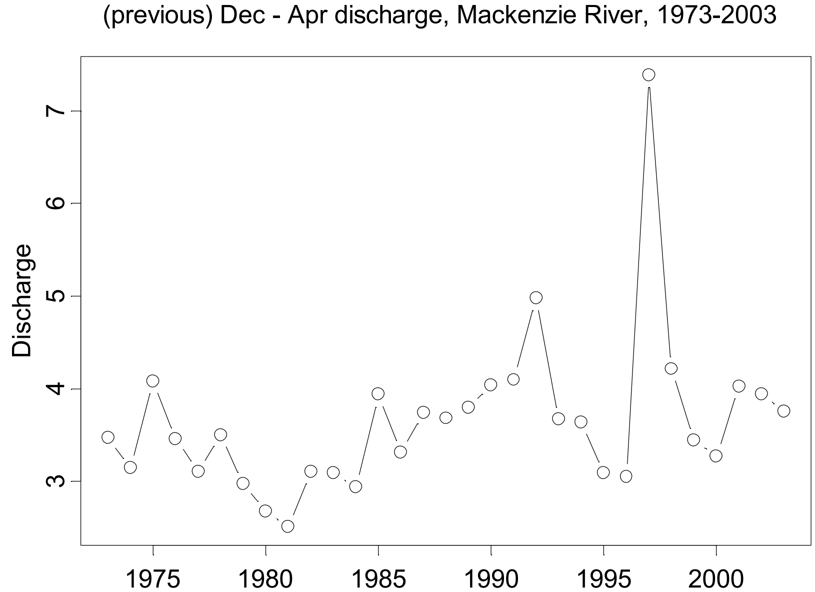


Figure 11. Mackenzie River discharge summed over (previous) December–April by year, 1973–2003.

Assessment: It is unknown to what extent discharge rates measured at Norman Wells and in the Arctic Red river reflect discharge rates in the spawning and rearing areas of Arctic cisco because these areas are largely undiscovered. However, the similarity between discharge rates at the two stations for which data exist suggests that rates may be similar throughout much of the Mackenzie drainage. Correlations between the three discharge indices suggest that discharge rates differed among seasons but that both spring and summer discharge rates are related to discharges during the previous winter. May discharge was uncorrelated with summer totals ($r = 0.104$, $p = 0.578$), suggesting that the spring and summer discharge rates reflect different processes. May discharges most likely reflect the timing (onset) of spring melt because an earlier spring implies larger May discharges. In contrast, summer discharges are more likely to reflect both the volume of the winter snow pack, as well as the amount of summer precipitation. The summer and winter indices were significantly correlated ($r = 0.380$, $p = 0.035$), as were the winter and May indices ($r = 0.421$, $p = 0.036$). One conspicuous outlier occurred in 1997 (Figure 11) resulting from the large discharge recorded at Norman Wells in December 1996 (Figure 7).

AIR TEMPERATURES

Rationale: We examined variability in air temperature as a proxy for water temperatures, which could affect the survival of Arctic cisco in the Mackenzie River. Temperatures are known to affect the growth and survival of juvenile anadromous fishes (e.g., Murray and Beacham 1986, Mortensen et al. 2000, Mueter et al. 2002), including Arctic cisco (Fechhelm et al. 1993), during and after outmigration. In addition, winter temperatures may affect the survival of eggs and early larvae. For example, winter temperatures have been shown to be correlated with egg-to-fry survival in Atlantic salmon (Chadwick 1982). However, most of the spawning areas on the Mackenzie are covered by ice in winter and variability in winter air temperature can only affect Arctic cisco eggs indirectly (e.g., through effects on ice thickness).

Data: Unfortunately, few direct long-term measurements of water temperature are available for the Mackenzie River or for the coastal waters. However, coastal temperatures (at least in ice-free regions) are typically strongly correlated with air temperatures, and air temperatures may be used as proxies for ice thickness in the Mackenzie (and its effects on egg survival) and for coastal summer temperatures off the mouth of the Mackenzie (and its effects on juvenile survival). Therefore, we used air temperatures as a proxy to reflect temperature conditions in the Mackenzie River region. Air temperature records were obtained for two locations: Inuvik on the lower Mackenzie River (68°18' N, 133°29'W) and Tuktoyaktuk near the Mackenzie River delta (69°27'N, 133°02'W). Indices based on the monthly temperature series from Inuvik (1957–2004, with some missing values) were used in the analyses because temperature records at Tuktoyaktuk only started in 1974 and had a number of missing values. Tuktoyaktuk temperatures were included here for comparison to show that Inuvik temperatures should provide a reasonable proxy for the Mackenzie delta region. Monthly means of daily minimum temperatures at Inuvik show a very regular pattern of seasonal variability (Figure 12). Monthly mean temperatures showed a very similar pattern (not shown). Winter and summer temperatures at Tuktoyaktuk showed very similar seasonal variability to that observed at Inuvik (Figure 13).

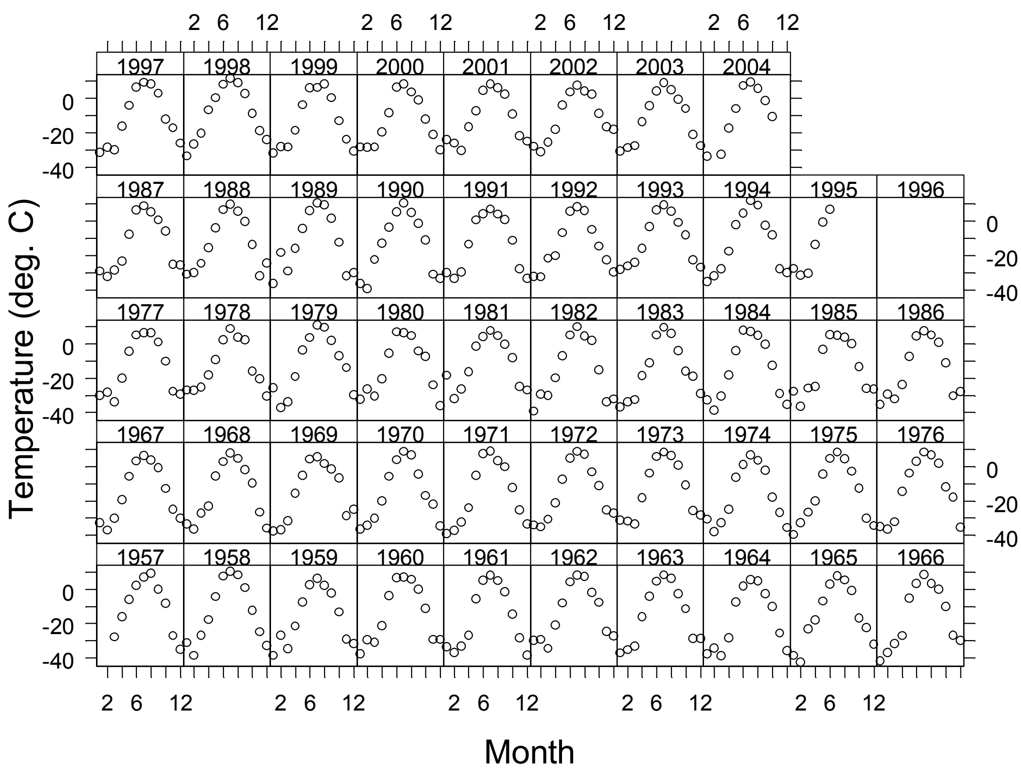


Figure 12. Monthly mean minimum air temperature at Inuvik, Northwest territory, from 1957–2004.

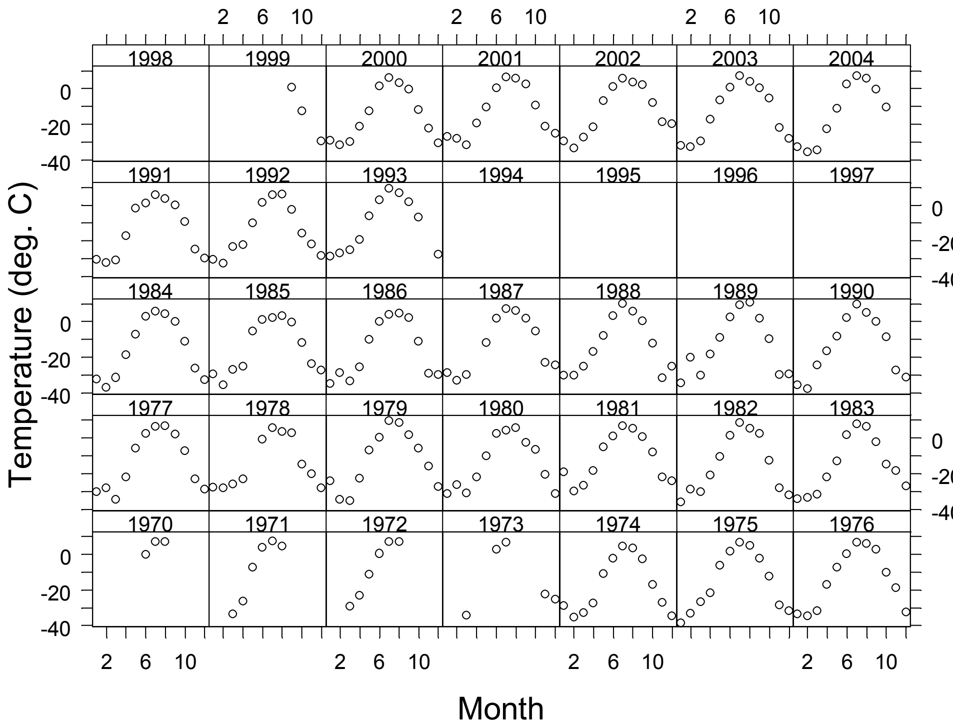


Figure 13. Monthly mean minimum air temperature at Tuktoyaktuk, Mackenzie delta.

Indicators: The hypothesized effects of temperature occur either during and immediately following outmigration into the coastal Beaufort Sea or during the winter months prior to outmigration. Therefore, we developed two temperature indices for analyses of temperature effects:

- Winter minimum temperature (Inuvik.minT.win, Tuk.minT.win): The means of daily minimum temperatures between December and March were computed as an index of the coldest conditions experienced by eggs in the Mackenzie River. Mean minimum temperatures instead of mean temperatures were selected for the winter index because extreme winter temperatures have been shown to be related to spawner-to-recruit survival in salmon.
- Summer mean temperature (Inuvik.avgT.sum, Tuk.avgT.sum): We averaged mean daily temperatures between June and September, approximately corresponding to the ice-free season. The period from June through September always included the summer peak in monthly mean temperature and showed relatively little variability from month to month.

Assessment: Winter and summer indices were computed for both Inuvik and Tuktoyaktuk and both the winter and summer air temperature indices increased significantly over time. The mean minimum temperature at Inuvik showed a near linear increase from the beginning of the time series to the present (Figure 14), slope = 1.4°C / 10 yr, $t = 7.00$, $p < 0.001$), implying a

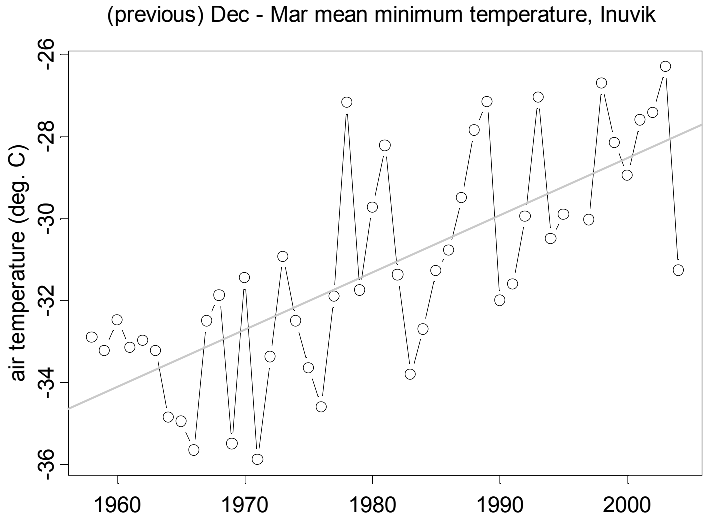


Figure 14. Mean minimum winter temperature in Inuvik from 1958 to 2004, with linear fit.

substantial increase in mean minimum temperature over the past 48 years (>6°C). A similar, but somewhat weaker, trend was obvious in the mean December through March temperatures at Inuvik. Average summer temperatures at Inuvik also increased significantly, but at a slower rate of increase (Figure 15), slope = 0.3°C / 10 yr, $t = 2.45$, $p = 0.019$). However, summer temperatures in the first years of the time series (1957–1958) were of similar magnitude as in recent years. The 1958 summer average was the highest on record (possibly reflecting the strong 1957–1958 El Niño). In contrast, the 1957–1958 winter temperatures were not unusually high.

Air temperature indices for Tuktoyaktuk showed similar interannual trends to those observed at Inuvik. However, the observed increasing trends between 1974 and 2004 were not significant for either the winter index (Figure 16), slope = 0.5°C / 10 yr, $t = 1.28$, $p = 0.213$) or the summer index (Figure 17), slope = 0.2°C / 10 yr, $t = 0.84$, $p = 0.408$). Annual winter minima were strongly correlated between Inuvik and Tuktoyaktuk both prior to ($r = 0.904$, $p < 0.001$) and after removing the linear trends ($r = 0.943$, $p < 0.001$). Similarly, mean summer temperatures at Tuktoyaktuk were strongly correlated with summer temperatures at Inuvik ($r = 0.945$, $p < 0.001$).

The strong positive correlations between air temperature indices at Inuvik and Tuktoyaktuk support the use of the more extensive and complete Inuvik temperature series in the analysis. The summer and winter indices capture at least somewhat independent aspects of temperature variability as they are only moderately correlated with each other ($r = 0.305$, $p = 0.042$).

REGIONAL SEA-SURFACE TEMPERATURES

To examine the effects of ocean temperatures on the early ocean phase of Arctic cisco after outmigration, we also used an estimate of sea-surface temperatures during the time when young-of-the-year Arctic cisco first enter the coastal ocean in July. The index is based on model-based, gridded SST obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center in Boulder, Colorado, and is described in detail in the section on environmental indicators for the Beaufort Sea.

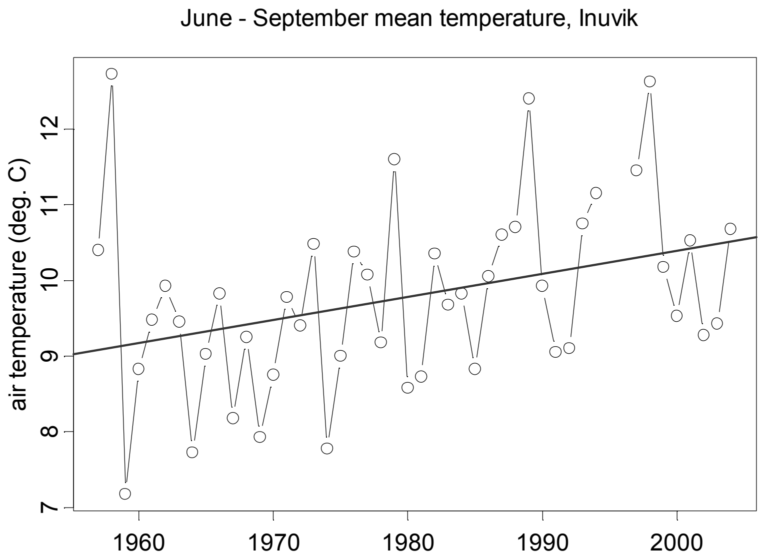


Figure 15. Mean summer air temperatures (June–September) at Inuvik, Northwest Territory, with linear fit.

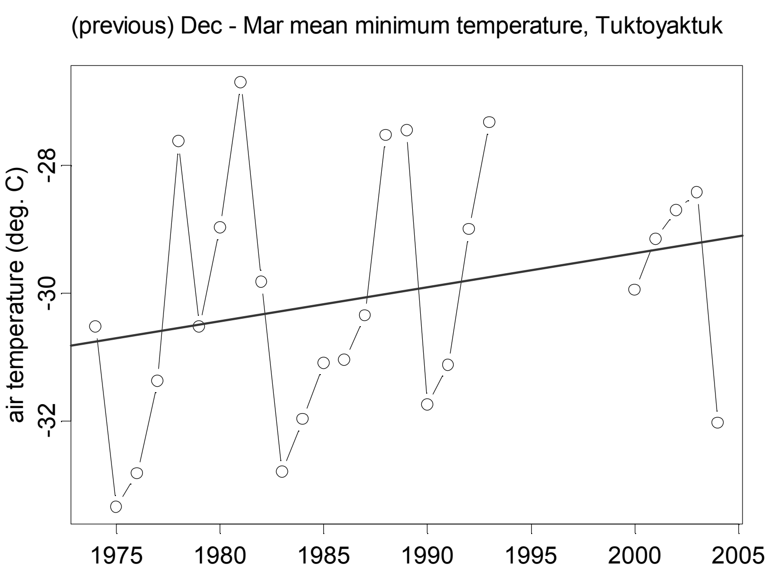


Figure 16. Mean minimum winter temperature in Tuktoyaktuk from 1974 to 2004, with linear fit.

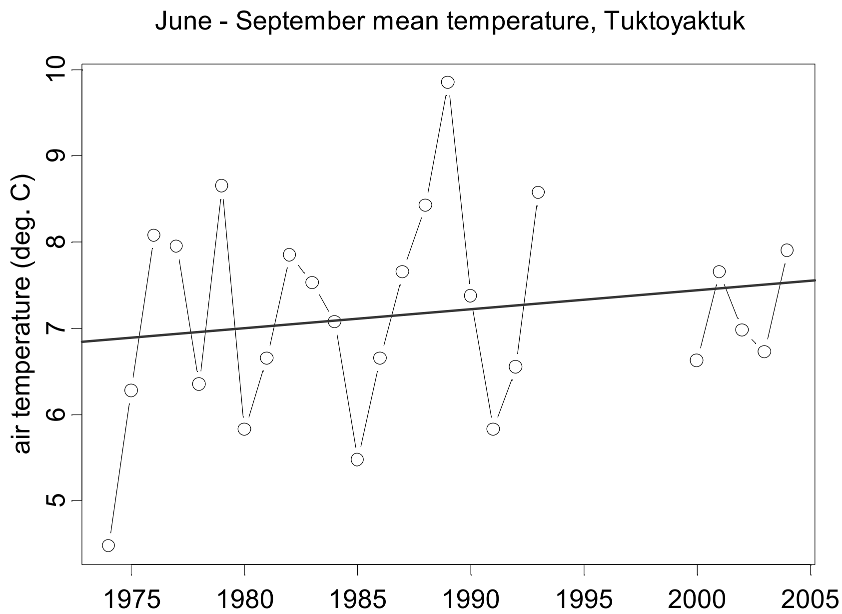


Figure 17. Mean summer temperature in Tuktoyaktuk from 1974 to 2004, with linear fit.

SPRING ICE CONCENTRATIONS

In addition to indices of coastal sea-surface temperature, we developed an index of spring ice conditions derived from gridded ice concentrations obtained from the NOAA Climate Diagnostics Center. The index is described in detail in the section on environmental indicators for the Beaufort Sea.

COMBINED CLIMATE INDEX

A climate index for the Mackenzie River region that combines indices of temperature, ice conditions, and discharge (all of which were moderately to strongly correlated with each other) into a single index was developed as described below.

ENVIRONMENTAL INDICATORS FOR THE COASTAL BEAUFORT SEA

After juvenile Arctic cisco outmigrate from the Mackenzie River into the coastal Beaufort Sea, they spend much of their first summer in nearshore waters between the Mackenzie delta and the Prudhoe Bay region. Environmental conditions in this area may affect coastal currents and prey availability. These changes, in turn, are likely to affect the recruitment of young-of-the-year Arctic cisco to the Prudhoe Bay region and survival during the first summer at sea, which is a critical period for juvenile anadromous fishes (Peterman 1987). Three sources of environmental variability in the coastal Beaufort Sea were examined and quantified for analysis. They include summer winds, summer sea-surface temperatures, and ice concentrations during both the spring and fall seasons.

WINDS

Rationale: There is a well-established relationship between wind strength and direction and the transport of age-0 Arctic cisco from the Mackenzie River delta west to Alaska (Fechhelm and Griffiths 1990) that has held up over time (Fechhelm et al. 2006). Therefore, any wind effects on recruitment need to be accounted for when examining the effect of other environmental or human impacts on Arctic cisco recruitment.

Data: We obtained wind data for the coastal regions of the Beaufort Sea, which are a good proxy for alongshore transport near the relatively straight coastline (Tom Weingartner, UAF, March 2005, pers. comm.). Several sources of wind data are available, including measured winds at coastal weather stations such as Barter Island, Deadhorse, and Barrow, and modeled winds from the National Center for Environmental Prediction (NCEP/NCAR) reanalysis (available on a 2.5° latitude by 2.5° longitude grid). The high-quality hourly wind data at the Barrow observatory (71.32°N, 156.6°W, available from NOAA Climate Monitoring and Diagnostics Laboratory) and at the Deadhorse Airport (70.20°N, 148.48°W, maintained by the National Weather Service, available from the National Climatic Data Center NCDC, Asheville, North Carolina) provide the most complete record for measured winds. Wind data at Barter Island may reflect coastal winds along the coast more accurately, but they are incomplete and do not span the length of available biological data series. We obtained the Barrow data (hourly, 1973–2004), daily data from Deadhorse for 1999–2005, and summary data for Deadhorse (summer averages of easterly winds, 1976–2005). In addition, we obtained daily modeled NCEP/NCAR winds for selected locations along the Beaufort Sea coast. We selected grid points centered at 70°N (13 grid cells between 162.5°W and 127.5°W), as well as grid points centered at 72.5°N between 160°W and 150°W. Recently, a compilation of historical winds and hourly measurments at five coastal locations became available in print (Hoefler Consulting Group 2006) and on the Internet (http://www.resdat.com/mms). These data were published too late to be included here, but some conclusions from the study are incorporated by reference.

Indicators: To model and account for the known effects of transport on the young-of-year recruitment of Arctic cisco to Prudhoe Bay, we used two indices of westward transport. No direct measurements of transport are currently available except for short periods of time in the Prudhoe Bay region. Therefore, indices were based, as in previous studies, on available wind data.

- Average easterly summer wind speeds at Deadhorse (Wind.Dhse): Following Fechhelm and Griffiths (1990), we used a index of average easterly winds between July 1 and August 31. These authors argued that variable ice cover in June and September may bias estimates of wind-driven transport outside the July–August period. While the original index was based on Barter Island winds, more recent analyses have used wind data from the Deadhorse airport. We obtained average hourly wind speeds (m/s) for the period July 1–August 31, 1976–2005 from Table 4 in Fechhelm et al. (2004), Figure 4-4 in Fechhelm et al. (2005), and Figure 1.3 in Fechhelm et al. (2006) (Figure 18).

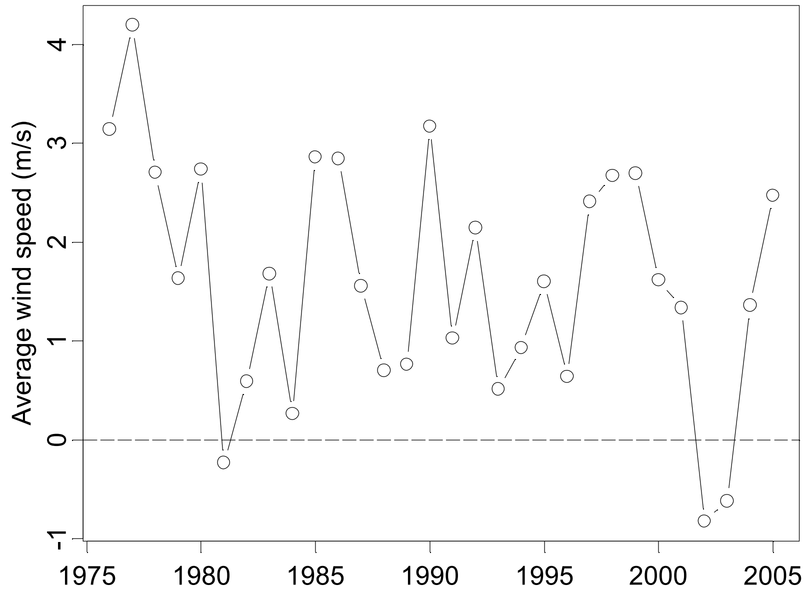


Figure 18. Average easterly wind speed during July and August at Deadhorse Airport, 1976–2005.

- Average summer wind speed along the coast (Wind.avg): An alternative index was derived by averaging alongshore wind speed (m/s) from July 1 through August 31 of each year (1961–2004) across numerous coastal locations in the Beaufort Sea, based on model-derived NCEP/NCAR winds. This index uses only the alongshore component of easterly winds as described in detail below.
- Sum of easterly winds during summer (Wind.E): A third index based on model-derived NCEP/NCAR winds was obtained by computing the sum of all positive (easterly) daily wind speeds between July 1–August 31 across the coastal Beaufort Sea. This index is described in detail below.

The following considerations guided the development of an index of wind-driven transport based on modeled NCEP/NCAR winds:

- Because the inner portion of the coastal boundary layer (where Arctic cisco are believed to aggregate during westward migration; e.g. Thorsteinson et al. 1991) is very shallow (<4–5 m), water mass transport is essentially aligned with wind direction (Niedoroda and Colonell 1990; Tom Weingartner, pers. comm.). Therefore, average easterly summer winds can be used as a good proxy for westward transport in the coastal boundary layer.
- The first young-of-the-year (YOY) Arctic cisco in 1985 and 1986, years of steady easterly winds (positive winds), appeared east of the Mackenzie delta (Kay Point off the mouth of Babbage River, about 60 miles east of the delta) on July 12 and July 13, respectively (and first arrived off the Colville River on August 26, 1985). YOY Arctic cisco arrive at Prudhoe Bay throughout the summer until at least the middle of September in some years. Therefore, winds between early July and late August are likely to be important to transport and recruitment success of YOY Arctic cisco.

- When winds switch to a westerly direction (negative winds), water flow quickly reverses (within hours to less than a day; Niedoroda and Colonell 1990); hence, YOY Arctic cisco may be transported back to the east. In that case, average alongshore winds should provide a good indicator of maximum westward transport during the summer. However, when winds reverse, young Arctic cisco may move into delta and stream habitat and thereby avoid being transported eastward (Gallaway and Colonell 1990). Thus, the sum total of easterly winds (sum of positive winds) may be a better predictor of westward transport than the sum total of both east (-) and west (+) winds.
- In all years where YOY did not arrive in Prudhoe Bay by August 31, the resulting year-class was very small as estimated by age-0 catch-per-unit-effort (CPUE) during that year, age-1 CPUE in the following year, and age-2 CPUE 2 years later (Figure 19).
- Based on these considerations, we constructed two alternative indices of westward transport from modeled NCEP/NCAR winds: 1) Mean alongshore easterly winds from July 1–August 31 of each year (Wind.avg), and 2) Cumulative sum of easterly winds from July 1–August 31 of each year (Wind.E).

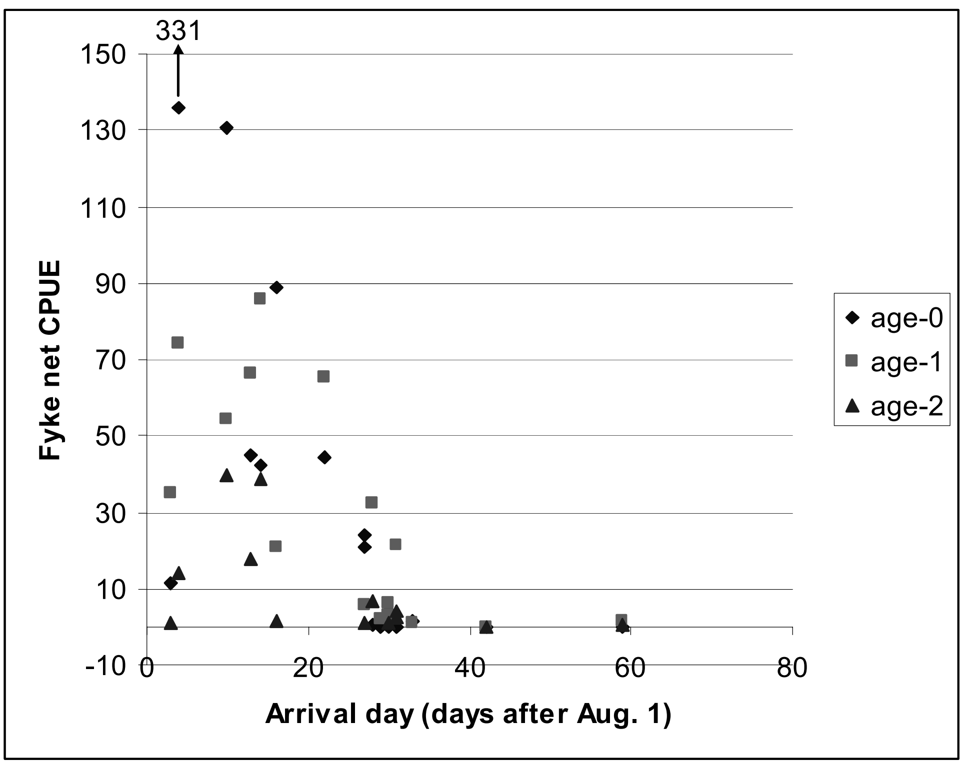


Figure 19. Fyke net catch-per-unit-effort (CPUE) for age-0, age-1, and age-2 Arctic cisco as a function of arrival date at Prudhoe Bay of the corresponding year-class. Most dates after Aug 29 are "plus dates," (i.e., sampling terminated on that date and CPUE is shown through last day of sampling). Note that CPUE generally was close to zero if fish did not arrive by August 3.

To derive transport indices based on modeled winds from the NCEP/NCAR reanalysis, we used wind speed estimates for the following locations between Mackenzie delta and Bullen Point just east of Prudhoe Bay in the coastal Beaufort Sea: 70°N and 137.5°, 140°, 142.5°, 145°, and 147.5°W. Winds at the three easternmost locations were rotated by 25° to obtain the easterly component of wind that is lined up with the coastline, which is oriented along 115–295° true North between the Mackenzie delta and Barter Island (thus using the direction of the coastline as the new "east"). Similarly, we rotated winds at the three westernmost locations by 15° to line up with the coastline between Barter Island and Prudhoe Bay (105–285° true N). To obtain alongshore components for the approximate period of summer transport, we averaged daily rotated winds across the three easternmost grid points for the month of July and across the three westernmost grid points for the month of August (Figure 20). [Note that winds at 142.5°W (near Kaktovik) were used in both averages.] We used July and August averages for the eastern and western regions, respectively, because YOY cisco arrived near Barter Island around the end of July in a good recruitment year (1990 year class; see Underwood et al. 1992). The two final indices were obtained by combining July daily averages from the eastern region with August daily averages from the western region and then (1) averaging daily alongshore wind speeds between July 1 and August 31 (Figure 21) and (2) computing the cumulative sum of westward flowing alongshore winds (i.e., ignoring all days with westerly winds, Figure 22).

Assessment: A comparison of daily alongshore wind indices (derived from the NCEP/NCAR reanalysis data) with winds measured at Deadhorse showed substantial differences between the two measures of wind speed. Daily average alongshore wind speeds were highly variable and often shifted from easterly to westerly winds (Figure 20). While alongshore easterly winds predominated, average wind speed was negative (from WNW to ESE) in 18 out of 44 years between 1961 and 2004 (Figure 21). Thus negative (westerly) winds in the NCEP/NCAR dataset were much more frequent than in the measured Deadhorse or Barter Island winds (Fechhelm and Fissel 1988, Fechhelm and Griffiths 1990, Fechhelm et al. 1999). Furthermore, the magnitude of average winds from the NCEP/NCAR data was considerably smaller than that from measured data. NCEP reanalysis winds may not accurately reflect winds in this region because of the sparsity of data in the Arctic and because of topographic steering effects related to the vicinity of the Brooks Range, particularly in the eastern portion of the study area (Hoefler Consulting Group 2006). Therefore, we continued to use the Deadhorse index (Wind.Dhse: average summer wind speed at Deadhorse) used in previous analyses in addition to or instead of the NCEP/NCAR wind indices. The Deadhorse index averages all east (+) and west (-) winds over the summer (July–August) period as described above.

A more detailed analysis of the model-derived NCEP/NCAR winds and a comparison with measured winds at Barrow and Deadhorse are included as Appendix H.

REGIONAL SEA-SURFACE TEMPERATURES

Rationale: Sea-surface temperatures (SST) are likely to affect Arctic cisco throughout their life history from the Mackenzie River to the Colville delta. Temperatures impact the growth and abundance of the zooplankton prey that serve as food for Arctic cisco in or near the Colville

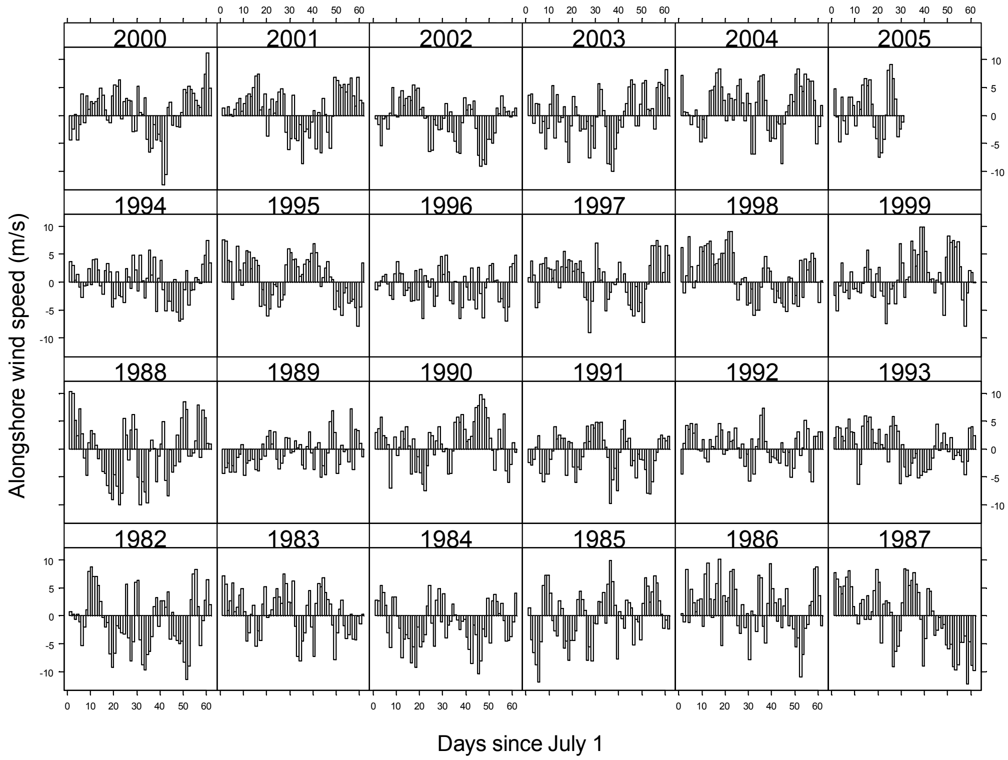


Figure 20. Daily average wind speeds along the Beaufort Sea coast as estimated by NCEP/NCAR for July and August of each year from 1982–2005. Positive winds denote alongshore wind component from ESE to WNW.

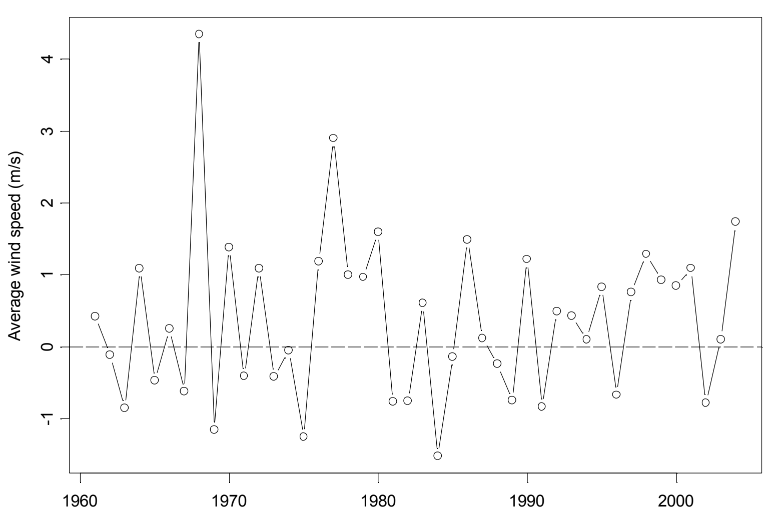


Figure 21. Average July–August alongshore wind speed in coastal Beaufort Sea from 1961–2004.

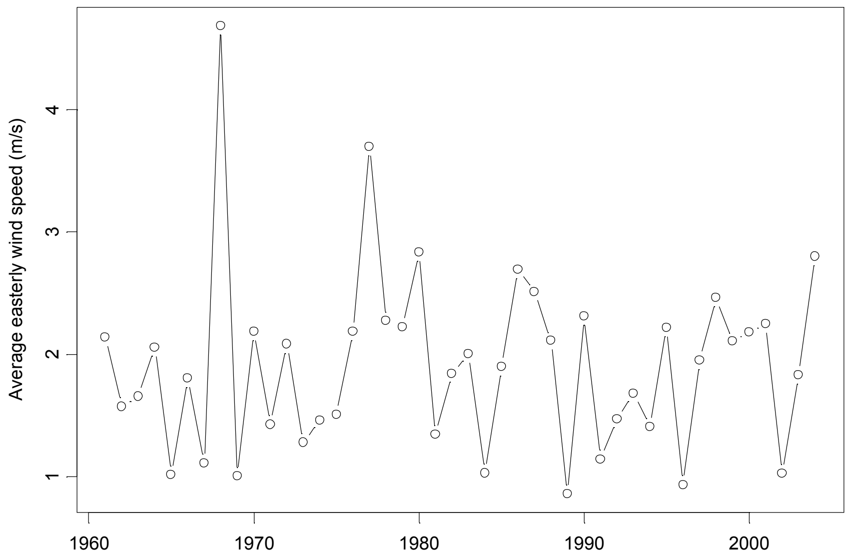


Figure 22. Sum of easterly alongshore wind speed during July and August in coastal Beaufort Sea, 1961–2004.

delta. Temperatures have been shown to affect the growth and survival of juvenile anadromous fishes (e.g., Murray and Beacham 1986, Mortensen et al. 2000, Mueter et al. 2002), including Arctic cisco (Fechhelm et al. 1993), during and after outmigration.

Data: Because there are very few direct long-term observations of sea-surface temperature in the Beaufort Sea, we obtained monthly NOAA extended SST data from the Climate Diagnostics Center, Boulder, Colorado, USA (http://www.cdc.noaa.gov/). We combined Reynolds reconstructed SST for 1900–1981 with monthly Optimum Interpolation version 2 SST (OIv2) from 1982–2005. Both data sets combine ship-based and satellite-derived SST estimates. Reynolds SST data are averaged over a very coarse grid (2° latitude by 2° longitude) and may be too coarse to adequately represent coastal conditions; they are included here for comparison purposes and to extend the SST series back in time. The OIv2 data are interpolated on a 1° by 1° grid and should reflect temperature conditions over the shelf, including conditions in the coastal boundary layer.

Indicators: Estimates of SST are only available and appropriate for the open-water season. We derived three SST indices, two alternative indices for spring–early summer conditions off the Mackenzie River and one index for summer conditions in the primary summer feeding area to the east and west of the Colville delta:

- July SST off Mackenzie River (Mack.OISST.Jul): For a spatially restricted index of early ocean temperature conditions off the mouth of the Mackenzie River, we averaged July temperatures from the OI v.2 dataset over the area 69–70°N, 136–142°W, which includes five 1×1° cells. Monthly SSTs displayed a regular seasonal cycle with temperatures generally near the minimum in winter (reflecting modeled SST based on ice cover), increasing in June, and typically peaking in July or August (Figure 23). In some years (e.g., 1982, 1985, 1986), SST did not peak until September. Because Arctic cisco outmigrate in July and are quickly transported to the west (Bond and Erickson 1987), we used July SST for this region only as an index of ocean temperatures during the early ocean phase (see Figure 27). Arctic cisco that migrate or are transported to the Prudhoe Bay region are most likely no longer in this area after July.
- July Reynolds SST off Mackenzie (Mack.ReySST.Jul): To extend the period of coverage back as far as possible, we used Reynolds SST averaged over three grid cells centered on 70°N (69–-71°N, 135-141°W). Monthly SSTs show a very regular seasonal cycle with winter temperatures reflecting ice conditions and summer temperatures usually peaking in July or August (Figure 24). Over the period of overlap (1982–2003) the July temperature index based on Reynolds SST data (see Figure 27) is only poorly correlated with the OI SST index ($r = 0.23$), which may be due to the much larger area of coverage that includes a considerable offshore region. Therefore, the Reynolds SST index is unlikely to adequately reflect nearshore SST conditions and was not used in the analyses.
- Summer SST, western Beaufort Sea (Col.OISST.sum): Similar to the Mackenzie River index, we used OI SST data (1982–2004, Figure 25) to derive a summer index for the Colville River–Prudhoe Bay region as an index of temperature conditions in the summer feeding area. For an annual index, we averaged SST from July through September and over the area 70–71°N, 146–152°W (see Figure 27). Summer temperature generally peaked during this period (Figure 25). Variability in spring and fall conditions was captured in a separate ice index (see below).

Assessment: Do these SST indices adequately reflect nearshore temperature conditions in the habitat occupied by Arctic cisco? Although temperatures in the nearshore region are generally much warmer than the mean temperatures over these relatively large regions (Figure 26), it is nevertheless likely that they reflect interannual variability in coastal temperature conditions. We compared interannual trends in model-based SST to measured local temperatures where available (see below). For example, for years with available measurements between 1982 and 2004 ($n = 19$), mean SST over the sampling season (ranging from 49–58 days) at Heald Point (at the east entrance to Prudhoe Bay; also known as Herald Point) was well correlated with the Colville summer (July–September) SST index ($r = 0.61$, Figure 26). However, the 3 years with unusually high SST at Heald Point (Figure 26) did not show unusually high SSTs in the modeled series, and may reflect spatially restricted (local) warming in shallow nearshore areas.

The estimated Reynolds SSTs provide an opportunity to examine longer-term variability in temperature conditions going back to the turn of the 20th century. Estimates are available from 1854–2003, but data quality prior to the 1950s is believed to be poor (Tom Royer, University of Rhode Island, pers. comm.). Thus, we examine only SST records since 1950. Temperatures have shown a very regular seasonal pattern but summer temperatures show considerable

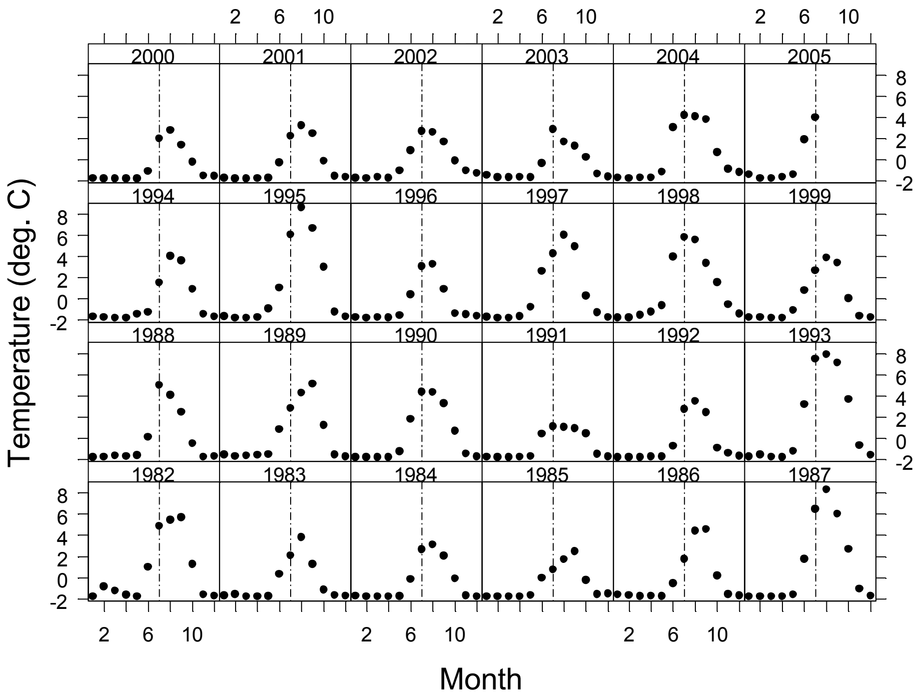


Figure 23. Average sea-surface temperature (Optimum Interpolation v.2 SST) off the mouth of the Mackenzie River (69–70°N, 136–142°W) by month and year, 1982–2005.

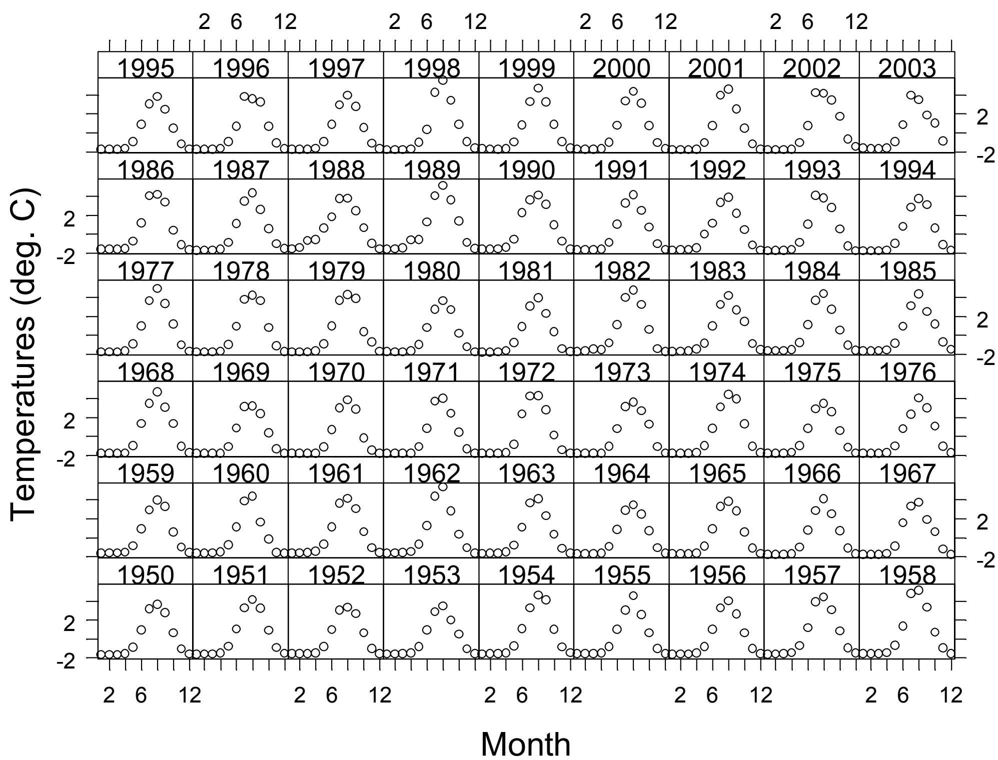


Figure 24. Average sea-surface temperature (Reynolds reconstructed SST) off the mouth of the Mackenzie River (69–71°N, 135–141°W) by month and year, 1950–2003.

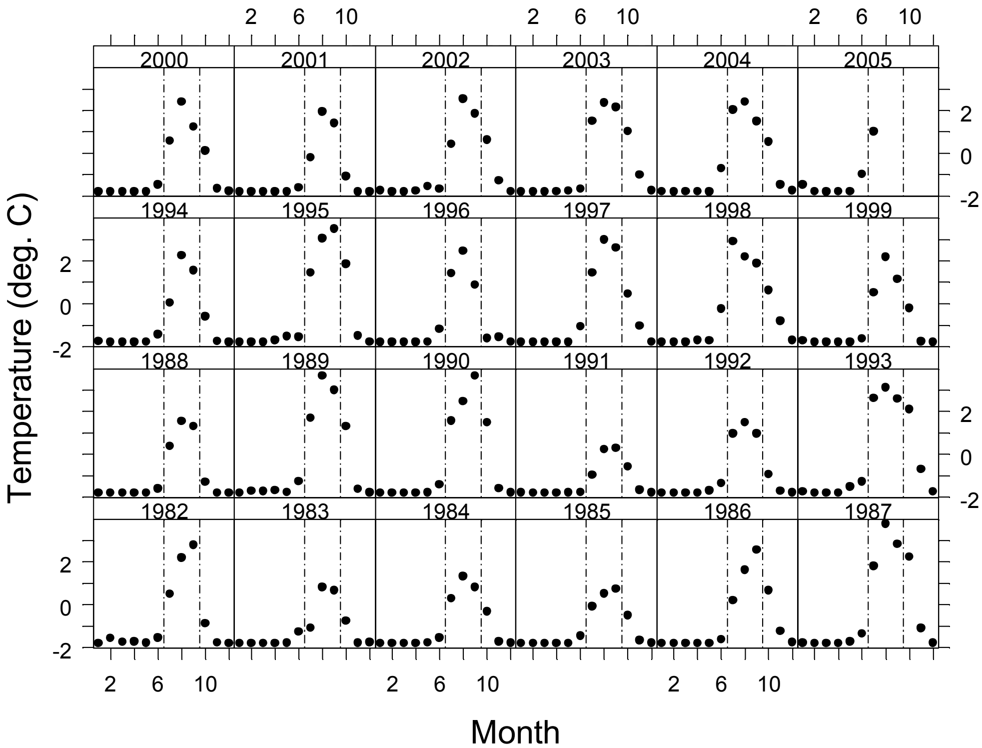


Figure 25. Average sea-surface temperature (Optimum Interpolation v.2 SST) off the Colville River / Prudhoe Bay region (70–71°N, 146–152°W) by month and year, 1982–2005.

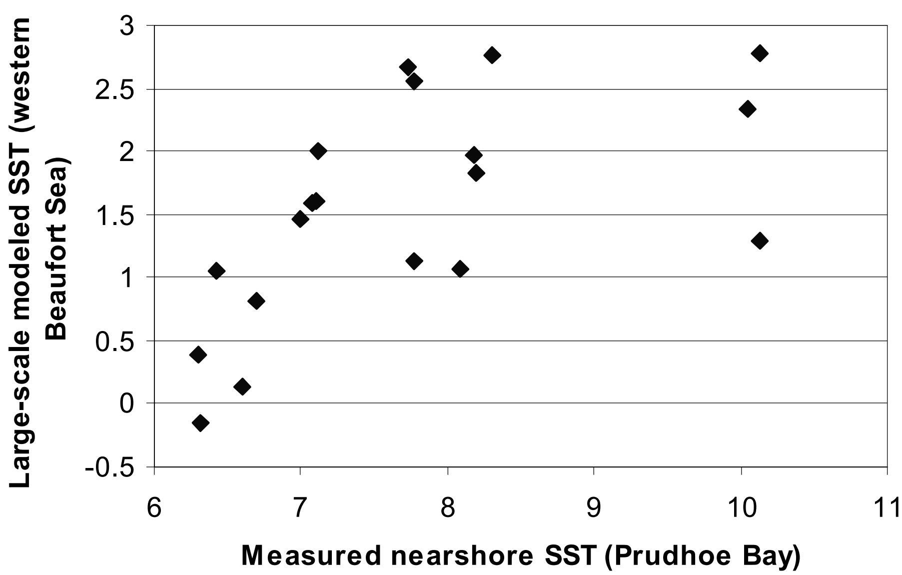


Figure 26. Comparison of measures sea-surface temperatures (SST) at Heald Point in Prudhoe Bay and large-scale model-based SST for the western Beaufort Sea.

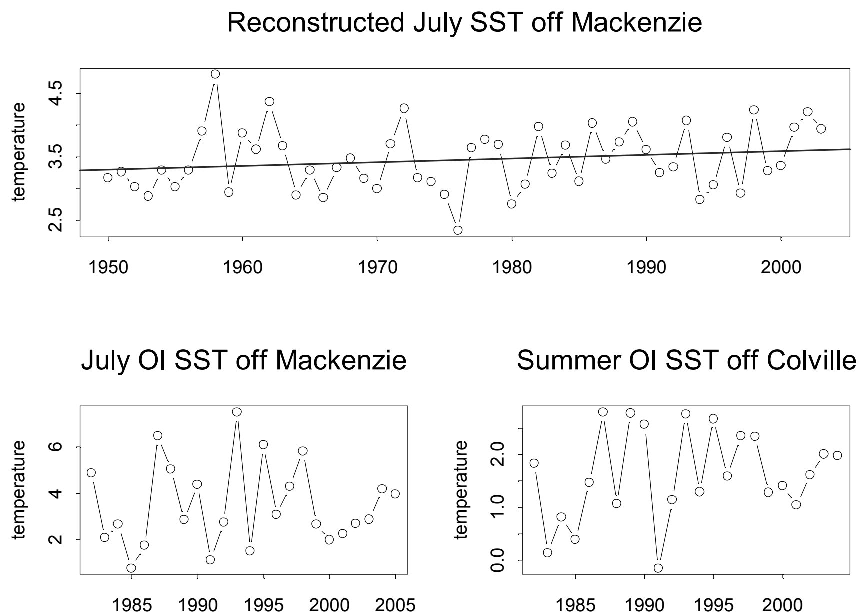


Figure 27. Interannual variability in three sea-surface temperature (SST) indices: July SST off the mouth of the Mackenzie River based on Reynolds reconstructed SST from 1950–2003 and NOAA Optimum Interpolation v. 2 SST off the Mackenzie (July SST, bottom left) and off the Colville River / Prudhoe Bay region (July–September).

interannual variability. The Reynolds SST record suggests a long-term increase in July SST of approximately 0.3°C since 1950 (Figure 27), although this linear trend was not significant (t-test: $t = 1.35$, $p = 0.182$). The OI v.2 index for the Mackenzie region shows a similar rate of increase since 1982 (0.01°C y-1, $t = 0.188$, $p = 0.85$), with very high interannual variability (Figure 27). July SSTs in the Mackenzie region are strongly correlated with summer SSTs in the Colville region ($r = 0.749$, $p < 0.001$) and the Colville SSTs show a similar increasing trend (0.03°C y-1, $t = 1.13$, $p = 0.27$; Figure 27).

ICE CONCENTRATIONS

Rationale: Ice cover in nearshore areas of the Beaufort Sea may affect Arctic cisco that feed in the area during summer by determining the length of the production season and by reducing water temperatures. Ice cover also may affect the transport of juveniles through its impact on wind-driven transport along the coast. Therefore, spring ice conditions may be important to the timing of migration and to the survival of both age-0 fishes after their outmigration from the Mackenzie River and to both juveniles and adults moving into nearshore areas around the Colville River to feed. Fall freeze-up may also be important to juveniles and adults in the western Beaufort Sea because an early freeze-up may shorten the feeding season.

Data: We obtained monthly ice concentrations from the NOAA Climate Diagnostics Center, Boulder, Colorado, USA (http://www.cdc.noaa.gov/). These data are monthly averages of the weekly median percentage of area covered by ice. Data are interpolated on a 1×1° grid and should adequately reflect ice concentrations along the coast.

Indicators: As an indicator of spring sea-ice conditions, we used the average June ice concentrations in two regions: one region off the mouth of the Mackenzie River (69–70°N, 136–139°W) and one region encompassing the Colville delta and Prudhoe Bay (70–71°N, 146–152°W).

- Average June ice concentration, Mackenzie (Mack.ice): Off the mouth of the Mackenzie delta, ice concentrations are typically close to 100% from November–May and often close to zero percent from July–September (Figure 28). Therefore, we chose mean ice concentrations in June, when ice cover was most variable, as an indicator of spring ice conditions.

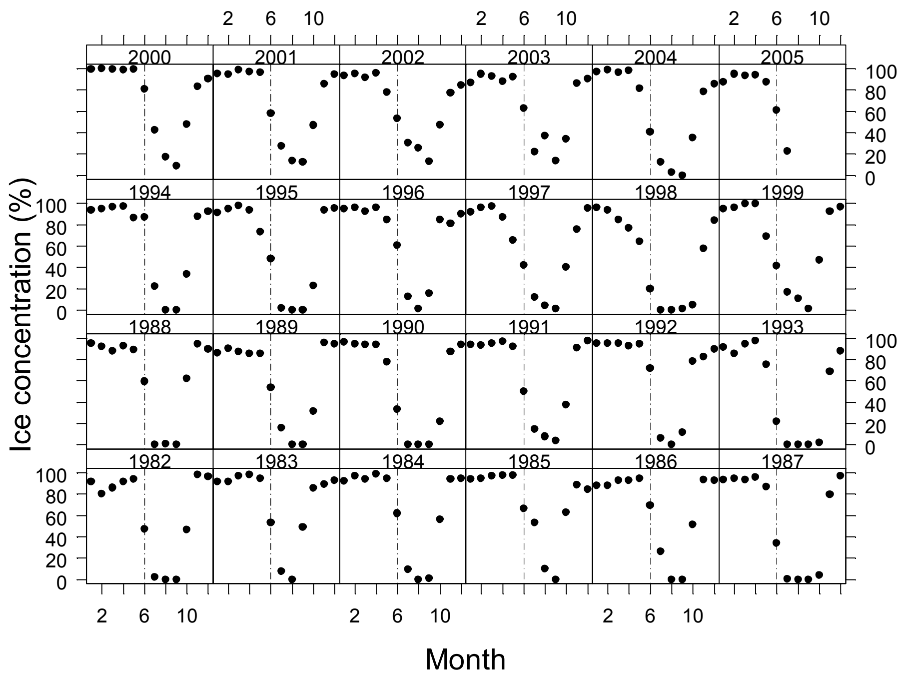


Figure 28. Average ice concentrations in 1° latitude by 3° longitude box off the mouth of the Mackenzie River by month and year, January 1982–July 2005. Vertical dashed lines indicate month of June for each year

Average spring ice concentrations, Colville (Col.ice.Spr): Ice concentrations near the Colville delta show a similar seasonal pattern but ice tends to go out somewhat later with June ice concentrations typically close to 100% (Figures 29 and 30). Therefore, we averaged ice concentrations near the Colville delta for the months of both June and July over 70–71°N, 146–152°W for an index of early ice conditions in the summer feeding area. The index is likely to reflect the timing of break-up (with lower ice concentrations reflecting an earlier break-up) (Figure 31).

- Average fall ice concentrations, Colville (Col.ice.Oct): In addition, we used October ice concentrations as an index of the timing of freeze-up by averaging October ice concentrations over the same geographical area as the spring index (70–71°N, 146–152°W).

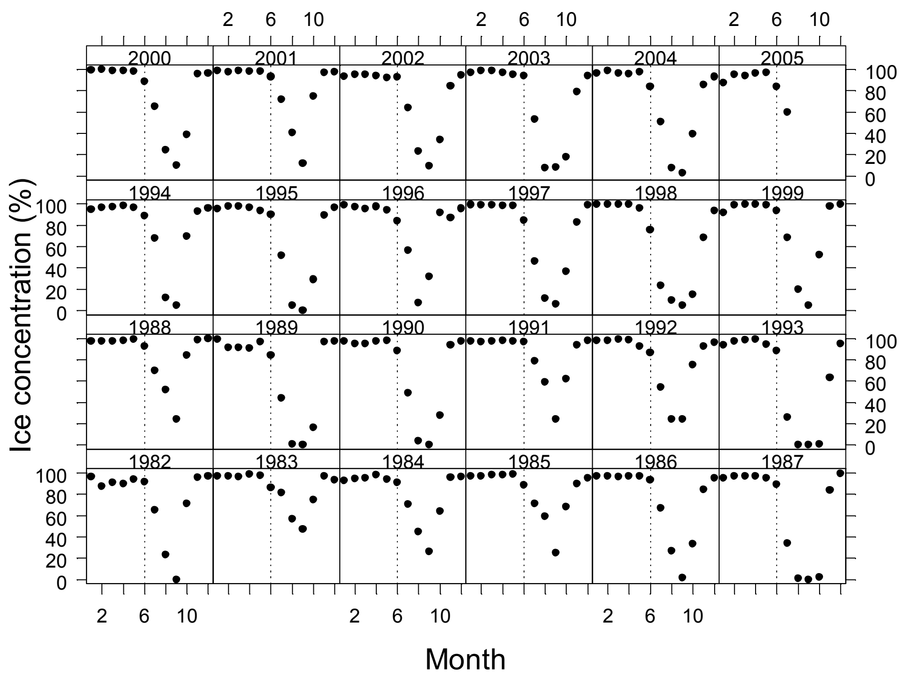


Figure 29. Average ice concentrations in 1° latitude by 6° longitude box off the Colville River / Prudhoe Bay region by month and year. Vertical dashed lines indicate month of June for each year.

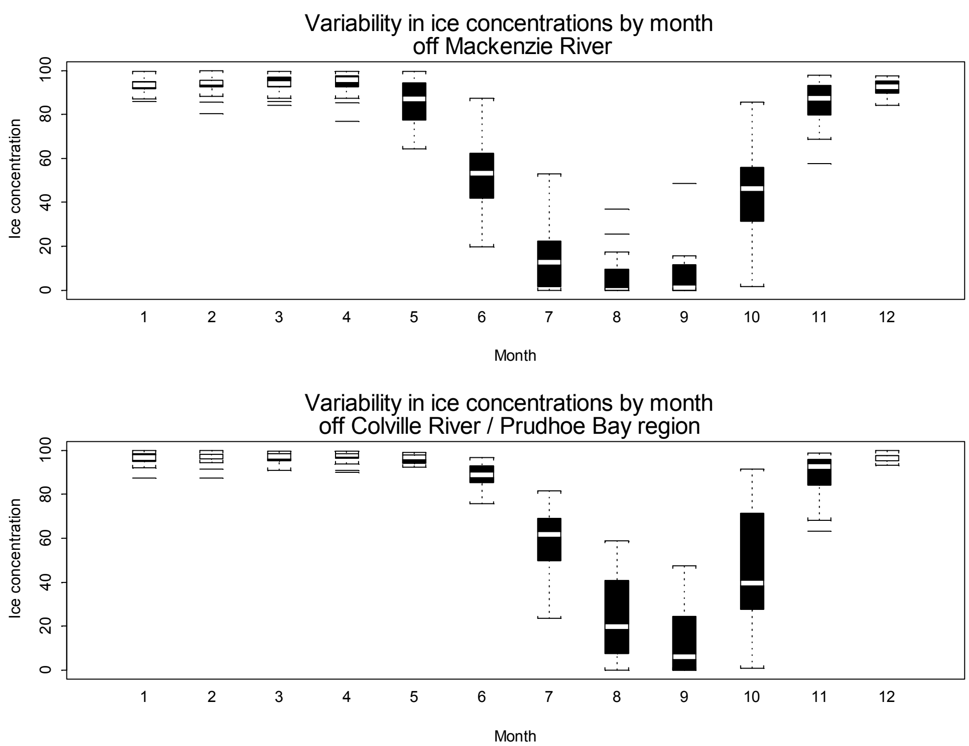


Figure 30. Boxplots of variability and range of ice concentrations by month for two regions, 1982–2005.

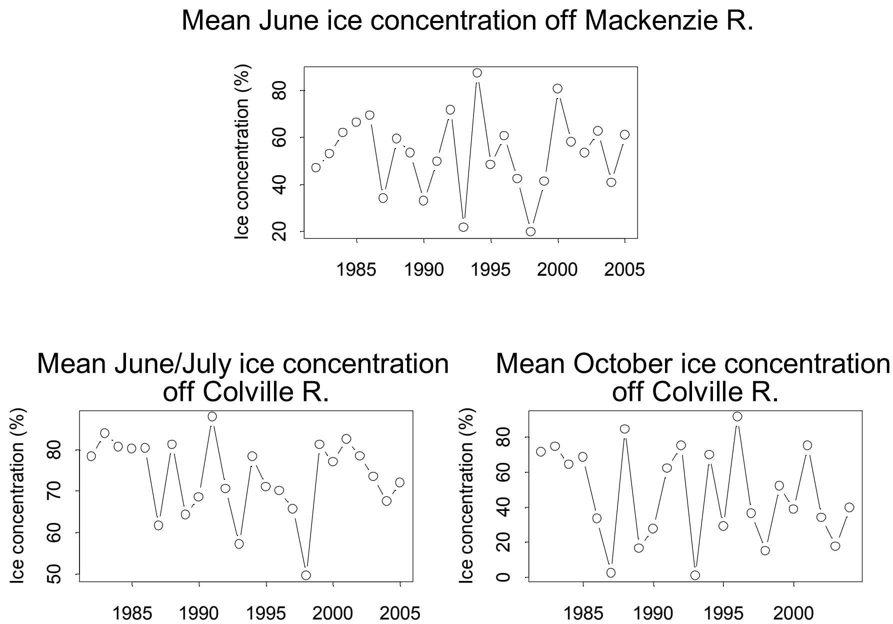


Figure 31. Ice concentrations during spring in the Mackenzie River and Colville River regions and during fall (October) in the Colville River region.

Assessment: There is substantial interannual variability in the ice indices but no clear trends. Average June ice concentrations in the Mackenzie region varied from 20% to over 80% cover, whereas average June–July ice cover in the Colville–Prudhoe Bay region ranged more narrowly from 50–80%. Minimum ice concentrations occurred in 1987, 1993, and 1998 (Figure 31). Off the Colville–Prudhoe Bay region, ice concentrations show a (non-significant) decreasing trend over time, consistent with an increase in temperatures. Like sea-surface temperatures, spring ice concentrations were strongly correlated between the two regions ($r = 0.610$, $p = 0.002$). In addition, ice concentrations in the Colville–Prudhoe Bay region in spring are strongly correlated with those in October ($r = 0.671$, $p = 0.0005$).

ENVIRONMENTAL INDICATORS FOR THE COLVILLE RIVER–PRUDHOE BAY REGION

Although Arctic cisco originate from the Mackenzie River, they spend the first 6–8 years of their lives in the western Beaufort Sea and the Colville delta. They spend each winter during these years in the Colville River followed by summer feeding forays along the western portion of the coastal Beaufort Sea. The center of their distribution is believed to be the Colville River region and the Prudhoe Bay region, where large numbers of juveniles and subadults feed during the summer. Therefore, conditions in these areas are likely to affect the survival of juvenile and subadult Arctic cisco. Sources of environmental variability that were examined and quantified for analysis include air temperatures (summer and winter), river discharge, summer sea-surface temperatures, summer sea-surface salinities, ice concentrations, and large-scale climate indices.

AIR TEMPERATURES (BARROW)

Rationale: Summer air temperatures are moderately to strongly correlated with coastal water temperatures and provide an alternative index for summer temperature conditions. Winter temperatures may affect ice conditions and overwintering survival of Arctic cisco in the delta. This relationship is particularly true when extreme temperatures result in heavy ice and, therefore, a reduced volume of water beneath, which could limit overwintering habitat.

Data: We obtained monthly averages of daily minimum, mean, and maximum air temperatures at the Barrow airport for the period 1950–2004 from the Western Regional Climate Center, Reno, Nevada (http://www.wrcc.dri.edu/summary/climsmak.html).

Indicators: We developed indices of mean summer temperatures from June through September (Barrow.avgT.sum) and both mean and mean minimum winter temperatures from December through March (Barrow.avgT.win, Barrow.minT.win). Average summer temperatures show high interannual variability (negative autocorrelation at 2-year lag) and a significant increasing trend over time at the rate of 0.26°C / 10 yr ($t = 2.56$, $p = 0.013$; Figure 32). However, the long-term trend was not linear and showed decreasing temperatures early in the

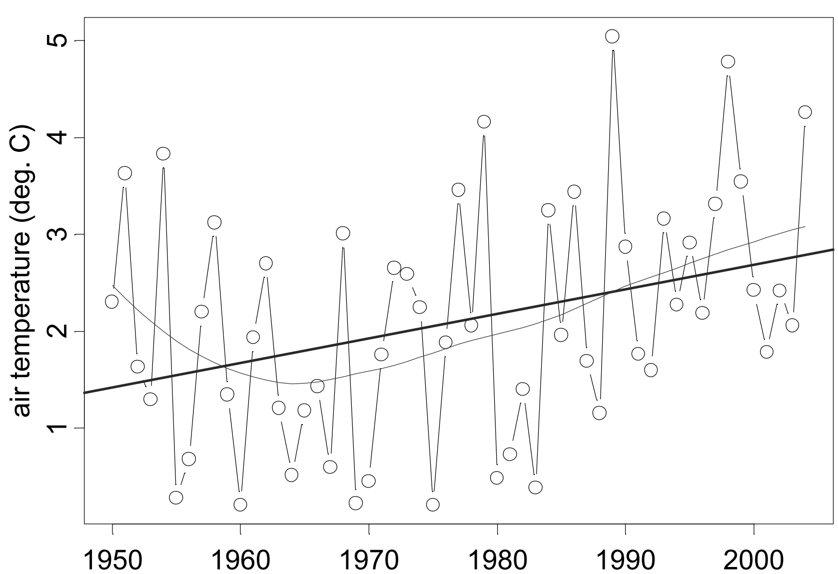


Figure 32. Summer (June–September) mean temperatures at Barrow airport from 1950–2004, with linear fit and LOWESS smooth fit.

time series with unusually low temperatures in the 1960s and early 1970s (Figure 32). Winter average temperatures show high interannual variability and have increased at an average rate of 0.56°C / 10 yr ($t = 4.36$, $p < 0.001$) since 1950 (Figure 33). Winter minimum temperatures were relatively weakly correlated with summer temperatures ($r = 0.285$, $p = 0.035$) because of differences in the long-term trend. Unlike summer temperatures, winter temperatures were relatively cold throughout the early part of the time series.

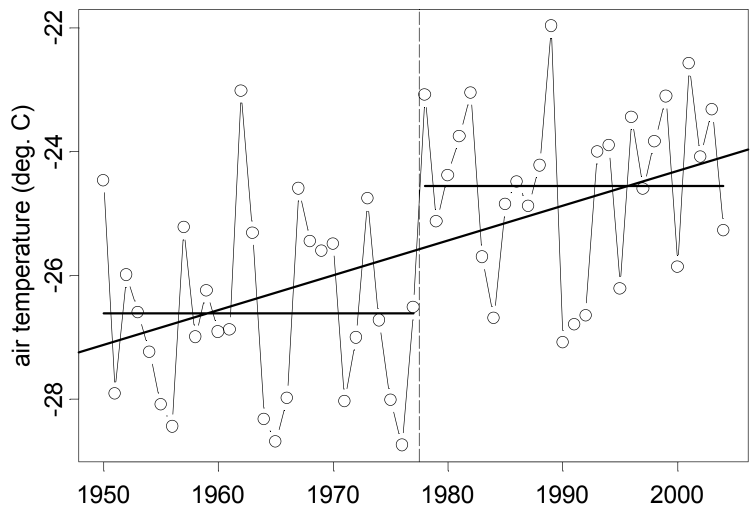


Figure 33. Winter mean temperatures at Barrow observatory from 1950–2004, with linear fit and one-step intervention model fit. The one-step intervention model provides a better statistical fit.

Although the linear model fit the winter data reasonably well, there appears to be a step increase in winter temperatures in the late 1970s corresponding to the well-known climate regime shift of 1976–1977 in the Bering Sea and Gulf of Alaska. This shift was confirmed by an intervention analysis that showed a highly significant increase of 2°C after 1977 ($p < 0.001$). The one-step model resulted in a better statistical fit with a much lower residual sum of squares and coefficient of determination (RSS = 349, $R^2 = 0.35$ vs. RSS = 396, $R^2 = 0.26$ for the linear model), as well as a smaller value of the small-sample Akaike Information Criterion (AICc), a commonly used model selection criterion (Difference in AICc values: AICc = 6.97). The model suggests that winter temperatures increased by approximately 2°C after the regime shift.

Assessment: Summer air temperatures at Barrow are strongly correlated with summer sea-surface temperatures ($r = 0.54$, $p = 0.008$) and provide an alternative index of temperature conditions experienced by Arctic cisco in nearshore waters. Unlike sea-surface temperatures, air temperatures are available prior to 1982. Winter air temperatures can affect Arctic cisco only indirectly through their impact on ice conditions. Warmer winter temperatures after 1976–1977 may imply less ice on the Colville River with potential effects on overwintering Arctic cisco.

RIVER DISCHARGE

Rationale: River discharge and winds are the primary drivers of coastal oceanographic processes and determine the salinity and temperature conditions encountered by coastal fishes. The input of freshwater by major rivers is likely to affect primary and secondary productivity along the coast by diluting nutrient-rich marine waters and affecting stratification and nutrient fluxes across the shelf. Salinity may also have direct effects on the distribution of Arctic cisco during their migrations and in summer feeding areas.

Data: The largest rivers draining into the summer feeding areas of Arctic cisco in the central Beaufort Sea are (from west to east) the Colville, Kuparuk, and Sagavanirktok rivers. Although the Colville has the largest discharge, streamflow of the Colville River has only been monitored by the USGS since August 2002. However, peak discharge rates, the date of peak discharge during breakup, and the date of first flowing water have been recorded every year since 1992 and for selected years between 1962 and 1977. Daily streamflow has been recorded at a station on the mainstem of the Sagavanirktok River near Pump Station 3 on the Trans-Alaska Pipeline (Figure 1) since September 1982 (http://waterdata.usgs.gov/nwis/). Summer season streamflows in the Sagavanirktok delta were monitored in 1982 and from 1985 through at least 1993 (Bjerklie 1994). Another USGS gauge station was maintained on the Sagavanirktok River near Sagwon from August 1970 through September 1978. A USGS station on the Kuparuk River has been maintained since June 1971 to measure daily mean streamflow.

Indicators: Based on the availability of data, we used two annual indices of discharge rates. We computed average daily discharge rates for the entire spring–summer period from May 1 through September 30. Discharge outside this period was typically zero or close to zero (but was not always measured prior to May 1). The resulting indicators covered the period 1972–2004 for the Kuparuk (Kup.dis) and 1983–2004 for the Sagavanirktok (Sag.dis).

Assessment: We compared daily and/or monthly discharge rates for the relatively brief periods of overlap between rivers. First, we examined agreement among daily discharge rates at four measuring stations on three rivers in the region. The correlation coefficients and the number of overlapping days (all p-values < 0.001, not adjusted for autocorrelation) are shown in Table 6.

Table 6. Correlations among daily discharge rates of major rivers draining into the western Beaufort Sea and number of overlapping days (in parentheses). Both Sagwon and Pump Station 3 are located on the Sagavanirktok River. Colville (Umiat) leads discharge at Pump Station 3 by 2 days and at Sagwon by 3 days. Other correlations correspond to lag 0.

Locations	Kuparuk River	Pump Station 3
Sagwon	0.48 (2680)	
Pump Station 3	0.53 (8066)	
Colville River	0.70 (772)	0.68 (772)

There is relatively poor agreement between Kuparuk River and Sagwon and between Kuparuk River and the Pump Station 3 (Table 6). However, correlation coefficients between the Kuparuk River and both Sagavanirktok River stations are about the same, suggesting that the two Sagavanirktok River stations have similar variability. Unfortunately, there was no overlap between measurements at Sagwon and measurements at Pump Station 3. There is relatively good agreement between daily Umiat (upper Colville River) and Kuparuk discharge rates (r = 0.70), which suggests that Kuparuk discharge may be a reasonable proxy for freshwater discharge into the summer feeding grounds of Arctic cisco in the region (which range from at least the Colville delta to the Sagavanirktok delta). The Colville River is responsible for by far the largest volume of freshwater input to the Beaufort Sea with a drainage area of 20,670 square miles (above

Nuiqsut), compared to 3,130 square miles for the Kuparuk River and 1,860 square miles for the Sagavanirktok River above Pump Station 3.

Total annual discharge rates show fair agreement between the Kuparuk River and Pump Station 3 on the Sagavanirktok River (r = 0.50) for 1983 – 2004 (through Julian date 272), but moderate agreement between Kuparuk and Sagwon (r = 0.37) for 8 years of overlap from 1971 to 1978.

Because Pump Station 3 has the most complete record for the Sagavanirktok River, we assessed whether discharge variability near Pump Station 3 is reflective of overall Sagavanirktok discharge as measured in the delta. Detailed measurements of mean stream flow in several channels of the river delta were obtained during 1983–1993 for the summer period June 25–September 13 (Julian dates 175–255), and we compared the mean flow in the delta with discharge at Pump Station 3. Because the latter is a considerable distance upstream, we lagged the discharge estimate by one week (June 18–September 6 at Pump Station 3). The resulting index was highly correlated with the estimated stream flow in the delta for the period 1983–1993 (r = 0.80), suggesting that discharge at Pump Station 3 is a good estimator of final discharge.

SEA-SURFACE TEMPERATURES

Rationale: Sea-surface temperatures are likely to affect Arctic cisco throughout their life history and particularly during the 5–8 years they spend feeding in the western Beaufort Sea. Temperatures may impact prey availability and have been shown to affect the growth of Arctic cisco (Fechhelm et al. 1993).

Large-scale Sea-surface Temperature (SST)

An index of large-scale summer (July–September) sea-surface temperature in the western Beaufort Sea (Colville–Prudhoe Bay region) was developed as described above in the section,"Environmental Indicators for the Coastal Beaufort Sea, Regional Sea-Surface Temperatures."

Local SST (Prudhoe Bay)

- **Data**: Time series of nearshore sea-surface temperatures are available for several index stations in the Prudhoe Bay region, which have been sampled repeatedly as part of the Prudhoe Bay fish monitoring project since 1982 (e.g., Fechhelm et al. 2006). These data were extracted from tables and data appendices in annual (1988–2005) reports to BP Exploration, Inc. by LGL (1990, 1991, 1992, 1993, 1994a, 194b, 1995, 1996, 1997, 1999a, 1999b). The most complete data series available were those for two fyke net stations located on the east and west side of Prudhoe Bay, respectively (Stations 214 and 218). Temperatures (and salinities) at these stations were measured daily from the surface to the bottom in 50-cm increments throughout much of the summer season. We used temperatures at the surface (0 m) because lower layers were sampled less frequently. Water depth was very shallow at each station, and there were relatively few measurements at 1 m or deeper. The number of days with surface measurements ranged from 33–62 days. Near-daily measurements were available from at least one of the stations for 1988 through 2004, with the exception of 1997 and 1999–2000 (Figures 34 and 35). From 1988 to 1995, temperature and salinity were measured at the onshore and

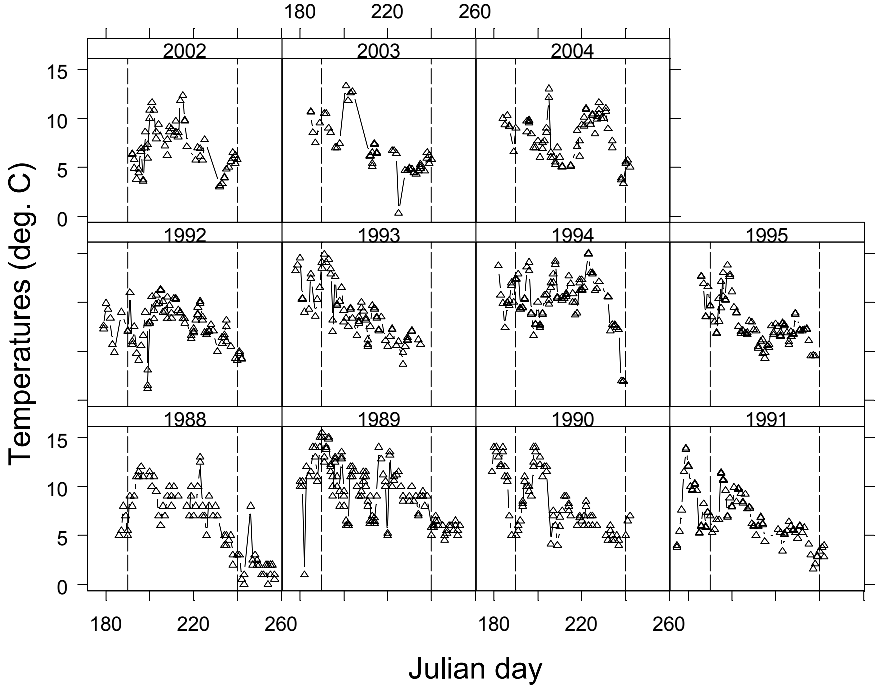


Figure 34. Daily sea-surface temperature measurements at station 214 in Prudhoe Bay, 1988–2004 (except 1996–2001). Vertical dashed lines indicate July 10 (Julian day 190) and August 29 (Julian day 240).

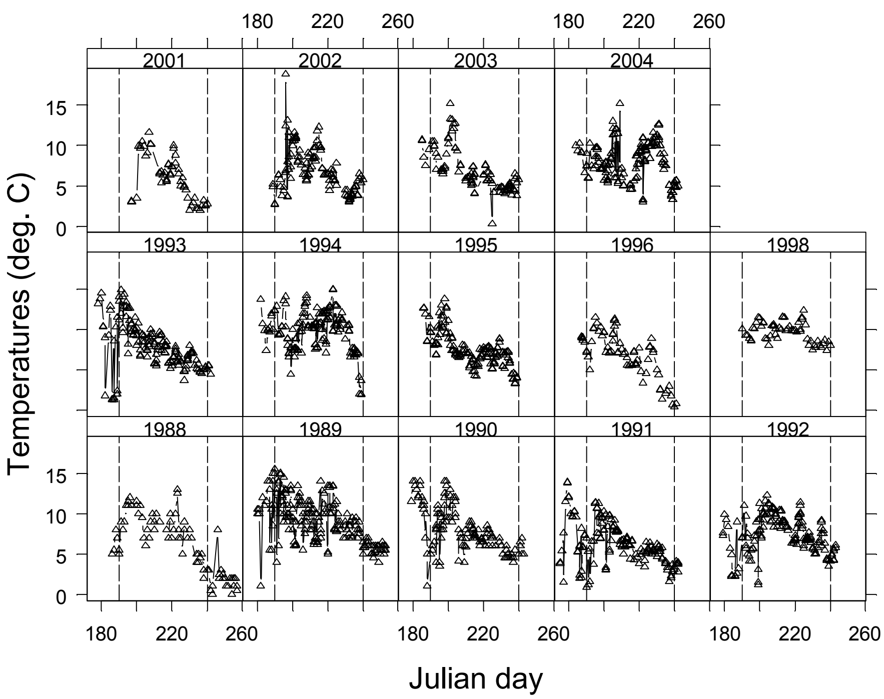


Figure 35. Daily sea-surface temperature measurements at station 218 in Prudhoe Bay, 1988–2004 (except 1997, 1999, 2000). Vertical dashed lines indicate July 10 (Julian day 190) and August 29 (Julian day 240).

offshore ends of the net. Offshore and onshore measurements generally were very similar. Correlations between the series of daily onshore and offshore temperatures ranged from 0.93 at station 214 in 1992 to 0.99 or higher in most cases. Therefore, we averaged onshore and offshore measurements for years where both measurements were taken (1988–1995). Temperatures typically increased rapidly in the spring and decreased gradually over the course of the season.

Indicators: Local SST, Prudhoe Bay (PB.SST). An annual index of local SST for a single station (Station 214) in Prudhoe Bay was obtained by combining several data sources:

- 1982–1986 average summer temperatures for Station 214 were taken from the 1991 LGL report (LGL 1993). No data are available for 1987.
- Daily temperatures were averaged over the period July 10–August 29 for all years with data between 1988 and 2004. Only measurements from the "onshore" side of the fyke net were used because the onshore records were more complete and were very strongly correlated with "offshore" measurements (correlation in a given year ranged from 0.97 to 1.0).
- Three years had no data for Station 214 (1996, 1998, 2001). Mean summer temperatures for these three years were estimated by linear regression of annual mean temperatures at Station 214 on annual mean temperatures at station 218 ($R^2 = 0.89$, $n = 10$, $F = 62.2$, $p < 0.0001$).

Assessment: Seasonal trends in daily temperatures were very similar between stations (compare Figures 34 and 35). Similarly, interannual variability in mean summer temperatures showed very similar patterns at the three stations and the trends were strongly correlated with each other (pair-wise correlation coefficients ranging from 0.79 to 0.94; Figure 36). The good agreement suggests that average temperatures are representative of a larger area rather than reflecting small-scale, local conditions. As shown above, the index based on nearshore measured SSTs agrees reasonably well with the Colville summer index based on large-scale, interpolated data (Figure 27).

SEA-SURFACE SALINITY, PRUDHOE BAY

Rationale: Salinity in the summer feeding grounds of the nearshore Beaufort Sea affects the distribution of Arctic cisco and may have indirect effects on food availability and, hence, on growth and survival of Arctic cisco. However, few studies have examined effects of salinity. Laboratory studies have not shown any direct effects of salinity on growth or condition of Arctic cisco over a range of salinities from 6–30 ppt (Fechhelm et al. 1993).

Data: The only long-term measurements of salinity in the coastal region of the western Beaufort Sea were taken at fyke net stations that were sampled during the Prudhoe Bay fish monitoring project between 1982 and 2005. The data were collected in the same manner as the temperature data described above and were treated in the same way to develop annual indices of mean summer salinity. Daily salinity measurements are shown for two stations in Figures 37 and 38. Seasonal patterns in salinity differed among years. The most common pattern was

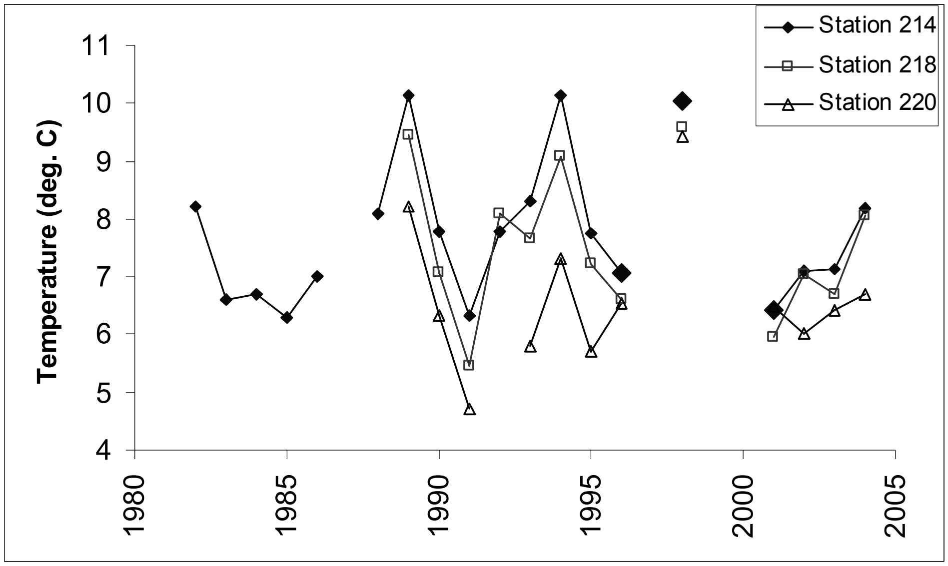


Figure 36. Trends in mean summer sea-surface temperature at three nearshore stations sampled in the Prudhoe Bay region, 1982–2004. Large symbol sizes denote estimates based on linear regression of temperatures at station 214 on temperatures at station 218.

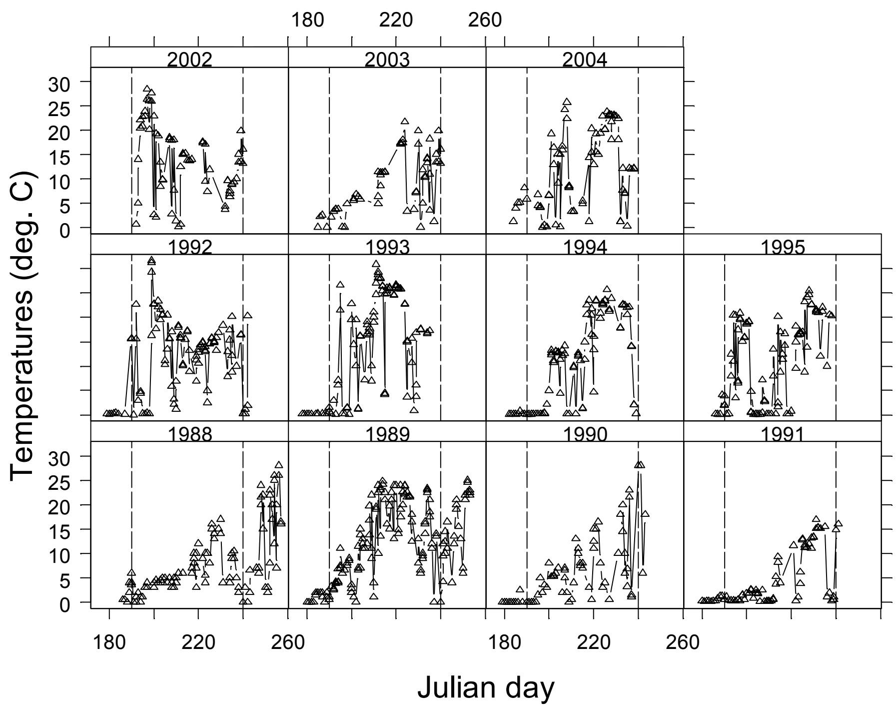


Figure 37. Daily sea-surface salinity measurements at station 214 in Prudhoe Bay, 1988–2004 (numerous missing years). Vertical dashed lines indicate July 10 (Julian day 190) and August 29 (Julian day 240).

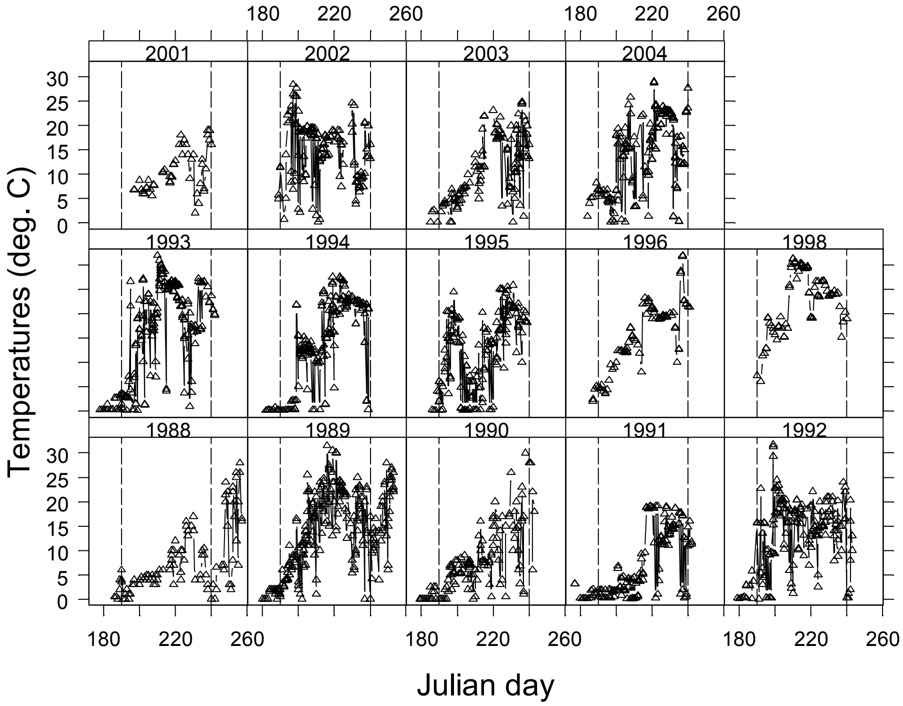


Figure 38. Daily sea-surface salinity measurements at station 218 in Prudhoe Bay, 1988–2004 (numerous missing years). Vertical dashed lines indicate July 10 (Julian day 190) and August 29 (Julian day 240).

characterized by low early-season salinities that increased gradually to the highest salinities later in the season and typically peaked sometime in August. The number of days with salinity measurements ranged from 30 to 61 and, as for temperature, we averaged salinities over the period from July 10 to August 29 to obtain a consistent annual index.

Indicator: An annual index of local sea-surface salinities for Station 214 in Prudhoe Bay was obtained in the same way as the index of local SST described above. Mean summer salinities for 1996, 1998, and 2001 were estimated by a linear regression of annual mean salinity at Station 214 on annual mean salinity at station 218 (n = 10, $R^2 = 0.90$, F = 76.4, $p < 0.0001$). The resulting index of annual mean surface salinities for station 214 (PB.sal) is shown in Figure 39, along with mean summer salinities at station 218 and 220.

Assessment: Seasonal trends in daily salinities were very similar between stations (compare Figures 37 and 38), although the absolute salinities differed considerably. Interannual variability in mean summer salinities showed very similar patterns at the three stations and the trends were strongly correlated with each other (pair-wise correlation coefficients ranging from 0.83 to 0.96; Figure 39). The good agreement suggests that average salinities are representative of a larger area, rather than reflecting only small-scale, local conditions.

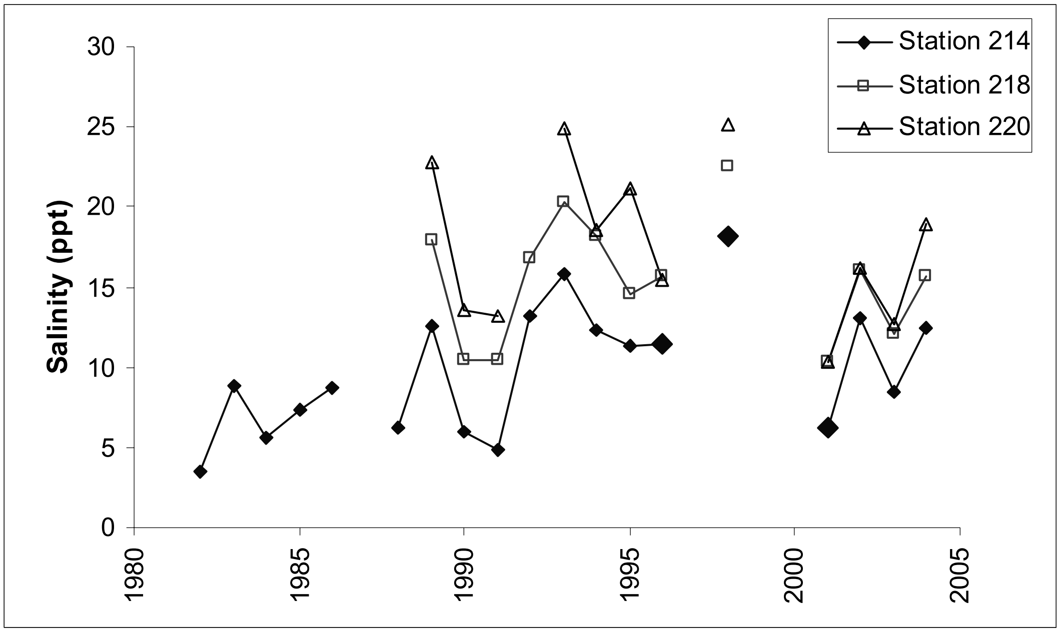


Figure 39. Trends in mean summer sea-surface salinity at three nearshore stations sampled in the Prudhoe Bay region, 1982–2004. Large symbol sizes denote estimates based on linear regression of salinities at station 214 on salinities at station 218.

FALL SALINITIES, COLVILLE DELTA

Rationale: The distribution of Arctic cisco in the Colville delta appears to be affected by salinity (Moulton 1994). Therefore, salinity may directly affect catch rates of Arctic cisco in the fishery and the apparent abundance of Arctic cisco in the Colville, as estimated from catch rates (see below). This local effect of salinity on catch rates should be accounted for when examining the impacts of other environmental or human factors on Arctic cisco abundances.

Data: Local salinities have been measured at three sites in the Niġliq channel of the Colville River during harvest monitoring studies from 1986–2005 (Moulton and Seavey 2005). Salinities were measured throughout the fishing season, which typically lasts from mid- or late-October through late-November. Sites were located near the major fishing areas along the Upper Niġliq, in the Nanuk Lake region, and in the Niġliq delta. Salinities were measured from the surface to the bottom in 0.5-m increments (Moulton and Seavey 2005). Salinity profiles generally show a freshwater surface layer extending to 1 or 2 m below the ice overlaying a higher salinity bottom layer (Figure 6 in Moulton and Seavey 2005). Salinities in the bottom layer typically were uniform between about 3 m and the bottom (3.5–5 m in the Upper Niġliq area, 5.5–7 m in the other areas).

Indicators: To obtain an index of annual average salinity, we first averaged salinities between 3 and 4 m as a measure of bottom-layer salinity. We then averaged any replicate salinity measurements in this depth range by year, Julian date, and area for the three main sampling areas (610, 650, 670). Finally, we fit an analysis of covariance model of salinity with year and location as factors and Julian date as a numeric covariate. Julian date was included in the model to capture the average seasonal trend in salinity, which was very pronounced. We fit a series of models that included polynomials of increasing order for Julian date and found that a fifth-order polynomial provided an adequate fit to the seasonal pattern (higher-order terms did not significantly improve the fit) (Appendix I, Model IV.5.1). The seasonal trend indicated a strong increase in salinity during the first part of the fishing season and a more gradual increase thereafter. The estimated year effect (Figure 40) was used as an indicator of annual average salinities in the Colville delta during the fall fishery (Col.sal).

Assessment: The model explained over 97% of the variability in salinity and showed a very strong seasonal increase in salinity, as well as a strong decrease in salinity from the Niġliq delta to the upriver stations (Figure 40). Although we were unable to fit interaction terms, the large coefficient of determination ($R^2 = 0.97$) suggests that the estimated year effect provides a very good index of interannual variability in salinity. The estimated annual average salinities varied by as much as 15 ppt and showed a pronounced 5–7 year cycle, which should provide sufficient contrast to test the effects of local salinity on average annual catch rates.

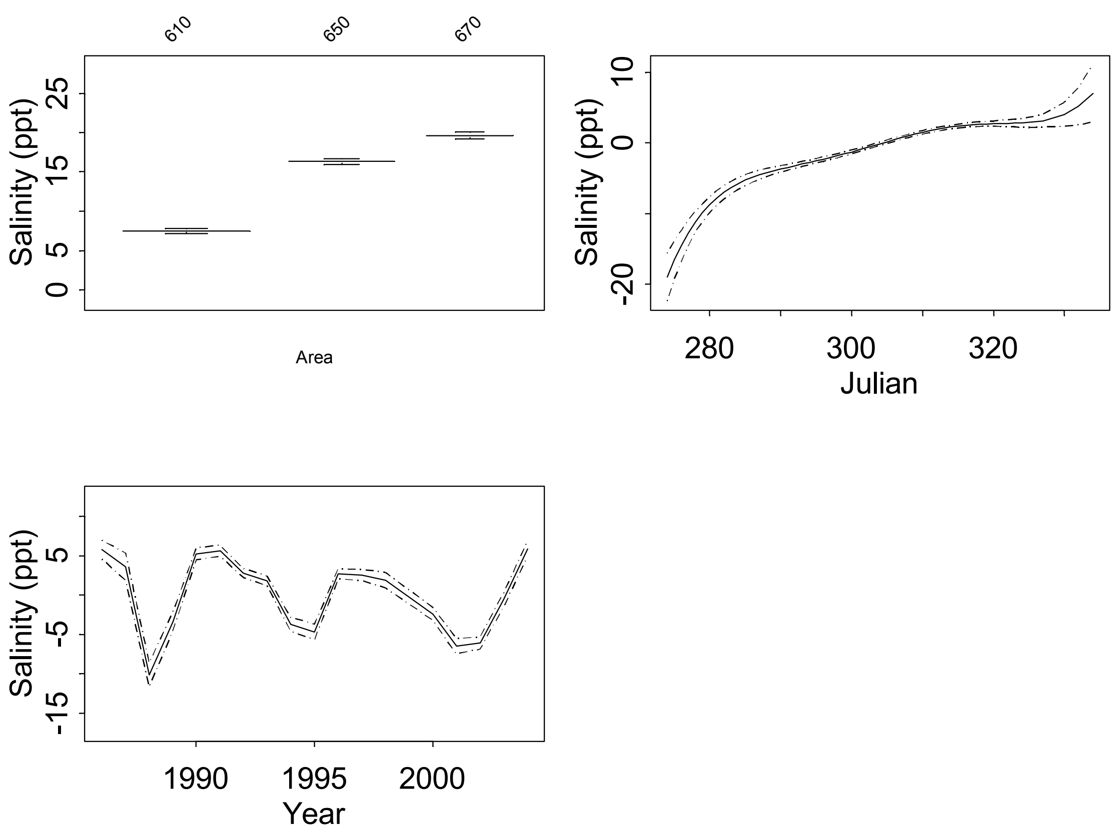


Figure 40. Modeled trends in average salinity at 3–4 m below the ice. Differences among the three main fishing areas (Area), a seasonal trend (Julian), and interannual trends (Year) were estimated using an analysis of covariance model with a fifth-order polynomial term for Julian day. Fishing areas are 610: Upper Niġlik, 650: Nanuk Lake region, and 670: Niġliq delta. All y-axes are on the same relative scale; top left panel shows actual average salinities by region, other panels show deviations from regional averages with 95% confidence bands.

ICE CONCENTRATIONS

An index of spring (July) and fall (October) ice conditions in the Colville–Prudhoe Bay region was developed as described above under “Environmental Indicators in the Beaufort Sea.”

ARCTIC OSCILLATION

Rationale: The Arctic Oscillation Index (AO) reflects the major mode of Arctic climate variability and is based on daily 1000-millibar-height air pressure anomalies poleward of 20°N. Variability in the Arctic Oscillation reflects the location and intensity of the dominant pressure system over the Arctic, which determines the strength and direction of large-scale winds. Atmospheric circulation over the Arctic is dominated by cyclonic (counter-clockwise) winds in the upper atmosphere. Periods of above normal sea-level pressure (negative AO or “cool” phase) lead to weaker westerlies in the upper atmosphere (particularly during winter) and anti-cyclonic (clockwise) winds at the surface. This implies strong easterly winds along the Beaufort Sea coast and enhanced flow in the clockwise Beaufort Sea gyre. Recent periods with a strong negative AO include 1977–1988 and 1998–2001, and the negative phase was considered the “normal” pattern until recently. Periods of below normal sea-level pressure (positive AO or “warm” phase; e.g., 1989–1997 and 2002) are associated with strong westerlies (cyclonic winds) in the upper atmosphere and near the surface. These strong westerlies push against the clockwise Beaufort Sea gyre. The positive phase tends to bring increased precipiation to Alaska, resulting in larger freshwater discharges into the coastal Beaufort Sea. Arctic cisco are primarily affected by associated changes in summer winds with more frequent westerly (west to east; i.e. unfavorable) winds during the positive phase of the AO and stronger easterly, or favorable, winds during the negative phase. Changes in the large-scale circulation of the Beaufort Sea gyre also may affect the advection of nutrients and organisms onto and along the shelf.

Indicator: Monthly values of the Arctic Oscillation index were obtained from the Climate Prediction Center, National Weather Service, NOAA (http://www.cpc.ncep.noaa.gov). Because the AO has the largest variability during the cold season, we computed the December through March average as an indicator of interannual variability in large-scale atmospheric circulation. The AO index was below the average for the reference period for most of the time series and shifted to mostly positive values in 1989 (Figure 41).

FLOW THROUGH THE BERING STRAIT

Rationale: The inflow of relatively warm water through Bering Strait affects the distribution and abundance of marine fish species in the eastern Chukchi Sea (Barber et al. 1997) and possibly in the western Beaufort Sea. Such effects may result from direct advection of more southerly species along the Beaufort Sea coast, as well as from indirect effects on fish due to changes in the distribution and abundance of prey.

Indicator: We obtained estimated annual water transport (in Sverdrup) through Bering Strait from Roach et al. (1995) for 1950–1998. Transport through Bering Strait was largely above average through 1968, largely below average from 1969–1988, and variable since then (Figure 42). A sharp increase in northward flow from 1988 to 1989 coincided with the marked step-increase in the Arctic Oscillation at the same time.

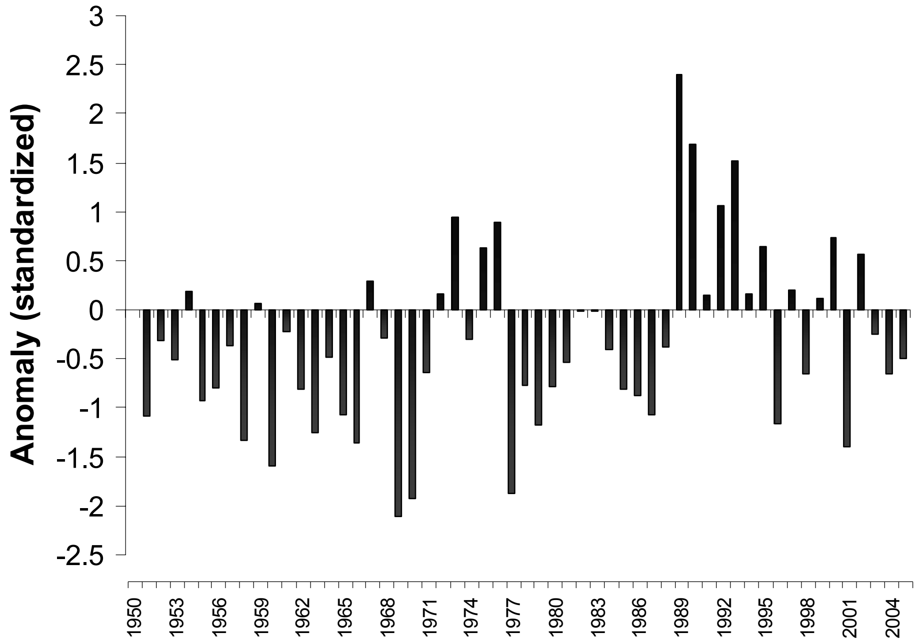


Figure 41. Standardized anomalies (differences from long-term mean) of the (previous) December–March average of the Arctic Oscillation index, 1951–2005.

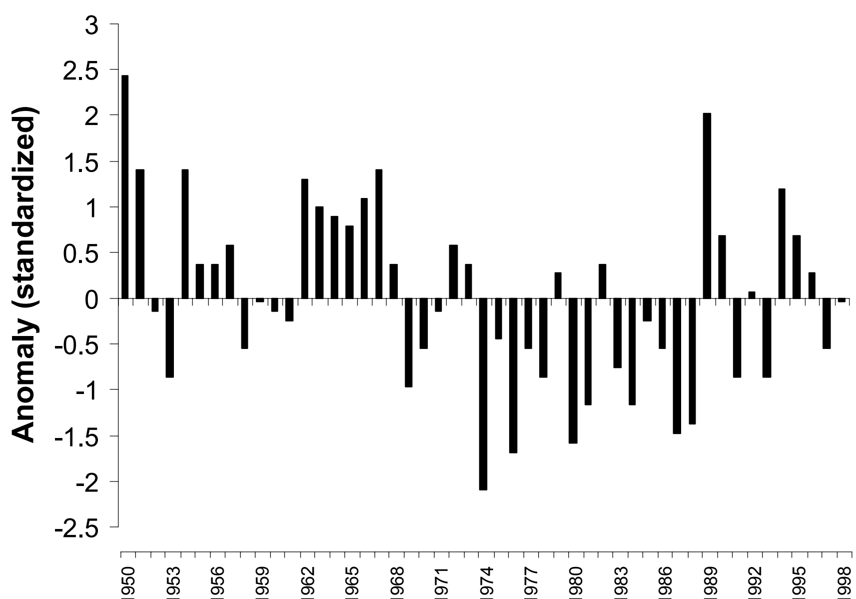


Figure 42. Standardized anomalies (differences from long-term mean) of northward flow through Bering Strait, 1950–1998.

COMBINED CLIMATE INDEX

As for the Mackenzie region, we developed a climate index for the Colville River region that combines indices of temperature, ice conditions, and discharge (all of which were moderately to strongly correlated with each other) into a single index as described below under '*Principal Components Analysis of Climate Variables*'.

BIOLOGICAL INDICATORS

ARCTIC CISCO SPAWNING ABUNDANCES, MACKENZIE RIVER

Few quantitative assessments have been undertaken of spawner abundance in the Mackenzie River. Harvest data (numbers caught) were collected by the Inuvialuit Harvest Study in various communities in the Inuvialuit Settlement Region in 1999 and 2001–2003 (Stephenson 2004) and by the Gwich'in Harvest Study from 1995–2003 (http://www.grrb.nt.ca/Harvest_Study.html). However, neither sampling program was sufficient to develop a quantitative index, and they only covered a few years. A monitoring program on the Peel River, a large tributary to the Mackenzie River, began in 1999. The study did not result in a useful quantitative index of abundance but did provide information on length, weight, sex composition, and age composition (see below).

ARCTIC CISCO ABUNDANCES IN THE COASTAL BEAUFORT SEA

At least three monitoring programs provide abundance indices for Arctic cisco in the Beaufort Sea: (1) a 1988–1991 U.S. Fish and Wildlife Service monitoring program off the coast of the Arctic National Wildlife Refuge (ANWR) (Fruge et al. 1989; Palmer and Dugan 1990; Underwood et al. 1992, 1994), (2) the Endicott development fish monitoring program in an around the Prudhoe Bay region from 1985–present (Fechhelm et al. 2006), and (3) a harvest monitoring program in Nuiqsut that has estimated catch rates of Arctic cisco since 1985 in both the subsistence and commercial fisheries in the Colville River (Moulton and Seavey 2005). We developed indices of age-0 abundances off ANWR, age-0 and age-1 abundance in the Prudhoe Bay region, and abundances of subadults (ages 5–8) in the Colville River.

Age-0 Arctic Cisco off the Arctic National Wildlife Refuge

Rationale: The four-year monitoring program off the coast of the Arctic National Wildlife Refuge is the only multi-year sampling program for Arctic cisco in marine waters outside the Prudhoe Bay region. This program provides independent estimates of year-class strength to compare to the estimated year-class strength at Prudhoe Bay.

Data: The program used fyke nets to sample a number of stations in Camden Bay (Simpson Cove), Kaktovik Lagoon, Jago Lagoon, and Beaufort Lagoon. Sampling locations varied among years, but the first three areas were sampled every year, while Beaufort Lagoon was sampled in 3 of the 4 years. Within each area, one or two stations were sampled consistently throughout the sampling period.

Indicators: For those stations with sufficient coverage, we developed indices of age-0 abundance (details of the analysis are summarized in Appendix J). First, we estimate the proportion of age-0 fish at each station based on the length-frequency distribution, which typically showed more or less complete size separation between age-0 and older fishes. We then multiplied the total catch at each station by the estimated proportion of age-0 fish to obtain the estimated number of age-0 fish by station / year / day. CPUE of age-0 Arctic cisco varied greatly throughout the season and among years. We obtained an annual index of year-class strength for each station by computing the average CPUE as cumulative catch divided by cumulative effort between Julian dates 200 and 258. This period was chosen because most stations were sampled daily over this period in some or all years. Sampling effort prior to Julian date 200 (July 19) was typically zero except in Beaufort Lagoon. In Beaufort Lagoon, we included Julian dates 190–258 because a considerable number of fish were caught prior to Julian date 200. Cumulative CPUE values by station show the highest CPUE in 1990 and the lowest CPUE in 1991 at all stations (Table 7).

Table 7. Estimated cumulative catch per unit effort (CPUE) of Arctic cisco at various stations off the Arctic National Wildlife Refuge by year.

Year	BL02	JL12	JL14	KL05	KL10	SC01	SC04
1988		13.56	18.76	4.86	19.12	2.29	
1989	52.54	19.92	8.63	1.20	2.09	1.49	6.99
1990	466.21	438.69	488.13	433.07	30.84	14.17	43.11
1991	7.57	0.06	0.47	0	0	0.05	0

To obtain a single index of annual CPUE, we fit a linear model (ANOVA) of log(CPUE) on year and station and used the estimated annual means ("year effect") as our final CPUE index (Appendix I, Model V.II.1). The resulting indices on the log-scale and on the back-transformed CPUE scale (ANWR.age0) are summarized in Table 8.

Table 8. Cumulative log(CPUE) and CPUE of Arctic cisco at off the Arctic National Wildlife Refuge by year as estimated by a two-factor ANOVA of log(CPUE) by year and station.

.	1988	1989	1990	1991
Log-scale	2.556	2.027	4.924	0.377
CPUE	16.859	9.521	189.496	1.020

Assessment: The ANWR index is too short for a meaningful analysis but it can serve as a check on Arctic cisco CPUEs estimated at Prudhoe Bay. The CPUEs of age-0 Arctic cisco at Prudhoe Bay may be low even if their CPUE off ANWR is high because age-0 fish may be transported by currents to ANWR but not as far as the Prudhoe Bay region. However, any strong year-class in Prudhoe Bay should also be caught in large numbers off ANWR on their westward migration. For the 4 years that were sampled both off ANWR and in Prudhoe Bay (1988–1991), there was very good agreement between CPUEs in the two areas (Pearsons's correlation:

r = 0.998, p = 0.0023). However, the high correlation and statistical significance are largely driven by the unusually large CPUE in 1990, which was apparent both at Prudhoe Bay and off ANWR. A comparison of the indices on the log-scale shows good agreement (r = 0.912, p = 0.088; Figure 43), although the rank order of CPUEs for 1988 and 1990 was reversed in Prudhoe Bay compared to ANWR.

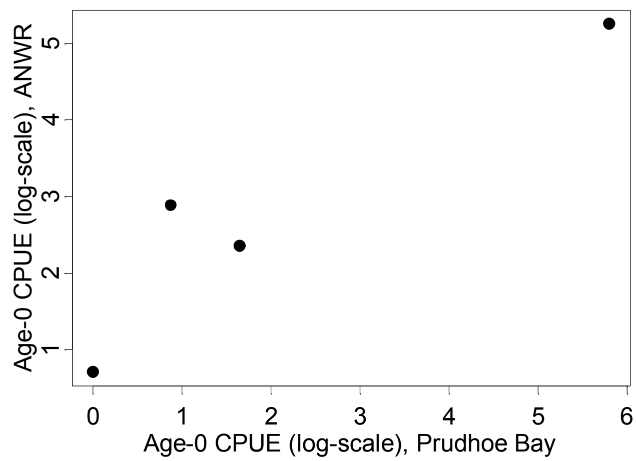


Figure 43. Comparison of age-0 catch-per-unit-effort of Arctic cisco at Prudhoe Bay and off the Arctic National Wildlife Refuge, 1988–1991.

Juvenile Arctic Cisco in Prudhoe Bay

Recruitment Indices

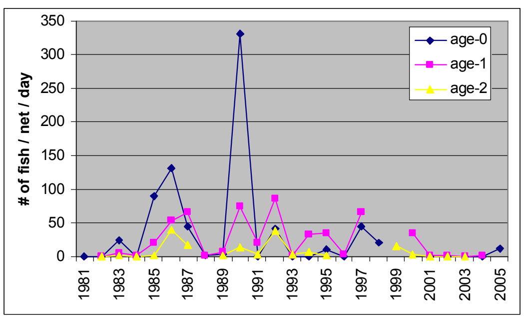
Rationale: Before Arctic cisco become available to be caught in the Colville River fishery they must successfully recruit to the Colville–Prudhoe Bay region. Recruitment may be estimated at different ages and reflects the influence of different mechanisms on the initial abundance of a cohort (year-class) and its cumulative survival to different ages. Recruitment at younger ages provides early indices of abundance and may be used to predict the abundance of Arctic cisco entering the fishery many years later (e.g., Moulton and Seavey 2004). Recruitment of young-of-the-year fishes to Prudhoe Bay also provides the primary index for testing the effects of wind, other environmental factors, and human factors on Arctic cisco abundances in the Colville region. Unless otherwise noted, recruitment refers to an index of Arctic cisco abundance at age-0 (i.e.,young-of-year Arctic cisco).

Data: Indices to estimate year-class strength of Arctic cisco recruiting to the Colville River were based on age-specific abundances in the Prudhoe Bay region. Prudhoe Bay abundances should provide a suitable index for the Colville River because all or most of the young Arctic cisco arriving in Prudhoe Bay are believed to overwinter in the Colville River as subadults, although younger age classes may overwinter in the Prudhoe Bay region. We obtained estimates of age-0, age-1, and age-2 abundances in the Prudhoe Bay region from various reports that summarize the results of annual fish surveys conducted in the Prudhoe Bay region between 1981 and 2005. All surveys were conducted using fyke nets as described in Fechhelm et al. (2005).

A complete recruitment failure of age-0 fish in 1981 was reported by Moulton (1989). Catch-per-unit-effort (fish/net/24hr) at ages 0, 1, and 2 for 1982–2002 were taken from Table 4 in Fechhelm et al. (2003). Catch-per-unit-effort during 2003–2005 were estimated from data provided in Fechhelm et al. (2004, 2005, 2006). Because of low abundances in 2003–2004, ages 1 and 2 were reported as a single cohort (combined CPUE). Therefore, we allocated CPUEs for these years between age-2 and age-1 fishes based on the average ratio of age-2 to age-1 CPUE from the 1982–2001 year classes. First, we estimated Age-2 CPUE by multiplying age-1 CPUE in the previous year by 0.37. Second, we computed age-1 CPUE as the difference between the combined CPUE and the estimated age-2 CPUE. In 2005, CPUEs were reported for age-1 and age-2+ fishes. The CPUE for age-2 fish was estimated as for 2003 and 2004.

Indicators: We used two alternative indicators of recruitment in subsequent statistical analyses. These included the estimated abundances of age-0, age-1, and age-2 fishes as described above, and a combined index of recruitment (Figure 44).

- CPUE in Prudhoe Bay by year class (PB.age0, PB.age1, PB.age2). We used CPUE values for the youngest 3 age classes on an untransformed (number of fish / net / year of age-0, age-1, and age-2 fish) scale. Because the distribution of CPUE of young Arctic cisco was highly skewed, we used log-transformed CPUE values for most analyses.



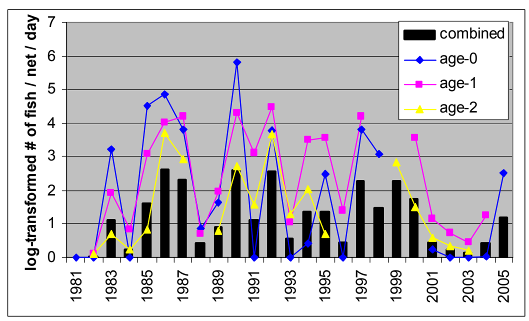


Figure 44. Catch-per-unit-effort (CPUE, left) and log-transformed CPUE (right) for three age groups of Arctic cisco in Prudhoe Bay by year class. Black bars denote combined index of year-class strength (mean of normalized age-specific indices).

The age-specific indices showed similar interannual patterns of variability, suggesting that survival rates from age-0 to age-1 and from age-1 to age-2 are relatively constant. Therefore, we combined age-specific indices into a single index of year-class strength (combined recruitment index [PB.YCS]). In some years, no age-0 fish were sampled because of either low abundance or late arrival (i.e., after sampling terminated), but fish from the same year class were sampled in subsequent years as age-1 or age-2 fish. This suggests using age-1 and age-2 abundances to improve the estimate of young-of-the year recruits. However, if low CPUE values of age-0 fish resulted from late arrivals, as was the case in at least some years, the combined index would be biased low in these years due to “false” zeros. There was no indication of a systematic bias in age-0 CPUEs in scatterplots of age-2 or age-1 CPUE against age-0 CPUE. The combined index was computed by (1) log-transforming each age-specific index [time series of log(CPUE+1)] , (2) standardizing each series by dividing each value by the standard deviation of the index across only those years for which all three CPUE indices were available, and (3) averaging the standardized indices within each year across the three year classes. In years where one or two of the age-specific indices were not available, the combined index was computed across the available age-specific indices.

Recruitment Anomalies

Rationale: There is overwhelming evidence that recruitment of age-0 cisco to the Prudhoe Bay region is primarily driven by wind-induced coastal currents (Fechhelm and Griffiths 1990, Fechhelm et al. 2006). Therefore, to examine effects of other variables on recruitment, the effect of wind-driven transport should be accounted for first. We accounted for wind effects by modeling recruitment indices as a function of easterly winds, similar to Fechhelm and Griffiths (1990).

Data: Data needed to fit the model are the recruitment indices described above and indices of easterly winds described in section 'Environmental Indicators for the Coastal Beaufort Sea: Winds'. We used either age-0 recruitment or the combined recruitment index as dependent variables and one of the three wind indices as independent variable (2 model-based indices of easterly winds during summer and average easterly winds at Deadhorse during summer).

Indicators: We modeled recruitment as a function of easterly winds using a linear regression with a threshold (no recruitment if winds are westerly on average) as described in Chapter 5 (Hypothesis Testing). The average east-west wind speed at Deadhorse during summer was a much better predictor of recruitment than either of the model-based average alongshore wind indices. Therefore, we used the residuals (difference between observed and modeled values) from a model of age-0 recruitment as a function of average summer wind speed at Deadhorse (Age0.resid). For comparison, we also computed residuals from a model of the combined recruitment index as a function of winds (YCS.resid) (Figure 45). We refer to the residuals, which reflect variability in recruitment after accounting for the effects of wind-driven transport, as recruitment anomalies.

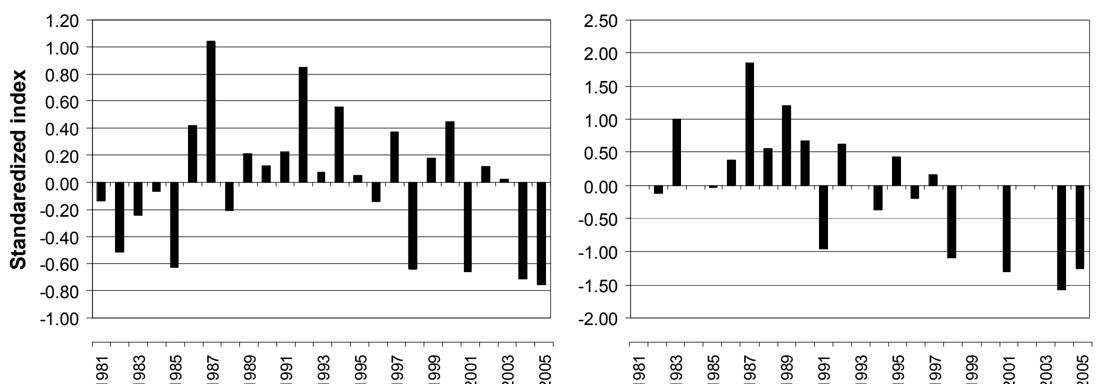


Figure 45. Recruitment anomalies of Arctic cisco at Prudhoe Bay, 1981–2005. Anomalies were defined as residuals from linear regressions of combined recruitment index (see text, left panel) and age-0 recruitment (right panel) on average easterly wind speeds during summer (July 1 and August 31) at Deadhorse. Recruitment anomalies for the age-0 index are missing in 1999 and 2000 and were equal to 0 in 1981, 1984, 1993, 2002, and 2003.

Assessment: Both recruitment anomalies show a decreasing trend in recruitment since 1987, after accounting for the effects of wind-driven transport. After two complete recruitment failures in 2002 and 2003 as a result of primarily westerly winds, intermediate and strong easterly winds were observed in 2004 and 2005, respectively. However, recruitment was much lower than expected in these years based on our model, resulting in strong negative recruitment anomalies in both 2004 and 2005.

Juvenile and Subadult Arcitc Cisco in Prudhoe Bay

Rationale: The Prudhoe Bay area is an important part of the summer feeding area for the Arctic cisco population overwintering in the Colville River. Therefore, catches in the Prudhoe Bay region should provide an index for the abundance of subadult Arctic cisco for this population, which is one of the primary variables of interest in the study.

Data and Indicators: Two sources of data are available to estimate abundances of Arctic cisco in the Prudhoe Bay region

- Age 2+ CPUE (PB.age2+): This index was based on catch rates (CPUE) of Arctic cisco in the fish monitoring program conducted in the Prudhoe Bay region in most years from 1985–2005. Catch rates for age 2+ Arctic cisco were reported in Fig. 1.8 in Fechhelm et al (2006) and provide an index of the abundance of a number of age classes (age 2 through adult) combined.
- Mark-recapture estimates of abundance (PB.MR): Mark-recapture estimates of abundance have been reported for 1982–1984 and 1988–1993 based on tag returns reported in the Prudhoe Bay fyke net monitoring program.

Assessment: These indicators, although roughly comprising the same age classes were negatively correlated with each other ($N = 5$ years of overlap, $r = -0.81$, $p = 0.093$) and were poorly correlated with indices of abundance obtained from the Colville River fishery (see below). The large negative correlation likely resulted from uncertainty in the individual indices, suggesting that one or both indices are not good indicators of abundance. Thus, their use in analyses may be problematic. Furthermore, the indices are available for a limited number of years only and were insufficient for many of the statistical analyses.

Subadult Arctic Cisco in the Colville River

Abundances of Subadult Arctic Cisco

Rationale: The abundance of subadult Arctic cisco in the Colville River is the primary variable of interest because it determines the catch rates and total harvests of Arctic cisco in the Nuiqsut subsistence fishery. This study was prompted, in large part, due to concerns over declining abundances as reflected in poor catches from 1998–2002. The major goal of the study is to examine the causes of variability in Arctic cisco abundance. Therefore, appropriate indicators of abundance are critical to identifying these causes.

Data: Fishery data for the commercial and subsistence fisheries were obtained from data tables in several fishery reports (Moulton and Seavey 2004, 2005; Moulton et al. 2006) or were provided by Larry Moulton (MJM Research).

Indicators:

- CPUE of Arctic cisco by age (ages 5–8) in the Niġliq channel fishery (Col.age5, Col.age6, etc.). Arctic cisco have traditionally been caught in several regions of the Colville delta. While the spatial distribution of fishing effort has shifted towards the outer delta over time, three areas of the Niġliq channel have been fished consistently from 1982–2005 (Figure 3) and show consistent patterns of variability in CPUE (Appendix K). Therefore, the average catch rates in the Niġliq channel by age for each fishing season (as reported in Moulton and Seavey, 2005) were used as indices of Arctic cisco age-specific abundances in the Colville river during the fall fishery (Figure 46). When lined up by year class, the age-specific indices were moderately to strongly correlated with each other (Table 9).
    - To obtain the age-specific indices, total CPUE was assigned to age-specific cohorts based on age compositions estimated from the commercial fishery. This assumes that the age composition in the Niġliq channel is the same as in the outer Colville delta, where the commercial fishery takes place (Moulton and Seavey 2005).

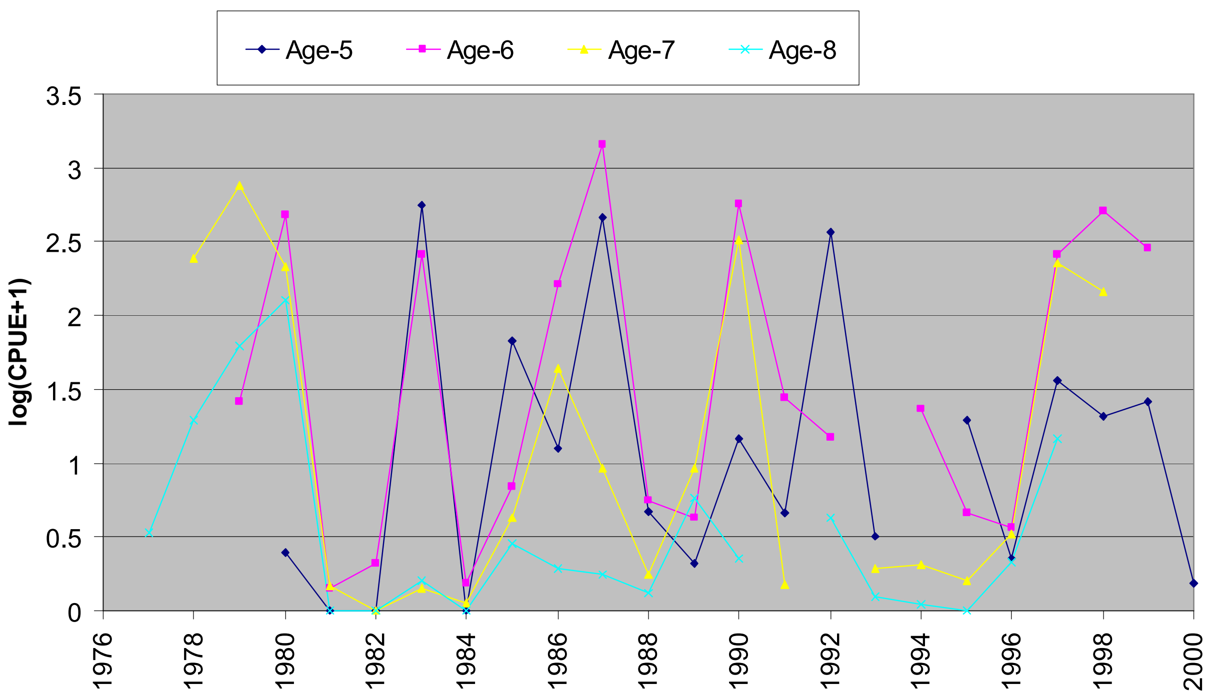


Figure 46. CPUE of three age classes of Arctic cisco in the Niġliq channel fishery aligned by year class (1977–2000).

Table 9. Spearman rank correlations among age-specific CPUEs for Arctic cisco caught in the Niġliq channel fishery, Colville River, 1982–2005.

Age Class	Age 5	Age 6	Age 7
Age 6	0.693	1.0	
Age 7	0.370	0.628	1.0
Age 8	0.298	0.504	0.867

- CPUE of Arctic cisco by age (ages 5–8) in the commercial fishery (Helm.age5, Helm.age 6, etc.). Estimates of total CPUE and age composition for the commercial fishery are available from 1984–2002, which were used to obtain age-specific CPUEs for ages 5–8 (Moulton and Seavey 2004) (Figure 47). When lined up by year class, the age-specific indices were moderately to strongly correlated with each other (Table 10).
    - o The indices from the commercial fishery also were strongly correlated with age-specific CPUE indices from the Niġliq channel fishery (with rank correlations ranging from 0.38 to 0.90), suggesting that both provide good indicators of abundance.

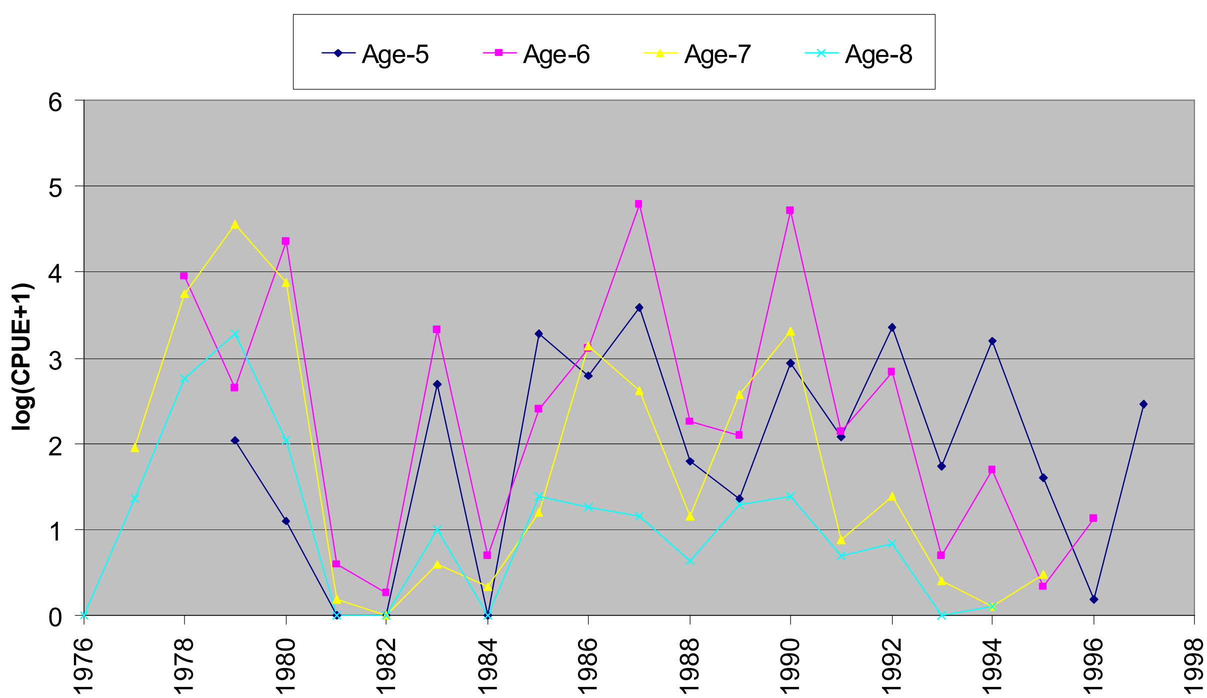


Figure 47. CPUE of Arctic cisco in the commercial fishery by age for year classes, 1976–1997.

Table 10. Spearman rank correlations among estimates of age-specific CPUEs for Arctic cisco caught in the commercial Colville River fishery, 1984–2002.

Age Class	Age 5	Age 6	Age 7
Age 6	0.682	1.0	
Age 7	0.378	0.805	1.0
Age 8	0.399	0.754	0.905

- Total Arctic cisco CPUE, Niġliq channel (Niġliq.ARCS). We used the total CPUE of all age groups combined in the Niġliq channel fishery as reported in Moulton and Seavey (2005) for 1985–2005 (no data for 1999) as an index of overall Arctic cisco abundance in the Colville delta during fall (Figure 48). Catches generally consist of several year classes from ages 4–9, and the abundance index reflects abundances of all subadults during a given year, as opposed to the abundance of a given cohort.

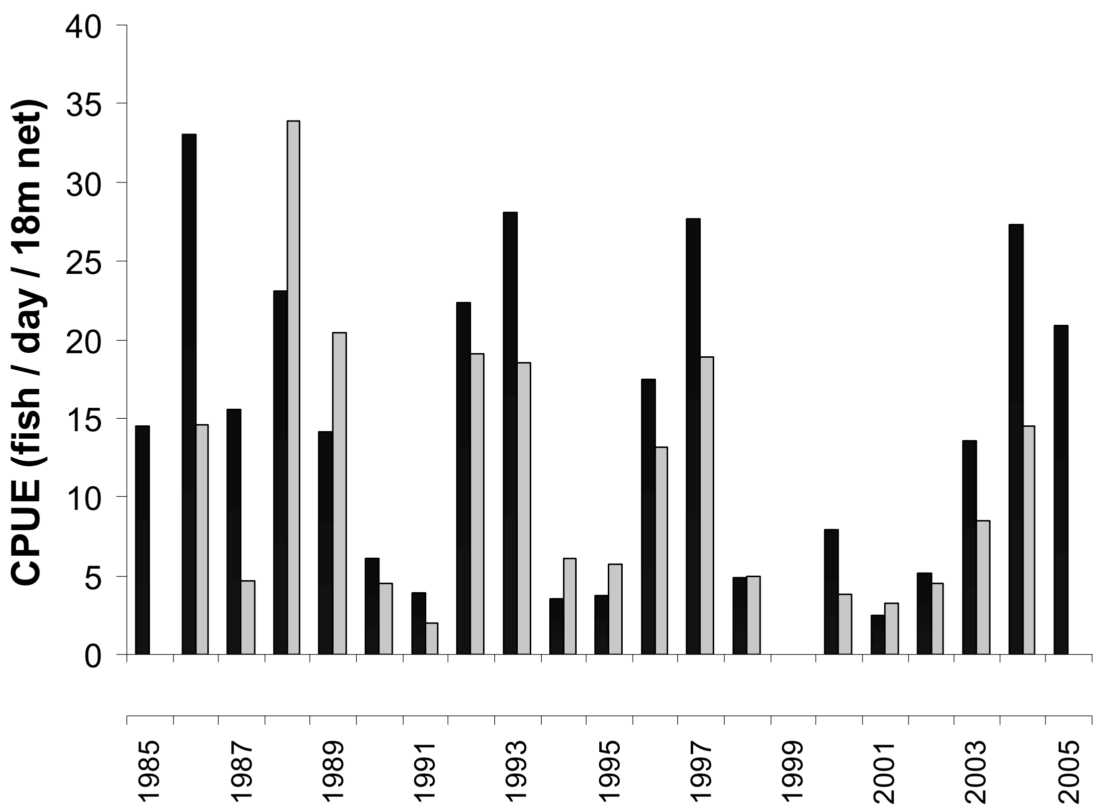


Figure 48. Total average CPUE (black) of Arctic cisco caught in the Niġliq channel fishery, 1985–2005 (except 1999), by year of capture and CPUE adjusted for effects of local salinity and seasonal depletion (gray, no data for 1985 and 2005).

- Salinity-adjusted CPUE, Niġliq channel (Nig.ARCS.sal). An analysis of catch rates (CPUE) of Arctic cisco in relation to local salinity in the Colville River suggested a strong influence of salinity on CPUE. Therefore, variability in CPUE, both for individual nets and the average annual CPUE, may vary due to interannual variability in salinity conditions. To take these interannual fluctuations into account, we adjusted annual average CPUE estimates for the effects of salinity. A closer examination showed that daily average CPUE values differed non-linearly with salinity and decreased during the course of the fishing season, possibly as a result of local depletion by the fishery. Therefore, daily CPUE values were modeled as a function of year (to estimate annual mean CPUE), Julian date (to account for depletion) and daily average salinity (to account for effects of salinity). The model is described in Chapter 5 (Hypothesis Testing: model III.1.3) and the estimated yearly means from the model were used as an adjusted index of annual average CPUE in the Niġliq channel fishery (Figure 48).
- Effort-adjusted CPUE, Helmericks fishery (Helm.ARCS.adj). Total CPUE of Arctic cisco in the commercial fishery is significantly negatively correlated with total effort in the fishery (Figure 49), $r = -0.451$ between effort and log(CPUE), $p = 0.0058$, presumably reflecting local depletion in years with large effort. Therefore, CPUE values were adjusted by removing the estimated effect of differences in total effort (see Appendix K). The effect of effort was estimated using a regression of annual average log (CPUE) on total effort from 1967–2002. The adjustment had the effect of slightly increasing CPUE values when effort was low and decreasing CPUE values when effort was high, but interannual variability in CPUE was very similar (Figure 50).
- Arctic cisco CPUE, Helmericks fishery (Helm.ARCS). Total CPUE of Arctic cisco in the commercial fishery was quantified from 1967–2002 and provides the single longest index of Arctic cisco abundance that is currently available (Figure 51). Unfortunately, data on the commercial fishery have not been available for the most recent years and it is uncertain whether the fishery is active.
- Effort-adjusted CPUE, Niġliq channel (Nig.ARCS.adj). We found a similar but weaker (and non-significant) relationship between total effort and CPUE in the subsistence fishery in the Niġliq channel. A detailed examination of daily catch rates shows some evidence that local depletion is occurring in some years (Appendix K). Therefore, we used the same approach to compute an effort-adjusted CPUE index for the Niġliq channel fishery. The resulting index was very similar to the raw index (not shown). It should be noted that the salinity-adjusted CPUE index for this fishery described above also implicitly accounts for a decrease in CPUE over the season (by incorporating Julian date as a covariate).

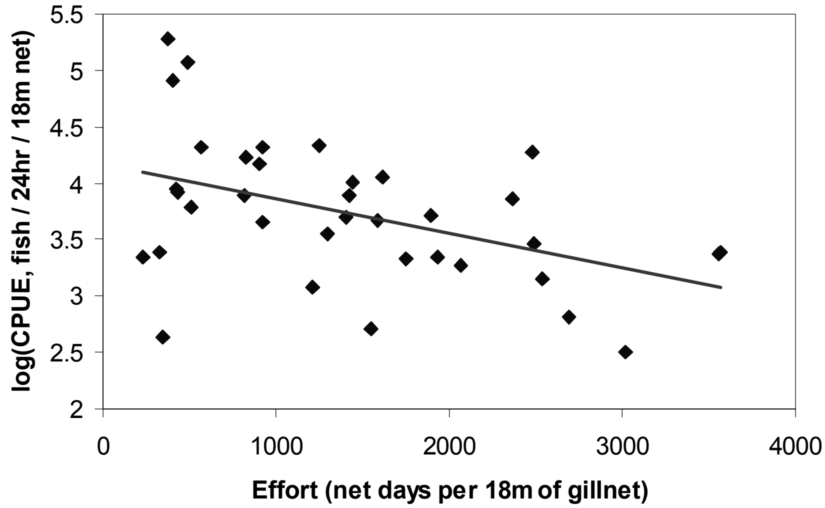


Figure 49. Annual average catch rate (log-transformed CPUE) versus total fishing effort in the commercial Arctic cisco fishery, 1967–2002, with linear regression line (p = 0.0058).

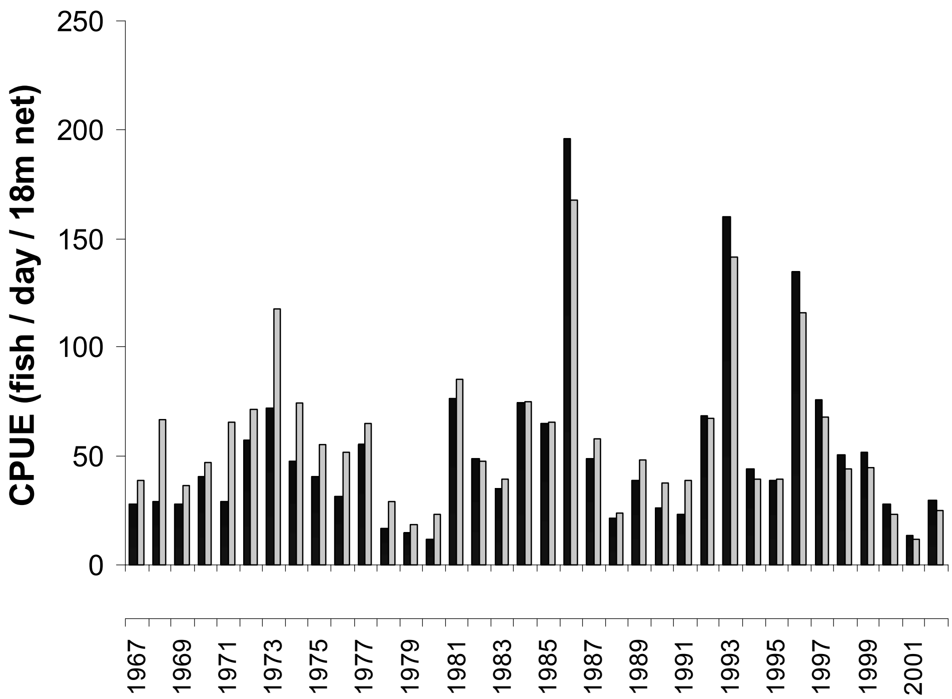


Figure 50. Total average CPUE (black) of Arctic cisco caught in the commercial fishery, 1967–2002, by year of capture, and CPUE adjusted for effects of differences in total annual effort (gray).

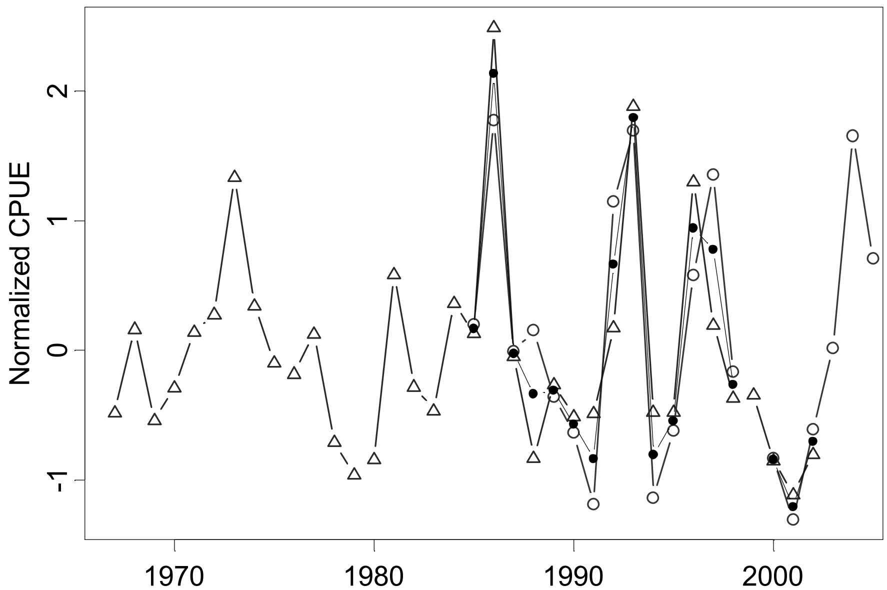


Figure 51. Adjusted CPUE index for Arctic cisco caught in the commercial fishery (triangle), the subsistence fishery (open circle) and combined index for period of overlap (solid circle).

- Combined CPUE index (Col.ARCS). We obtained an index of abundance for all years in which catch rates for either the commercial or subsistence fishery (or both) were monitored (1967–2005). This measure was achieved by combining the two indices into a single index, after first normalizing each index relative to the period of overlap (1985–2002 except 1999). The index combines the normalized index for the commercial fishery for 1967–1984 (and 1999), with an average of the two normalized indices for the period of overlap (1985–2002, except 1999, correlation = 0.82, $p < 0.001$), and the normalized Niġliq index for 2003–2005 (Figure 51).
- Area-specific CPUE for three major fishing areas (CPUE.610, CPUE.650, CPUE.670). To examine variability in CPUE on a smaller scale, we used area-specific CPUE estimates for three of the major fishing areas that were sampled in most years since 1985 (Area-specific data for 2005 was not yet available). CPUE values for the three areas (Upper Niġliq = areas 610 and 630, Nanuk Lake = 650, and Niġliq delta = 670) were computed by dividing total catch in a given year by total effort.
- Mark-recapture estimates of abundance, Colville River (Col.MR). Estimates of abundance based on tag returns from the Colville fall fishery were reported for nine individual years between 1976 and 1988 in Moulton et al. (1990). However, the index is poorly correlated with other indices and is not sufficiently long for a meaningful statistical analysis.

Assessment: Catch rates of Arctic cisco in the commercial and subsistence fisheries provide the only long-term abundance indices for the Colville River population of Arctic cisco besides catch rates in the fyke net monitoring program in Prudhoe Bay. The indices reflect variability in the abundance of subadults (primarily ages 5–8), but may be affected by a number of factors. For example, as shown above, catch rates are affected by variations in local salinity and may be affected by other environmental variables. Catch rates, although based on nets of the same mesh size, are likely to be affected by differences in fishing location, differences among individual fishermen, differences in soak time, differences in net length, and other differences among individual nets. We assume that such differences contribute to random variability in the data but that no source of systematic bias occurs. Another important factor affecting catch rates of Arctic cisco is variability in average size-at-age among years because the gill nets used in the fishery are highly size-selective. In particular, small size-at-age in some recent years may have resulted in underestimates of the abundance of age classes 5 and 6, many of which may have been too small to be caught.

In general, there is good agreement between indices from the commercial and subsistence fisheries (Figure 51), in spite of very different fishing areas. This agreement suggests that the indices reflect real variability in abundance of Arctic cisco in the region. However, both indices are similarly affected by differences in size-at-age and other factors. The only fishery-independent indices available are catch rates of age-2+ or age-3+ Arctic cisco at Prudhoe Bay and mark-recapture estimates of abundance for some earlier years (see above). However, both of these indices include fishes age-2 and older and, not surprisingly, are uncorrelated with catch rates of Arctic cisco in the Colville River. Age-specific indices, on the other hand, suggest that there is reasonable agreement between catch rates of juvenile cisco in the Prudhoe Bay region and catch rates of Arctic cisco in the Colville River for 5, 6, 7, or 8 years later.

Better estimates of abundance and recruitment than those based on simple CPUE indices could be obtained by fitting an age-structured population dynamics model to the data. Such a model would follow each cohort (all fish from a given year-class) over time and, by making some assumptions about natural mortality and emigration, would reconstruct recruitment and population abundance. However, largely because of the small number of age classes caught in the fishery and the difficulty of separating natural mortality from emigration, we were unable to fit an age-structured model (see also discussion in Chapter 6).

Abundance (CPUE) Anomalies

Rationale: Because of the importance of wind to recruitment and subsequent abundance of Arctic cisco in the Colville delta, we adjusted CPUE-based indices of abundance for the estimated effects of wind. The resulting indices reflect the remaining variability in abundance that is unrelated to the effects of wind. These indices will be used to examine effects of other environmental and human factors on Arctic cisco abundances.

Data: The data used to adjust for the effects of wind on abundance are the CPUE values described above and indices of easterly winds described in "Environmental Indicators for the Coastal Beaufort Sea, Winds." We used total CPUE in each of the two fisheries and the combined CPUE from the commercial and subsistence fishery to derive abundance anomalies (i.e., abundances larger or smaller than the long term average).

Indicator: We modeled CPUE as a function of easterly wind speeds and examined residuals from the best models as an index of anomalously low or high CPUEs.

- CPUE anomalies, Helmericks fishery (CPUE.H.anom). We modeled total adjusted CPUE from the commercial fishery (Helm.ARCS.adj) as a function of winds and then used residuals from the model (CPUE anomalies = difference between observed and modeled CPUE values) as indicator of unusually low or high catch rates (Figure 52). Because the Deadhorse wind series was too short, we used average easterly wind speed estimated from NCEP/NCAR winds (Wind.avg) as described above. CPUE anomalies were computed as residuals from a simple linear regression of the commercial CPUE (Helm.ARCS) on a weighted average of mean summer wind speeds (July 1–August 31) at three lags: 5, 6, and 7 years earlier. Wind speed at each lag was weighted by the average proportion of 5-, 6-, and 7-year-olds in the catches (30, 41, and 21%, respectively). Before computing anomalies the commercial CPUE values were log-transformed. The index shows pronounced negative anomalies in CPUE in recent years, particularly in 2001.
- CPUE anomalies, Niġliq fishery (CPUE.Nig.anom). An index of abundance anomalies based on estimated CPUE in the Niġliq channel fishery was developed similarly to the indices for the commercial fishery described above. CPUE anomalies were computed as residuals (Figure 53) from a simple linear regression of the effort-adjusted Niġliq channel CPUE (Niġliq.ARCS.adj) on a weighted average of mean summer wind speeds at Deadhorse (Jul 1–Aug 31) at four lags: 5, 6, 7, and 8 years earlier. Wind speed at each lag was weighted by the average proportion of 5-, 6-, 7-, and 8-year-olds in the catches (30, 41, 21, and 8%, respectively, as estimated from age composition in commercial fishery).
- Combined CPUE anomalies (CPUE.Col.anom). An index of abundance anomalies based on the combined CPUE index for the subsistence and commercial fishery from 1967–2005 was developed as for the separate fisheries described above. CPUE anomalies were computed as residuals (Figure 54) from a simple linear regression of the combined CPUE (Col.ARCS) on a weighted average of mean summer wind speeds at Deadhorse (July 1–August 31) at four lags: 5, 6, 7 and 8 years earlier. Wind speed at each lag was weighted by the average proportion of 5-, 6-, 7-, and 8-year-olds in the catches (30, 41, 21, and 8%, respectively, as estimated from age composition in commercial fishery).

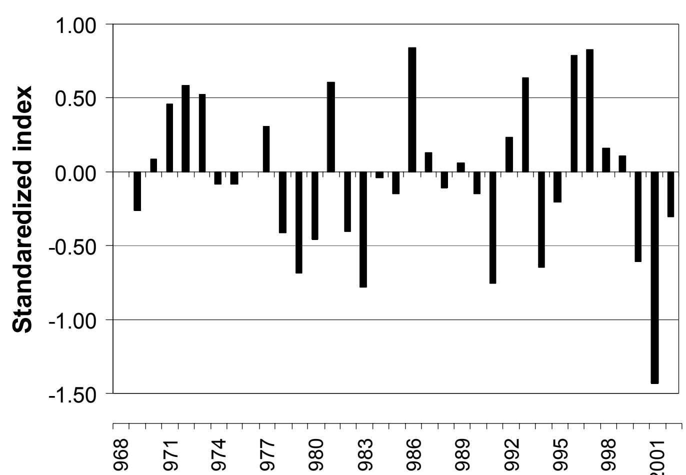


Figure 52. CPUE anomalies (log-transformed) in the commercial fishery, 1968–2002 based on effort-adjusted CPUEs, which were further adjusted for effects of wind. For details, see text.

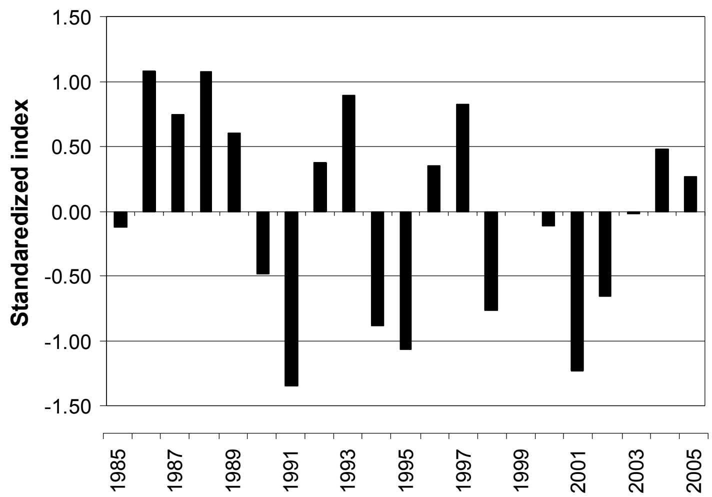


Figure 53. CPUE anomalies in the subsistence fishery, 1985–2004, after adjusting for wind effects, 1985–2005. For details, see text.

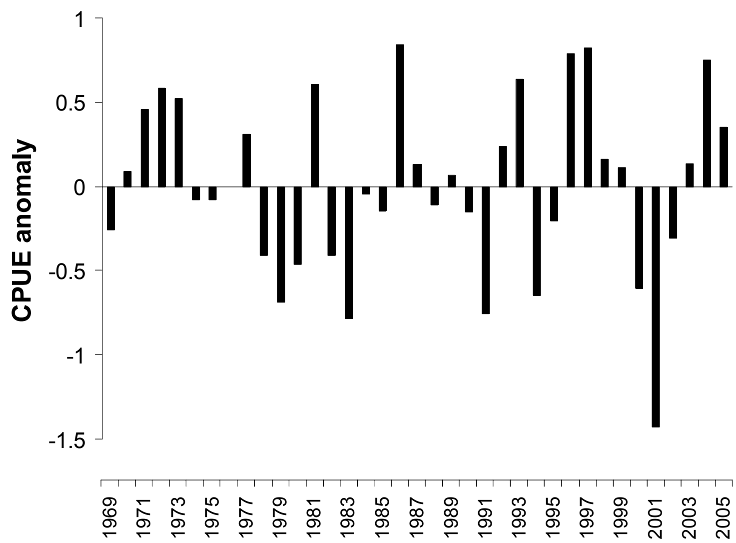


Figure 54. CPUE anomalies (log-transformed scale) in the Colville River fishery (based on combined CPUE in subsistence and commercial fishery) after adjusting for wind effects, 1969–2005. For details, see text.

Assessment: The above CPUE anomalies are based on the known relationship between easterly winds in the Beaufort Sea and recruitment to Prudhoe Bay, as well as the relationship between the number of age-0 recruits and catches in the fishery 5–8 years later. While both of these relationships are well established and highly significant, the relationship between winds and total CPUE in the fishery (i.e., several age-classes combined) is relatively weak and not always significant. This relationship may be a result of variable survival from age-0 to the time fishes are caught in the fishery and to differences in age composition among years. The regressions of total CPUE on a weighted measure of wind speed use the average age composition across all years, whereas the true age composition varies from year to year. Furthermore, we had to use NCEP/NCAR winds for modeling CPUEs prior to 1976. These wind indices show a much weaker relationship with recruitment than measured winds at Deadhorse. Finally, it is unclear whether the effort-adjusted CPUE values used in this analysis are more appropriate indicators of abundance than the un-adjusted values. Therefore, the CPUE anomalies should be interpreted with caution and values in specific years are likely to be highly uncertain because of the many sources of uncertainty.

SURVIVAL OF ARCTIC CISCO FROM AGE-0 TO AGE-5

Survival Rate Anomalies Based on Age-Specific CPUE in Commercial Fishery

Rationale: While recruitment of age-0 fishes to Prudhoe Bay is directly related to wind speed and other factors, abundances of other age-classes are a function of the initial number of recruits and their subsequent survival rate. To examine the effects of environmental or human factors on these survival rates, which ultimately determine the abundance of adult Arctic cisco, we developed indices of survival from the early juvenile stage to the maturing stages (age 5–7).

Data: Survival anomalies were based on relative changes in abundance from age-0 recruits to adult Arctic cisco caught in the commercial Colville fishery.

Indicators: We computed linear regressions of age-5, age-6, and age-7 CPUE on the combined recruitment index (Figure 55) and on age-0 CPUE (Figure 56). The residuals from

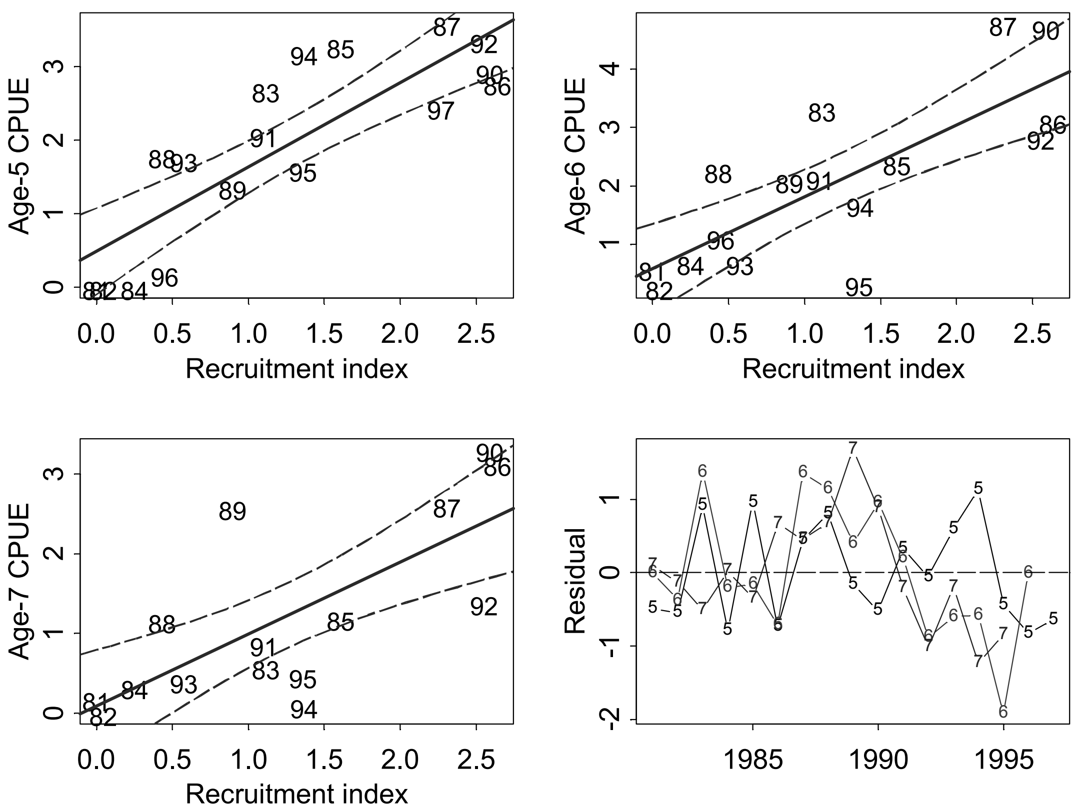


Figure 55. Relationship between CPUE at various ages in the commercial fishery and the combined recruitment index of the corresponding year class (Linear regression lines with 95% confidence bands). Time series of residuals are shown in the lower right for each age class (ages 5–7).

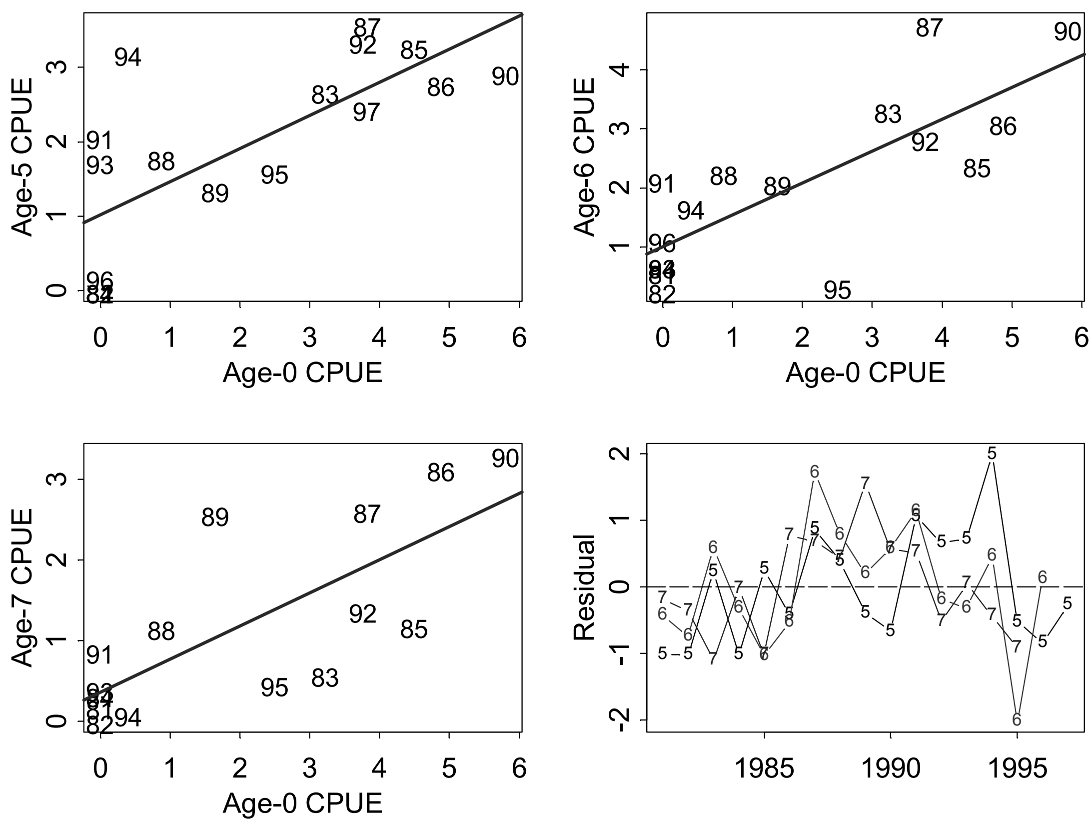


Figure 56. Relationship between CPUE at various ages in the commercial fishery and the age-0 recruitment index (age-0 CPUE) of the corresponding year class. Time series of residuals are shown in the lower right (numbers 1–3 denote ages 5–7, respectively). Years with zero CPUE on the x-axis (overlapping labels) include ’81, ’82, ’84, ’91, ’93, and ’96 (’02 and ’03 are not included because no data on CPUE of older ages is available for these year classes).

these fits (survival rate anomalies = difference between observed and expected CPUE) show similar patterns for ages 5 and 6, and ages 6 and 7, respectively, but correlations are moderate for these age groups and are negative between survival anomalies at age-5 and age-7 (Table 11).

Table 11. Spearman rank correlations among age-specific survival rate anomalies of adult Arctic cisco caught in the commercial Colville River fishery.

Age Class	Age 5	Age 6	Age 7
Age 5	1.0		
Age 6	0.316	1.0	
Age 7	-0.315	0.531	1.0

In relating adult CPUE estimated from the commercial fishery to recruitment at age 0, we did not fix the intercept at zero (although zero recruitment should result in zero CPUE for older ages) because some recruitment may occur after age-0. This is suggested by the estimated intercepts, which are all larger than zero (although only slightly so for age-7 CPUE). Age-5 CPUEs show the tightest relationship with the recruitment index, while CPUE at ages 6 and 7 are much more variable and show a decreasing trend over time for year classes after 1987 (age 6) or 1989 (age 7; Figure 55, lower right panel). Because of the poor correlation among indices and the good fit for age-5, we used the residuals from the age-5 fit as an index of age-0 to age-5 survival anomalies.

Assessment: The index has to be interpreted with caution because age-5 fishes may not be fully recruited to the fishery, depending on their size. Therefore, low apparent survival in some years may be a result of poor growth and, hence, smaller average size, which reduces their catchability in the gill net. On the other hand, survival of older fishes is confounded with emigration because variable proportions of Arctic cisco may mature at ages 6 or 7 and start their return migration. On balance, the survival anomalies based on age-5 seem to provide the most reliable indicator of survival rate anomalies because the relationship with the recruitment index is much tighter than for the other ages. The index cannot be interpreted as an estimate of actual survival rates (for example, as the percentage of fish that survive from age-0 to age-5) because the recruitment indices and the CPUE indices in the fishery are measured on very different scales and do not reflect measures of absolute abundance.

Results were much more variable but otherwise similar when using the age-0 index as independent variable. Correlations among the survival anomalies to different ages were also low, in particular between the age-5 and age-7 indices (Table 12).

Table 12. Spearman rank correlations among age-specific survival rate anomalies based on relative changes in CPUE from age-0 to adult Arctic cisco caught in the commercial Colville River fishery.

Age Class	Age 5	Age 6	Age 7
Age 5	1.0		
Age 6	0.467	1.0	
Age 7	-0.067	0.493	1.0

The time trends in survival were more pronounced with: mostly negative survival anomalies for the 1981 to 1985 year classes, higher survival for the year classes through 1994 and very low survival for the 1995 year class. The large intercept for the age-5 regression suggests that considerable recruitment may occur after age-0 (or after sampling ends), as is evident in the age-1 and age-2 indices.

Survival Rate Anomalies Based on Age-Specific CPUE in The Niġliq Fishery

Indices of age-0 to age-5 survival based on data from the Niġliq channel fishery were computed as described for the commercial fishery in the previous section but using CPUE estimates for ages 5–8 from the Niġliq channel fishery. The age data used to compute age-specific CPUEs were the same for both the commercial and subsistence fisheries.

Relationships between age-specific CPUEs and the recruitment index are not as tight as for the commercial indices but show significant linear increases in Niġliq channel CPUE with the combined recruitment index (Figure 57). Residuals from these regressions (Figure 58) show large variability over time and opposite patterns for younger and older age classes, similar to the commercial fishery data. The relationships between age-specific CPUE and the age-0 recruitment index showed similar variability, but were significant in all cases (not shown).

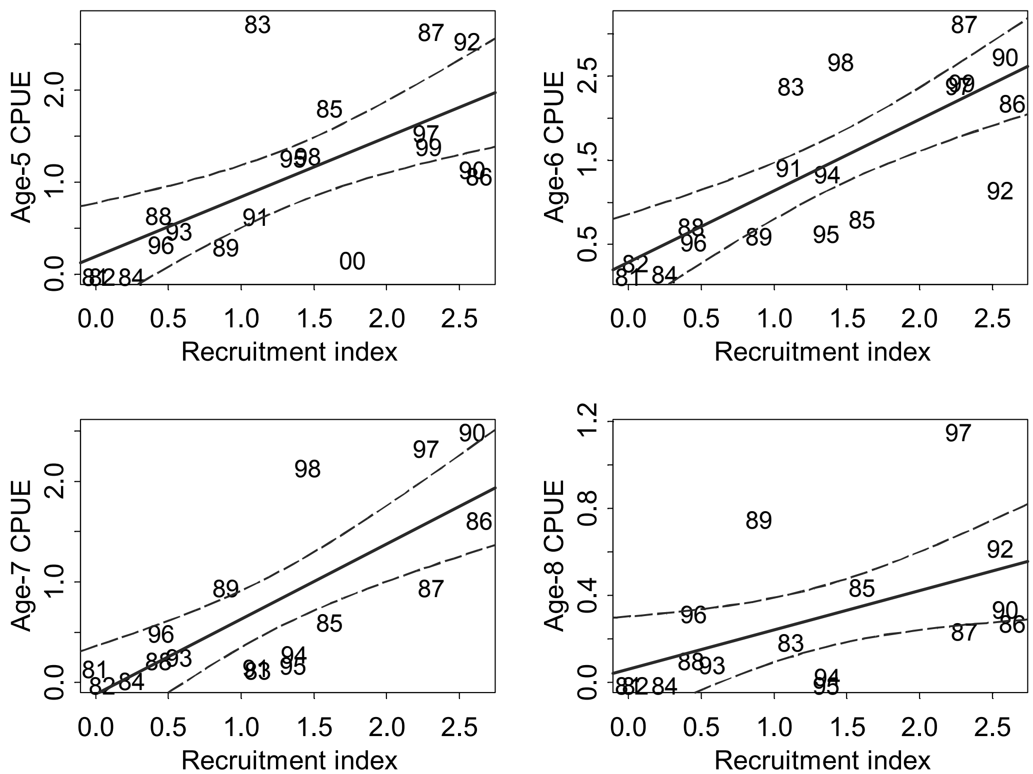


Figure 57. Relationship between CPUE at various ages in the subsistence fishery and the combined recruitment index of the corresponding year class with linear regression lines and 95% confidence bands.

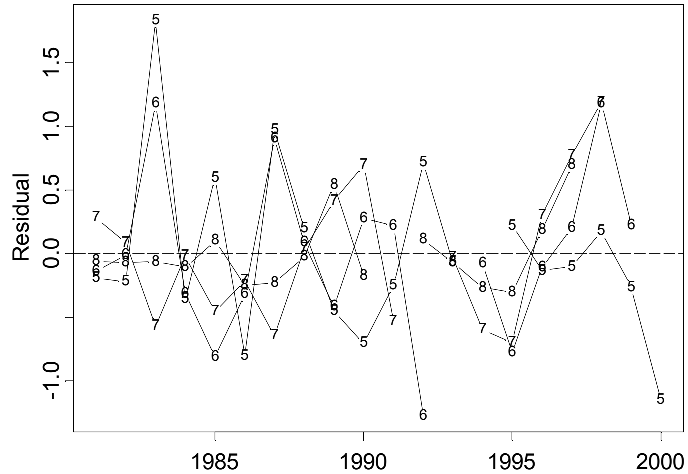


Figure 58. Survival rate anomalies of Arctic cisco in the subsistence fishery for ages 5–8.

We combined survival rate anomalies from both the subsistence and commercial fisheries into a single survival rate index from age-0 to age-5. In both the subsistence and commercial fisheries, survival of the same cohort to age-6, -7, or -8 showed different trends than survival to age-5, implying that year classes that show up as a strong year class of age-5 fish may subsequently experience higher mortality or increased emigration (e.g., due to density-dependent effects). Therefore, we constructed an index that reflects survival from age-0 to age-5 only and examined survival of older age classes separately (see below). Our final index of age-0 to age-5 survival anomalies (Surv.age-5) consisted of the averaged residuals from the regression of age-5 CPUEs in the commercial and the Niġliq channel fisheries, respectively, and on the combined recruitment index (Figure 59). It should be noted that estimates of age-specific CPUEs were not independent for the two data sources because the same age composition data were used to compute age composition of both the commercial and subsistence catches.

SURVIVAL OF ARCTIC CISCO FROM AGE-5 TO AGE-7

Rationale: Abundances of subadult Arctic cisco in the Colville delta reflect variability in recruitment to the Colville region, variability in survival from age-0 to the youngest age-class caught in the fishery (see above), and variability in survival of older age-classes of Arctic cisco from year to year. For age-classes that are fully recruited to the fishery and are not yet mature (i.e., have not yet started their return migration), survival anomalies can be constructed based on variations in CPUE among years. Presumably, variability in their survival reflects environmental conditions, such as summer feeding conditions experienced by these age classes between consecutive fishing seasons.

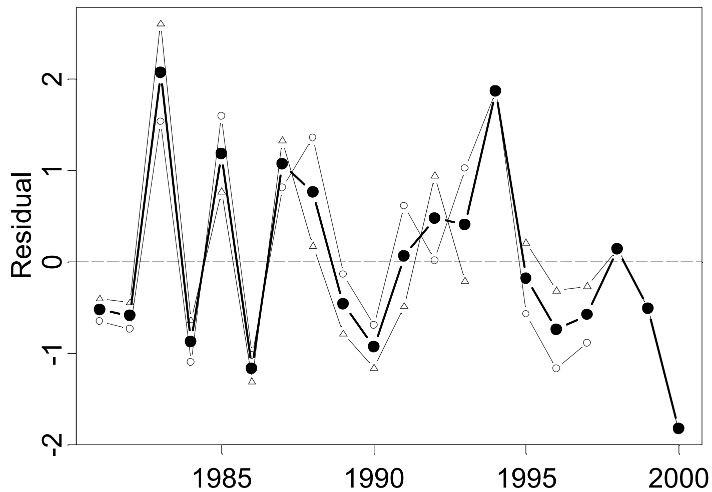


Figure 59. Survival anomalies from age-0 to age-5 based on commercial fishery (open circle) and subsistence fishery (triangle) and combined index of survival anomalies for Colville river Arctic cisco (solid circle). Survival anomalies are shown by year class, i.e., the residual for 2000 reflects anomalous survival between young-of-year Arctic cisco arriving in Prudhoe Bay in 2000 and age-5 Arctic cisco caught in the fishery in 2005.

Data: Catch rates (CPUE) of age 5–7 Arctic cisco in the commercial and subsistence fisheries.

Indicators: Regressions of age-6 CPUE in year t on age-5 CPUE in year t-1 and regression of age-7 CPUE in year t on age-6 CPUE in year t-1 suggest a linear and reasonably consistent relationship that is consistent between the two age groups. We combined residuals from both regressions into a single index of adult survival anomalies by averaging residuals for each year. Again, the anomalies may reflect observation error, natural variability in survival, variability in size (which affects catchability), and/or variability in the onset of maturation and emigration to the Mackenzie River. We are primarily interested in variability in survival in this analysis and assume that the index provides a suitable index of this variability. The index could be misleading if it is dominated by other sources of variability.

The estimated CPUE of successive year classes of the same cohort in the commercial fishery were highly variable but showed a clear and significant ($p < 0.05$) linear relationship (Figure 60). Residuals from this relationship (Figure 60, bottom panel) reflect differences in survival, as well as observation errors. There was good agreement between the survival anomalies (= residuals from straight-line relationship) for the two consecutive cohorts, so we averaged residuals across the two cohorts (Figure 60).

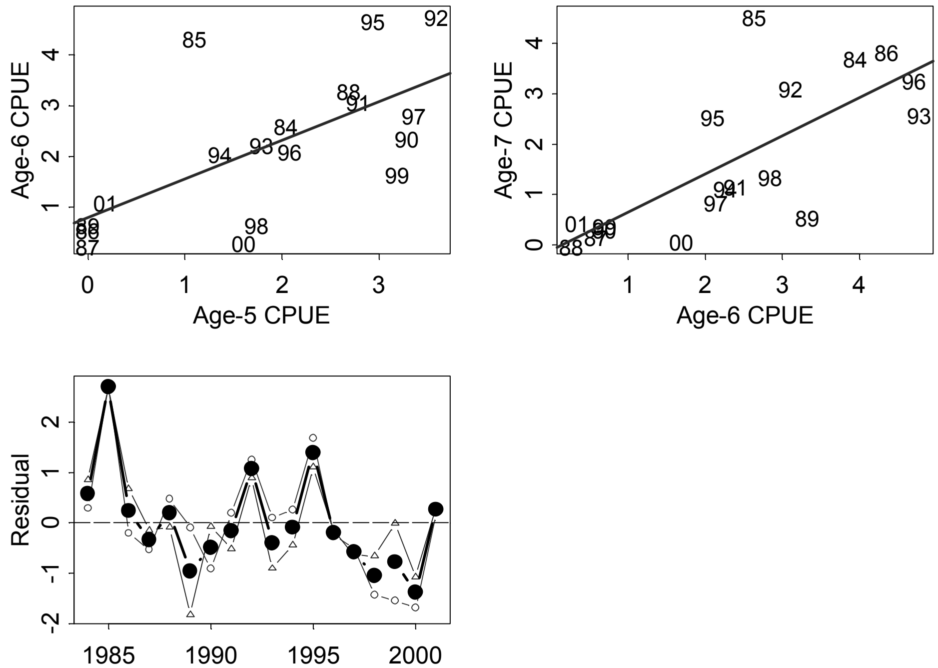


Figure 60. Scatterplots of age-6 vs. age-5 CPUE reflecting “survival anomalies” of age-6 fish (top left), of age-7 vs. age-6 CPUE reflecting “survival anomalies” of age-7 fish (top right), and residuals from the “expected” relationships (bottom panel) based on CPUE data from the commercial fishery. Years in the top panel correspond to the year class. Open circles and triangles in the bottom panel denote age-5 to age-6 and age-6 to age-7 survival anomalies, respectively. Survival anomalies (bottom) for a given year reflect survival from Oct/Nov of the previous year to Oct/Nov of the current year. Black solid circles denote the average of the two survival anomalies in a given year.

Estimated CPUE values from the subsistence fishery were more variable, but were also significantly correlated with CPUEs of the same cohort during the previous year (Figure 61). As for the commercial fishery, we averaged residuals across the two cohorts (Figure 61, bottom panel).

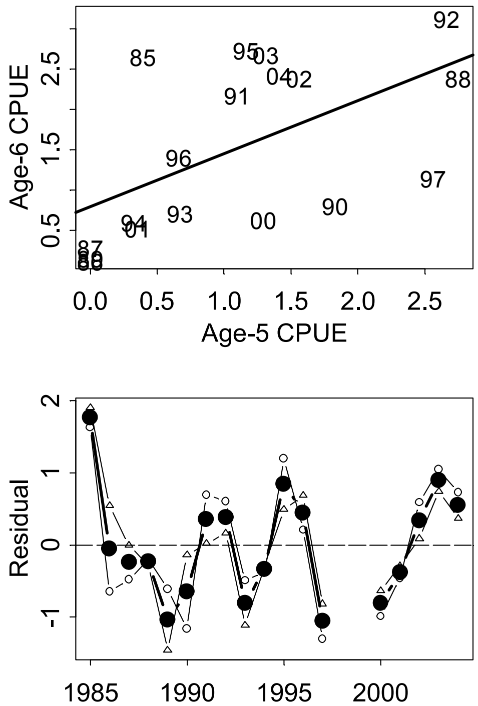


Figure 61. Scatterplots of age-6 vs. age-5 CPUE reflecting “survival anomalies” of age-6 fish, of age-7 vs. age-6 CPUE reflecting “survival anomalies” of age-7 fish, and residuals from the “expected” relationships (bottom panel) based on CPUE data from Niġliq channel fishery. Open circle and triangle lines in bottom panel denote age-5 to age-6 and age-6 to age-7 survival anomalies, respectively, while the black heavy line denotes the average of the two survival anomalies in a given year. Survival anomalies for a given year reflect survival from Oct/Nov of the previous year to Oct/Nov of the current year.

For the final survival index (Surv.567), we combined the averaged residuals from the commercial fishery and the average residuals from the subsistence fishery (which showed excellent agreement) into a single index as illustrated in Figure 62.

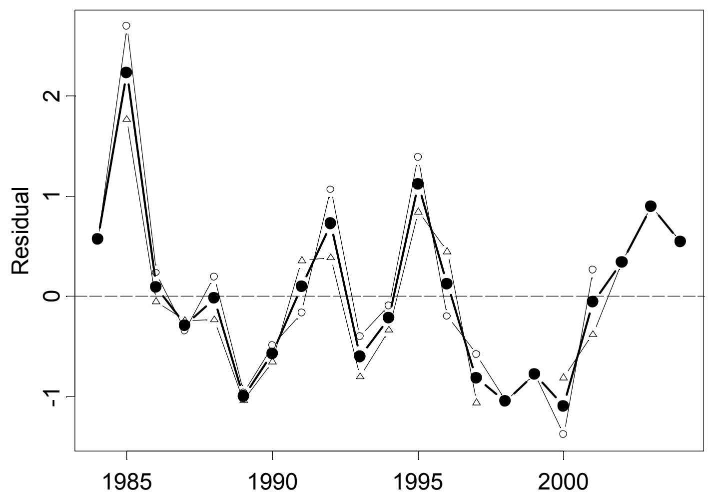


Figure 62. Averaged residuals from the commercial (open circle) and subsistence (triangle) fisheries and combined index of survival anomaly (solid circle), based on age-5 to age-6 and age-6 to age-7 survival of two consecutive cohorts during a given year. Survival anomalies for a given year reflect survival from Oct/Nov of the previous year to Oct/Nov of the current year.

Assessment: The survival rate anomalies of two different age groups from two consecutive cohorts and the survival rate anomalies based on the commercial and subsistence fishery show very similar patterns. The good agreement in survival rates of two age groups from two different cohorts (age-5 to age-6 survival of cohort 1 and age-6 to age-7 of the preceding cohort) suggests that the indices reflect real variations in survival between the early winter of one year and the early winter of the following year. In contrast, patterns in the commercial and subsistence fishery would be expected to be very similar because age-specific CPUE estimates from the two fisheries do not provide independent indices of survival; both are based on the same sample of aged fish and assume the same age distribution in both fisheries.

The indices computed here cannot be interpreted as estimates of actual survival rates (for example, as the percentage of fish that survive from age-5 to age-6) because catch rates at different ages are not directly comparable. This difference is because they are affected both by the selectivity of the fishing gear and by emigration. For example, the CPUE of age-6 fishes in a given year was often higher that that of age-5 fishes in the previous year. This difference reflects greater vulnerability of age-6 fish to the fishing gear rather than an actual increase in the number of fish of that cohort (i.e., survival over 100%, which could only result from immigration).

The survival anomalies may be due to observation error, differences in winter survival rates, and/or differences in summer survival rates. It is unclear whether they primarily reflect winter or summer conditions; therefore, we will examine relationships between the survival anomalies and environmental conditions during both summer and winter. The combined index suggests that survival was poor during the period from 1997–2000; however, data for 1998 and 1999 are based on the commercial fishery only.

SIZE-AT-AGE OF ARCTIC CISCO, PRUDHOE BAY

Trends in Size-at-Age

Rationale: Size of Arctic cisco at a given age reflects summer growth conditions experienced by a cohort over several years and was used as an index of condition in the absence of a direct estimate of condition or actual growth data. Changes in size-at-age most likely reflect changes in feeding conditions during the short, summer feeding season. It is generally assumed that little, if any, feeding occurs during the winter months.

Data: To examine size-at-age, we used length-at-age in the Prudhoe Bay region as reported in Fechhelm et al. (2005) and final size at the end of the summer for age-0 and age-1 cohorts. Length-at age-was measured for ages 2–6 in 1988–1996 and 2001–2003, although sample size was too small to be useful for some age classes in some years. Length measurements were generally based on fishes collected in late summer and presumably were strongly impacted by growth conditions during that summer.

Indicator: Three indices reflecting variability in size-at-age were obtained:

- Maximum size at age-0 (PB.age0.fin). The maximum size of age-0 fish at the end of the sampling season was obtained from the cohort definitions that were used to distinguish different cohorts in various reports (Fechhelm et al. 2003 and reports cited therein) (Figure 63).

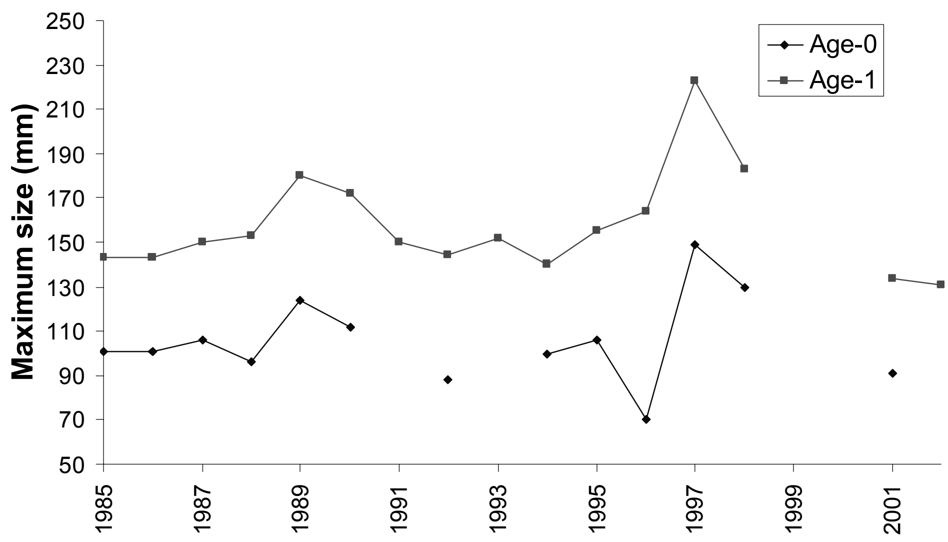


Figure 63. Maximum end-of-season length of age-0 and age-1 Arctic cisco sampled in the Prudhoe Bay region during the summer, 1985–2002.

- Maximum size at age-1 (PB.age0.fin). The maximum size of age-1 fish at the end of the sampling season based on cohort definitions as for age-0 above (Figure 63).
- Relative size, ages 2–6 (PB.size.rel): We derived a combined indicator of relative size by standardizing the sizes of each age class relative to maximum size (i.e., dividing the time series of age-X sizes by its maximum), then averaging relative sizes across age-classes within each year (Figure 64).

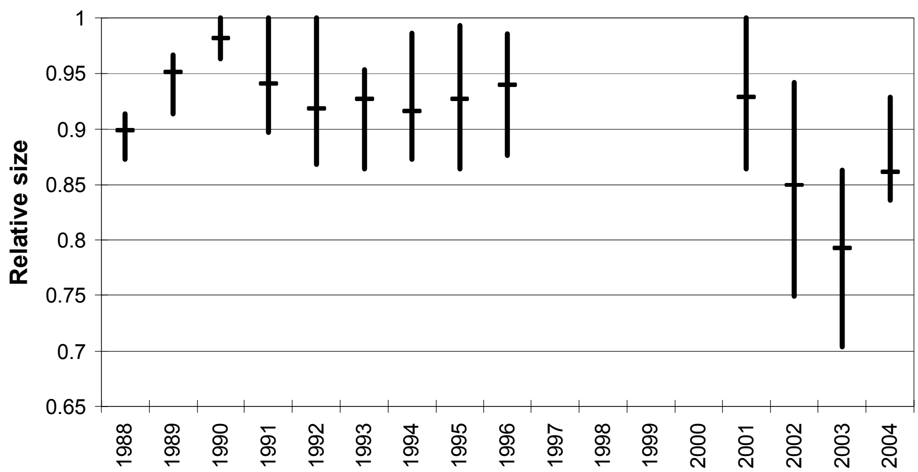


Figure 64. Combined index of relative size across age-classes 2–6 by year. Vertical bars indicate average relative size across age classes. Ends of horizontal bars indicate minimum and maximum of relative size by year. No length-at-age data were available for 1997–2000.

Assessment: Size-at-age reflects the growth history of a fish and is likely to integrate conditions over an extended period. However, most of the growth of Arctic cisco takes place during a brief, summer feeding period each year, and most of the growth before age 6 (up to 55%) occurs during the first year of life (Chris Zimmerman, USGS, pers. comm.). Because length measurements were collected in late summer, observed size differences among years, particularly for the younger age classes, likely reflect growth conditions during the current summer. The use of size-at-age as an inidcator of growth during a single summer is supported by the simultaneous decrease in size-at-age of all age classes in 2002 and the quick "recovery" of most age-classes to near-normal sizes in 2004 (Fechhelm et al. 2005). These data suggest that growth conditions during a single summer are reflected in the absolute size of a given age class (and not only in the growth increment since the preceding summer). Therefore, we used relative size-at-age in late summer as an indicator of growth conditions during the summer. It is possible, however, that additonal growth may have occurred after the end of the sampling period. Because much of the growth occurs early in life, prey availability and growth during the early life stages may be particularly important to Arctic cisco.

ABUNDANCES OF OTHER SPECIES, PRUDHOE BAY

Rationale: The abundance of other fish species was examined because they may compete with and/or feed on young Arctic cisco. Competition, which reduces food intake, and predation may be important sources of mortality for Arctic cisco. Other species also may be indicators of environmental influences that affect their distribution and abundance and may simultaneously affect the distribution and abundance of Arctic cisco.

Data and Indicators: Estimates of log-transformed abundances were obtained from Fechhelm et al. (2006) for the following species**:**

- Least cisco (PB.LSCS): Estimated log(CPUE+1) of "large" least cisco (>180 mm)
- Broad whitefish (*Coregonus mukon*) (PB.BDWF): Estimated log(CPUE+1) of age 3+ broad whitefish
- Dolly Varden (*Salvelinus malma*) (PB.DLVD): Estimated log(CPUE+1) of large dolly varden (>350 mm)
- Arctic flounder (PB.ARFL): Estimated log(CPUE+1) of all Arctic flounder
- Rainbow smelt (PB.RBSM): Estimated log(CPUE+1) of all rainbow smelt
- Fourhorn sculpin (PB.FHSC): Estimated log(CPUE+1) of all fourhorn sculpin
- Arctic cod (PB.ARCD): Estimated log(CPUE+1) of all Arctic cod

Assessment: Estimates are based on standard monitoring stations and confidence intervals have been estimated for all species except Arctic cod (Fechhelm et al. 2006). The 95% confidence intervals suggest that changes in the estimated abundances over time are highly significant. Therefore, the indices are likely to reflect real changes in abundance and species composition.

ABUNDANCES OF OTHER SPECIES, COLVILLE DELTA

Rationale: The abundance of other species during the fall fishery may impact Arctic cisco abundances or catch rates due to potential interactions among species in their over-wintering area.

Data and Indicators: Catches of least cisco have been quantified for the subsistence and commercial fisheries as for Arctic cisco, and catch rates (CPUE) in fish per net per day were obtained from Moulton et al. (2006) and earlier reports.

- CPUE of least cisco in the subsistence fishery (Niġliq.LSCS) (Figure 65)
- CPUE of least cisco in the commercial fishery (Helm.LSCS) (Figure 65)
- Effort-adjusted CPUE of least cisco in the commercial fishery (Helm.LSCS.adj). As described for Arctic cisco above and in Appendix K, there was a strong linear relationship between CPUE and effort in the fishery that may reflect serial depletion of least cisco within a season. Therefore, we removed the effect of effort on CPUE by regressing log (CPUE) of least cisco on effort in the Helmericks fishery and using the residuals as the effort-adjusted CPUE index.

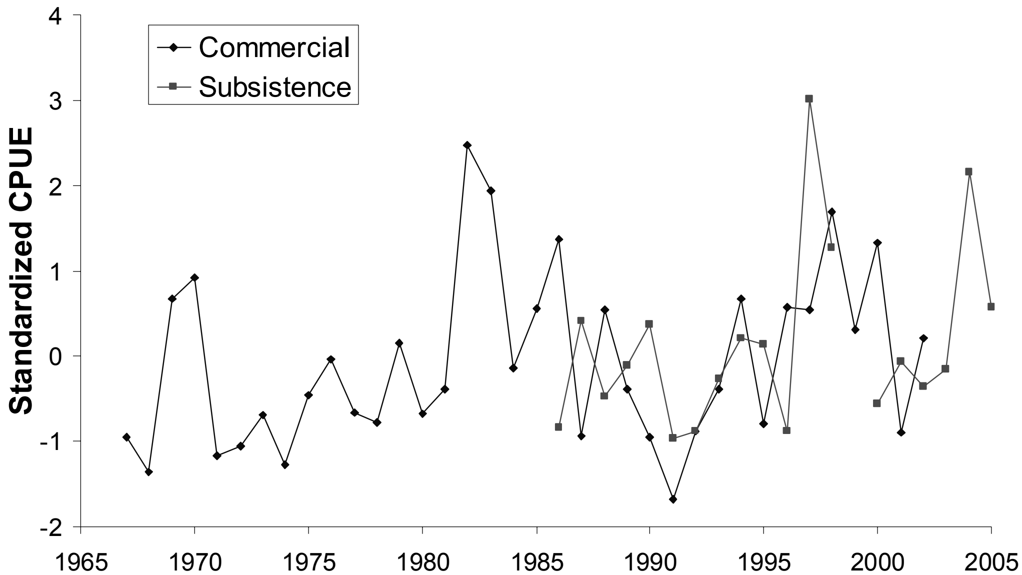


Figure 65. Catch-per-unit-effort of least cisco in the commercial fishery, 1967–2002, and in the subsistence fishery, 1986–2005 (except 1999).

Assessment: CPUE indices for the commercial and subsistence fisheries are only weakly correlated ($r = 0.197$, $p = 467$), suggesting that the index is not a good index of least cisco abundance in the Colville delta or that abundances differ between the main channel, where the commercial fishery takes place, and the Niġliq channel, where the subsistence fishery takes place. Nevertheless, least cisco CPUE is likely to reflect local abundances that may affect Arctic cisco catch rates in the same area. Therefore, both indices were retained for further analyses but are were not combined into a single index of abundance.

RELATIVE SPECIES COMPOSITION

Rationale: We developed indices of relative species composition for the Colville River fall fishery and for the Prudhoe Bay monitoring program to examine changes in species composition over time. Such changes could reflect environmental changes that may not be obvious otherwise. For example, Hare and Mantua (2000) have shown that regime-like changes in the North Pacific were more clearly apparent in biological time series than in environmental series.

Colville River Catch Composition

Rationale: Changes in the composition of catches may reflect important environmental changes. A multivariate index based on a number of species should be a more robust indicator of such changes than changes in abundance of any one species.

Data: The catch composition in the fall subsistence fishery in the Niġliq channel of the Colville River was reported in Moulton and Seavey (2005) and was used as input in the analysis.

Indicator: We computed a multivariate index of species composition based on an ordination of the relative catch composition of 8 species in fishery catches (Figure 66). Differences in species composition among years were quantified using the Bray-Curtis dissimilarity measure. These differences were used as input to a multivariate ordination in one dimension (non-metric multidimensional scaling) and the resulting scores were used as an index that reflects relative species composition. For details on the method, see Mueter and Norcross (1999).

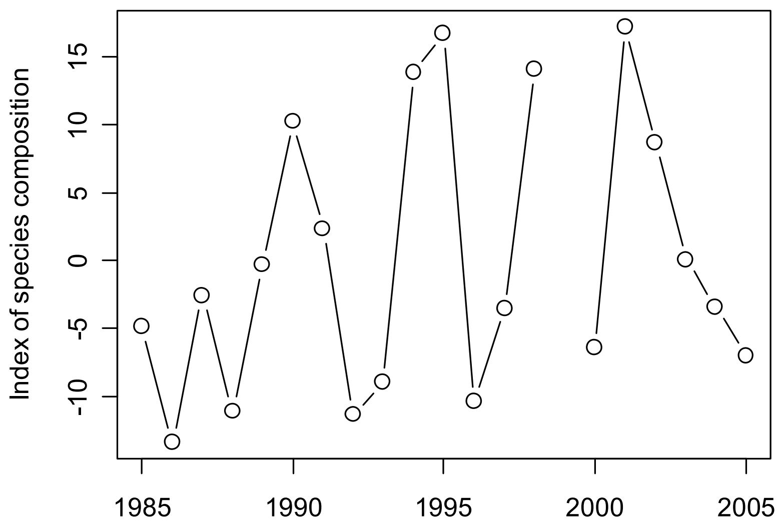


Figure 66. Multivariate index of species composition in the Niġliq channel fall fishery from 1985–2004 (1999 is missing). Large values of the index reflect small catches of Arctic cisco and large catches of other species.

Assessment: The quality of the index is difficult to evaluate. The index primarily reflects changes in the catches of Arctic cisco, least cisco, humpback whitefish, and burbot. Small values of the index imply relative large catches of Arctic cisco and small catches of all other species. This relationship is indicative of an inverse relationship between Arctic cisco and all of the other species, which is also apparent in correlations among catches over time. It is unclear whether the inverse relationship reflects local competitive exclusion (i.e., if Arctic cisco are abundant, other species may not be able to compete), an inverse relationship in the true abundances of Arctic cisco and other species, or another mechanism.

Prudhoe Bay Survey Catch Composition

Rationale: Changes in the composition of catches may reflect important environmental changes. A multivariate index based on a number of species should be a more robust indicator of such changes than changes in abundance of any one species.

Data: Species composition data by year for sampling stations in Prudhoe Bay were extracted from LGL reports to BP for 1989–2005. No compositional data were available for 1997–2000. We used data from two stations (218 and 220) that were sampled in each year and are assumed to be representative of the Prudhoe Bay region. Arctic cisco and other species were collected throughout the study region during the summer feeding period, but we did not examine spatial patterns in distribution. We used a second data source consisting of annual log-transformed CPUE estimates for 8 species from the Prudhoe Bay monitoring program (Fechhelm et al 2006) as described above. The species for which long time series of CPUE were available included Arctic cisco, least cisco, broad whitefish, dolly varden, Arctic flounder, rainbow smelt, fourhorn sculpin, and Arctic cod.

Indicator: We constructed two multivariate indicators of species composition. The first index followed the same method as described for the Colville catch data above. Catch data were first summed across stations 218 and 220 for each species and year, resulting in a year-by-species matrix of catch in numbers. We eliminated all species that occurred at three or fewer stations, as well as species for which less than 10 specimens were caught across all years combined, to reduce the influence of rare species. A total of 19 species were included in the analysis, which consisted of computing differences in species composition between years using the Bray-Curtis dissimilarity measure. These differences were used as input to a multivariate ordination in one dimension (non-metric multidimensional scaling) and the resulting scores (Figure 67) were used as an index that reflects relative species composition. Because of extremely large numbers of Arctic cod in 2002, a fourth-root transformation was used on all numbers to reduce the influence of very large catches. For details on the method, see Mueter and Norcross (1999). A second index was computed in the same way based on the CPUE data for eight species (Figure 68).

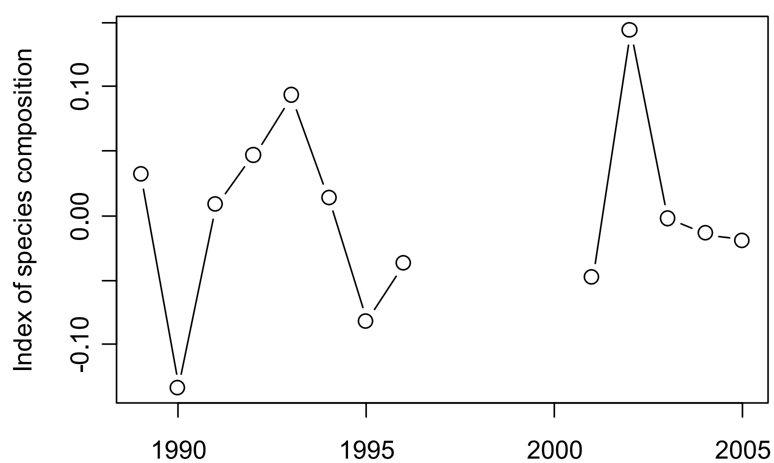


Figure 67. Multivariate index of species composition in fyke net catches from Prudhoe Bay, 1989–2005 (1997–2000 missing). For interpretation, see text.

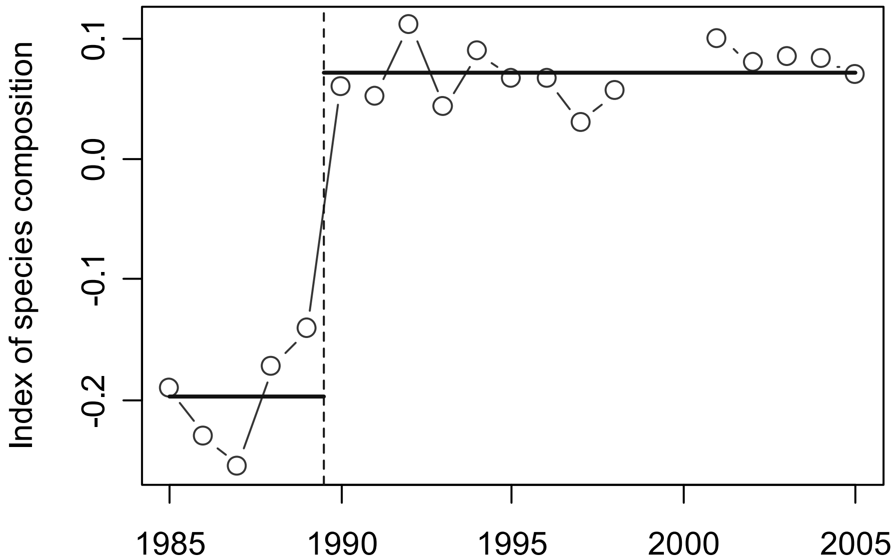


Figure 68. Multivariate index of species composition based on CPUEs of eight species collected by fyke net in Prudhoe Bay, 1985–2005 (1999/2000 missing), with one-step intervention model fit (solid black lines). For interpretation, see text.

Assessment: Based on 13 years with species composition data for all species, the first multivariate index shows no apparent trend or pattern in species composition over time (Figure 67). Two years, 1990 and 2002, appear to be unusual in their species composition. Large values of the index, such as in 2002, imply high abundances of Arctic cod (*Boreogadus saida*) and low abundances of most other species, in particular, least cisco, Arctic flounder (*Pleuronectes glacialis*), saffron cod (*Eleginus gracilis*), and fourhorn sculpin (*Myoxocephalus quadricorus*). The multivariate index based on CPUEs of eight species collected in Prudhoe Bay shows a very pronounced increase between 1989 and 1990. The index is negatively rank correlated with the CPUE of Arctic cod ($r = -0.36$) and fourhorn sculpin (-0.56), which decreased in abundance, and strongly positively correlated with CPUEs of all other species ($r > 0.6$ except for dolly varden (*Salvelinus malma*): $r = 0.45$). The strong step increase in the multivariate index was confirmed by fitting a one-step intervention model to the time series, which showed a highly significant step between 1989 and 1990 ($p < 0.001$).

INDICATORS OF POTENTIAL HUMAN IMPACTS ON ARCTIC CISCO

DISTURBANCE INDICATORS

Rationale: Human activities associated with oil and gas development in the Beaufort Sea and the Colville delta have the potential to affect Arctic cisco during critical life-history stages. These activities include the migration of juveniles (e.g., seismic activity), feeding and growth of juveniles and subadults in the nearshore areas (e.g., from offshore drilling activities), and overwintering mortality in the Colville delta (e.g., channel crossings). Therefore, we developed indicators to try to quantify the potential impacts of development activities on Arctic cisco. These indicators were developed by the scientists and presented to the Panel of Experts. Some rankings were modified to reflect the panel's concerns over specific activities (e.g., ice bridges and spills).

Data: We compiled a comprehensive database of activities related to oil and gas development in the Beaufort Sea and the Colville delta. These include most of the activities that occurred in the areas of interest, although the dates (in some cases years) of the activity were not always available. Activities were summarized by area and season. The broadest geographic divisions consisted of three broad coastal sections (Figure 4):

- East: from the Canadian border to, and including, the Sagavanirktok delta
- Central: between the Sagavanirktok delta and Oliktok Point (east of the Colville delta)
- West: between Oliktok Point and Cape Halkett.

These sections were chosen to examine potential effects of development on Arctic cisco during specific stages of their life history, specifically:

- during the westward migration of juveniles from the Mackenzie River to Prudhoe Bay in the open water season
- during the summer feeding season in the western Beaufort Sea (West and Central regions combined), and
- during the over-wintering season in the Colville delta

To examine potential effects of human activities on over-wintering Arctic cisco, we summarized activities on two spatial scales. First, we summarized all winter activities (frozen water season) in the Colville delta where the fishery takes place and where the center of the over-wintering distribution is believed to be. Second, because the spatial distribution of Arctic cisco during winter is not well known, and because distant activities associated with noise and vibrations may affect Arctic cisco in the Colville delta, we summarized winter activities within the broader coastal section between Oliktok Point and Cape Halkett (western section).

The types of activities and impacts in the database include drilling operations (301 entries), construction and traffic including channel crossings (118), seismic-acoustic surveys (40), breaching of causeways (3), and spills (2). Most activities cannot easily be quantified and are simply enumerated with the exception of seismic surveys, which are summarized in terms of the total length of seismic lines surveyed and/or the number of 5-km seismic blocks surveyed. Activities ranked here include the construction and breaching of causeways, but the impact of the causeways themselves was evaluated separately (see next section). Activities that were not quantified were ranked for their disturbance potential as follows:

- Rankings during the summer open water season were largely based on the duration of the activity. If an activity occurred throughout much of the open-water season disturbance potential was ranked as "high" (ranking: 2). If activity occurred only over a limited period (<1 month), for example only at the end of the summer feeding season, it was rated as low impact (ranking: 1). Activity in the eastern section, which would affect Arctic cisco during their juvenile transport–migration phase were only rated as having an impact if they occurred before September 1 because migration is generally completed by that date.
- Activities during the winter were rated as high impact (ranking: 3), medium impact (2), and low impact (1) based on where they occurred. Drilling activities and construction occurring on land or ice in the vicinity of the Colville delta region (but not within the delta) were rated as low impact (e.g., drilling operations at Cape Halkett). Activities within the Colville delta were rated as medium (drilling or construction activities on land or offshore of the delta) or high (any channel crossings, as well as two spills of 'waste' and drilling mud, respectively, that occurred in the delta in 1998 and 1999).

These rankings provide a qualitative assessment of potential disturbance from each activity, but are very coarse because activities were rarely quantified and different activities are not easily comparable. The only activities that were quantified in at least some years were seismic activities (distance of seismic lines surveyed and/or number of seismic blocks surveyed) and, in some cases, drilling operations (hours).

Indicators: We developed indicators for the overall level of industrial activity in different regions of the Beaufort Sea in Alaska (east, west, and west; Figure 4) and for a subregion of the western section (Colville) to account for the development activity that has occurred on the Colville delta. Hence, these activities, mostly associated with oil exploration and development, have occurred on the delta, in nearshore waters (i.e., <3 miles of mainland shores and under State of Alaska juristiction), and in adjacent outer continental shelf (OCS) waters (>3 miles from coast and under federal [MMS] jurisdiction. We also stratified the disturbance data by season to reflect seasonal differences in habitat use by Arctic cisco, with the "open" season encompassing the ice-free period and the "closed" season encompassing the period of ice cover in the Colville River and Beaufort Sea. Different indicators were developed for specific types of disturbances (e.g., offshore seismic surveys). To obtain a total "disturbance indicator" for a given year, region, and season, we simply added the ranks of all activities documented for that year in a given region and season. This number provides a rough indicator of potential disturbance that has a high value during years when a large number of activities occurred (Figures 69 and 70).

- East, open-water season (East.open; Figure 69): The eastern section included the Beaufort Sea shelf from the Canadian border up to and including the Sagavanirktok delta (Figure 4). The East, open water season was usefule for examining potential impacts during the migration of juveniles from the Mackenzie delta to Prudhoe Bay. Only activities during the summer period through late August were included because the migration is typically completed by late August (Fechhelm and Griffiths 1990). To construct this and the following indicators, the disturbance potential rankings were summed by year. Development activities in this region of the coastal Beaufort Sea first occurred in 1982 and continued at low-to-intermediate levels through 1998, with no activities reported since then (Figure 69). Activities largely consisted of offshore seismic surveys conducted in most years between 1983 and 1998, and drilling operations conducted from drillships off the Arctic National Wildlife Refuge (OCS), from a gravel island at the Endicott development (nearshore), and from a gravel pad at the Niakuk development in the Sagavanirktok delta (nearshore).

- Central, open-water season (Central.open; Figure 69): The central section included the Beaufort Sea shelf between the Sagavanirktok delta and Oliktok Point (east of the Colville delta; Figure 4). This area includes an important section of the summer feeding distribution of Arctic cisco and includes the Prudhoe Bay area where much of the oil-related activities have taken place historically. Activities, which consisted largely of seismic surveys (OCS) and drilling operations conducted from gravel islands (nearshore), began in the summer of 1984 and continued through 1999, with additional drilling occurring at Northstar Island (nearshore gravel island 12 miles northwest of Prudhoe Bay in 12 m of water) during summer 2001.

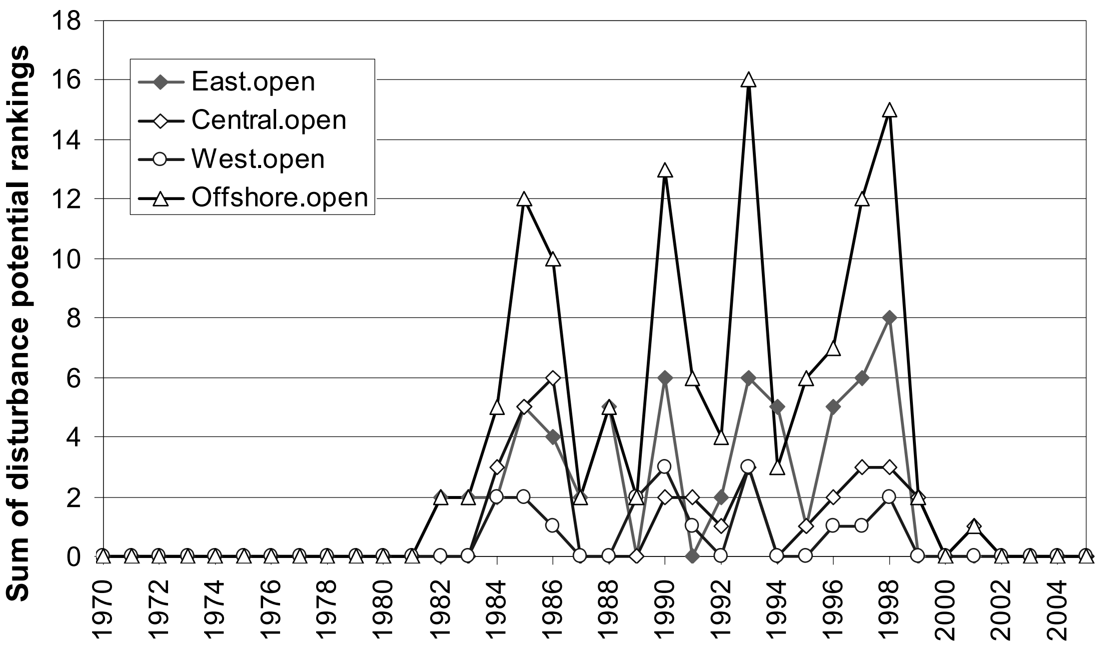


Figure 69. Sum of disturbance potential rankings for all documented oil development activities in the coastal Beaufort Sea and Colville delta for different regions during the open-water season. For description of regions, see text.

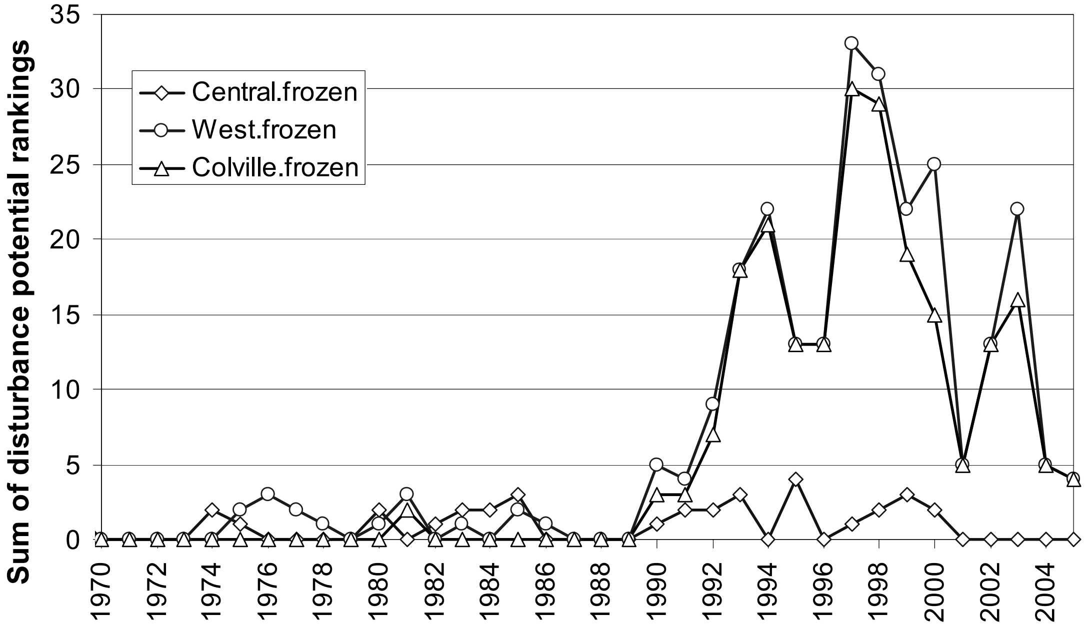


Figure 70. Sum of disturbance potential rankings for all documented oil development activities in the coastal Beaufort Sea and Colville delta for different regions during the frozen winter season. For description of regions, see text.

- West, open-water season (West.open; Figure 69): This section included nearshore and OCS waters between Oliktok Point and Cape Halkett, which is an important part of the summer feeding distribution of Arctic cisco. This section also includes the Colville delta, which is the main over-wintering area for subadult Arctic cisco. From the Colville delta, Arctic cisco disperse at the beginning of the open-water season and then return to the area at the end of the open-water season. Activities in this area consisted almost exclusively of seismic surveys in OCS waters conducted between 1984 and 1998, with some drillship operations offshore of the Colville in 1986, and exploration and development activities on the Colville delta, which began in the early 1990s and have continued since.
- Offshore, open-water season (Offshore.open; Figure 69): The distribution of juvenile and subadult Arctic cisco in marine waters during summer is poorly known, but human activities in nearshore and OCS waters have the potential to affect Arctic cisco migrating along the coast and feeding in coastal areas during summer. Offshore activity (includes both nearshore and OCS waters) was quantified by adding disturbance potential ranks of all three regions during the open-water season. Included are activities in all coastal sections between the Canada–Alaska boarder and Cape Halkett, consisting largely of seismic surveys and drilling operations in OCS waters. These activities occurred mostly from 1982–2001, and the number of activities varied greatly from year to year (Figure 69).

- Central, frozen season (Central.frozen; Figure 70): For the central section, we also constructed an indicator of disturbance for the frozen season because juvenile Arctic cisco are known to over winter in the Sagavanirktok River–Prudhoe Bay region. Winter activities related to oil development in this region that may impact Arctic cisco occurred during most years between 1974 and 2000. Development-related activities during this period of time include both nearshore and OCS waters.
- West, frozen season (West.frozen; Figure 70): The western section includes the only known over-wintering area of subadult Arctic cisco in Alaska, the Colville delta region. Because the spatial distribution of Arctic cisco during winter is not well known and because more distant activities associated with noise and vibrations may affect Arctic cisco in the Colville delta, we used an indicator of winter activities within the broader western section (between Oliktok Point and Cape Halkett), as well as within the Colville delta only (below). Hence, the category 'West.frozen' includes activities undertaken in OCS (>3 miles from mainland coast), nearshore (<3 miles from mainland coast), and in the terrestrial environment encompassed by the Colville delta. Much of the oil development activities in this region began much later than in the eastern and central sections, although some construction activities and drilling operations occurred as early as the winter of 1969–1970 (Figure 70). Activities include the full range of development-related activities, and the level of activity affecting Arctic cisco habitat was much higher than in the open-water season (Figure 69).
- Colville, frozen season (Colville.frozen): The Colville delta is believed to be the only major over-wintering area for subadult Arctic cisco. Activities within the delta have the largest potential for affecting Arctic cisco and their winter survival during this period. Therefore, we developed an index of total activities occurring within the delta during the frozen season. Restricting the geographical extent of activities that may affect over-wintering Arctic cisco to the Colville delta only shows that almost all of the increased activity after 1990 was due to development activities in the Colville delta (Figure 70). The last two indices are, therefore, strongly correlated with each other over the 1990–2004 period ($r = 0.96$). By definition, development-related activities in the Colville delta (Colville.frozen) category take place in the terrestrial or nearshore environments

In addition to indicators that include all development-related activities, a number of more specific indicators were constructed to examine potential effects of specific activities on biological response variables. These included:

- Seismic activity (Seismic.East, Seismic.West): Seismic surveys were, in most cases, quantified in terms of the length of seismic lines surveyed (km) and/or the number of seismic (5 × 5 km or OCS) blocks surveyed. Most surveys were done in the open-water season. To develop indicators of seismic activity that may affect juveniles during their westward transport (eastern Beaufort Sea) and juveniles and subadults on the summer feeding grounds (western Beaufort Sea), we included all surveys conducted during summer (prior to September 15) and added the total distance of seismic lines surveyed within the eastern and western Beaufort Sea (central and western regions as defined above), respectively, as well as the total distance for all regions combined (Figure 71).

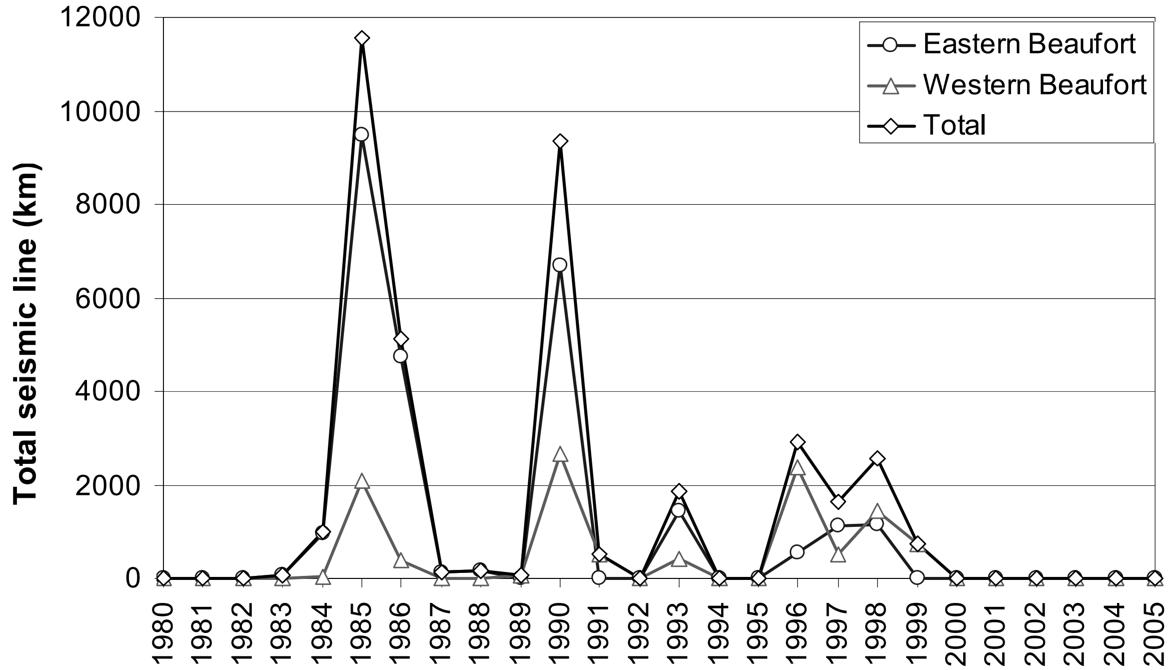


Figure 71. Total distance of seismic lines surveyed by year in the eastern Beaufort Sea (Canada-Alaska boarder to Sagavanirktok delta), western Beaufort Sea (Sagavanirktok delta to Cape Halkett), and combined.

- Ice bridges / channel crossings (Channels): The Nuiqsut Panel of Experts expressed concerns about the potential effects of channel crossings (ice bridges) on catch rates in the Colville delta. To examine their potential effects, we constructed an index that simply consisted of the number of channels constructed within the Colville delta in a given year (Figure 72).
- Drilling operations (Drilling): Concerns also were expressed by the Panel of Experts about the potential effects of vibrations from drilling operations on over-wintering Arctic cisco in the Colville delta. Unfortunately, hours of drilling activity in the Colville delta were not quantified. Therefore, we simply enumerated the number of drilling operations occurring in a given winter season (Figure 72).

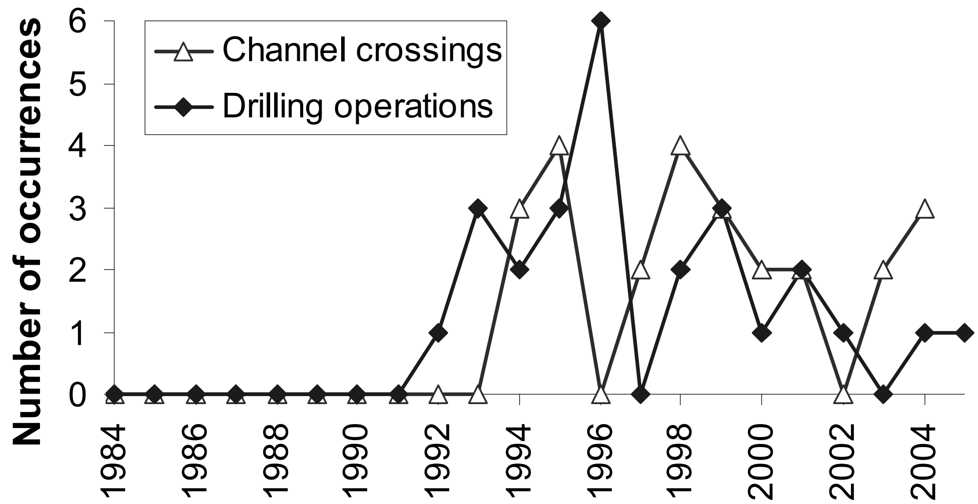


Figure 72. Total number of channel crossings (number of ice bridges) and number of drilling operations during the winter season in the Colville delta by year.

Other concerns regarding the effects of specific events, such as spills of drilling mud in the Colville River, on Arctic cisco were expressed by the Panel of Experts. While insufficient for a statistical analysis, we identified the years when such events occurred to examine whether unusual values for certain biological indicators may have coincided with such events.

- Drilling fluid spill events: Two spill events have been reported from the Colville delta: (1) a drilling mud spill occurred in fall 1998 during horizontal directional drilling of the crossing for the Alpine oilfield pipeline below the river (*Fairbanks Daily News-Miner* October 1, 1998) and (2) approximately 25,000 gallons of hazardous drilling fluids spilled at the Colville River pipeline crossing on March 5, 1999 (Alaska Department of Environmental Conservation 2004; On-line Spills Database [http://www.dec.state.ak.us/spar/perp/search/search.asp]).

Another concern that was expressed by the Panel of Experts concerned the observed silting in of large parts of Simpson Lagoon on the west side of West Dock at Prudhoe Bay. However, no data currently are available to quantify this siltation.

CAUSEWAY INDICATORS

Rationale: A long-standing concern has been the potential effect of the West Dock and Endicott causeways on the coastal migration of fishes in the western Beaufort Sea. In response to this concern, several breaches were added to the causeways that were meant to facilitate the coastal migration of fishes. Numerous studies have been conducted to study the effect of the causeways and breaches on the local hydrography and on fish movements. The most recent of these studies, based on catch rates and tagging studies, suggest that the West Dock causeway can inhibit the eastward passage of humpback whitefish (Fechhelm 1999) and least cisco (Fechhelm et al. 1999) around West Dock, at least prior to the breaching of West Dock in the winter of 1995–1996. However, the same studies did not find any effects of the Endicott causeway on the migration of coastal amphidromous species, which was attributed to hydrographic differences between the two areas. In this study, we examine overall biological responses of Arctic cisco (measures of recruitment and survival) in relation to various periods that are distinguished by different causeway configurations (Chapter 5).

Indicators: The explanatory variable that provides an indicator for examining impacts of causeways and/or breaching on Arctic cisco consists of a categorical variable (factor) with a different level for each of the following periods, thereby allowing us to test for differences in the response variable among these periods.

1. 1967–1974: the earliest year for which data are available through the last year prior to West Dock construction.
2. 1975–1985: From construction of West Dock through last year prior to Endicott construction (two extensions were added to West Dock in 1975–1976 and 1980–1981).
3. 1986–1993: From construction of Endicott (initially constructed with one breach, second breach added in 1986–1987) through last year prior to third Endicott breach.
4. 1994–1995: From breaching of Endicott through last year prior to breaching West Dock.
5. 1996–present: Post-construction and post-breaching period.

In addition, we quantified the potential impacts of constructing a causeway, and of breaching it, on Arctic cisco using relative indicators of "disturbance potential" (Indicator name: Causeways). The disturbance potential of a completed causeway without any breaches was given a rating of 4 to indicate a potentially high disturbance. Addition of a first breach was rated as -2 because it likely reduces the disturbance potential. For example, Fechhelm (1999) and Fechhelm et al. (1999, 2001) showed that the addition of the West Dock breach helped to mitigate hydrographic differences between the east and west side of West Dock and facilitated the eastward migration of humpback whitefish and least cisco. A single, short breach was added to the extension of West Dock in winter 1980–1981, but this breach filled in with gravel and sediment within several years of construction (BP Exploration [Alaska] Inc. 2001); therefore, no effect was assigned to this breach. The impacts of the addition of a second and third breach at West Dock were rated as -1 and 0, respectively. Fechhelm et al. (1999, 2001) showed that the addition of the third breach at Endicott had no discernable effect on hydrographical differences between the east and west sides of the causeway or on the movement of fishes. While Fechhelm et al. (2001) attributed the lack of an effect at Endicott to hydrographical differences between the West Dock and Endicott causeways, it is possible that adding a third breach between two already existing breaches simply did not result in any additional effects. The periods with different configurations of causeways and breaches and the cumulative disturbance potential of the West Dock (WestDock.cum) and Endicott (Endicott.cum) causeways, respectively, are summarized in Figure 73. The disturbance potential related to the presence of causeways was evaluated separately from the disturbance potential of other development activities (described in previous section). These respective indicators are not comparable and were not combined in our analysis of the effects of development on Arctic cisco (Chapter 5).

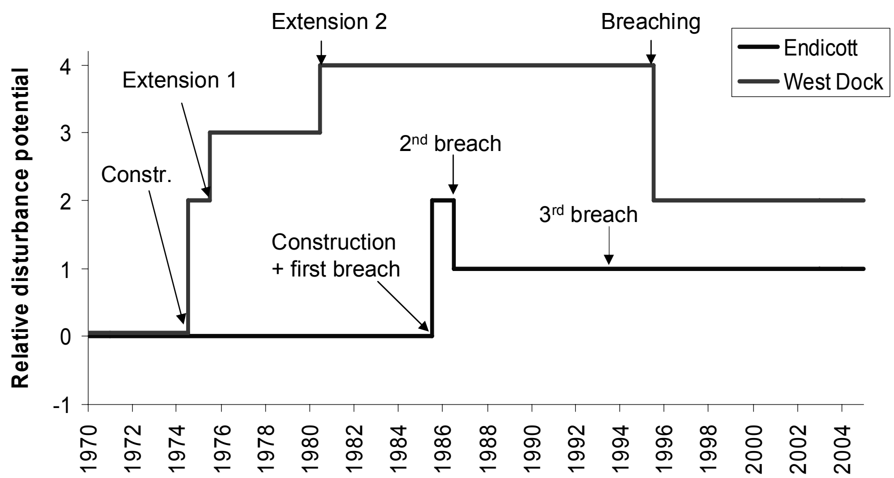


Figure 73. Relative disturbance potential of the Endicott (bottom line) and West Dock (top line) causeways over time with critical events indicated, based on rank-based qualitative assessment. The magnitude of disturbance potentials is not comparable between causeways.

RELATIONSHIPS AMONG INDICATOR VARIABLES

We explored relationships among environmental indicators, biological indicators, and between biological and environmental indicators. For this step in the data exploration, we used correlation analyses and various multivariate analyses. The primary purpose was to generate hypotheses that could be more formally tested in Chapter 5 (Hypothesis Testing), where possible. If data to test the hypotheses were insufficient, we identified critical data gaps (Chapter 6, Sensitivity Analysis). Where exploratory analyses suggested strong correlations among similar sets of variables, we used data reduction techniques, such as simple averaging or Principal Components Analysis, to combine variables and reduce the amount of redundant information in the data.

ENVIRONMENTAL INDICATORS:

Environmental indicators reflecting terrestrial influences, local and regional weather, regional oceanographic conditions, and large-scale climate conditions were first examined separately from the biological variables to identify patterns and redundancy in the indicator variables.

Correlations

Because all of the environmental variables were close to normally distributed, we computed Pearson's product moment correlations among all of the numerical environmental variables. The following groups of pair-wise correlations were judged to be of potential interest. Because of the large number of pair-wise correlations examined, only correlations that were significant at the 99% level or groups of similar correlations that are significant at the 95% level are discussed here:

- Time trends: We included year in the correlation analysis to identify potential time trends in the indicators.
    - o Air temperature measures at Inuvik (Mackenzie River, 1958–2004) and Barrow (1950–2004) showed strong positive correlations with year, suggesting a significant long-term increase in air temperature over time, as evident in Figures 14, 15, 32, and 33.
    - o Discharge in the Sagavanirktok River showed a significant increasing trend over time (positive correlation with year: $r = 0.61$, $p = 0.0029$), consistent with trends observed in other Arctic Rivers (Peterson et al. 2002).
- Average May discharge in the Mackenzie River is positively correlated with average summer salinities in Prudhoe Bay and negatively correlated with spring ice concentrations in the Colville region, suggesting a potential effect of Mackenzie River discharge on coastal conditions in the western Beaufort Sea.
- Summer discharge rates in the Sagavanirktok River are positively correlated with coastal SST during summer, as well as with air temperatures in the previous winter, and is negatively correlated with spring ice concentrations. This relationship may reflect effects of winter conditions on precipitation and snow melt in the following summer, as well as effects of runoff on coastal SST conditions.
- Unexpectedly, we found a significant positive correlation between Sagavanirktok River discharge and average summer salinities in Prudhoe Bay ($r = 0.60$, $p = 0.008$). It is unclear why salinities would be higher in Prudhoe Bay in years with high discharge east of Prudhoe Bay. The correlation reflects a strong increase in both salinity and river discharge after 1991 (Figure 74).

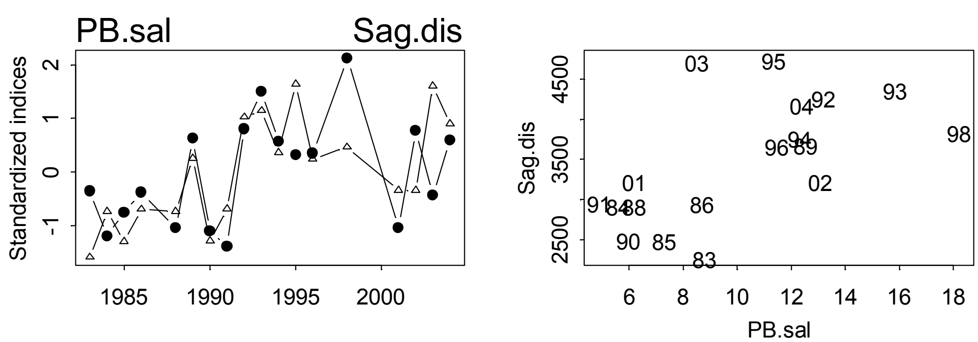


Figure 74. Time series of Prudhoe Bay salinity (PB.sal, circle) and Sagavanirktok River discharge (Sag.dis, triangle) and scatterplot of discharge against salinity.

- Strong positive correlations between temperature and ice conditions occurred within the Mackenzie region, within the Colville–Prudhoe Bay region, and between the two regions. Because of these strong correlations, a number of these variables were included in the data reduction described below.
    - Annual averages of summer and winter air temperatures at Inuvik, Tuktoyaktuk, and Barrow are strongly positively correlated.
    - Summer air temperatures are moderately to strongly correlated with summer sea-surface temperatures (measured nearshore SST as well as regional SST from interpolated NOAA data) (Figure 75). Strong positive correlations are observed both within and between regions. For example, coastal SST in the western Beaufort Sea during summer (July–September 1982–2004, NOAA OIv2 data) were positively correlated with Barrow summer temperatures (June–September, r = 0.54) as well as with summer air temperatures in Tuktoyaktuk (r = 0.62) and Inuvik (r = 0.61).
    - Ice concentrations in the western Beaufort Sea in both spring and fall are negatively correlated with both air and sea-surface temperatures. In contrast, spring ice concentrations (June) in the eastern Beaufort Sea (off Mackenzie delta) are only weakly correlated with air temperatures in the Mackenzie region, but are strongly correlated with SST and ice conditions in both the eastern and western Beaufort Sea. This suggests that ice concentrations in the eastern Beaufort Sea are largely determined by other factors besides local air temperatures such as winds and discharge (r = -0.31, June ice vs. May discharge).

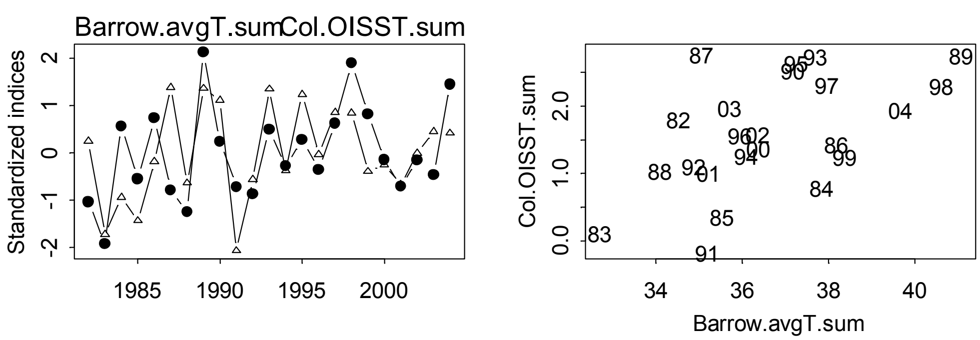


Figure 75. Time series of Barrow average summer air temperature (Barrow.avgT.sum, circle) and average summer SST in the Colville region based on satellite data (Col.OISST.sum, triangle) and scatterplot of SST against air temperature.

- Our three wind indices are strongly correlated with each other (pair-wise correlations from 0.70 to 0.92), and are weakly correlated with several other climate variables.
    - Easterly winds during summer are weakly negatively correlated with air temperatures during the previous winter at Barrow, Inuvik, and Tuktoyaktuk ($p < 0.05$), suggesting that cold winters tend to be followed by stronger easterly winds (Figure 76).
    - A moderate positive correlation exists between easterly winds at Deadhorse and average salinities in the Colville River during the fall fishery ($r = 0.49$, $p = 0.039$), suggesting that strong easterly winds during the summer enhance coastal salinities (through offshore Ekman transport and upwelling), which is reflected in higher salinities in the Colville delta. However, easterly winds were uncorrelated with summer salinities in Prudhoe Bay.

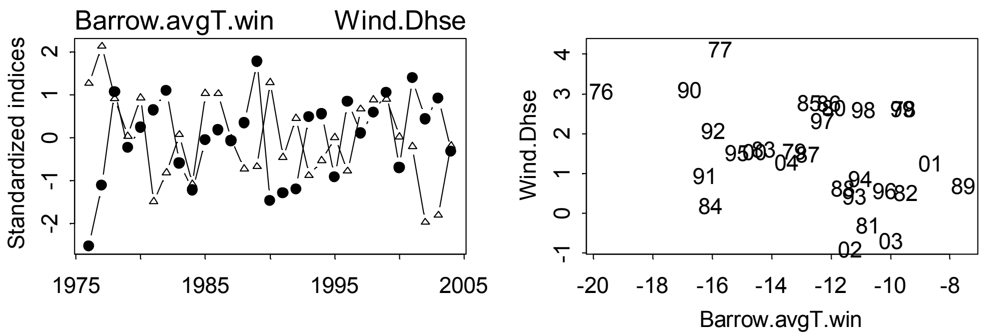


Figure 76. Time series of Barrow average winter air temperature (Barrow.avg.win, circle) and average wind speed at Deadhorse (Wind.Dhse, triangle) during the following summer (Jul–Aug) and scatterplot of wind speed against temperature.

- The climate indices for the Colville and Mackenzie region, which were derived from Principal Components Analyses (PCA), are strongly correlated with each of the component variables that were included in the PCA, as expected. The two indices were also strongly correlated with each other, suggesting that climate variability related to air temperature, SST, ice concentrations, and discharge is very similar in both regions (Figure 77).

Time Trends

We examined time trends in the environmental indices by fitting a linear regression over time, a non-parametric smoother (cubic spline), and a “regime-shift” model (intervention model) to each of the time series. These analyses revealed some notable trends and patterns. We tested

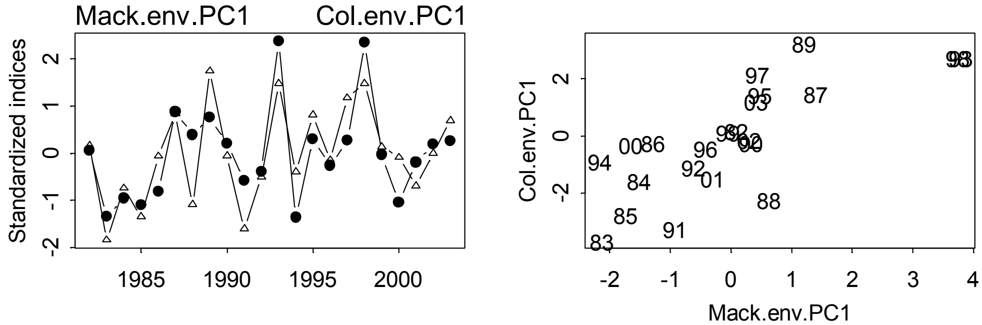


Figure 77. Time series of climate indices for the Mackenzie (Mack.env.PC1, circle) and Colville–Prudhoe Bay region (Col.env.PC1, triangle) reflecting major mode of climate variability and corresponding scatterplot.

for linear time trends using a linear regression with first-order auto-regressive residuals to account for potential autocorrelation in the time series. No higher-order, auto-regressive models were considered. As discussed previously, significant linear increases over time were evident in most air temperature series, implying a substantial warming in the Alaskan and Canadian Arctic. Other long-term trends included a significant increase in total summer discharge in the Sagavanirktok River (slope = 72 cfs / year, p = 0.0081) and in nearshore summer salinities in Prudhoe Bay (slope = 0.27 ppt / year, p = 0.029). While ocean sea-surface temperatures and ice variables did not show significant linear trends, intervention models suggested a significant step increases in SST in 1985–1986 (p = 0.031) and a significant step decrease in average spring ice cover in 1986–1987 (p = 0.045) in the Colville–Prudhoe Bay region. Significant step increases also were evident in local salinities in Prudhoe Bay and in Sagavanirktok River discharge between 1991 and 1992 (Figure 78). In both cases, the one-step intervention model provided a much better fit than either the linear model or the non-parametric smooth.

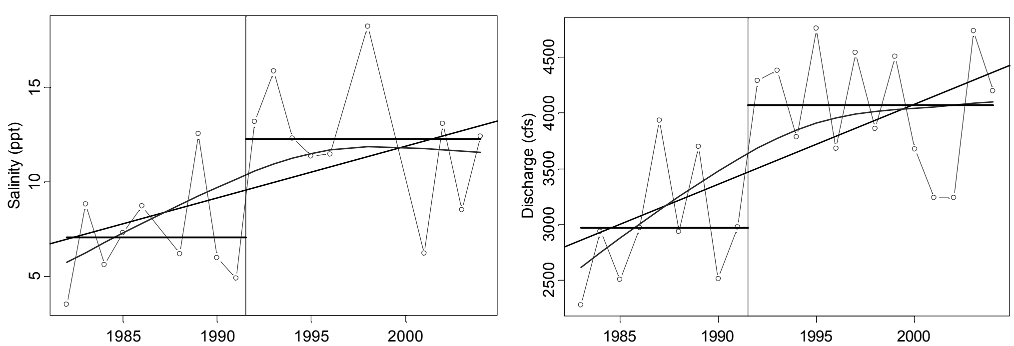


Figure 78. Time trends in salinity in Prudhoe Bay nearshore waters (left) and in Sagavanirktok River discharge at Pump Station 3 (right), with three model fits (linear, smoothing spline, and one-step intervention).

In addition to linear trends, we examined each time series for the presence of non-linear trends by first removing any linear trend over time and then fitting a non-parametric smoothing spline to each series over time. We tested whether the smoothing splines displayed significant trends using an approximate F-test to compare the estimated smooth trend to a constant mean model. We found the following significant trends:

- Flow through Bering Straight showed long-period variability with high flows in the 1950s and 1960s, decreased flow in the late 1960s through the late 1970s, and increasing flows thereafter (Figure 79).
- Average salinity in the Colville River during the fall fishery undergoes significant cyclic fluctuations with a period of approximately 6 years (Figure 79). The source of this variability is not known but may be related to wind conditions and associated sea level changes off the mouth of the Colville River prior to and during the fall fishery. We did not find a relationship between these cycles and variability in large-scale circulation as captured by the Arctic Oscillation Index (AO).
- Easterly wind speed anomalies (difference between annual wind speed and 1976–2005 average) at Deadhorse were high in the late 1970s and relatively steady through the late 1990s. After several years of strong easterly winds in the late 1990s, a sharp and significant decrease (to westerly winds) was apparent in 2002–2003.

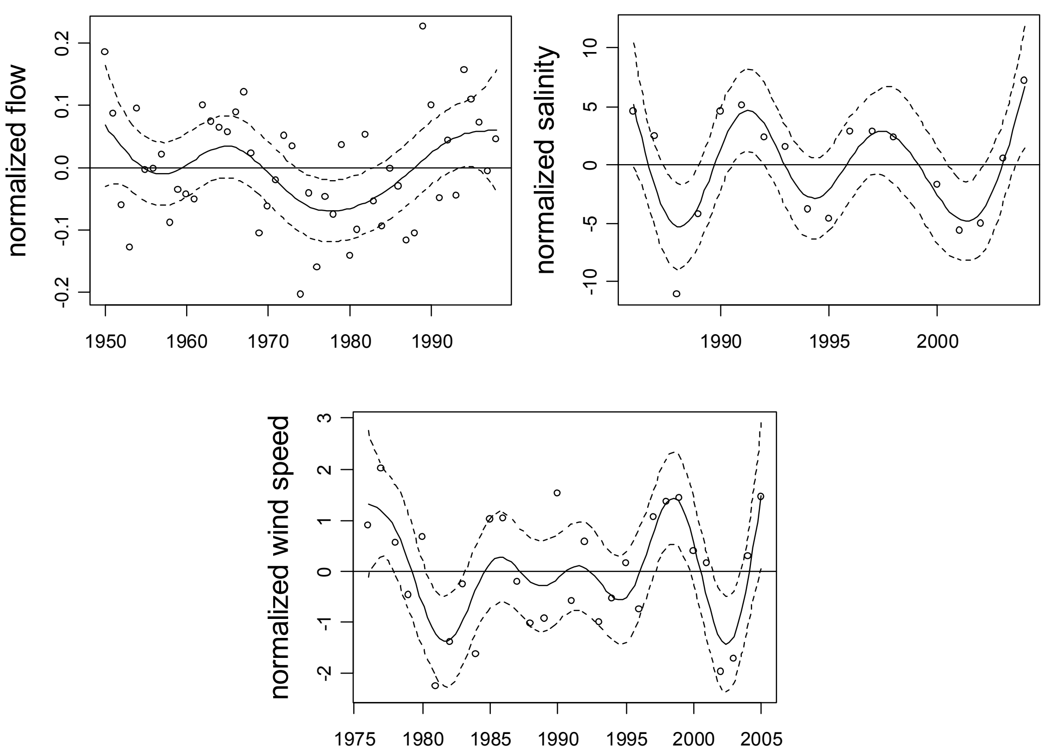


Figure 79. Estimated non-linear time trends with 95% confidence bands for Bering Sea flow, fall salinities in the Colville River, and Deadhorse wind speeds after removing any linear trends in the time series.

Data Reduction

Several groups of highly correlated variables were found in the data. To reduce the number of variables for testing specific hypotheses and eliminating redundancy in the data, a Principal Components Analysis (PCA) was used to extract the major mode of climate variability in the Colville River–Prudhoe Bay region and in the Mackenzie region.

Because of the large number of correlated variables, we used data reduction techniques to summarize environmental variability. We included the following environmental variables to compute the principal components of environmental variability in the Mackenzie River region. Only the first two principal components are shown in Table 13.

Table 13. Factor loadings of the first two principal components of environmental variability in the Mackenzie River region.

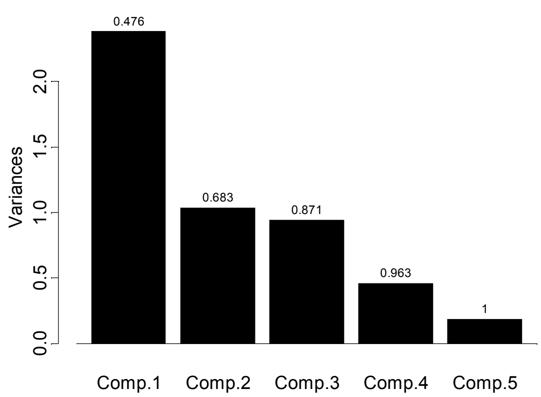
Variable	PC1	PC2
Dis.Mack.May	0.344	-0.437
Dis.Mack.sum	-0.115	-0.523
Dis.Mack.win	0.121	-0.681
Inuvik.avgT.win	0.434	–
Mack.ReySST.Jul	0.341	0.228
Mack.OISST.Jul	0.528	0.132
Mack.ice	-0.519	

Large values of the first principal component (PC) reflect warm temperatures, low ice cover, and large spring discharge. This PC explains approximately 35% of the overall variability in these variables. Summer and winter discharge did not contribute much to the first PC, and it is not clear how they might affect survival of Arctic cisco (especially summer discharge, which reflects discharge after outmigration). Therefore, we eliminated summer and winter discharge from the PCA. As before, the resulting first principal component reflects warm temperatures, light ice in spring, and large spring discharge (Table 14). The first PC accounts for 48% of the variability in these variables between 1982 and 2003 (Figure 80).

We similarly summarized environmental variability in the Colville region using the following variables, shown here with their loadings for the first two principal components. The first PC in this case accounted for 51% of overall variability between 1982 and 2004 (Figure 80). Like the first PC for the Mackenzie region, loadings are positive for temperature variables and discharge and negative for ice (Table 15).

Table 14 Factor loadings of the first two principal components of environmental variability in the Mackenzie River region, excluding summer and winter discharge from the Mackenzie River.

Variable	PC1	PC2
Dis.Mack.May	0.325	-0.317
Inuvik.avgT.win	0.452	0.467
Mack.ReySST.Jul	0.390	0.657
Mack.OISST.Jul	0.525	-0.312
Mack.ice	-0.513	0.391



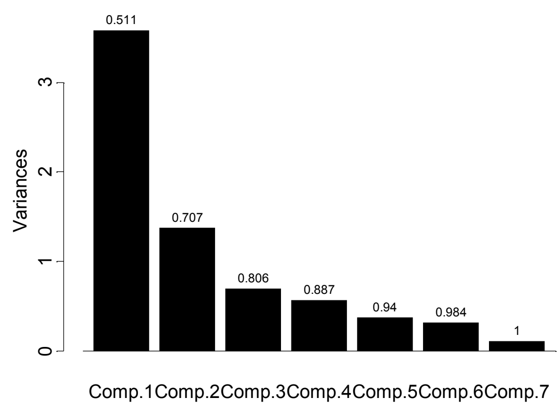


Figure 80. Screenplots for Principal Component Analysis of 5 environmental variables from the Mackenzie River region (left) and 7 environmental variables from the Colville River region.

Table 15. Factor loadings of the first two principal components of environmental variability in the Colville River region.

Variable	PC1	PC2
Barrow.avgT.sum	0.382	-0.127
Barrow.avgT.win	0.205	0.579
Col.OISST.sum	0.486	-0.106
Col.ice.spr	-0.440	0.286
Col.ice.Oct	-0.410	0.378
Sag.dis	0.371	0.268
Kup.dis	0.278	0.584

Both PCs, based on largely independent data sets, have the same interpretation with large values reflecting warm conditions, low ice cover in spring (and fall), and high discharge rates. The temporal patterns in these two indices are strongly correlated ($r = 0.76$; Figure 81) and show an increasing trend over time, although the linear trend is not significant ($t = 1.85$, $p = 0.078$ for Colville region and $t = 1.12$, $p = 0.278$ for Mackenzie region).

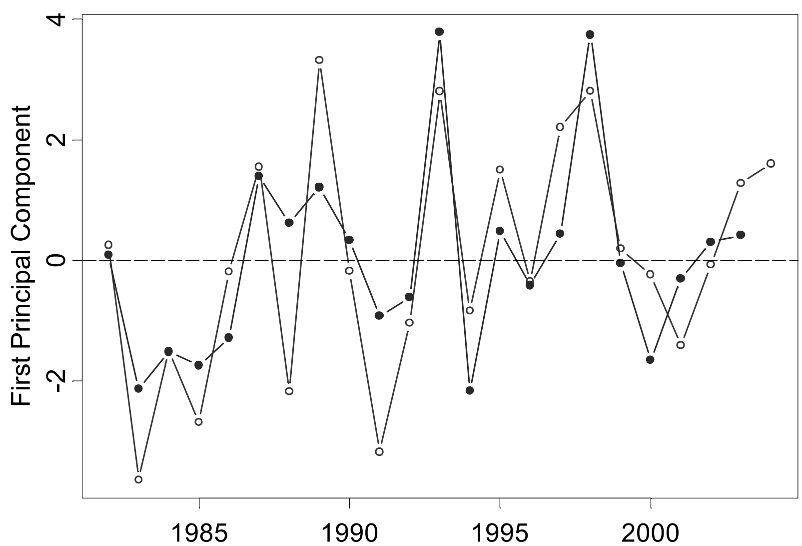


Figure 81. Major modes of environmental variability (first principal components of air temperature, sea-surface temperature, and discharge variables) in the central Beaufort Sea (open circle) and Mackenzie delta (solid circle).

Multivariate Relationships (Visualization)

We used the multivariate visualization tool GGOBI to examine relationships among a group of environmental variables. One of the limitations of the technique is that it cannot accommodate missing values. Therefore, we restricted analyses to a selected group of variables that were all measured over the same period of time. To examine relationships among environmental variables, we included air temperature, sea-surface temperature, ice cover, discharge, and wind speed variables, as well as the Arctic Oscillation index, for the years 1982–2004. Missing value of Sagavanirktok River discharge in 1982 and for Mackenzie ice variables in 2004 were filled in with the means of the available series.

Visualizations of the environmental variables clearly revealed the strong correlations among temperature and ice variables, both within the Mackenzie and Colville regions and between the two regions. These were captured in the principal components analysis as described above. The visualization also revealed unusual ice conditions in 1998 (Figure 82), a relatively warm year that had the lowest ice concentrations in the Colville region, the largest spring discharge from the Mackenzie River (Dis.Mack.May), but average and below average discharge, respectively, in the Sagavanirktok (Sag.dis) and Kuparuk rivers. Although there is a strong inverse relationship

Figure 82. Scatterplot matrix for selected environmental variables with the 1998 data point highlighted (square). Indices are plotted on a standardized scale. Labels in the lower right and upper left refer to variables plotted on the x- and y-axis, respectively.

between temperatures in the Colville region and spring ice conditions, the unusually low ice concentration in 1998 cannot be explained by a corresponding positive temperature anomaly (highlighted scatterplot in Figure 82). Instead, the low ice concentrations in June–July in the western Beaufort Sea likely resulted from an unusually large freshwater discharge into the coastal Beaufort Sea from the Mackenzie River, coupled with relatively strong easterly winds that may have advected the Mackenzie River plume to the western Beaufort Sea and resulted in an early ice melt. There is little evidence that the unusually mild ice conditions affected Arctic cisco recruitment, which was relatively high in 1998 but somewhat lower than what would have been expected based on observed easterly winds. As expected, good recruitment in 1998 resulted in above-average catches in 2004–2006.

Patterns in Environmental Data that may affect Arctic Cisco

Based on correlation analyses and multivariate explorations of the environmental data, coupled with knowledge of Arctic cisco life history, environmental conditions may affect Arctic cisco populations in a number of ways including, but not limited to, the following:

- The observed long-term trends in temperature and discharge may affect Arctic cisco populations in linear or non-linear ways.
- Mackenzie River discharge affects coastal conditions, and potentially Arctic cisco populations, in the western Beaufort Sea. The effects may include both a direct effect of alongshore transport of Mackenzie River outflow on the coastal Beaufort Sea (e.g., on ice conditions; Figure 82) and effects of atmospheric forcing that affect both discharge rates and coastal conditions in the Beaufort Sea simultaneously.
- Given the importance of easterly winds to Arctic cisco, recruitment may be enhanced following cold winters as suggested by the negative correlation between winter air temperatures and easterly winds.
- Pronounced step changes in both Sagavanirktok River discharge and salinity at Prudhoe Bay in the early 1990s (1991–1992) may affect the summer feeding population of Arctic cisco in the Prudhoe Bay region.
- Large interannual variability in climate conditions, as reflected in interrelated changes in SST, ice, and discharge, may affect Arctic cisco populations.

BIOLOGICAL INDICATORS:

Biological indicators reflecting variability in Arctic cisco recruitment, abundance, and size, and abundances of other species were examined separately from the environmental variables to identify patterns and redundancy in the indicator variables.

Correlations

Because many of the biological indicators were far from normally distributed, we computed Spearman's rank correlations among all of the numerical variables. The following groups of pair-wise correlations were judged to be of potential interest. Because of the large number of pair-wise correlations examined, only correlations that were significant at the 99% level or groups of similar correlations that are significant at the 95% level are discussed here:

- There were strong time trends (positive correlations with year) in several indicators:
    - Strong increasing trends were apparent in the abundances of Arctic cisco, least cisco, broad whitefish, Arctic flounder, and rainbow smelt in Prudhoe Bay.
    - Decreasing trends in the size of all age classes of Arctic cisco in Prudhoe Bay, but size-at-age increased in 2004.
    - Decreasing effort in the commercial fishery.
    - Decreasing trend in age-0 recruitment anomalies of Arctic cisco (after adjusting for wind effects).
    - Similar or opposite time trends in two series caused by unrelated factors can lead to significant correlations unless the trend is removed or they are adjusted for autocorrelation. Therefore, we computed correlations among trended series both before and after removing linear trends. The nature of the trends in various species was examined in more detail below to test for linear increases or abrupt changes in abundance over time.

- The age-0 recruitment index (CPUE) was positively correlated with age-1 and age-2 abundances in the following year and two years later, and with age-specific catch rates of 5–8 year old Arctic cisco caught in the fishery (both commercial and subsistence) 5–8 years later. Therefore, the index provides a reasonable estimate of catch rates 5–8 years later and has been used as a predictor of future catches (Moulton and Seavey 2005). Similarly, the combined recruitment index (ages 0–2) was correlated with catches of 5–8 year old Arctic cisco at the appropriate lags.
- The age-0 recruitment index was negatively correlated with the abundances of least cisco and broad whitefish in Prudhoe Bay, suggesting an inverse relationship between the abundance of these species in the Prudhoe Bay region and Arctic cisco recruitment. However, the relationship was due, at least in part, to strong increasing time trends in least cisco and broad whitefish (Figure 83). This relationship may suggest that factors leading to high recruitment (i.e., easterly winds) also result in lower abundances of least cisco and broad whitefish (which may rely on westerly winds for their summer feeding migration from the Colville River to Prudhoe Bay).

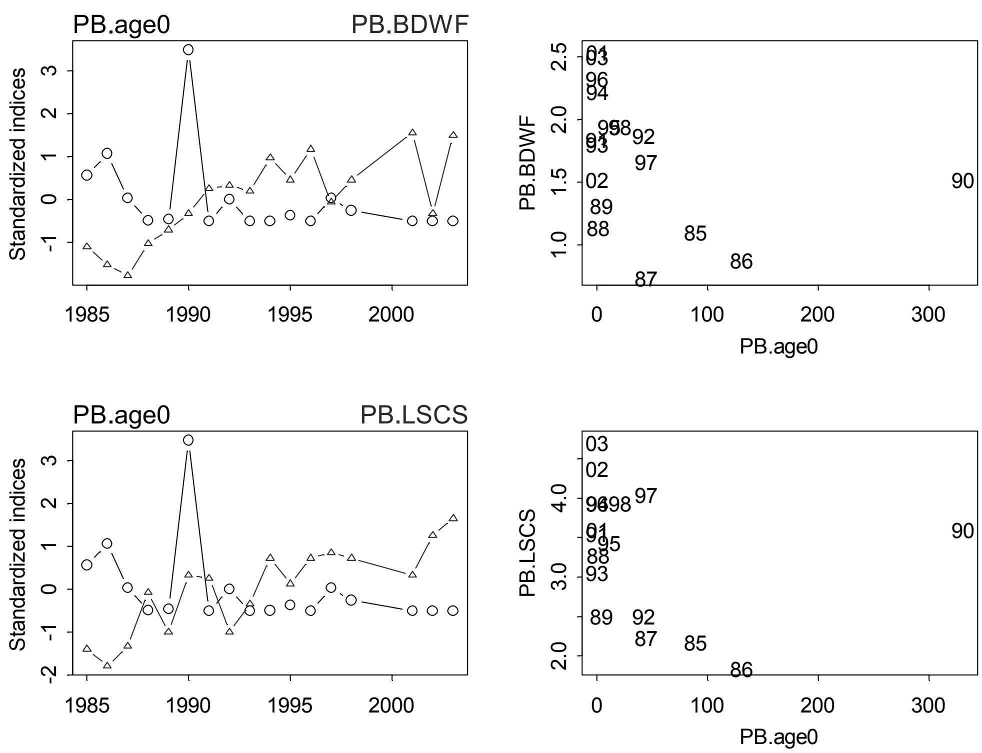


Figure 83. Time series and corresponding scatterplots of age-0 recruitment index (PB.age0, circle) and abundances of broad whitefish (PB.BDWF, triangle) and least cisco (PB.LSCS) in Prudhoe Bay.

- The recruitment indices were positively correlated with the size of older age classes in the Prudhoe Bay region, suggesting that conditions leading to high recruitment also result in favorable growth conditions for Arctic cisco. However, the time series of sizes were short (n = 12) and displayed a strong trend. The effect may also be due to density dependence because abundances of larger fishes tended to be low when recruitment was high.
- The abundance of age-2+ Arctic cisco in Prudhoe Bay was negatively correlated with recruitment of Arctic cisco (Figure 84). This relationship could be due to winds affecting both recruitment and the abundance of subadult Arctic cisco during summer, however, there is little indication that this is the case and the negative correlation also holds if recruitment anomalies (adjusted for wind effects) are used. The relationships suggest a possible negative effect of older Arctic cisco on the survival of new recruits, possibly as a result of competition for food, or another environmental effect that causes both large catches of age-2+ fish and small catches of age-0 Arctic cisco.

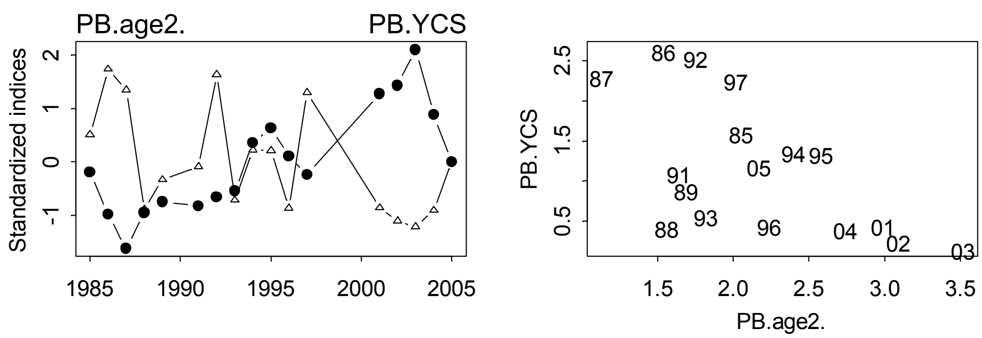


Figure 84. Time series of combined recruitment index (PB.YCS, triangle) and CPUE of older (age 2+) Arctic cisco in Prudhoe Bay (PB.age2, circle) during the same year and scatterplot of abundance against recruitment.

- The abundance of age-2+ Arctic cisco in Prudhoe Bay was strongly negatively correlated with the size of most of the age classes, particularly age-3, as was evident in the strong correlation with the combined size index ($r = -0.825$, $r < 0.001$) (Figure 85). This relationship again suggests possible competition effects that reduce growth when large numbers of Arctic cisco are present. The abundance of age-2+ Arctic cisco shows an increasing trend and was highest in 2001–2004, most likely due to strong year classes recruiting to the region between 1997 and 2000.

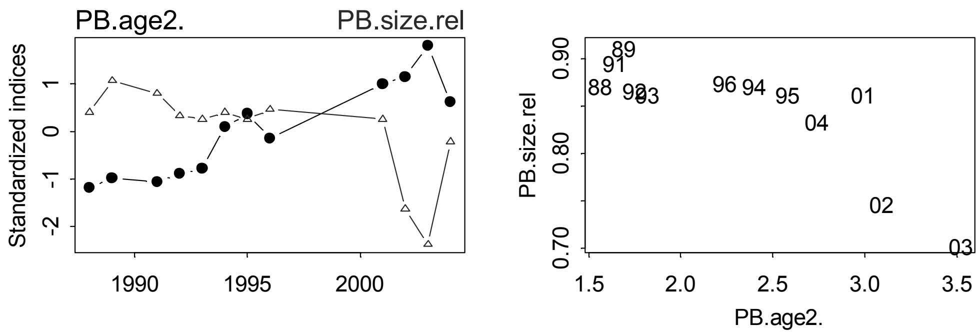


Figure 85. Time series of CPUE of age 2+ Arctic cisco in Prudhoe Bay (PB.age2, circle) and index of relative size (triangle) with scatterplot of relative size against abundance.

- Similarly, the abundance of least cisco and broad whitefish were negatively correlated with size-at-age of Arctic cisco, suggesting possible inter-specific competition.
- The abundance of age-2+ Arctic cisco in Prudhoe Bay was strongly positively correlated with abundances of least cisco, broad whitefish, Arctic flounder, and rainbow smelt. Correlations between the CPUE of different species in the Prudhoe Bay region were generally positive, except the Arctic cod CPUE was negatively correlated with the CPUE of most other species (not significant except for broad whitefish: $p = 0.036$).
- Strong positive correlations between catch rates of specific age-classes, as well as the overall catch rates in the commercial and subsistence fishery suggest that the catch rates reflect true variability in abundance representative of the larger Colville delta. These correlations were exploited in developing combined indices of abundance based on CPUEs in both fisheries (Col.ARCS).
- The combined index of total Arctic cisco abundance (Col.ARCS) is strongly positively correlated with the CPUE of each age group in the catches, as would be expected.
- We found a strong negative correlation between the age-0 recruitment anomalies (residuals from model accounting for wind effects) and the CPUE of broad whitefish in the Prudhoe Bay region (Figure 86). The negative relationship is due in part to an increasing trend in broad whitefish abundance over time and a decreasing trend in recruitment anomalies. It may reflect density-dependent effects such as competition or predation of juvenile Arctic cisco by broad whitefish. However, the trend is no longer significant after removing linear trends from both series.

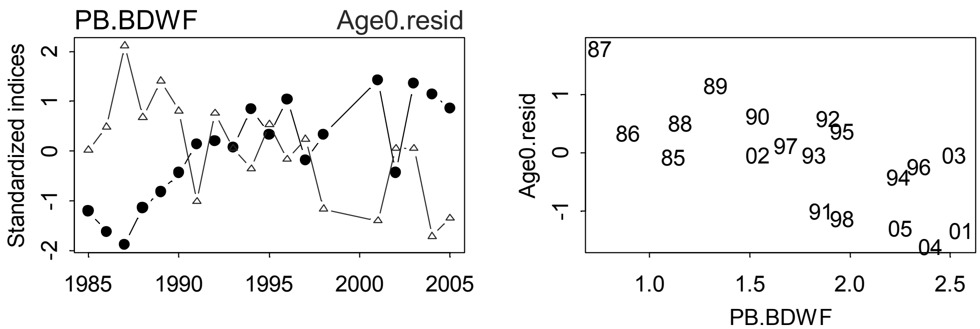


Figure 86. Time series of age-0 recruitment anomalies (Age0.resid, triangle) and CPUE of broad whitefish in Prudhoe Bay (PB.BDWF, circle) with scatterplot of recruitment anomalies against whitefish abundance.

- Survival rate anomalies of age-5 and age-6 fishes caught in the Colville River were negatively correlated with the size of these age classes in Prudhoe Bay. Thus, large sizes apparently were associated with decreased survival of Arctic cisco (Figure 87). Rather than decreased survival, negative survival rate anomalies during years when fish are larger than normal may reflect increased emigration (which cannot be distinguished from decreased survival) of age-6 and age-7 fishes that have grown large enough to mature and return to the Mackenzie River to spawn.

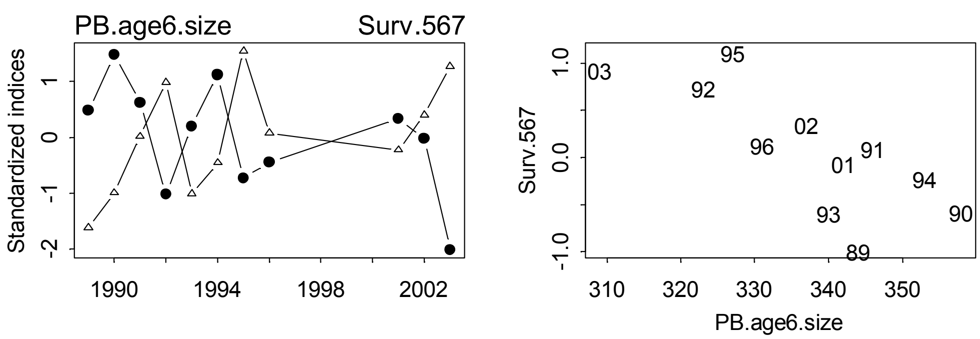


Figure 87. Time series of the size of age-6 Arctic cisco in Prudhoe Bay (PB.age6.size, circle) and survival rate anomalies for age-5/6 Arctic cisco (Surv.567, triangle), with scatterplot of survival anomalies against size.

- Lagged correlations suggest good agreement between indices of year-class strength of juvenile Arctic cisco recruiting to the Prudhoe Bay region and CPUE of older age classes recruiting to the fishery 5–8 years later (Figures 55 and 56).

Time Trends

As for the environmental indices, we examined linear and non-linear time trends in the biological indices by fitting a linear regression over time, a non-parametric smoother (cubic spline), and a “regime-shift” model (intervention model) to each of the time series. These analyses revealed a number of significant trends and patterns, which are summarized here:

- The combined recruitment index (PB.YCS) showed a step increase in 1984–1985 and a step-decrease in 2000–2001with low recruitment in the early 1980s and in 2001.
- After adjusting for effects of easterly winds on recruitment, the adjusted recruitment index (YCS.resid) showed a similarly significant increase between 1985 and 1986 and a decrease after 2000.
- Age-0 recruitment, adjusted for effects of easterly winds (Age0.resid), showed a highly significant, near-linear decrease from 1981 to 2005.
- A number of species whose abundances in Prudhoe Bay were monitored from 1985–2005 showed highly significant step-increases in 1989–1990 (Dolly varden, Arctic flounder, rainbow smelt), in 1990–1991 (broad whitefish), or in 1993–1994 (least cisco). The trend in the latter two species was better approximated by a linear increase over time. In contrast, fourhorn sculpin showed a significant step-decrease in 1991–1992.
- The relatively abrupt change in species composition reflected in these changes was evident in a strong step-change in the multivariate index of species composition based on these data (see below).
- The CPUE of Arctic cisco in the commercial fishery, adjusted for variable effort, showed a significant decrease between 1999 and 2000 (Figure 88). However, the index is only available through 2002, and CPUEs in the subsistence fishery, which are highly correlated with CPUEs in the commercial fishery, indicated a subsequent increase after 2002 (Figure 48). Nevertheless, CPUEs in the subsistence fishery, and in the combined CPUE index (Col.ARCS, Figure 51), were unusually low in the 2000–2002 period, particularly in 2001, compared to the full time series.

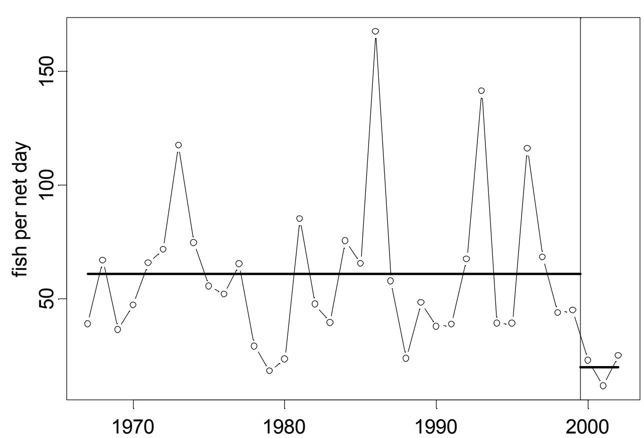


Figure 88. CPUE of Arctic cisco in commercial fishery adjusted for variable effort, 1967–2002 with one-step intervention model fit (p = 0.044).

- The combined survival rate index of age 5–6 and age 6–7 showed a significant step decrease after 1985 due to a very high survival rate in 1985.

Multivariate Relationships (Visualization / Ordination)

Multivariate Visualization

We used multivariate visualization (GGOBI) to examine relationships among a group of biological variables. The inability of the technique to accommodate missing values was particularly limiting in the analysis of biological data because many of the biological measures had missing values, and missing values occurred in different years for different variables. Therefore, we restricted analyses to a selected group of variables that were all measured over the same period of time. We examined relationships among the following variables that were available from 1985–2005: recruitment indices, recruitment anomalies, CPUE of Arctic cisco and six other species in Prudhoe Bay, age-specific CPUEs of Arctic cisco (ages 5–8) in the Niġliq channel fishery, total CPUE in the Niġliq channel fishery and combined CPUE index for both fisheries, survival anomalies of age 5–7 Arctic cisco, CPUE anomalies in the Colville fishery, and indices of species composition in the Colville and in Prudhoe Bay.

Visualizations revealed positive correlations among the CPUE series of a number of different species in Prudhoe Bay, which were further explored in the multivariate analysis described below. No other obvious patterns besides the pair-wise correlations described above were identified during visualization.

Some of the biological variables may show relationships at lags of one to several years; for example recruitment in Prudhoe Bay is related to the CPUE of age-5 fish in the fishery 5 years later. Using the visualization tool GGOBI, it is difficult to examine lagged relationships unless all lags of interest are included in the analysis as separate variables. Therefore, we used other tools, such as cross-correlation functions, to examine lagged relationships.

Ordination of Catch Composition in Prudhoe Bay Fyke Net Samples

To summarize variability in species composition in Prudhoe Bay during summer, we used an ordination of the species composition in fyke net catches from the Prudhoe Bay monitoring program (Fechhelm et al. 2006). The ordination was based on a matrix of log-transformed CPUE by year (1985–2005) of 8 species (Arctic cisco, least cisco, broad whitefish, dolly varden, Arctic flounder, rainbow smelt, fourhorn sculpin, and Arctic cod). We chose to use a correspondence analysis for the ordination, which is well-suited to species abundance data (Ter Braak 1995), and plotted the results of the ordination as a biplot (Figure 89). The biplot displays relationships (similarities) among both years and species simultaneously. Distances between years reflect similarities in species composition and distances among species reflect similarities in their CPUE trends over time. Moreover, the orientation of species in the biplot relative to years reflects the species composition in those years. For example, all of the early years (1985–1989) have large values along the first axis (CA1). Fourhorn sculpin and Arctic cod are located on the same side of the graph because there abundances are relatively high in the early years, while the abundance of all other species is higher in the later years (left side of graph). The first two axes account for 87% of the total variability in log(CPUE).

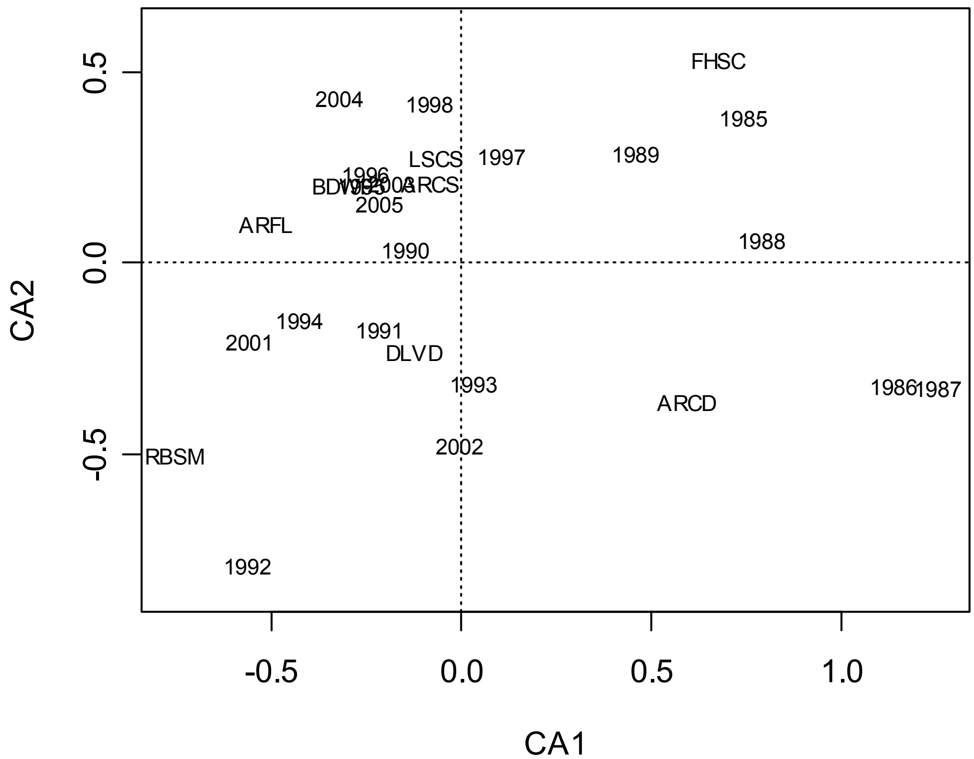


Figure 89. Unconstrained ordination plot of years and species from correspondence analysis, based on CPUE of 8 species caught by fyke nets in Prudhoe Bay, 1985–2005 (1999/2000 missing).

The first axis (CA1) of the ordination alone accounts for 68% of the overall variability in log(CPUE) and displays a strong time trend (Figure 90), with high values of the axis in earlier years and an abrupt shift to low values after 1988–1989. The abrupt shift is due to increases in abundance of several species around 1988–1989, in particular Arctic flounder, rainbow smelt, and Dolly varden (which are negatively correlated with the first axis.

To test for a significant shift in species composition, we fit an intervention model to the time series of CA1, which showed a highly significant change around 1989. The change follows the well known shift in the Arctic Oscillation Index between 1988 and 1989. The index is very similar to an index based on a different ordination (non-metric multidimensional scaling, not shown).

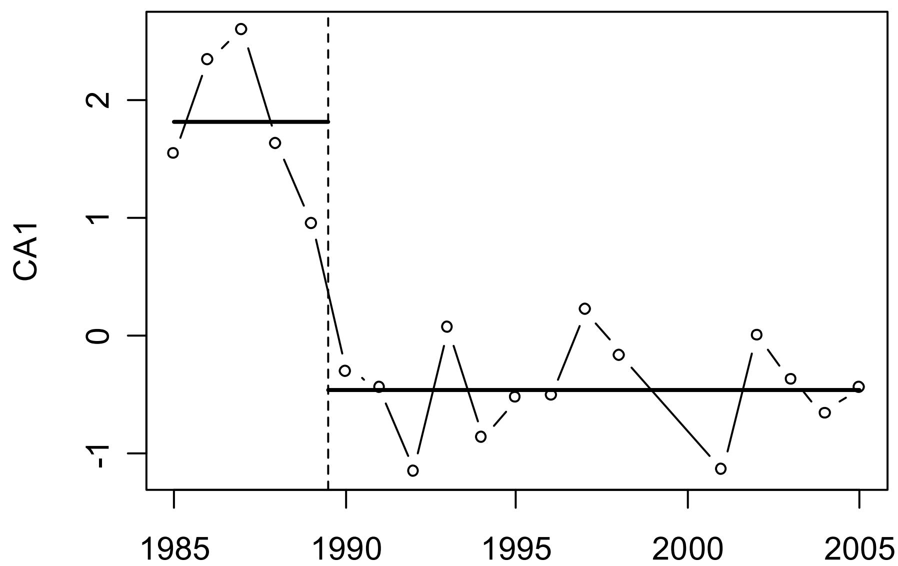


Figure 90. First canonical axis from correspondence analysis, based on CPUE of 8 species caught by fyke nets in Prudhoe Bay, 1985–2005 (1999/2000 missing), with intervention model fit.

Ordination of the Catch Composition in the Nuiqsut Fishery

To summarize variability in species composition in the fall fishery in the Colville River, we used an ordination of the catch composition from 1986–2004 in the subsistence fishery as reported in Moulton and Seavey (2005). We conducted a correspondence analysis based on a matrix of total estimated catches by year of eight species (Arctic cisco, least cisco, broad whitefish, humpback whitefish, rainbow smelt, round whitefish, saffron cod, and burbot; Figure 91). The ordination (first two axes of the correspondence analysis) accounts for 88% of the variability in catch composition, with the first axis accounting for 73%. The first axis scores (Figure 92) fluctuate widely over time and are negatively correlated (negative loading) with Arctic cisco catches and positively correlated with catches of all other species. Therefore, catches of Arctic cisco and other species tend to show opposite trends, which also was evident in the correlation analysis.

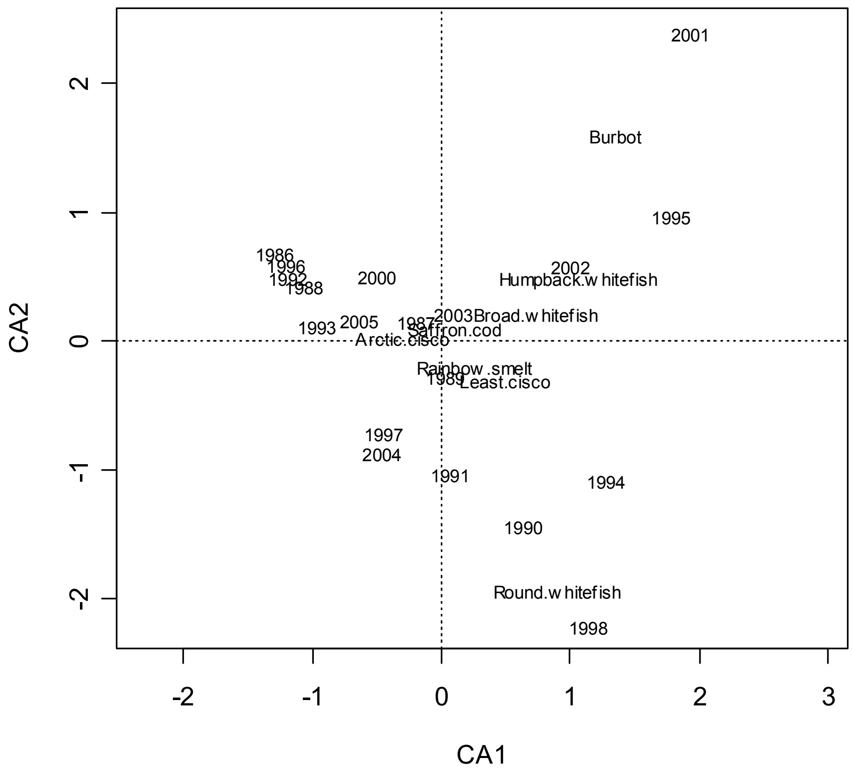


Figure 91. Unconstrained ordination plot of years and species from correspondence analysis, based on catch composition in Colville River subsistence fishery, 1985–2004 (1999 missing).

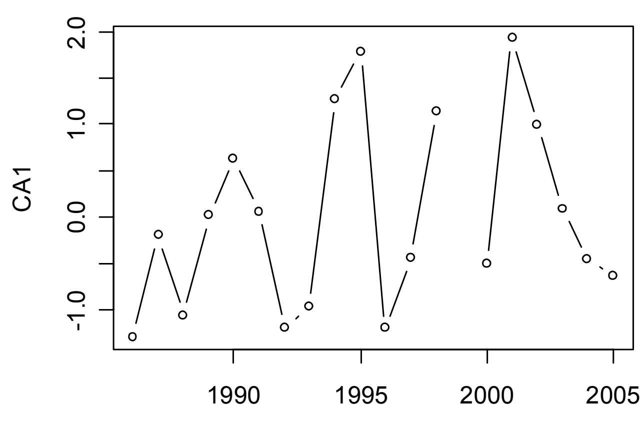


Figure 92. First canonical axis from correspondence analysis, based on catches of 8 species caught in the subsistence fishery, 1986–2005 (1999 missing).

Patterns in Biological Data and Tentative Hypotheses

- Recruitment in recent years, even after accounting for weak easterly (or reversal to westerly) winds in some years were unusually low and some indicators (Age0.resid) suggest a long-term decreasing trend in recruitment. This trend may reflect environmental effects, effects of development, or reduced spawning or survival in the Mackenzie River or eastern Beaufort Sea.
- Catch rates (CPUE) in the fishery ("raw" or adjusted for wind effects) have fluctuated widely but have not shown a long-term trend. However, unusually low catch rates occurred in 2001, suggesting a short-term event that reduced catches below expectation during 2001.
- A pronounced shift in the abundance of several species and in overall species composition in the Prudhoe Bay area were observed between 1988 and 1990, suggesting a shift in regional or large-scale environmental conditions that affected multiple species in the region simultaneously.
- A number of the observed correlations suggest density-dependent effects of Arctic cisco on the survival of new recruits of Arctic cisco. This effect was most evident in negative correlations between the abundance of large Arctic cisco in the Prudhoe Bay region and various measures of year-class strength from the same or subsequent years.
- Indications of density-dependence were apparent in the available size data. The size of most Arctic cisco age-classes was inversely related with their abundance and with the abundance of other species. This relationship could be due to competition or other factors. For example, productivity and prey availability in the summer feeding area may be impacted by alongshore winds, which affect the upwelling of deep, nutrient-rich waters onto the shelf.
- An alternative explanation of the observed patterns is that the same environmental conditions that tend to result in poor recruitment to the Prudhoe area, or in small sizes, may also concentrate adult Arctic cisco and other species along the coast, where they are caught in fyke nets. In other words, variability in the number of larger fishes caught in the Prudhoe Bay region may reflect differences in catchability rather than true differences in abundance. For example, westerly (downwelling) winds may concentrate fishes that prefer brackish water in a narrow band along the coast where they are more susceptible to being captured.

RELATIONSHIPS BETWEEN BIOLOGICAL AND ENVIRONMENTAL INDICATOR VARIABLES

CORRELATIONS BETWEEN BIOLOGICAL AND ENVIRONMENTAL VARIABLES

Because many of the biological indicators were far from normally distributed, we computed Spearman's rank correlations between each of the environmental variables and each of the biological variables. The following groups of pair-wise correlations were judged to be of potential interest. Because of the large number of pair-wise correlations examined, only correlations that were significant at the 99% level or groups of similar correlations that are significant at the 95% level are discussed here. Nonsensical correlations (e.g., biological indicator leading an environmental indicator) are not discussed.

- Strong positive correlations were evident between the recruitment indices and all three indices of easterly wind speed. Correlations were much stronger with summer wind speed at Deadhorse airport than with the other wind indices (Figure 93). The strong correlations reflect the importance of wind-driven transport to the recruitment of Arctic cisco.

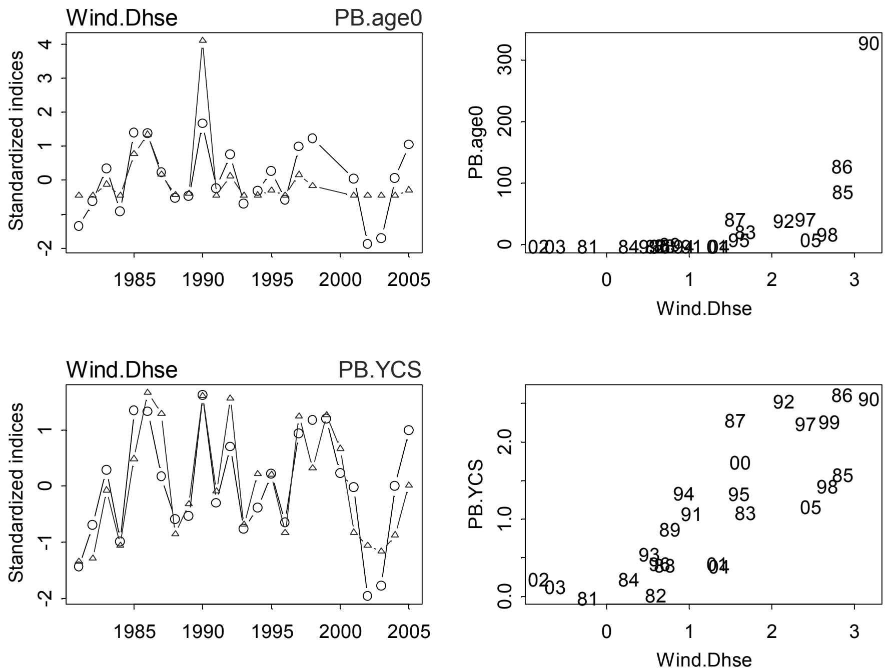


Figure 93. Time series of average easterly winds during summer at Deadhorse airport (circle) with CPUE of age-0 Arctic cisco (triangle) in Prudhoe Bay (top panels) and combined recruitment index for Arctic cisco (bottom panels). Age-0 CPUE is shown on un-transformed scale, whereas the combined index is an average of log-transformed CPUEs.

- The positive correlation between easterly wind speed and year-class strength is also apparent in the CPUE of older year-classes; for example, the CPUE of 6-year old Arctic cisco in the Niġliq fishery (Figure 94).
- We found a significant negative rank-correlation between the abundance of Arctic cod and flow through the Bering Strait and a positive correlation between the multivariate index of species composition and Bering Strait flow (Figure 95).
- The final maximum size of the age-0 and age-1 cohorts at the end of the sampling season was significantly higher in warm years with low ice concentrations in the spring and fall, suggesting that warm conditions may improve growth of young-of-the-year Arctic cisco. This result was evident in a strong positive correlation with the climate index (first PC of temperature, ice and discharge in western Beaufort Sea) (Figure 96).

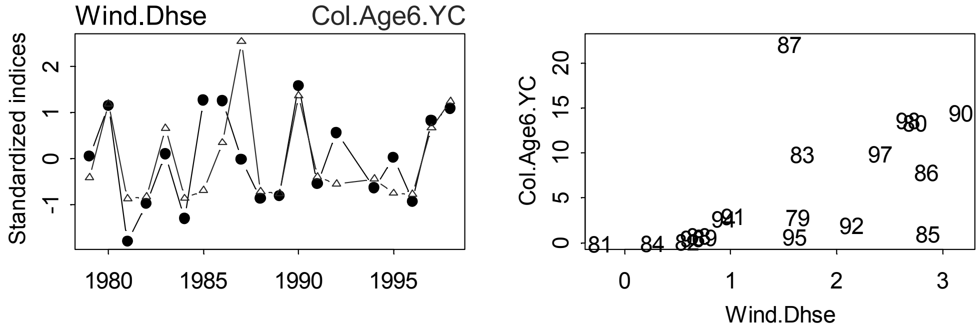


Figure 94. Time series of average easterly winds during summer at Deadhorse airport (Wind.Dhse, circle) and CPUE of age-6 Arctic cisco in the Niġliq fishery (Col.Age6.YC, triangle) and scatterplot of CPUE against wind speed.

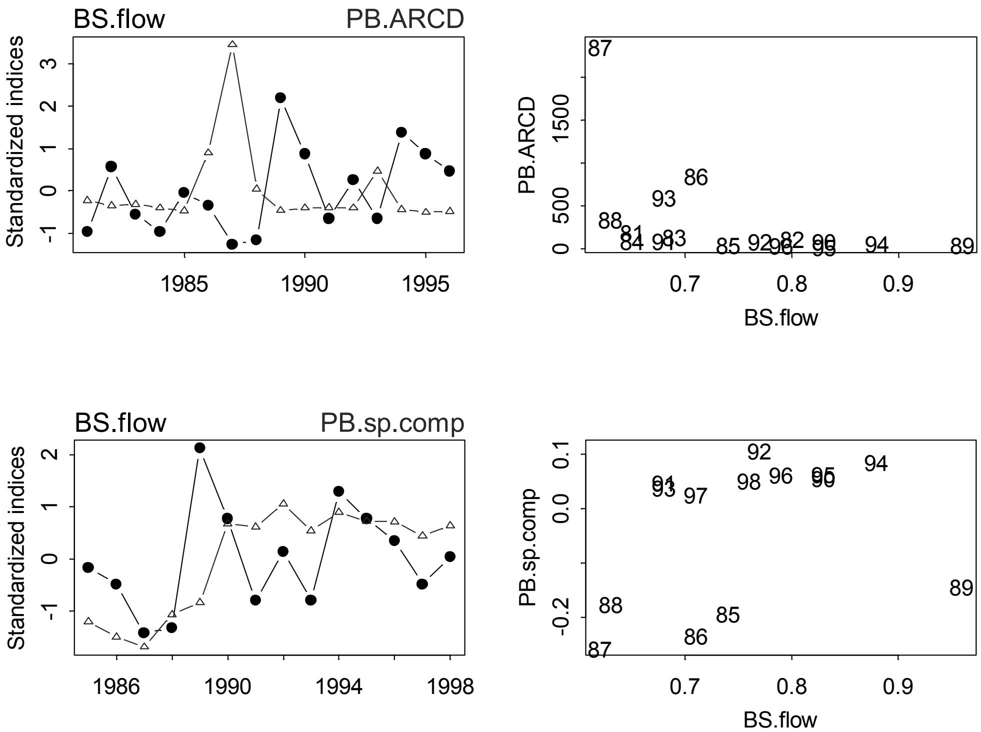


Figure 95. Time series and scatterplots of northward flow through Bering Strait (BS.flow, circle) compared to CPUE of Arctic cod in Prudhoe Bay (PB.ARCD, triangle top) and multivariate index of species composition in Prudhoe Bay (PB.sp.comp, triangle bottom).

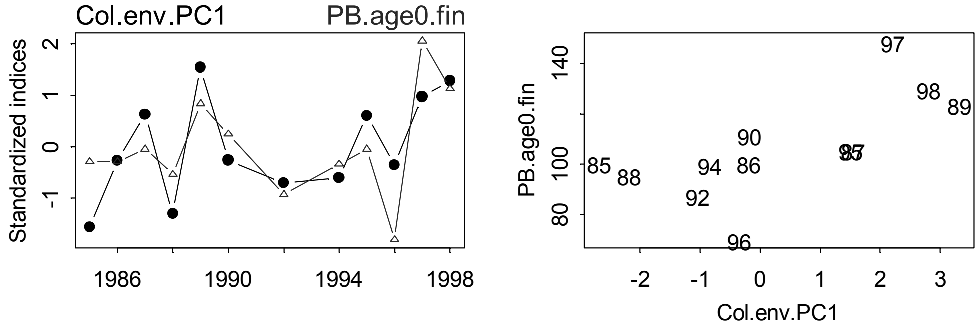


Figure 96. Time series of climate conditions in the Colville River–Prudhoe Bay region (Col.env.PC1, circle; large values reflect warmer conditions, less ice, and higher discharge) and final maximum size of age-0 Arctic cisco (PB.age0.fin, triangle) and scatterplot of size against climate index.

- The average size of age-3 and age-6 Arctic cisco were significantly and negatively correlated with discharge from the Sagavanirktok River (age-3: r = 0.547, p = 0.053; age-6: r = 0.731, p = 0.007).
- A strong positive correlation is apparent between the effort-adjusted catch rate of Arctic cisco in the Colville commercial fishery and the average fall salinity in the Niġliq channel of the Colville delta (Figure 97), suggesting a relationship between local salinities and Arctic cisco catch rates. This relationship was explored in more detail and at a finer spatial scale for the subsistence fishery (See Chapter 5).
- We found weak-to-moderate positive correlations between winter discharge in the Mackenzie River and the recruitment and abundance of the year-class that hatched during the following spring. However, the correlation was significant for age-5 fish only (both in the commercial and subsistence fishery). These correlations are likely to be spurious because the strongest correlations would be expected at younger ages. Moreover, there was no correlation between discharge and recruitment anomalies adjusted for the effects of wind-driven transport.
- We found several significant correlations between temperature and ice conditions in the Colville–Prudhoe Bay region and the survival anomalies of subadult Arctic cisco (ages 5–7). The strongest correlation was found with the PCA-derived climate index for the region (Col.env.PC1; Figure 98) and suggests that survival is enhanced during cold years. However, the correlation is strongly influenced by a single large survival anomaly in 1985, which was higher than expected.
- Total CPUE of Arctic cisco in the Colville commercial fishery, adjusted for the effects of wind-driven transport (CPUE.adj.anom) was positively correlated with salinities in the Colville delta, again suggesting an effect of local salinities on catch rates.
- The CPUE of fourhorn sculpin was positively correlated with summer SST and negatively correlated with ice conditions.

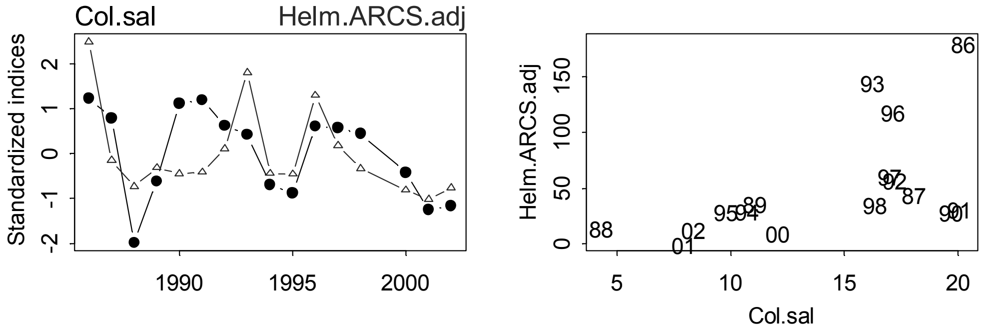


Figure 97. Time series of average fall salinities in the Colville delta (Col.sal, circle) and effort-adjusted CPUE of Arctic cisco in the commercial fishery.

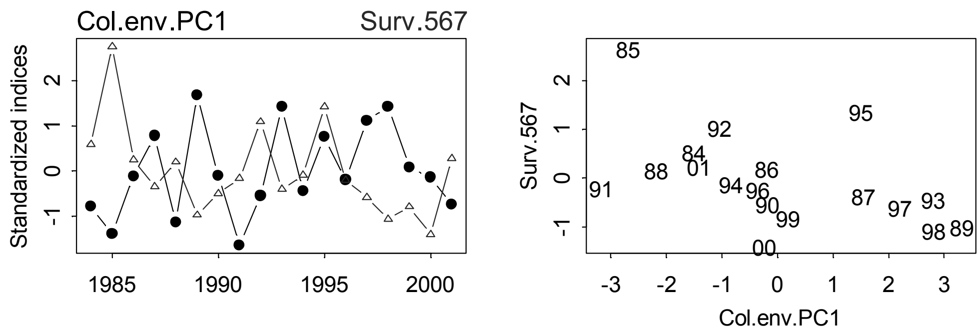


Figure 98. Time series of climate index for Colville region (Col.env.PC1, circle) and survival rate anomalies of age 5–7 Arctic cisco (Surv.567, triangle) and scatterplot of survival anomalies against climate index.

Multivariate Relationships (Visualization / Ordination)

Visualization

We used the multivariate visualization tool GGOBI to examine relationships between key biological variables and environmental variables for the Mackenzie and Colville river regions. Because of numerous years with missing values in many indices, we restricted analyses to two separate groups of variables that were available over different periods. First, we explored relationships between the combined recruitment indices (PB.YCS and YCS.resid) and a number of environmental variables (temperature and ice conditions, wind speed, discharge rates, and Arctic Oscillation). Second, we explored relationships between Age 0 recruitment indices, catch rates in the fishery, abundance of several other species (least cisco, broad whitefish, dolly varden, Arctic flounder, rainbow smelt, fourhorn sculpin) and the same environmental indices.

The analyses suggested some patterns in addition to those identified by correlation analyses:

- A strong positive correlation occurred between the Arctic Oscillation and the recruitment index (adjusted for wind effects: YCS.resid) after the 1989–1990 regime shift ($r = 0.660$, $p = 0.0054$), but not prior to the shift (1981–1989: $r = -0.071$, $p = 0.857$) (Figure 99).

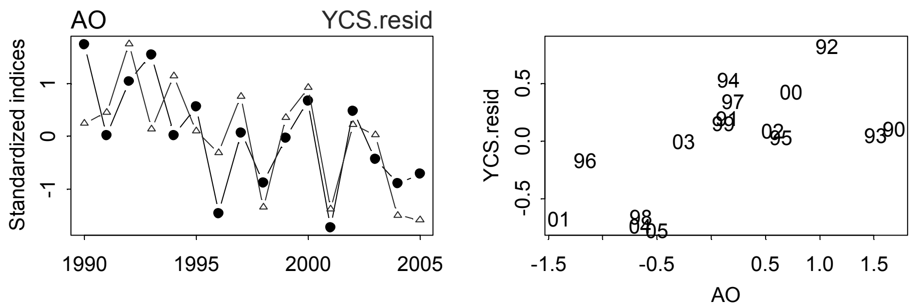


Figure 99. Time series of Arctic Oscillation index (AO, circle) and combined recruitment anomalies (YCS.resid, triangle; effect of wind on recruitment removed) and scatterplot of anomalies against Arctic Oscillation.

- An alternative interpretation is that there is a threshold relationship with the Arctic Oscillation: For positive values of the AO, recruitment residuals are generally above average, while for negative values of the AO, they are typically negative with the exception of 1986 and 1987 (Figure 100). Positive and negative values of the AO are (arbitrarily) defined relative to their long-term mean but appear to reflect different climate regimes. For example, a reversal in the sign of the Arctic Oscillation around 1988–1989 had apparent effects on fish communities in the southeast Bering Sea associated with a change in wind forcing on surface transport (Mueter et al. 2006, Wilderbuer et al. 2002).

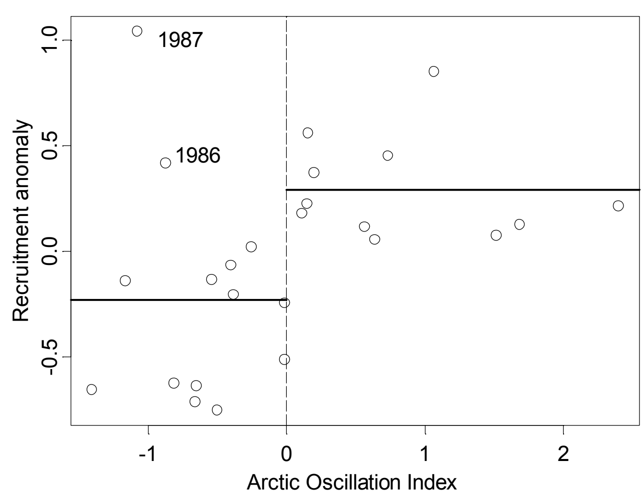


Figure 100. Scatterplot of recruitment anomalies (adjusted for wind effects) at Prudhoe Bay against the Arctic Oscillation Index, with mean recruitment anomalies for negative and positive values of the AO index (solid horizontal lines).

Ordination (Canonical Correspondence Analysis)

A canonical correspondence analysis relates patterns in a multivariate dataset, such as species compositions at a number of sites or over a number of years, to potential explanatory variables (Ter Braak 1986). Here, we use it to explore potential environmental drivers of differences in species composition in Prudhoe Bay and in the Nuiqsut fall fishery over time.

Catch Composition in Prudhoe Bay Fyke Net Samples

To examine potential relationships between species composition in Prudhoe Bay and current environmental conditions (no lags), we conducted a canonical correspondence analysis of species composition based on log(CPUE) values with the following explanatory variables: Arctic Oscillation (AO), Colville climate conditions (Col.env.PC1), Colville area summer sea-surface temperatures (Col.OISST.sum), Colville area ice conditions in spring (Col.ice.spr), and average easterly winds at Deadhorse (Wind.Dhse).

We first added one variable at a time to explore if any variable could account for a significant proportion of the variability in species composition. We found that the "best" variable, Sagavanirktok River discharge, accounted for only 8.3% of variability in species composition, which was not significant at the 95% confidence level ($p = 0.376$) based on a permutation test (Legendre and Legendre 1998). We also tested combinations of two variables and none explained a significant proportion of the variability in species composition.

Catch Composition in Nuiqsut Fishery

To examine potential relationships between the catch composition in the Nuiqsut fall fishery and current environmental conditions, we conducted a canonical correspondence analysis of catch composition (1985–2005) with the following explanatory variables: Arctic Oscillation (AO), Colville climate conditions during the previous year (Col.env.PC1), Colville area summer sea-surface temperatures (Col.OISST.sum), Colville area ice conditions in the fall (Col.ice.Oct), and Colville average salinities during the fishery.

The only variable that accounted for a marginally significant proportion (15.2%, $p = 0.076$) of the variability in catch composition was in-river salinity (Col.sal). None of the other variables added significant explanatory power. A biplot of the ordination with the salinity variable superimposed (Figure 101) shows that salinity is negatively correlated with the first constrained ordination axis (CCA1). This correlation implies that years with low salinity (right hand side of plot), such as 1995 and 2001, tend to be characterized by high abundances of burbot and humpback whitefish, while years with high salinity tend to be characterized by rainbow smelt, Arctic cisco, and round whitefish.

TENTATIVE HYPOTHESES

- Based on previous research and the strong correlations between wind speed and age-0 recruitment of Arctic cisco, we hypothesize that strong easterly winds enhance the recruitment of young-of-the-year Arctic cisco to Prudhoe Bay.

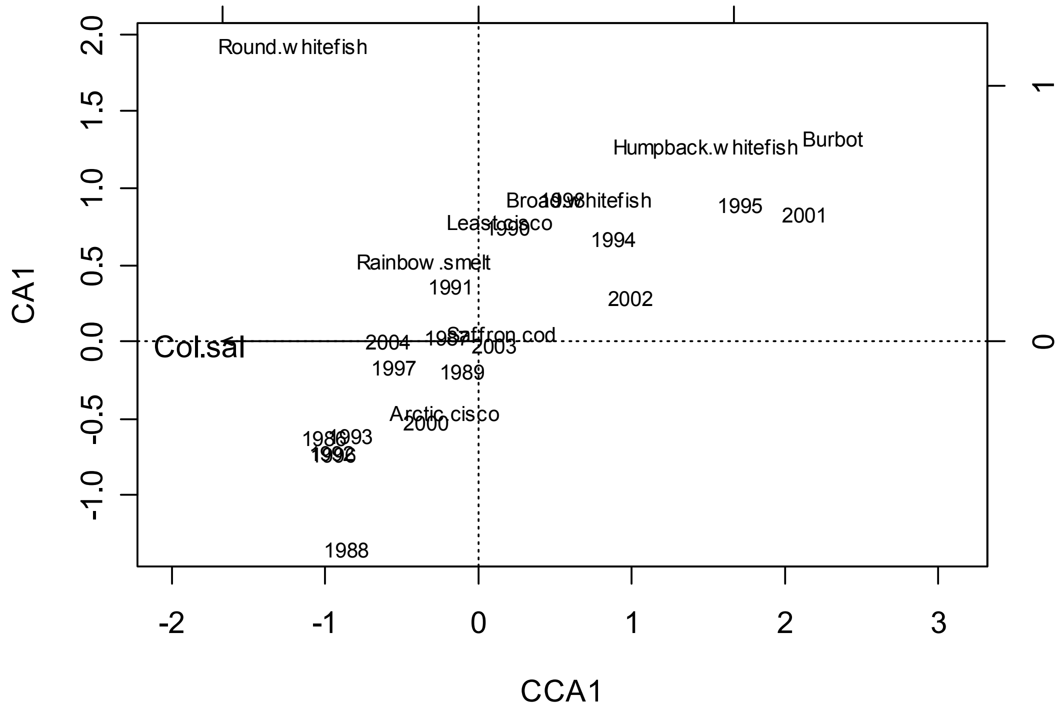


Figure 101. Constrained ordination plot of years and species from correspondence analysis, based on catch composition in Colville River subsistence fishery, 1985–2004 (1999 missing), with Colville fall salinities as a single explanatory variable.

- A positive correlation between our combined environmental index and the maximum size of age-0 Arctic cisco at the end of their first summer suggests that warm conditions enhance the growth of young Arctic cisco. A positive effect of water temperature on growth of Arctic cisco has been confirmed in laboratory studies (Fechhelm et al. 1993). Enhanced growth and larger size-at-age often implies enhanced survival. Therefore, we hypothesize that warmer ocean temperatures during the summer feeding period will result in higher survival rates of the affected year classes of Arctic cisco.
- In contrast to this hypothesis, warmer ocean temperatures during the first ocean year were associated with reduced survival, as indicated by a negative correlation between survival anomalies (difference between observed and expected survival) and our Colville region climate index. It is unclear why this would be the case and to fully investigate the influence of climate on age-0 to age-5 survival, we will examine environmental effects at multiple lags.

- Correlations between catch rates of Arctic cisco and water column salinities in the Colville River suggest that years with higher average salinities in the Colville delta will have higher overall catch rates of Arctic cisco, all else being equal.
- Based on patterns in the Arctic Oscillation index and in several biological variables, we hypothesize that a shift in the Arctic Oscillation in the late 1980s was associated with changes in the species composition in the Prudhoe Bay region, although interannual variability in the AO does not explain patterns in species composition.
- Large-scale climate patterns associated with variations in the AO may also affect the recruitment of Arctic cisco to the Prudhoe Bay region non-linear ways (Figure 100).

RELATIONSHIP BETWEEN BIOLOGICAL RESPONSES AND DEVELOPMENT INDICATORS

CORRELATIONS BETWEEN BIOLOGICAL AND DEVELOPMENT VARIABLES

Because both the biological indicators and indicators of human development often were far from normally distributed, we computed Spearman's rank correlations between each of the development variables and each of the biological variables. The following groups of pair-wise correlations were judged to be of potential interest. Because of the large number of pair-wise correlations examined, only correlations that were significant at the 99% level or groups of similar correlations that are significant at the 95% level are discussed here. Nonsensical correlations (e.g., biological indicator leading a development indicator) are not discussed. The 'causeway' variable was a categorical variable with more than 2 levels and was not included in the correlation analysis.

- Fishing effort in the commercial fishery was negatively correlated with the CPUE of Arctic cisco and least cisco, which may reflect the effect of local depletion on CPUE indices (increased effort reduces abundances sufficiently to result in decreased catch rates). This effect has been known for some time and is the reason for computing effort-adjusted catch rates of Arctic cisco (e.g., Moulton and Seavey 2005).
- Fishing effort was positively correlated with age-0 recruitment and other measures of year-class strength. This correlation may result from negative relationships both between effort and Arctic cisco CPUE and between CPUE and year-class strength. It is unclear whether this reflects causal relationships or indirect effects of other, unknown variables.
- The relative index of disturbance potential for the West Dock causeway was negatively correlated with the abundance of Arctic cisco, least cisco, broad whitefish, and Arctic flounder in the Prudhoe Bay area. For least cisco, this result is consistent with previous observations that West Dock, prior to breaching, provided a barrier to the migration of this species from the Colville delta into the Prudhoe Bay region (Fechhelm et al. 1999), and reflects an increase in the abundance of least cisco in Prudhoe Bay following the breaching of West Dock in 1995–1996. Similar increasing trends were evident in the abundance of age-2+ Arctic cisco (Figure 102) and broad whitefish. The increase for

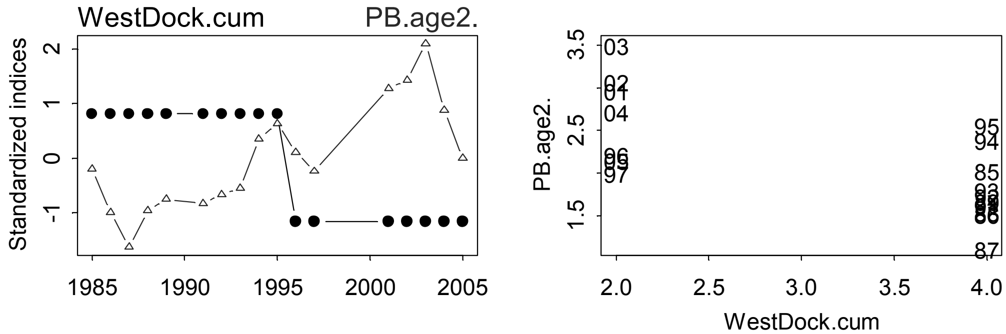


Figure 102. Time series of cumulative disturbance potential rating for West Dock causeway (WestDock.cum, circle) and CPUE of age 2+ Arctic cisco in Prudhoe Bay (PB.age2., triangle) and scatterplot of CPUE against disturbance potential.

broad whitefish started well before breaching and is, therefore, unlikely to be causally related to breaching. Moreover, the broad whitefish population in the Prudhoe Bay area is believed to reside primarily in the Sagavanirktok delta and is unlikely to be affected by the West Dock causeway.

- We found no evidence that catch rates of Arctic cisco in either the subsistence or the commercial fishery were negatively correlated with any of the indicators of disturbance. In particular, correlations between the disturbance potential rankings of winter activities in the Colville delta and various measures of adjusted CPUE of Arctic cisco in the fishery were not significant and generally were weak (Table 16).

Table 16. Spearman rank correlations between the disturbance potential rankings of winter activities in the Colville delta and western section of the Beaufort Sea and various measures of adjusted CPUE of Arctic cisco.

Variable	West.Frozen	Colville.Frozen
Helm.ARCS.adj	-0.126	-0.119
Nig.ARCS.adj	-0.072	-0.029
Nig.ARCS.sal	-0.118	-0.056
Col.ARCS	-0.049	-0.025
CPUE.Nig.anom	-0.285	-0.255
CPUE.Col.anom	0.077	0.120

Although none of the correlations were significant, most of the correlations were negative, which may suggest a marginal negative effect of winter activities in the Colville delta on catch rates of Arctic cisco (Figure 102).

- We found a significant positive correlation between the Endicott causeway indicator and recruitment anomalies (Age0.resid or YCS.resid) (Figure 103). The relationship was due to the fact that an increase in average recruitment anomalies around 1986–1987 coincided with the construction (winter of 1985–1986) and subsequent breaching (winter of 1986–1987) of the Endicott causeway.
- There was some indication of a negative correlation between winter development activities in the Colville delta and the survival of older (Age 5–7) Arctic cisco (Figure 104). In particular, the lowest survival anomalies in the years 1997–2000 corresponded to the 4 years with the most development activity in the Colville delta.

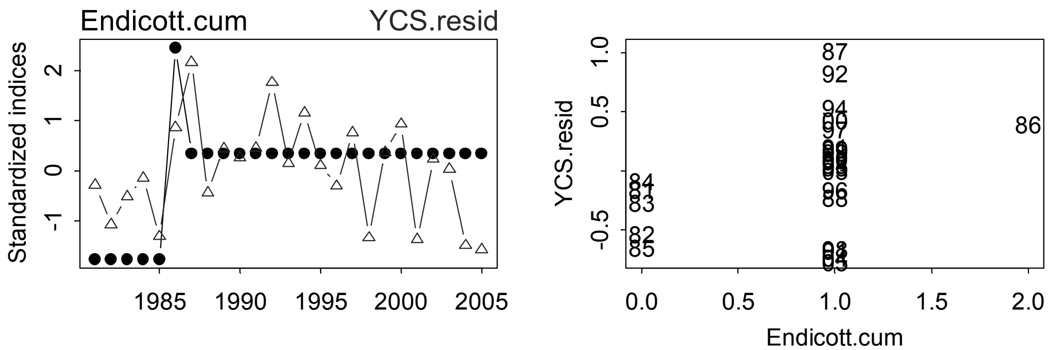


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Figure 103. Time series of cumulative disturbance potential rating for Endicott causeway (Endicott.cum, circle) and recruitment anomalies of Arctic cisco in Prudhoe Bay (YCS.resid, triangle) and scatterplot of anomalies against disturbance potential.

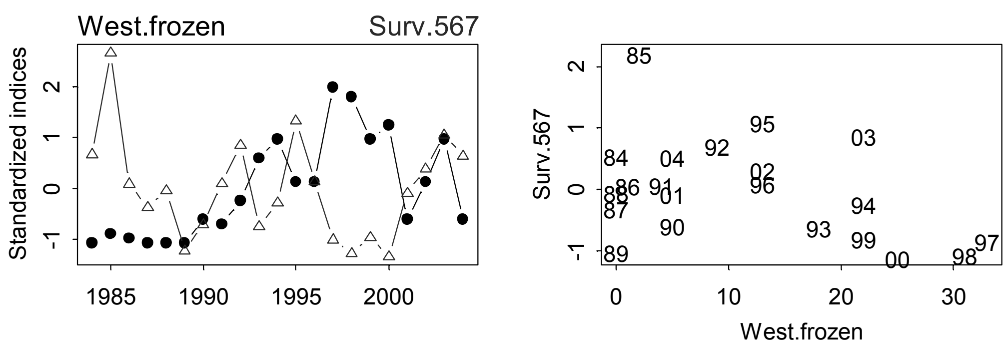

Figure 104. Time series of disturbance potential rating for development activities in the western Beaufort Sea (West.frozen, circle) during the frozen season and survival anomalies of age 5/6 Arctic cisco (Surv.567, triangle) and scatterplot of CPUE against disturbance potential.

PATTERNS IN DEVELOPMENT INDICATORS AND TENTATIVE HYPOTHESES

We found some correlations between biological response variables and the development indicators that suggest:

- A potential effect of West Dock on the abundance of several species in the Prudhoe Bay region.
- A potential effect of development activities in the Colville region (western region) on the survival of older age classes of Arctic cisco.

The identified relationships and tentative hypotheses will be further analyzed using appropriate statistical models to test specific hypotheses (Chapter 5).

5. HYPOTHESIS TESTING

We tested a number of hypotheses in a general modeling framework, with the goal of identifying the most plausible statistical model to describe likely effects of environmental and human influences on Arctic cisco population dynamics. Specific objectives were (1) to identify factors that have the strongest apparent effect on Arctic cisco recruitment, survival, abundance, or condition in the Colville River; (2) to test specific *a priori* hypotheses, as identified through a literature review and by the Panel of Experts; and (3) to test new hypotheses that emerged from exploratory analyses.

We distinguish between *a priori* and newly identified hypotheses because only *a priori* hypotheses allow valid statistical inferences to be made. Hypotheses that are based on the exploratory analyses are data driven and do not support valid, independent tests because the same data are used for testing the hypothesis that were used for suggesting the hypothesis in the first place. Nevertheless, models to test these tentative hypotheses are useful in identifying potential mechanisms that affect the response variables (recruitment, survival, abundance, or condition) and provide a basis for suggesting future research directions. The following general *a priori* null hypotheses were identified.

- Changes in oceanographic or hydrographic processes do not significantly affect the recruitment, survival, or abundances of Arctic cisco in the Colville River at any stage in their life history.
- Ecological processes and other species do not significantly affect recruitment, survival, or abundance of Arctic cisco in the Colville River.
- Human activities related to oil development or fishing do not significantly affect the recruitment, survival, or abundance of Arctic cisco in the Colville River.

These general hypotheses were refined into a set of testable hypotheses relating to specific environmental or human influences and to specific life-history stages. Hypotheses were based on a literature review and input from the Panel of Experts. We evaluated specific null hypotheses by formulating suitable statistical models that relate indices of Arctic cisco recruitment, survival, or abundance to one or more of the factors identified as potentially important.

Before identifying a useful model (or models) for drawing valid inferences, we carefully selected a limited set of candidate models to analyze. Studies of abundance and recruitment have often identified spurious relationships (relationships due to random variability in the data) that break down after more years of data are added (Myers 1998). Spurious relationships can easily result from analyzing a large number of factors, regardless of potential mechanisms, and from including factors that are averaged over a range of spatial and/or temporal scales. Therefore, we restricted the number of *a priori* candidate models to a set of reasonable models that included only likely explanatory factors, made biological sense, and reflected mechanisms thought to be likely. If too many models are examined, there is a high chance of selecting models that merely fit random patterns in the data, rather than approximating the underlying mechanisms. Once a set of potentially important variables was identified, we selected the best statistical model for each of the general hypotheses by following steps outlined in Burnham and Anderson (2002).

We developed a “global” model (or models) that included several or all of the selected explanatory factors. However, as indicated above, the large number of potential factors required that we use data-reduction techniques such as Principal Component Analysis or that we included only one among a set of interrelated factors in a particular model.

- We checked the fit of the global model (examining residuals, R^2, other goodness-of-fit criteria) and proceeded only if the global model provided an acceptable fit. Otherwise, we revised the global model until a suitable model was identified.
- We developed a set of plausible sub-models representing simplifications of the global model (i.e., we eliminated some or all of the explanatory factors from the model); only models that have a reasonable biological justification were considered. The resulting set of candidate models typically included a limited number of models that reflect alternative views (or hypotheses) about potential relationships between the response variables and various explanatory variables.
- Using appropriate model selection criteria, we selected the best model(s) (i.e., the combination of factors that best described the data) from the *a priori* set of candidate models.

To test the first general hypothesis regarding effects of oceanographic or hydrographic processes on Arctic cisco, we modeled indices of recruitment, survival, or abundance in year t (Yt) as a function of selected environmental indices during year $t-k$ ($X_{i,t-k}$):

$$Y_t = \alpha + \sum_i f_i(X_{i,t-k}) + \varepsilon_t$$

Here, α is the overall mean of Y, k reflects the lag between the life stage at which variable X_i acts and the response in year t, and ε_t is the unexplained residual variability. The functions $f_i(.)$ denote the assumed functional relationship between X_i and Y_i. To examine the likely form of the relationship, we generally started by fitting a Generalized Additive Model (GAM; Hastie and Tibshirani 1990). Unlike in linear regressions, no linear relationship between the predictor and response variables is assumed in a GAM. Instead, smooth, non-linear functions are used to quantify the response to predictor variables with the degree of smoothing determined by cross-validation. Whenever possible, nonparametric terms were replaced by a parametric (polynomial) term with equivalent degrees of freedom to that of the GAM in order to compare different models and test the significance of individual terms.

Appropriate submodels of the above “global” model included models with only a single explanatory variable, as well as a model without any environmental variables (null model). The best submodel (or models) was identified based on the small-sample Akaike Information Criterion (AIC_c; Burnham and Anderson 2002) and included only those factors that help explain a significant proportion of the variability in the response variable.

General hypotheses regarding the importance of biological and ecological factors on Arctic cisco recruitment, survival and abundance, such as the abundance of competing species, were examined in the same way. Depending on the number of biotic and abiotic factors that were found to be important, we combined environmental and biological indices into one or more plausible models that best explained natural variability in the response variable.

Two alternative approaches were used to examine human impacts on Arctic cisco recruitment, survival, or abundance. First, Arctic cisco abundance was modeled as a function of one or more indices of human impact, similar to the models examining the effect of natural variability. These models were used to identify any factors that can explain a significant proportion of the variability in the response variable. However, if there is known natural variability in the response, such variability can mask human impacts and should be accounted for before testing for impacts. Therefore, we also related residuals from the best model(s) of natural variability to indices of human impact. These residuals reflect unexplained variability in the response variable after the effects of environmental variability are accounted for. The unexplained variation may be a result of both human impacts and any remaining variability due to unknown factors and random chance. To test for human impacts, we fit Generalized Additive Models and, if adequate, linear regression models using the estimated residuals from the above models as the dependent variable and an index of human impact as independent variable. For example, a simple linear model may be as follows:

$$\hat{\varepsilon}_t = \beta_0 + \beta_1 H_t + \nu_t$$

Here, H_t may be any continuous or categorical variable reflecting human impacts, β_0 and β_1 are regression parameters, and v_t is the remaining residual variability. Because of the relatively short duration of the available data series, we were rarely able to include more than two or three environmental variables without over-parameterizing the models. Carefully selecting the candidate variables at the model development stage was an important step to help avoid such over-parameterization.

ENVIRONMENTAL EFFECTS ON ARCTIC CISCO RECRUITMENT

EFFECTS OF WIND-DRIVEN TRANSPORT ON YOUNG-OF-THE-YEAR RECRUITMENT

Background: A well-known relationship has been identified between wind-driven coastal transport and age-0 CPUE at Prudhoe Bay, as described, for example, in Fechhelm and Griffiths (1990). This relationship has held up through recent years (Fechhelm et al. 2005), but has not been quantified statistically since the early papers. It has variously been described as a linear or threshold relationship. This known relationship should be accounted for before examining the effects of other environmental or human impacts on recruitment. The relationship also was evident in positive correlations between indices of wind speed and indices of age-0 recruitment (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations).

Hypothesis: Recruitment of age-0 Arctic cisco to Prudhoe Bay increases linearly or non-linearly with average easterly wind speed. The relationship should be evident in the CPUE of age-0 Arctic cisco as well as in an index that combines CPUE of ages 0–2 (Chapter 4–Biological Indicators, Juvenile Arctic Cisco in Prudhoe Bay).

Methods: We first modeled the relationship between easterly winds as measured at Deadhorse and two recruitment indices at Prudhoe Bay using a non-parametric smoother (Generalized Additive Model, GAM, with thin-plate regression spline smoother; Wood 2000) to estimate the general form of the relationship. The recruitment indices include log-transformed age-0 CPUE and on a combined index of recruitment based on CPUE of ages 0–2 (Chapter 4–

Biological Indicators, Juvenile Arctic Cisco in Prudhoe Bay). The smoother and confidence interval suggest that a piecewise linear regression or a linear regression with a lower threshold (CPUE = 0 below threshold) may be most appropriate (Figure 105). We, therefore, fit a model to both recruitment indices with zero CPUE below an (estimated) threshold for wind speed and a linear relationship between CPUE and easterly winds above the threshold.

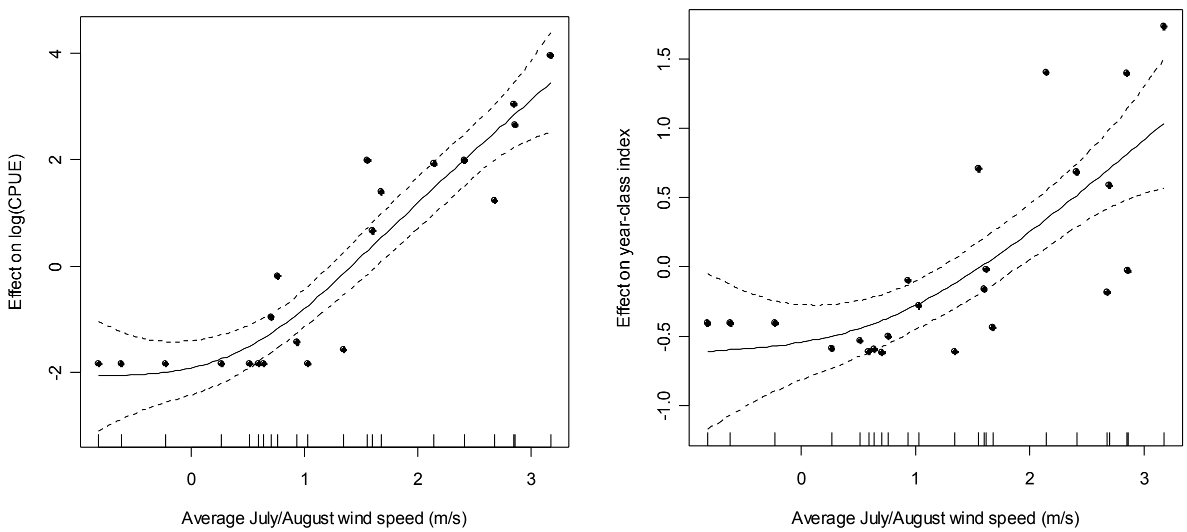

Figure 105. Estimated effects of average July 1–August 31 easterly winds at Deadhorse airport on log-transformed age-0 CPUE and on a combined index of recruitment of Arctic cisco at Prudhoe Bay.

Results: Average easterly wind speed explained approximately 80% of the variability in log(CPUE) of age-0 Arctic cisco and the estimated threshold suggested no recruitment below an average wind speed of 0.54 m/s or approximately 1 mile per hour (Figure 106; Appendix L, Model I.1.1a). A model with the threshold fixed at 0 m/s fit equally well (Appendix L, Model I.1.1b), but we chose to estimate the threshold instead of fixing it arbitrarily. Residual diagnostics indicated a good model fit with approximately normally distributed residuals. The model fit data below the threshold "perfectly" because there were complete recruitment failures in all years where average easterly wind speed was below the threshold. We similarly modeled the combined recruitment index as a function of wind speed. Results suggested a lower threshold for wind speed (0.02 m/s; Figure 107; Appendix L, Model I.1.2a) because some recruitment resulted from years with very low easterly wind speeds, as evidenced by the occurrence of age-1 and age-2 Arctic cisco in subsequent years. The model had a lower coefficient of determination ($R^2 = 0.70$) than the model using age-0 CPUE only and was almost indistinguishable from a model with the threshold fixed at 0 m/s (Appendix L, Model I.1.2b).

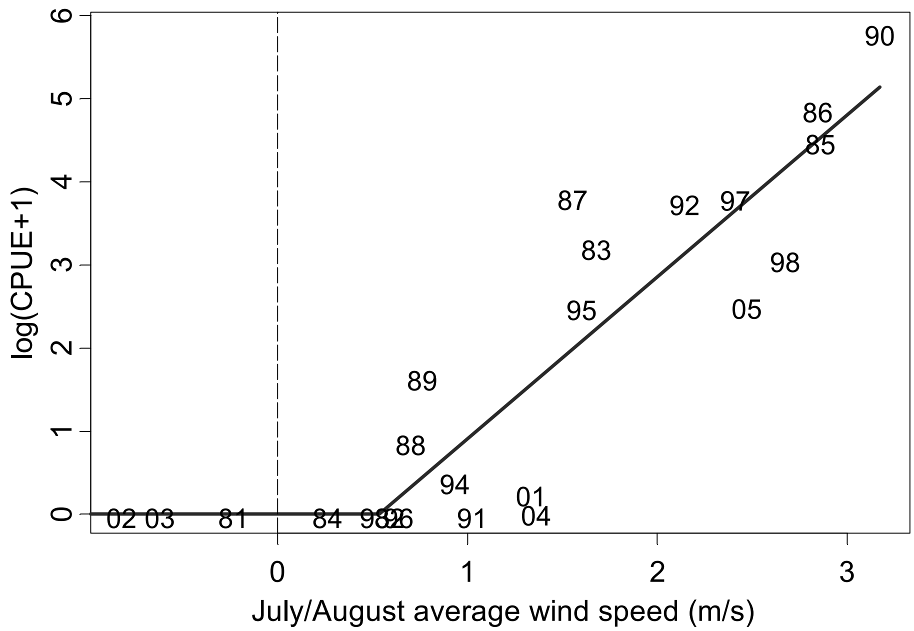

Figure 106. Log-transformed CPUE of age-0 Arctic cisco at Prudhoe Bay as a function of July 1–August 31 average easterly wind speed at Deadhorse airport.

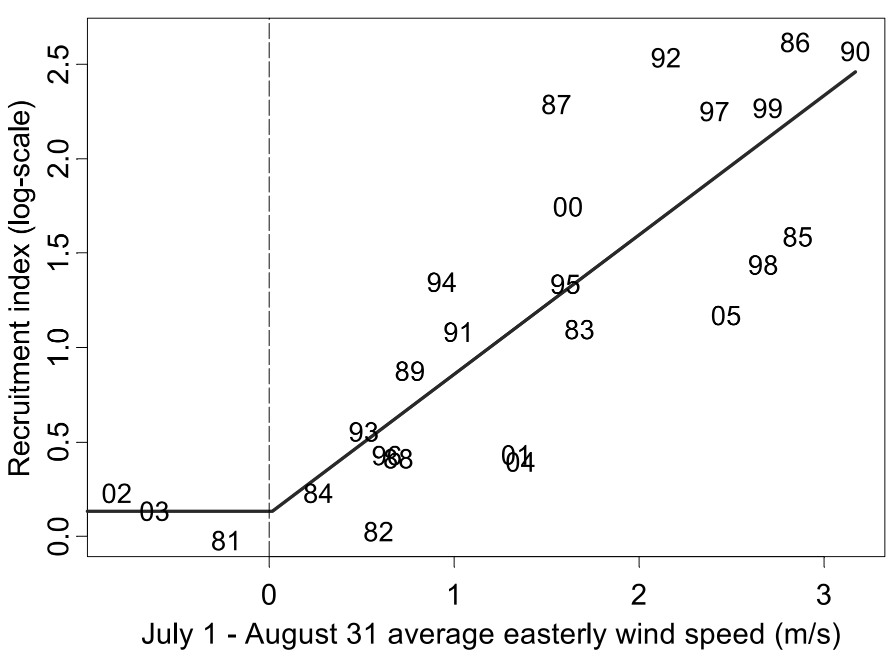

Figure 107. Combined index of year-class strength of age-0 to age-3 Arctic cisco at Prudhoe Bay as a function of July 1–August 31 average easterly wind speed at Deadhorse airport (linear model with threshold).

Conclusions: Much of the variability in recruitment of Arctic cisco to Prudhoe Bay is determined by the prevalence of favorable winds. Complete or near recruitment failures occur if winds along the Beaufort Sea coast (or at Deadhorse) are westerly on average. Successful recruitment occurs at higher wind speeds and recruitment strength appears to increase linearly with wind speed. The modeled relationship can be used to adjust for variability in wind-driven transport prior to examining effects of other factors on recruitment.

Alternative Models: We considered two alternative forms of the model: a simple linear regression model of the recruitment indices on wind speed and a simple threshold model or step model (low recruitment below threshold, high but constant recruitment above threshold). The linear model with threshold provided a better fit to the data than the simple linear regression model for the age-0 recruitment index (Appendix L, Model I.1.3), as indicated by lower values of the small-sample Akaike Information Criterion (AIC_c = 66.2 vs. 71.5). For the combined recruitment index, both models resulted in a similar fit (AIC_c = 43.1 for linear model with threshold [or 40.2 if threshold was fixed at 0], AIC_c = 42.2 for simple linear model). The threshold model (step-model) provided the best fit for the age-0 recruitment index (Figure 108; Appendix L, Models I.1.4; AIC_c = 62.0), and a similar good fit for the combined recruitment index (AIC_c = 43.5). Therefore, either the linear model with threshold or the step model provided good fits to both recruitment indices.

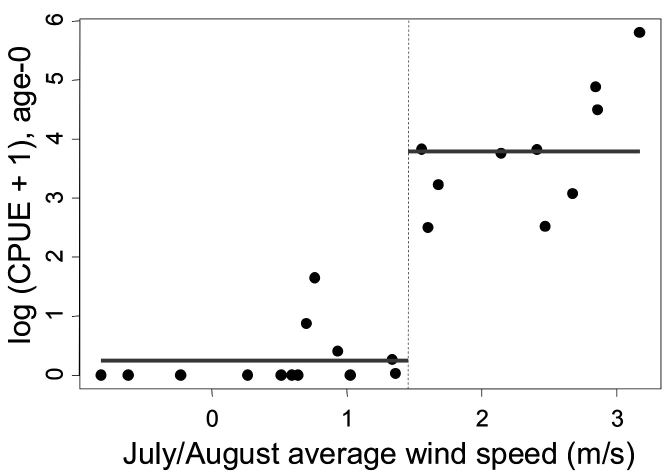

Figure 108. Index of age-0 abundance of Arctic cisco at Prudhoe Bay as a function of July 1–August 31 average easterly wind speed at Deadhorse airport (Threshold or “one-step intervention” model).

In addition to the alternative model structure, we examined the relationship between the recruitment indices and other indices of easterly winds. In particular, we developed two alternative wind indices derived from model-based wind speeds from the Climate Diagnostic Center (Chapter 4–Environmental Indicators for the Coastal Beaufort Sea, Winds). Although these indices were tailored to specifically reflect summer, wind-driven transport along the coast of the Beaufort Sea between the Mackenzie and Colville rivers, they were much poorer predictors than measured winds at Deadhorse, with R^2 values between 17 and 29% (Appendix L, Models I.1.5 and I.1.6). Although significant in all cases, the poor performance of the modeled winds suggests either that measured winds at Deadhorse provide a better index of westward transport than model-based wind speeds in this region, that the above relationship reflects a different mechanism not related to wind-driven transport, or that the relationship is spurious (due to random variability). However, the relationship is unlikely to be spurious because it has held up for over two decades since it was first hypothesized. More likely, the poor relationship with modeled winds may reflect problems with the wind models, which are affected by proximity to the Brooks Range in the eastern Beaufort Sea (see Appendix H).

EFFECTS OF TEMPERATURE AND ICE CONDITIONS ON ARCTIC CISCO RECRUITMENT

Background and Hypotheses: Because of the widespread effects of temperature on early marine survival of many fish species, we hypothesized that warmer temperatures in the coastal Beaufort Sea would be associated with higher recruitment of young-of-the-year Arctic cisco to the Prudhoe Bay region. Evidence is strong from other anadromous species, such as salmon in Alaska, that warm temperatures during early ocean life are associated with enhanced survival. Exploratory analyses provided some evidence for effects of temperature conditions on Arctic cisco growth and survival (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations and Tentative Hypotheses), but no evidence for effects on recruitment. Nevertheless, we tested for effects of temperature variables because of the importance of temperature to many biological processes.

Methods: We modeled and tested for potential effects of temperature and ice conditions in the coastal Beaufort Sea on both recruitment and on recruitment anomalies of Arctic cisco (i.e., remaining variability in recruitment after removing effects of wind-driven transport). As indicators of temperature and ice conditions, we used the first principal components of environmental variability in the central Beaufort Sea (Col.env.PC1, Chapter 4–Relationships Among Indicator Variables, Environmental Indicators, Data Reduction) and the Mackenzie River regions (Mack.env.PC1), respectively. These indicators reflect climate conditions in the respective regions, and both indicators were included to examine potential effects of temperature on outmigrating juveniles in the Mackenzie delta region and during coastal migrations in the coastal Beaufort Sea. We used a Generalized Additive Model to test for the presence of non-linear relationships and substituted linear regression models where appropriate to test for significant effects of the environmental variables on recruitment anomalies.

Results: We found no apparent effects of temperature and ice conditions during the early juvenile phase on recruitment of Arctic cisco to the Prudhoe Bay region (before or after removing wind effects). The GAM model showed no evidence of non-linearity, and a multiple linear regression did not suggest a significant effect of environmental conditions in either the Mackenzie region or in the central Beaufort Sea on recruitment ($p = 0.518$; Appendix L, Model I.2.1) or recruitment anomalies (Appendix L, Model 1.2.2, $p = 0.154$). The estimated effects were similar (and non-significant) if we simultaneously modeled the recruitment index (PB.YCS) as a function of easterly winds at Deadhorse and the two environmental indices (not shown).

Using residuals from the age-0 CPUE transport model (age0.resid) as an index of recruitment anomalies (Chapter 4) resulted in an apparent non-linear effect of Mackenzie conditions on recruitment that was significant ($p = 0.020$) and accounted for 45% of the variability in these anomalies. However, the shape of the relationship was highly non-linear and does not appear biologically reasonable (Figure 109); therefore, it is likely to be a result of random variability. Furthermore, if easterly winds and the Mackenzie index were included in a single model, the Mackenzie index was no longer significant.

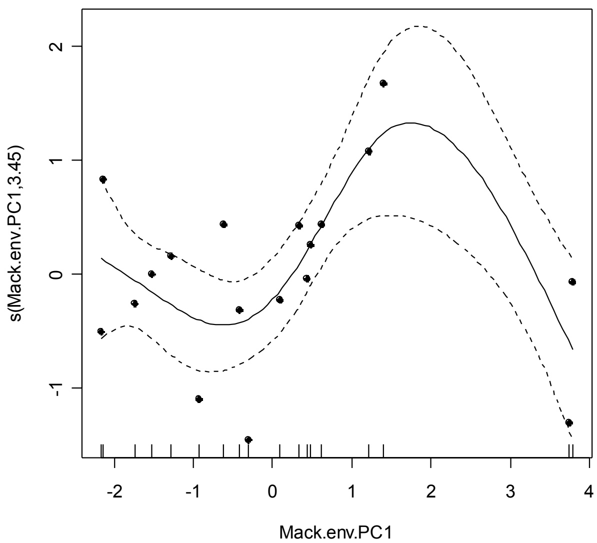

Figure 109. Estimated effect of environmental index in Mackenzie region on recruitment anomalies (age0.resid) of Arctic cisco. Note small number of observations with values above 1 that drive the apparent dome-shaped relationship.

Conclusions: Because the combined recruitment index did not show any significant relationship and because of the unreasonable shape of the estimated effect of Mackenzie conditions on age-0 CPUE, we concluded that there was no significant effect of temperature and ice conditions during early ocean life on the recruitment of Arctic cisco to Prudhoe Bay. However, when testing for effects of potential competitors on recruitment (see below), we found a significant effect of temperature conditions on recruitment.

EFFECTS OF FRESHWATER DISCHARGE IN THE WESTERN BEAUFORT SEA ON ARCTIC CISCO RECRUITMENT

Background and Hypothesis: Because freshwater discharge strongly affects the coastal environment of the Beaufort Sea and coastal salinities have been shown to affect the distribution of Arctic cisco, we examined potential relationships between river discharge, recruitment, and recruitment anomalies. We hypothesize that river discharge affects the number of young-of-year Arctic cisco caught in Prudhoe Bay, but the direction of a potential effect is not specified. Exploratory analyses suggested weak correlations between discharge in the Sagavanirktok River and recruitment (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations).

Methods: Recruitment and recruitment anomalies (variability in recruitment remaining after effects of wind-driven transport were removed; see Chapter 4–Biological Indicators, Arctic Cisco Abundances in the Coastal Beaufort Sea) were modeled as a function of discharge in the

Kuparuk or Sagavanirktok rivers using non-parametric and linear regression models. The discharge series from the two rivers (Chapter 4–Environmental Indicators for the Colville River–Prudhoe Bay Region, River Discharge) did not cover the same time period; hence, results are not directly comparable. Only discharge was included as an explanatory variable in most of these models because the length of the discharge series did not match that of other data series. However, for a reduced set of years, temperature and discharge effects were examined in a multiple linear regression model. The discharge series showed a strong linear trend (see Figure 74), which was removed by computing residuals from a linear regression on year. Analyses were done with both the raw discharge series and the detrended series.

Results: While a regression of recruitment anomalies on Sagavanirktok River discharge was not significant (Appendix L, Model I.3.1a), we found a significant positive relationship between the detrended discharge series and recruitment anomalies (Figure 110; Appendix L, Model I.3.1b). However, the relationship was not significant if the age-0 recruitment index was used instead of the combined recruitment index. Moreover, there was no apparent relationship with Kuparuk River discharge, suggesting that the Sagavanirktok River discharge effect may be spurious (due to random chance).

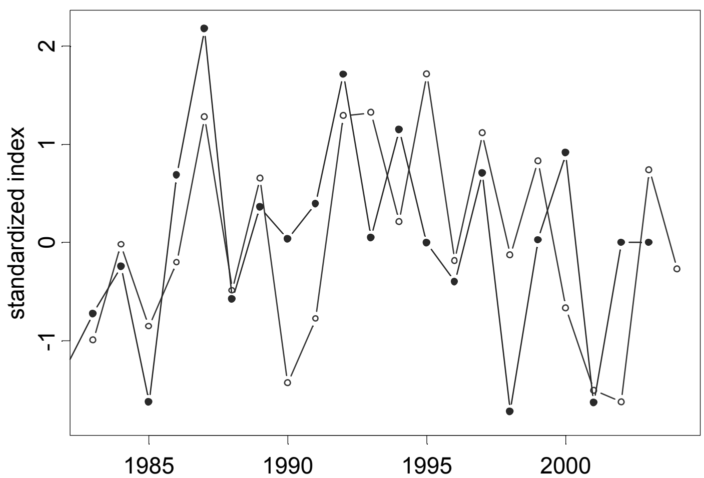

Figure 110. Time series of de-trended river discharge (open circles) and recruitment anomalies of age-0–2 Arctic cisco to the Prudhoe Bay region (closed circles).

We found no significant linear or non-linear relationships between discharge rates in the Mackenzie River and recruitment or recruitment anomalies at Prudhoe Bay (not shown).

Conclusions: Although Sagavanirktok River discharge potentially affects the number of young-of-the-year Arctic cisco in the Prudhoe Bay region, the evidence for a significant relationship is weak and we conclude that river discharge is not a strong determinant of year-class strength. The apparent relationship could be due to effects of discharge on the distribution of Arctic cisco and their availability to the fyke nets used in the monitoring program.

EFFECTS OF ENVIRONMENTAL CONDITIONS IN THE MACKENZIE RIVER REGION ON ARCTIC CISCO RECRUITMENT

Background: Environmental conditions in the Mackenzie River may affect young Arctic cisco prior to and during outmigration. Although we found no evidence for linear relationships between recruitment and any one variable in the correlation analyses (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations), we examined potential synergistic effects and non-linear effects of Mackenzie River discharge and temperature conditions on recruitment (or on recruitment anomalies).

Hypotheses: Based on results from other anadromous fish species in Arctic or subarctic rivers, we hypothesize that (1) high discharge rates in the winter and spring in the Mackenzie River increase the survival and, hence, recruitment of young Arctic cisco and (2) cold winter temperatures reduce survival and subsequent recruitment to Prudhoe Bay.

Methods: We modeled recruitment anomalies as a function of winter or spring discharge rates, minimum winter temperatures, and spring ice conditions using non-parametric and multiple linear regression models. We included one of the discharge variables with the other two variables in a single model and used a model selection approach to select the most parsimonious submodel.

Results: There was no evidence that winter or spring conditions in the Mackenzie River region had a significant (linear or non-linear) effect on recruitment anomalies. The full models with either winter or spring discharge were not significant (Appendix L, Models I.4.1a,b) and the most parsimonious reduced model was a simple mean model that included none of the variables.

Conclusions: We conclude that winter and spring temperatures, discharge, and ice conditions in the Mackenzie River and delta have no discernible effect on the recruitment of Arctic cisco to the Prudhoe Bay region, after accounting for the effects of wind-driven transport.

ENVIRONMENTAL EFFECTS ON ARCTIC CISCO SURVIVAL

EFFECTS OF SUMMER TEMPERATURE AND WIND CONDITIONS ON ARCTIC CISCO SURVIVAL

Background and Hypotheses: Because of the widespread effects of climate conditions on the survival of marine and anadromous fishes, we hypothesized that favorable climate conditions, in particular warmer temperatures and upwelling conditions in the Beaufort Sea, would be associated with higher survival rates of Arctic cisco from age-0 to the time they are caught in the fishery. Upwelling was not measured in the Beaufort Sea but we used the average squared easterly wind speed in July and August as a proxy for upwelling, which is roughly proportional to the square of alongshore wind speed. Exploratory analyses revealed a significant negative relationship between temperature and survival of adult cisco (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations).

Methods: We related indices of survival rate anomalies between age-0 and age-5 (Chapter 4–Biological Indicators, Survival from Age-0 to Age-5) and combined annual survival anomalies of 5- and 6-year olds (Chapter 4–Biological Indicators, Survival of Arctic Cisco from Age-5 to Age-7) to environmental variables measured in the western Beaufort Sea, specifically to the first principal component of temperature conditions (Chapter 4–Relationships Among Indicator Variables, Environmental Indicators, Data Reduction) and to averaged squared easterly wind speed (Chapter 4–Environmental Indicators for the Coastal Beaufort Sea, Winds). Because climate may affect the survival of Arctic cisco at any or all stages between the age of recruitment (age-0) and age-5, we examined relationships at multiple lags. In addition, we modeled age-0 to age-5 survival rate as a function of environmental conditions averaged over the previous 6 years.

Results: We found some evidence that summer temperature conditions on the central Beaufort Sea shelf (Col.env.PC1) during the first summer (age-0 stage) were related to the subsequent survival of Arctic cisco (Surv.age5; Appendix L, Model II.1.1), but temperature during later summers was not. In addition, there was an apparent relationship between summer temperature conditions and the year-to-year survival of subadults at ages 5–7 (Surv.567; Appendix L, Model II.1.2). We found no evidence that survival at any stage was related to average upwelling conditions (wind speed squared). Contrary to expectations, the relationships between survival and temperature conditions were negative in both cases (Figures 111 and 112), suggesting that survival of both young-of-the-year recruits and of subadults was apparently reduced during summers with above-average temperatures. The regression of age-0–5 survival was strongly affected by several influential outlier years (1989, 1991, 1994), but the relationship generally improved when these outliers were removed. The regression of subadult survival on the temperature index was influenced by a single large outlier (1985) and was no longer significant if the outlier was removed or if a robust regression was used (Model II.1.2, Figure 112).

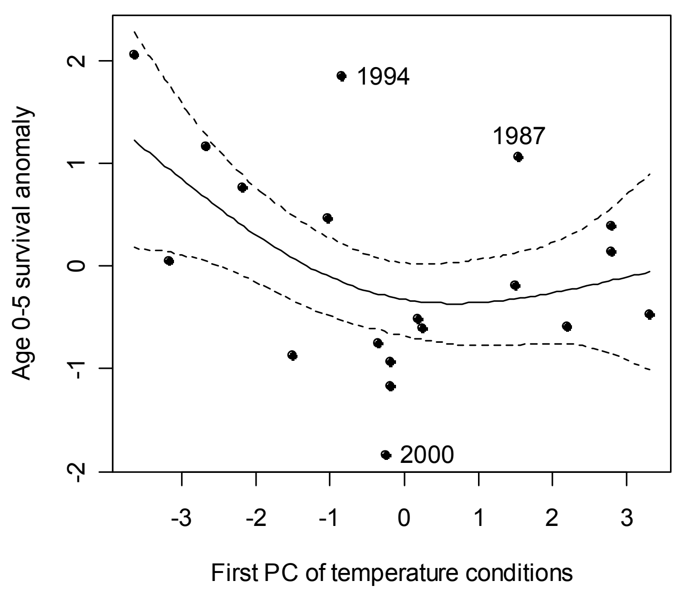

Figure 111. Scatterplot of Age 0-5 survival anomalies of Arctic cisco against the first principal component of climate conditions (larger values reflect warmer years) with best-fit model and 95% confidence band. Three influential outliers are identified.

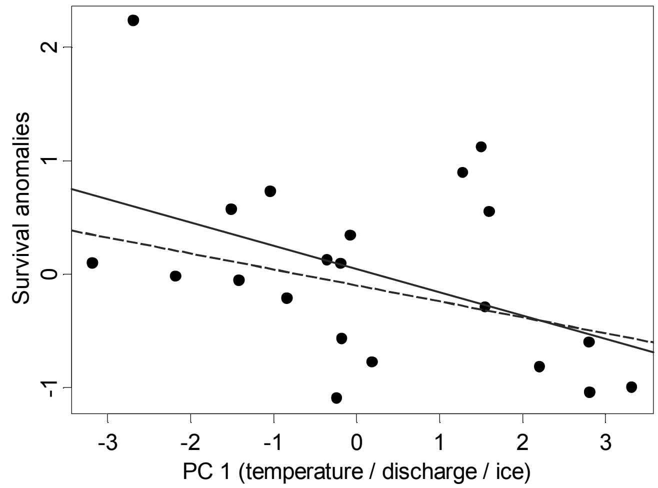

Figure 112. Relationship between age 5–7 survival anomalies of Arctic cisco and environmental conditions in central Beaufort Sea as summarized by PC 1 (higher values denote higher temperature and discharge, reduced ice). Solid line denotes least-squares fit, dashed line is from robust regression that lessens the effect of the outlier.

Conclusions: Temperatures at the juvenile (age-0) and subadult (ages 5–7) stages appear to negatively affect survival of Arctic cisco. However, the estimated effect is relatively weak and may result from a few influential outliers.

ENVIRONMENTAL EFFECTS ON ARCTIC CISCO CATCH RATES

EFFECT OF LOCAL SALINITIES ON DAILY CATCH RATES OF ARCTIC CISCO

Background: Arctic cisco have a preference for brackish waters (e.g., Fechhelm et al. 1993); hence, their distribution is likely to be affected by salinity. Differences in within-river salinities may, therefore, affect the catch rates of Arctic cisco (e.g., Moulton and Seavey 2005)

Hypothesis: CPUE of Arctic cisco at a given site in the Niġliq channel of the Colville delta is affected by salinities in the brackish-water bottom layer (Chapter 4–Environmental Indicators for the Colville River–Prudhoe Bay Region, Fall Salinities, Colville Delta). We hypothesize a dome-shaped relationship between local salinity and CPUE because Arctic cisco presumably prefer brackish water of intermediate salinity, avoiding both fresh and marine waters.

Methods: To examine the influence of salinity on catch rates of Arctic cisco, we examined the relationship between daily CPUEs and bottom layer salinities as measured on the same day. Salinities in the bottom layer were estimated by averaging salinities across the 3-m, 3.5-m, and 4-m depth increments at each of the three main sampling sites (Upper Niġliq, Nanuk, Niġliq delta) and for each day measurements were taken. Catch-per-unit-effort was averaged across all nets fished at a given site on a given day. Therefore, variability among individual fishers or nets is not accounted for in this model, which is a potential source of bias. There were a total of 609 days with both CPUE estimates and salinity estimates obtained on the same day (251 at Upper Niġliq, 210 at Nanuk, 148 at Niġliq delta).

To examine the effects of salinity on CPUE at a local scale, we modeled daily average CPUE of Arctic cisco as a function of local salinity alone and also as a function of local salinity, year, location, and day of year (Julian date). We used log-transformed CPUE to normalize the CPUE values prior to modelling relationships using GAM. Year and location were included as explanatory variables to account for differences in overall abundance among years and inherent differences among locations within the Niġliq channel that are unrelated to the effects of salinity. Julian date was included to account for any reduction in CPUE resulting from depletion over the course of a fishing season (reduction in local fish density due to the removal of fish).

Results: A non-parametric regression of average daily CPUE on average bottom layer salinity suggests an increasing or slightly dome-shaped relationship between salinity and the average CPUE of Arctic cisco (see fitted line in Figure 113). However, there is very high variability in the residuals and the regression accounts for only 13% of the overall variability in log(CPUE+1) (Appendix L, Model III.1.1). When year, fishing area, and Julian date were included in the model, the GAM accounted for approximately 58% of the overall variability in log-CPUE (Appendix L, Model III.1.2). The model fit suggests that CPUE increases with salinity up to at least 25 ppt and decreases rapidly at higher salinities (Figure 114). Arctic cisco CPUE decreases on average over the course of the sampling season, suggesting that local depletion is occurring. We approximated the estimated effects of salinity and Julian date using a linear model with a 7th-order polynomial for salinity and a 5th-order polynomial for Julian date, as suggested by the equivalent degrees of freedom estimated from the GAM (Appendix L, Model III.1.2). The model was further simplified by removing the (non-significant) effect of fishing area ($F = 1.65$, $p = 0.192$), as suggested by a step-wise regression. Our final model included year, salinity, and Julian date as independent variables (Appendix L, Model III.1.3). Although there is a large difference in average CPUE among fishing areas, this difference appears to be a result of differences in salinity among areas and is, therefore, attributed to the salinity effect in our model. This relationship implies that when salinities are similar at upstream and downstream locations, catch rates will also be of similar magnitude. However, because there is a downstream gradient in salinity, with salinities increasing towards the ocean, catch rates tend to be higher at downstream locations farther from the village of Nuiqsut. Therefore, the relative effects of salinity and distance from the mouth of the river on catch rates are difficult to evaluate.

Similar to the GAM model, the results of our final linear model suggest a significant effect of salinity on CPUE ($p < 0.0001$), as well as large interannual variability in CPUE (as evident in a highly significant year effect: $p < 0.0001$), and a strong decrease in CPUE over the course of the sampling season ($p < 0.0001$). Interannual differences account for most of the variability in average CPUE (39%), followed by salinity (12%) and Julian date (7%). These percentages are based on Type III sum of squares, which describe the reduction in sum of squares resulting from removing one variable at a time. The Type III sum of squares provide estimates of the lower end of likely effects of a variable. However, the estimated effects of salinity, Julian date, and year were difficult to separate because average salinities and the seasonal distribution of samples differed considerably among years (i.e., effects are confounded).

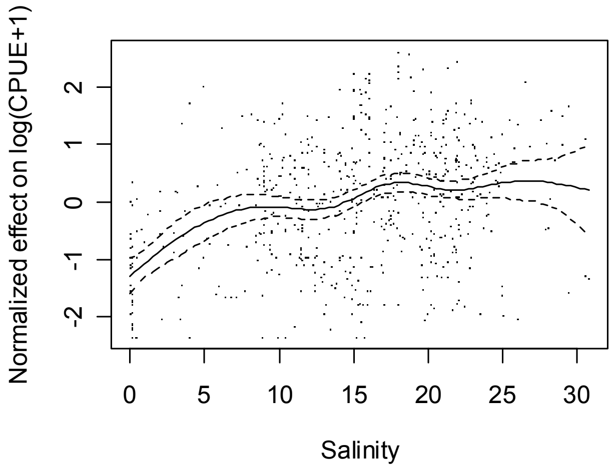

Figure 113. Estimated effect of salinity on average daily CPUE of Arctic cisco across all years and locations (dashed lines denote 95% confidence band for the estimated mean effect).

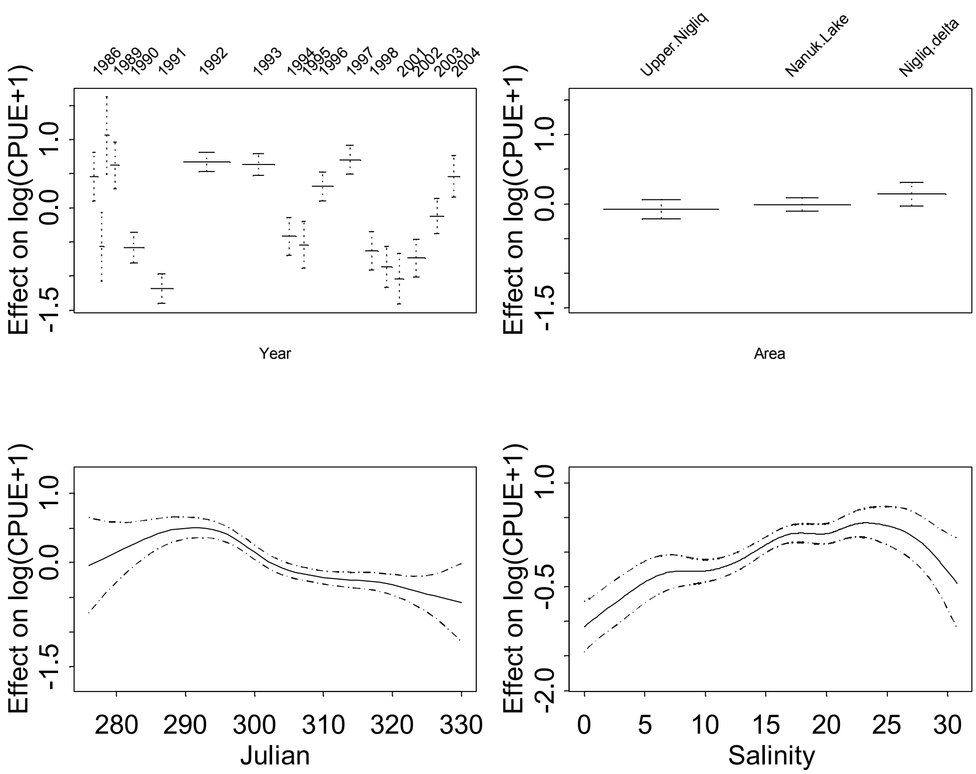

Figure 114. Estimated effects of year, fishing area, Julian date, and salinity on log(CPUE+1) of Arctic cisco in the Niġliq channel fishery. Lines denote the estimated mean effect on a normalized scale (all y-axes are on the same scale) with 95% confidence bands or confidence intervals. Width of horizontal bars is proportional to number of observations in a given year and area. The area effect was not significant.

Conclusion: We found a significant effect of local salinities on daily catch rates (CPUE) of Arctic cisco, which tended to be lower when the salinity was low and also decreased at very high levels of salinity, consistent with our expectations. Therefore, variability in local salinities, which may be related to variability in alongshore wind direction (Moulton 1994), may affect overall catch rates of Arctic cisco in the Colville River. For example, local residents in the 2003 Arctic cisco workshop reported that westerly winds during fall raise the water level and bring higher-salinity water along with Arctic cisco into the river. To examine the effects of salinity on annual differences in catch rate, we modeled annual average catch rates as a function of annual average salinities in the river.

EFFECT OF SALINITY ON ANNUAL AVERAGE CATCH RATES OF ARCTIC CISCO

Background: Because daily catch rates of Arctic cisco in the Niġliq channel were affected by local salinities as shown above, the annual average catch rate (CPUE) may be affected by annual average salinities, if these vary considerably from year to year. Effects of salinity on annual catch rates have previously been suggested by Moulton (1994), and local residents in the 2003 Arctic cisco workshop reported that westerly winds during fall raise the water level and bring higher-salinity water along with Arctic cisco into the river. Exploratory analyses showed a positive correlation between average in-river salinity and average catch rates. This effect is considered a "nuisance effect" and is expected to be independent of any fluctuations in overall abundance of Arctic cisco. Variability in CPUE that is related to fluctuations in average salinity may not reflect true differences in abundance. Therefore, if there is a strong effect, it should be accounted for in calculating an index of abundance before examining the effects of other variables on abundance.

Hypothesis: Interannual variability in CPUE is affected by average salinities in the Niġliq channel. We expected an increase in CPUE with average salinity because daily catch rates increase with salinity over most of the range in salinity. There could be a dome-shaped relationship if the decrease in daily catch rates at very high levels of salinity is evident in the annual averages.

Methods: To test for an effect of interannual differences in average salinity in the Colville delta on average annual CPUE of Arctic cisco, we modeled Colville CPUE anomalies (adjusted for wind effects, Chapter 4–Biological Indicators, Arctic Cisco Abundances, Subadult Arctic Cisco in the Colville River) as a function of the estimated average salinity in the Colville delta during the fishing season (Chapter 4–Environmental Indicators for the Colville River/Prudhoe Bay Region, Fall Salinities, Colville delta). We found no evidence of non-linearity in the relationship between average Arctic cisco CPUE and average salinity (GAM, $F = 1.822$, $p = 0.149$). Therefore, average annual CPUE was modeled as a simple linear regression on average fall salinity. In addition, we examined whether seasonal or interannual differences in salinity were related to differences in wind forcing by modeling salinities as a function of average easterly wind speeds during the fishing season.

Results: A scatterplot of CPUE anomalies against the salinity index suggests a moderate positive relationship that was statistically significant (Figure 115; Appendix L, Model II.2.1, $p = 0.022$). The annual catch rate of Arctic cisco in the Colville River (adjusted for wind effects) increases with salinity (over the range of past observed average salinities). There was no evidence that the average catch rate decreased at high levels of average annual salinity.

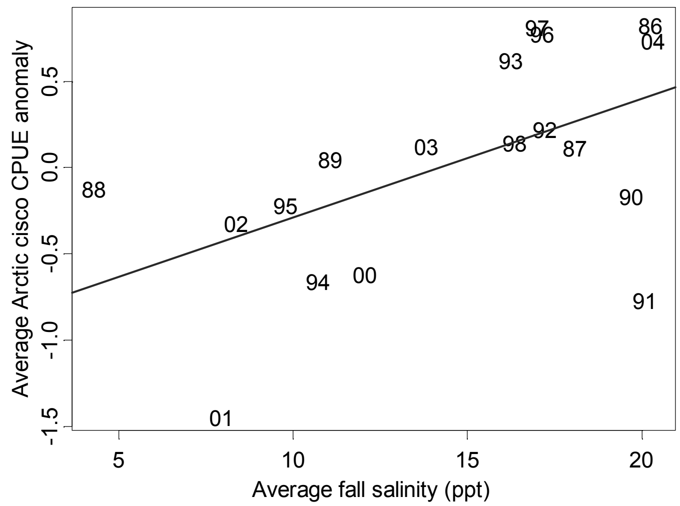

Figure 115. Relationship between average salinity in the Niġliq channel during fall and average annual CPUE of Arctic cisco with simple linear regression (Numbers denote years).

We found no evidence that interannual salinity differences in the Colville River were related to differences in wind forcing as suggested by Moulton (1994). In particular, a regression of average salinity in the Niġliq channel on average easterly wind speeds off the mouth of the Colville River during the fishing season (estimated from NCEP/NCAR winds) was not significant (p = 0.354; Figure 116).

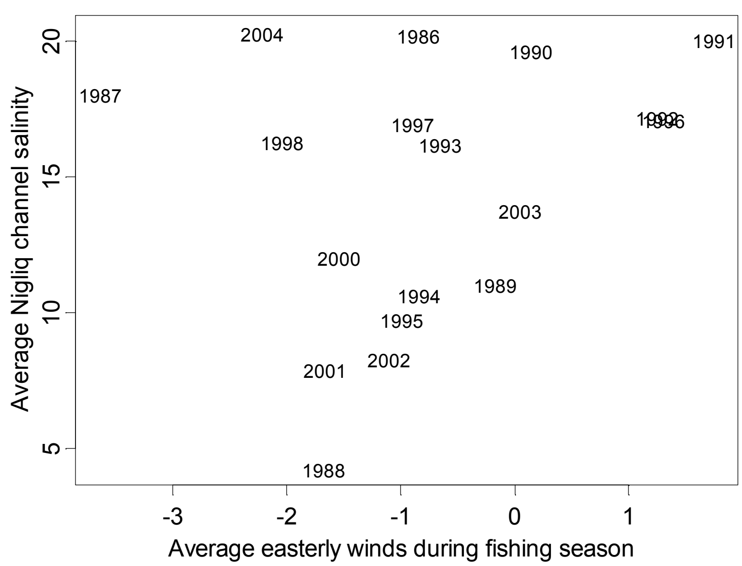

Figure 116. Scatterplot of average annual salinity in the Niġliq channel during the fishery on average easterly winds off the mouth of the Colville River during the same period.

Conclusion: Catch rates in the Niġliq channel appear to vary partly in response to fluctuations in average annual salinities because of the effect of local salinities on daily catch rates. Although subsistence fishers may change fishing locations in response to local fishing conditions, the effect of fluctuating salinity on catch rates nevertheless appears to be reflected in average annual catch rates. Therefore, variability in average annual salinity is important in understanding variability in catch rates. Because of the salinity effect, we developed a CPUE-based index of abundance that accounts for interannual variability in salinity (Nig.ARCS.sal; see Chapter 4).

EFFECT OF SUMMER COASTAL CONDITIONS ON ARCTIC CISCO CATCH RATES

Background: We found several significant correlations between summer temperature conditions and catch rates of Arctic cisco during the following fall fishery (Chapter 4). It is unclear what mechanisms might cause such relationships, but we explored and tested for potential effects of summer conditions (including temperature, ice cover, and winds) on catch rates.

Methods: Because of the apparent effects of in-river salinities during fall (see above), we modeled CPUE as a function of both fall salinity and summer conditions or we removed the effects of salinity on catch rates first. To test for potential effects of temperature conditions during summer, we used either the first principal component of the climate data (Col.env.PC1) or model-based SST (Col.OISST.sum) as an explanatory variable in these models. In addition, we tested whether fall (October) ice cover, which is strongly negatively correlated with summer temperatures, is significantly related to catch rates. As there was no evidence for non-linearity in any of these relationships, based on Generalized Additive Model fits, we used a multiple linear regression model to relate CPUE to temperature variables and salinity. Because the abundance of Arctic cisco and, therefore, catch rates, may reflect environmental conditions over many years, we also related catch rates and catch rate anomalies to a 6-year average of summer temperature and wind conditions.

Results: Both fall salinities in the Colville River and temperature conditions during the previous summer were significantly related to catch rates of Arctic cisco ($p = 0.0004$; Figure 117), which tended to be higher when salinities in the river were higher on average (as shown above) and when warmer conditions prevailed during the previous summer (Appendix L, Model III.3.1a). We removed one outlier year (1988) with exceptionally low average salinities (<5 ppt) and with relatively high catch rates from the final model for estimating effects of salinity and temperature on CPUE anomalies. The model accounted for approximately 67% of the variability in CPUE anomalies and suggests a similar magnitude for the effects of salinity and temperature conditions. When OIv2 SST (Chapter 4–Environmental Indicators for the Colville River/Prudhoe Bay Region, Sea-Surface Temperatures, Large-Scale Sea-Surface Temperature) was substituted as an explanatory variable instead of the first principal component, the temperature effect was still significant ($p = 0.016$), but the model accounted for only 58% of the variability in CPUE anomalies (Appendix L, Model III.3.1b). October ice cover did not add significant explanatory power in a multiple regression of CPUE anomalies on salinity and ice cover (Appendix L, Model III.3.1c, $R^2 = 0.40$, $p = 0.282$ for ice cover effect).

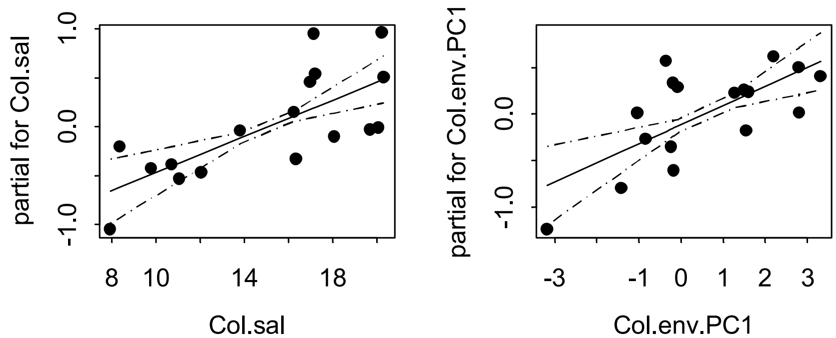

Figure 117. Estimated effects of average annual salinity (Col.sal) and climate conditions (Col.env.PC1) on average annual CPUE anomalies in the Niġliq channel. Effects denote partial effects (estimated effect at a given level of the other variable) based on a multiple linear regression.

We found a strong negative relationship between catch rates of Arctic cisco in a given year and easterly winds averaged over the preceding six summers (Figure 118). This relationship held regardless of whether salinity effects were included or not (Appendix L, Model III.3.2). There was no significant relationship between catch rates and temperature conditions averaged over the preceding 6 years.

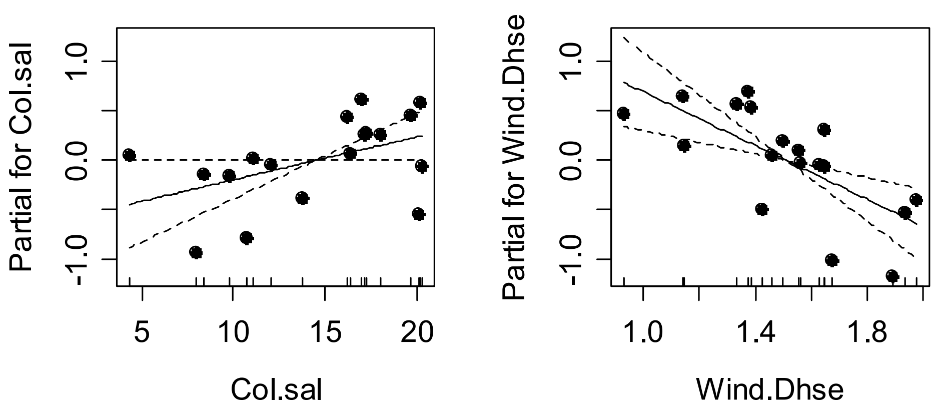

Figure 118. Estimated effects of average annual salinity (Col.sal) and 6-yr average summer wind speeds (Wind.Dhse) on average annual CPUE anomalies in the Niġliq channel. Effects denote partial effects (estimated effect at a given level of the other variable) based on a multiple linear regression.

Conclusions: In addition to the positive effect of local salinities on catch rates in the Colville River, warm conditions in the coastal Beaufort Sea during the preceding summer were associated with enhanced catch rates in the fishery. It is unlikely that these relationships reflect a causal relationship between temperature in the Beaufort Sea and subsequent abundance of Arctic cisco in the Colville River. We reached this conclusion regarding lack of causality because we found no evidence for a positive relationship at any other lag or between a long-term average of temperature and catch rates. Therefore, the relationship may be a result of random variability or it may reflect unknown mechanisms that affect both temperatures in the coastal Beaufort Sea and the abundance or availability of Arctic cisco in the Colville River.

The apparent strong negative effect of average summer upwelling conditions (easterly winds during July and August) on catch rates may also be spurious (a result of random variability). There is no *a priori* reason to believe that catch rates in the fall fishery should be negatively affected by easterly winds in the summer, nor is there an obvious mechanism linking fall catch rates to summer winds. If these relationships reflected real effects of temperature or wind conditions during the summer on Arctic cisco abundances in the fall, they must affect abundances through effects on summer survival because conditions in a given summer or over several summers can only affect future catch rates through changes in survival. Therefore, we would expect a positive effect of temperature on survival and a negative effect of wind on survival. However, as shown above and as evident in the exploratory analyses (Chapter 4), we found a negative relationship between temperature conditions and survival and no apparent relationship between wind conditions and survival after reaching the Colville River (from age-0 to age-5 or older). The apparent negative effect of temperature on survival and the apparent positive effect on catch rates found in this section are not consistent with each other, suggesting that one or both of these effects are not real.

ENVIRONMENTAL EFFECTS AND EFFECTS OF OTHER SPECIES ON ARCTIC CISCO SIZE-AT-AGE

Background: Besides the abundance of Arctic cisco, size (or weight) of an individual fish is an important determinant of the total weight of the catch. Size varies with age and, therefore, depends on the age composition of the population. In addition, size at a given age varies in response to variable growth conditions resulting from environmental variability and its effects on prey availability. A decrease in size- or weight-at-age in the Arctic cisco population in 2002 and 2003 was noted by subsistence fishers in Nuiqsut and was confirmed in the available age-at-size information (Chapter 4–Biological Indicators, Size-At-Age of Arctic Cisco, Prudhoe Bay). Here we test whether the available measures of size-at-age are related to temperature, upwelling conditions, and the abundance of potential predators in the coastal Beaufort Sea. Water temperature affects the growth of many fish species, including Arctic cisco (Fechhelm et al. 1993), and growth often increases with temperature over the range of temperatures typically encountered. Prey availability is an important determinant of growth and size, but no measures of prey availability are available for the coastal Beaufort Sea. However, primary and secondary productivity in many coastal systems are related to upwelling-favorable winds, and upwelling along the coast of the Beaufort Sea, driven by easterly winds, should enhance the supply of deep, nutrient-rich waters onto the shelf. Conversely, a lack of upwelling (westerly winds) may reduce nutrient supplies and prey availability. The presence of a large number of competitors may reduce prey availability for Arctic cisco and, therefore, reduce their growth. Exploratory analyses showed a positive correlation between temperature conditions and the size of age-0 and age-1 Arctic cisco and a negative correlation between discharge and size-at-age for several age groups of Arctic cisco (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations).

Hypotheses: Based on these tentative mechanisms and the available data on size-at-age, we test the following hypotheses:

- Size-at-age of Arctic cisco is higher in warm years.
- Size-at-age of Arctic cisco is reduced during years with westerly win.
- Size-at-age of Arctic cisco is inversely related to the abundance of other species, in particular other coregonids that may feed on similar prey.

Methods: We modeled the final size at age-0 (as measured at Prudhoe Bay) and our index of relative size-at-age of older (age-2+) fish in Prudhoe Bay (Chapter 4–Biological Indicators, Size-At-Age of Arctic Cisco, Prudhoe Bay) to temperature conditions (PC1 or SST estimates, Chapter 4–Environmental Indicators for the Colville River/Prudhoe Bay Region, Sea-Surface Temperatures), a proxy for upwelling (easterly wind speed), and the abundance of other species (Chapter 4–Biological Indicators, Abundances of Other Species, Prudhoe Bay). Because of the limited length of the data series, we first examined the effects of environmental variables and of the abundance of other fish separately and tested for linear or non-linear relationships. To examine environmental effects on size-at-age, we modeled size-at-age as a smooth function of temperature and wind speed, simplifying terms as appropriate. Finally, we combined environmental effects and effects of other species in a single model.

Results: The best model (lowest AIC_c) for final size-at-age-0 was a simple linear regression on the first principal component of climate variables (Col.env.PC1; Appendix L, Model IV.2). The model explained 42% of the variability in size-at-age ($p = 0.0095$) and confirmed our hypothesis that the size of young-of-year Arctic cisco at the end of their first growing season was higher following warmer summers. Substituting estimated summer SST in the coastal Beaufort Sea (Col.OISST.sum, Chapter 4–Environmental Indicators for the Colville River/Prudhoe Bay Region, Sea-Surface Temperatures, Large-Scale Sea-Surface Temperature) for the first principal component of climate variables also suggested a significant positive effect of water temperature (Appendix L, Model IV.3), but explained only 25% of the variability in final size-at-age. A model that fit approximately equally well was one that included a smooth, increasing function of PC 1 and a linear function of wind speed (Appendix L, Model IV.1). The model result suggests that final size-at-age-0 increases with temperature (Col.env.PC1) and with the magnitude of easterly winds at Deadhorse (Figure 119). We found no evidence that final size-at-age-0 was related to the number of adult Arctic cisco or to the total number of coregonids (Arctic cisco, least cisco, and broad whitefish) in Prudhoe Bay.

The index of relative size-at-age of larger Arctic cisco (ages-2–6) in Prudhoe Bay was significantly related to both wind speed and the abundance of other species, but not to temperature conditions (Appendix L, Models IV.4, IV.5, IV.6). The apparent effect of wind speed on size confirmed our hypothesis that size-at-age is reduced when average winds during the summer are from the west (Figure 120). The best overall model was one that estimated a reduced size for years with westerly winds (2002 and 2003) and a constant, larger size when winds were predominantly easterly, along with a linear effect of the abundance of all coregonids (Appendix L, Model IV.7). During periods of easterly winds, size decreases with the abundance of potential competitors (abundance of all coregonids; Figure 120). The model explained 94% of the variability in relative size, largely because of the apparent strong effect of the 2 years with westerly winds (2002, 2003) on size.

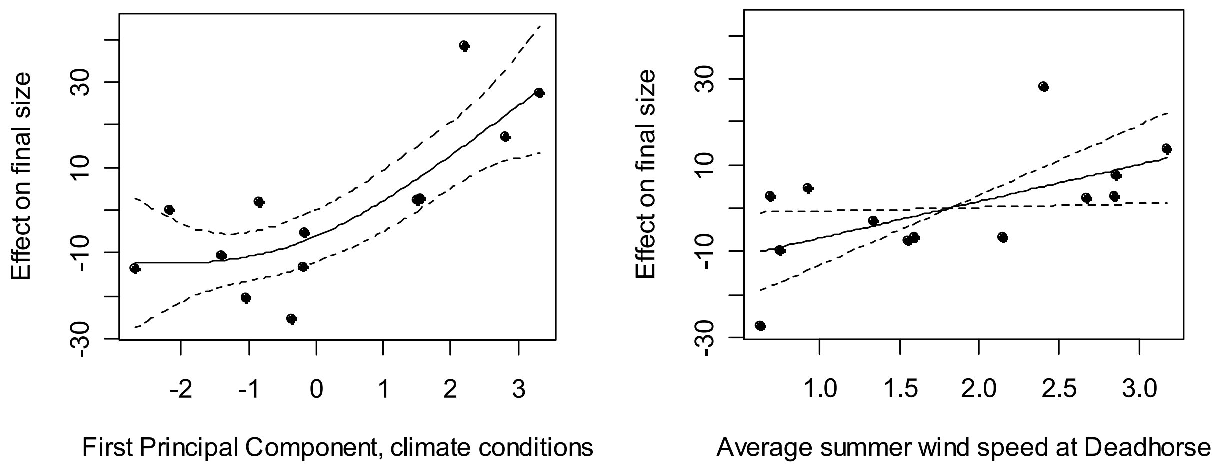

Figure 119. Estimated effects of climate conditions (larger values reflect warmer conditions) and average easterly wind speeds on final size of age-0 Arctic cisco at the end of their first summer at sea.

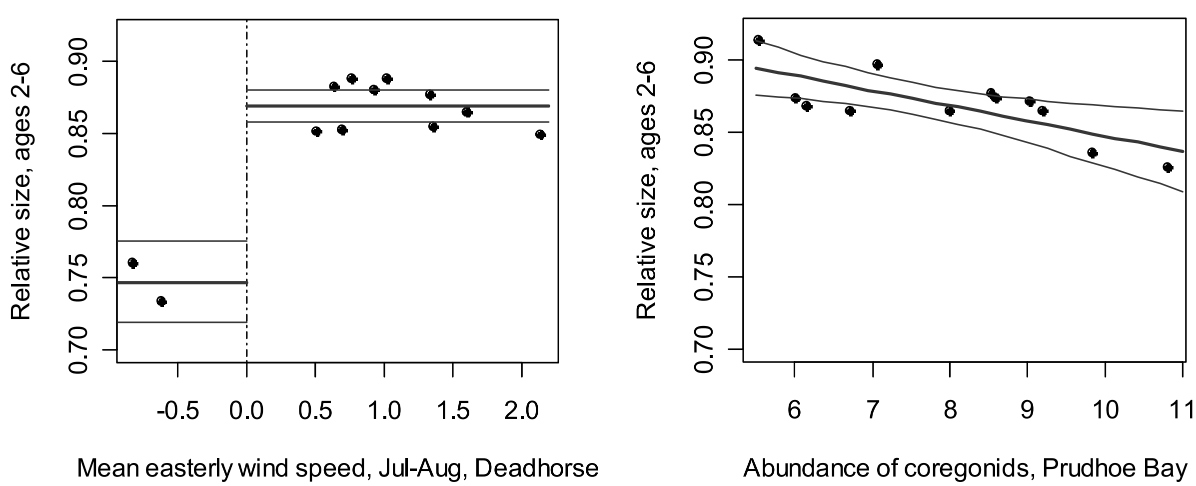

Figure 120. Estimated effects of average easterly wind speed and abundance of major coregonids (Arctic cisco, least cisco, broad whitefish) in Prudhoe Bay on relative size of age-2–6 Arctic cisco with 95% confidence bands.

Conclusions: The size of young-of-year Arctic cisco at the end of the first summer at sea increased with temperature as expected and as indicated by positive correlations in the exploratory analysis (Chapter 4–Relationships Between Biological & Environmental Indicator Variables, Correlations). There also was limited evidence that final size increases with the magnitude of easterly winds, which may be a proxy for upwelling strength (and for productivity and prey availability) along the Beaufort Sea coast. However, the estimated effect of wind speed was small and only marginally significant ($p = 0.052$). In combination, these two variables may explain a large proportion of the variability in final size (63% in the full model). In contrast to the effect of environmental variables, we found no evidence for any effects of subadult Arctic cisco or of other species on the size of juvenile Arctic cisco; neither the abundance of Arctic cisco nor the abundance of all coregonids in Prudhoe Bay was related to the size of age-0 Arctic cisco at the end of their first summer. Thus, we found no evidence for competition between juvenile Arctic cisco and larger fishes in the Prudhoe Bay region. This result was not unexpected because age-0 Arctic cisco and adult coregonids are likely to have very different diets or at least feed on different size classes of prey.

In contrast to the size of young-of-year Arctic cisco, the size of older juvenile and subadult Arctic cisco (ages 2–6) in Prudhoe Bay decreases somewhat with the abundance of other fishes (coregonids) in the region, which is consistent with an effect of competition for prey among similar species. The 2 years with the smallest size-at-age (2002 and 2003) coincided with the only 2 years in the last two decades that had predominantly westerly winds during summer. This is consistent with our hypothesis that prey availability and, therefore, growth and size are reduced during years without consistent upwelling in the coastal Beaufort Sea. This conclusion is based on only 2 years of westerly winds but provides a compelling argument for the importance of upwelling (easterly) winds to the productivity of the coastal Beaufort Sea. The reduced growth of Arctic cisco was readily apparent in size-at-age across numerous age classes and their sizes recovered quickly after a single summer of “normal” easterly winds.

While size-at-age of adult fishes directly affects catches in the fishery (reduced catch weight), the effect of size-at-age of juvenile Arctic cisco on catches will only become apparent many years later. There is evidence from many fish species that reduced growth and smaller sizes are associated with reduced survival. Therefore, we examined the relationship between final size at age-0 and subsequent survival. We found no apparent relationship between the size of juvenile Arctic cisco at the end of their first summer and the subsequent survival of this year class to age-5, which suggests that there are no lasting effects of variability in juvenile sizes on the Arctic cisco population.

EFFECT OF OTHER SPECIES ON ARCTIC CISCO RECRUITMENT

Background and Hypothesis: The presence of older juvenile and subadult Arctic cisco or other species in the Prudhoe Bay region may affect the abundance of juvenile (age-0) Arctic cisco. Other fish may compete with or prey on juvenile Arctic cisco as well. We, therefore, hypothesize that the CPUE of age-0 Arctic cisco is inversely related to the abundance of older Arctic cisco and/or to the abundance of all other species combined. Exploratory analyses revealed a negative correlation between least cisco–broad whitefish abundance in Prudhoe Bay and recruitment (abundance of age-0 Arctic cisco) (Chapter 4–Relationships Among Indicator Variables, Biological Indicators, Correlations).

Methods: We tested for significant relationships between potential competitors or predators and recruitment anomalies of Arctic cisco (after accounting for effects of wind-driven transport) using correlation analyses and regression models. As a measure of the abundance of interacting species, we used the summed abundance of large (>180 mm) least cisco, age-3+ broad whitefish, and age-2+ Arctic cisco (Chapter 4–Biological Indicators, Abundances of Other Species, Colville Delta). Although the abundance of these other fishes is likely to be highly uncertain, we used it as an explanatory variable in regression models to test for simultaneous effects of climate conditions and competitors or predators. We found no evidence for non-linearity in these relationships and, therefore, modeled age-0 recruitment anomalies (Age0.resid) and combined recruitment anomalies (YCS.resid) as a function of the total abundance of coregonids in Prudhoe Bay and of the first principal component of climate variability (Cor.env.PC1). We then identified the most parsimonious submodel and identified the climate variable that had the strongest apparent effect on recruitment anomalies.

Results: In contrast to the lack of effect on age-0 cisco growth, age-0 recruitment anomalies apparently were negatively affected by the abundance of large fish of the major coregonid species (Arctic cisco, least cisco, and broad whitefish) in the Prudhoe Bay region on ($p = 0.002$; Appendix L, Model V.1a). There was also a positive effect of temperature conditions (Col.env.PC1) on age-0 recruitment ($p = 0.045$). When we used individual climate variables instead of the first principal component as explanatory variable, the large-scale measure of summer SST (Col.OISST.sum) provided the best fit ($p = 0.0098$, not shown), suggesting that recruitment tends to be enhanced during warm years. The effect of climate conditions on recruitment anomalies was not significant if the combined recruitment index was used (YCS.resid) and the best model was one that only included the abundance of potential competitors/predators ($p = 0.061$; Appendix L, Model V.1b).

Conclusions: An inverse relationship between the abundance of coregonids and recruitment anomalies of young-of-year Arctic cisco suggests that larger coregonids may interact with juvenile Arctic cisco through competitive interactions or predation. However, total coregonid abundance shows a strong increasing trend over time, while there is a simultaneous decreasing trend in recruitment anomalies (Figure 121). Therefore, the correlation may be the result of similar long-term trends in both series caused by other, unknown gradients. After removing linear trends from both the recruitment anomalies and total coregonid abundance, there was no longer a significant effect of coregonid abundance on recruitment anomalies (Appendix L, Model V.2). Therefore, interannual variability in detrended coregonid abundance does not appear to be related to interannual variability in detrended recruitment anomalies.

EFFECTS OF CAUSEWAYS AND BREACHING ON ARCTIC CISCO

EFFECTS OF CAUSEWAYS AND BREACHING ON RECRUITMENT

Background: There have long been concerns that causeways in the Prudhoe Bay region may disrupt the coastal migrations of juvenile and adult Arctic cisco and other species. A number of process studies using a before-after-control-impact (BACI) study design have not found significant effects of the causeways on the distribution and abundance of juvenile Arctic cisco east and west of the Endicott causeway (Fechhelm et al. 1999). For this study, we did not

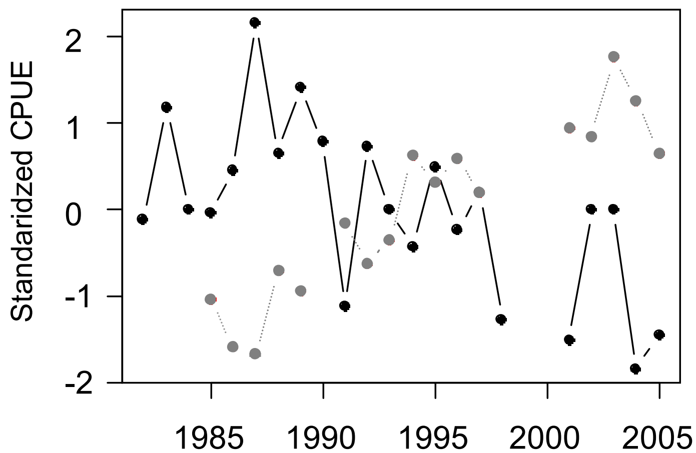

Figure 121. Age-0 recruitment anomaly of Arctic cisco in Prudhoe Bay (black/solid) and standardized index of combined abundances of three coregonids (least cisco, broad whitefish, and Arctic cisco) in Prudhoe Bay (grey/dashed).

reexamine the small-scale distributional data, but instead examined potential effects of the causeways at the population level; that is, we examined whether time series of recruitment, survival, and abundance showed any trends or changes associated with the construction and/or breaching of the two major causeways (West Dock and Endicott). If the causeways disrupt coastal migrations, they may reduce the recruitment of juvenile Arctic cisco to areas west of the causeways, including Prudhoe Bay and, ultimately, to the Colville delta. One way in which the causeways could disrupt coastal migrations is through changes in circulation and sedimentation patterns. Changes in sedimentation to the west of West Dock were reported by the Panel of Experts. Disruptions in the coastal migration may also affect feeding migrations of juvenile and subadult Arctic cisco and may reduce their survival and subsequent recruitment to the fishery. If breaching is effective in mitigating the potential negative effects of causeways, they would be expected to enhance recruitment of Arctic cisco to the Prudhoe Bay region and their subsequent survival. Although exploratory analyses did not reveal any relationships between causeways and Arctic cisco, we specifically tested for potential effects because of concerns from previous work and from the Panel of Experts.

Hypotheses: We hypothesize that recruitment anomalies of Arctic cisco tend to decrease after the construction of a major causeway, but tend to increase after breaching.

Methods: We examined potential effects of the Endicott causeway (and the breaching of West Dock) on overall recruitment by comparing average recruitment anomalies (adjusted for effects of wind-driven transport) among different periods delineated by major construction and breaching activities. Specifically, recruitment anomalies (Chapter 4–Biological Indicators, Arctic Cisco Abundances in the Coastal Beaufort Sea, Juvenile Arctic Cisco) were compared among the following periods using an analysis of variance: pre-1985 (prior to Endicott construction), 1986–1993 (Endicott construction to beginning of breach building), 1996–2005 (end of breaching through present). In addition, we modeled recruitment anomalies as a function of a cumulative indicator of potential disturbance related to the Endicott causeway (Chapter 4–Indicators of Potential Human Impacts on Arctic Cisco, Disturbance Indicators). The effect of West Dock construction on recruitment cannot be evaluated because West Dock was constructed in 1975–1976 and recruitment anomalies are not available prior to 1981. The potential effects of increased sedimentation on Arctic cisco could not be examined because we were unable to quantify the changes in sedimentation that were reported by members of the Panel of Experts.

Results: We found significant differences in recruitment anomalies between periods corresponding to different configurations of causeways and breaches (Appendix L, Model VI.1). However, the signs of the observed differences were opposite to those hypothesized in each case (Figure 122). For example, both the age-0 and combined recruitment anomalies decreased significantly after the addition of breaches to the Endicott causeway (in 1993 and 1994) and the West Dock causeway (in 1995 and 1996). Moreover, the age-0 index increased significantly after the construction of Endicott. Therefore, our hypothesis that breaching is beneficial to Arctic cisco

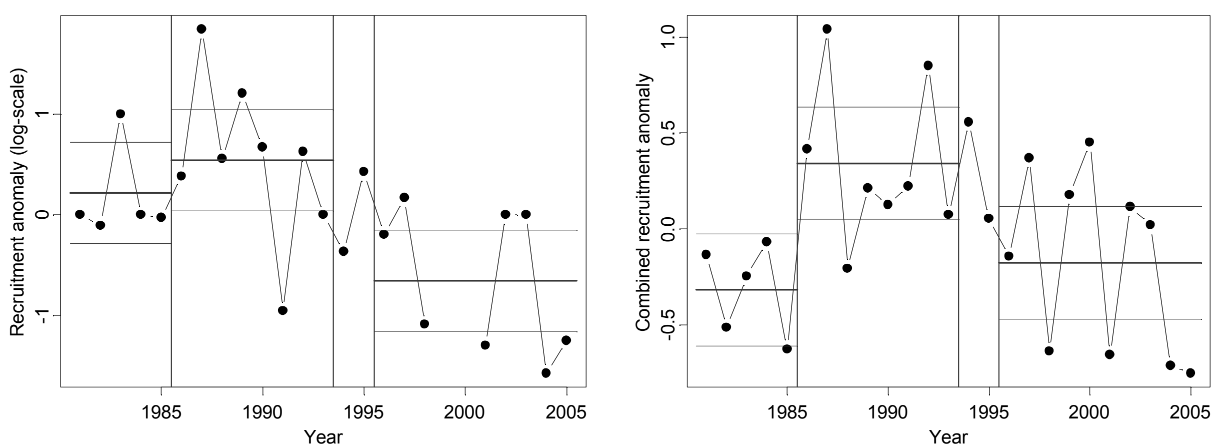

Figure 122. Time series of recruitment anomalies of Arctic cisco based on age-0 CPUE (left) and combined recruitment index (ages-0–2, right) with mean recruitment anomaly by period and 95% confidence bands. Vertical lines denote construction of Endicott causeway in 1985–1986 and period of breaching 1994–1995.

recruitment is clearly not supported. The observed decline in recruitment anomalies either must be due to other factors or breaching had in fact a detrimental effect on recruitment, contrary to expectations. We found no significant relationship between recruitment anomalies and the indicator of cumulative disturbance potential for the Endicott Causeway.

Conclusions: The construction of the Endicott causeway did not appear to have a detrimental effect on recruitment. We found a significant change in recruitment anomalies after breaching. Although average recruitment decreased after breaching, there was a lack of a significant relationship with cumulative disturbance potential, and recruitment anomalies started declining several years prior to breaching (Figure 122). This result suggests that the decline is due to other factors not related to breaching. It is possible that the decline in recruitment reflects a delayed response to causeway construction, although it is unclear what mechanisms might cause an initial increase in recruitment followed by a gradual decline.

EFFECTS OF CAUSEWAYS AND BREACHING ON SURVIVAL ANOMALIES

Background and Hypotheses: The survival of juvenile or subadult Arctic cisco may be impacted by causeways if their migration to and from summer feeding grounds is impeded by these structures. Survival also may be impacted if water circulation is changed and this, in turn, affects the distribution and abundance of prey organisms. Therefore, we hypothesize that the survival of Arctic cisco tends to be reduced after the construction of a major causeway and tends to increase after breaching.

Methods: The effect of causeways on survival anomalies (age-0 to -5 [Surv.age5] and ages-5–7 [Surv.567], Chapter 4–Biological Indicators, Survival from Age-0 to Age-5 and Age-5 to Age-7) was examined as described above for recruitment anomalies by comparing survival anomalies among periods and modeling survival anomalies as a function of cumulative disturbance potential (Endicott).

Results: We found no significant differences in age-0 to age-5 survival prior to and after construction of Endicott or prior to and after breaching of Endicott and West Dock (Appendix L, Model VI.3a). There was a non-significant decrease in age-0 to age-5 survival after 1995 (following breaching), relative to the preceding period, although the decrease was largely due to an unusually low survival anomaly in 2000. The survival of adult fishes (age-5 to age-6 and age-6 to age-7) was significantly lower in the period after the construction of Endicott compared to the 2 years prior to its construction, but there was no significant difference in adult survival anomalies prior to and after the breaching of Endicott and West Dock in 1994 and 1995 (Figure 123; Appendix L, Model VI.3b). Only 2 years of data were available prior to the construction of Endicott in 1985–1986 and the difference in survival of adult fish is entirely due to an unusually large survival anomaly in 1985. There was no significant relationship between the cumulative disturbance potential of the Endicott causeway and survival anomalies.

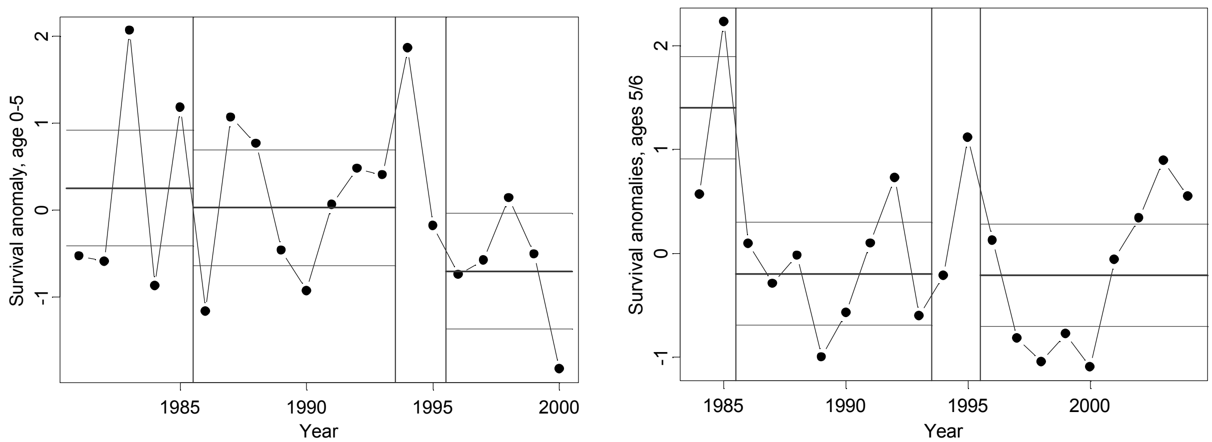

Figure 123. Time series of survival anomalies of Arctic cisco from age-0 to age-5 (left) and survival anomalies of adults (ages-5–6) with mean values by period and 95% confidence bands. Vertical lines denote construction of Endicott causeway in 1985/86 and period of breaching 1994/95.

Conclusions: We found some evidence for decreased survival of adult Arctic cisco after the construction of Endicott, although the relationship was driven entirely by a single year (1985) with unusually high survival just prior to construction. Unfortunately no additional data are available to confirm or reject this tentative relationship. However, extended time series of catch rates (see next section) provide no evidence for detrimental effects of the causeways on subsequent Arctic cisco catch rates.

EFFECTS OF CAUSEWAYS AND BREACHING ON CATCH RATES

Background and Hypotheses: Any cumulative effects of the causeways on survival at any stage will ultimately impact the abundance and, therefore, catch rates of adult Arctic cisco (ages-5–8) in the subsistence and commercial fisheries. Therefore, we hypothesize that catch rates of Arctic cisco tend to decrease following the construction of major causeways and tend to increase after breaching.

Methods: The effect of causeways on catch rate anomalies (differences between observed catch rates and expected catch rates as predicted from easterly wind speed during the first year of life, see Chapter 4–Biological Indicators, Arctic Cisco Abundances in the Coastal Beaufort Sea, Subadult Arctic Cisco in the Colville River) was examined as described above for recruitment and survival anomalies by comparing catch rate anomalies among periods and modeling anomalies as a function of the cumulative disturbance potential for West Dock and Endicott (Chapter 4–Indicators of Potential Human Impacts on Arctic Cisco, Causeway Indicators). Because it is not clear at what stage the causeway effects may occur, we shifted the catch rate series in time relative to causeway construction–breaching to capture effects during the juvenile (age-0) stage or at any subsequent stage. We tested for significant effects at any lag from 6 years prior to fishing (because the average age of Arctic cisco caught in the fishery is approximately 6 years) to the same year.

Results: We found no evidence that catch rates of Arctic cisco in the fishery differed under different causeway configurations (Figure 124), regardless of the lag time assumed between construction or breaching events and any effects on catch rates (Appendix L, Model VI.5). Moreover, the mean catch rate increased after the construction of the Endicott causeway, contrary to the hypothesized effect. Likewise, we found no significant relationships between catch rates and cumulative disturbance indicators for West Dock and Endicott (not shown).

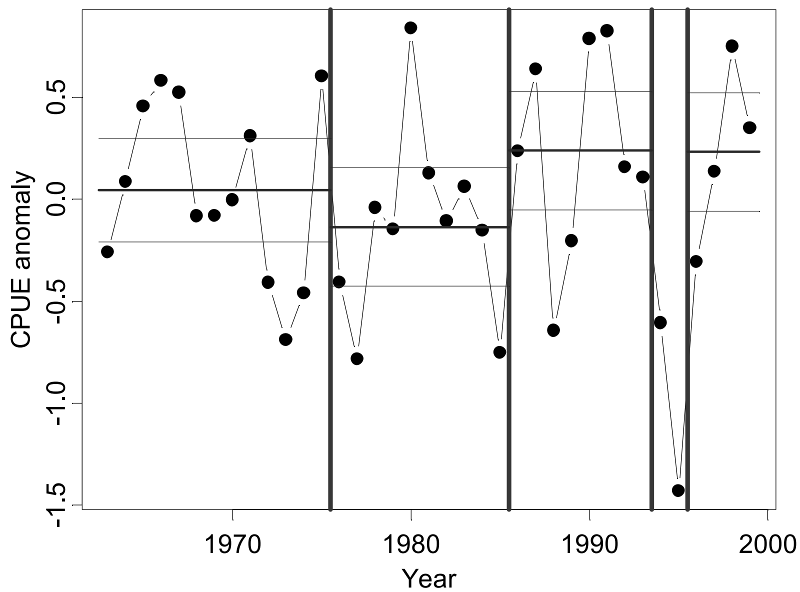

Figure 124. Catch rate (CPUE) anomalies of Arctic cisco (adjusted for wind effects) lined up by approximate year class (shifted by 6 years, the average age in the fishery) relative to the construction and breaching of major causeways. Vertical bars denote construction of West Dock causeway in 1975–1976, Endicott in 1985–1986 and breaching of both causeways in 1994–1996. Horizontal bars denote means by period with 95% confidence bands.

Conclusions: The construction or breaching of West Dock and Endicott has not had a noticeable effect on average catch rates in the fishery during the same year or in subsequent years. Therefore, the recent period of very poor catches (2000–2002) cannot be attributed to any detrimental effects of causeways.

EFFECTS OF OTHER DISTURBANCES ON ARCTIC CISCO

Like the analysis of potential causeway effects, we conducted a retrospective analysis of patterns in time series of recruitment, survival, and catch rates and related these to potential disturbance indicators to test whether potential disturbances have had an effect on population demographics. The analysis related population level indicators of annual recruitment, survival, and abundance to annual measures of total development activity, as quantified by our coarse measures of “disturbance potential” or other measures of development activity (Chapter 4–

Indicators of Potential Human Impacts, Disturbance Indicators). Although we did not find any significant relationships in the correlation analyses (with one possible exception), we tested a number of specific hypotheses based on factors and potential mechanisms identified by the Panel of Experts to account for potential non-linear effects that may not be evident in linear correlations. These non-linear effects include potential effects of summer development activities (drilling, seismic, etc.) on recruitment and winter activities (construction, ice roads, drilling, spills, etc.) on survival.

SUMMER DEVELOPMENT ACTIVITIES IN EASTERN BEAUFORT SEA AND ARCTIC CISCO RECRUITMENT

Background and Hypotheses: Activities related to oil development have taken place throughout the Beaufort Sea. Activities in the eastern section as defined here (Canadian border to Sagavanirktok River), consisting largely of seismic and drilling operations, have the potential to affect juvenile migrants along the Beaufort Sea coast during summer because juvenile fish are sensitive to noise and vibrations. We hypothesize that years with higher levels of development activity are associated with reduced recruitment, after accounting for the effects of other variables (wind-driven transport).

Methods: We modeled recruitment anomalies (age-0 and combined index) as a function of the total potential disturbance indicator for the eastern section (east of Sagavanirktok River) during the open-water season (East.open) and as a function of the total seismic activity (Seismic.East). We used a Generalized Additive Modeling approach to test for non-linear or threshold relationships.

Results: We did not find any significant effects of seismic activity or total disturbance potential on Arctic cisco recruitment anomalies. Only the results for the combined recruitment index are shown (Appendix L, Models VII.1.1 and VII.1.2) but results were very similar and non-significant for the age-0 recruitment anomalies.

Conclusions: Based on our indicators of seismic and drilling activity in the eastern Beaufort Sea, which may be incomplete for the 1980s, we found no evidence that these activities have affected the overall level of recruitment of Arctic cisco to the Prudhoe Bay region. Because recruitment anomalies were relatively high (positive) in the 1980s, underestimating development activities in the 1980s would increase the chance of identifying negative effects of development activities on recruitment. Conversely, if true development activity was higher in the 1980s, the high recruitment observed in the 1980s (in spite of potentially higher development activities) strengthens our conclusion of no significant effects.

SUMMER DEVELOPMENT ACTIVITIES IN WESTERN BEAUFORT SEA AND ARCTIC CISCO SURVIVAL

Background and Hypotheses: Arctic cisco feed in the coastal Beaufort Sea during summer and may be negatively affected by development activities associated with noise or other disturbances. We hypothesize that survival of Arctic cisco is lower during or following years with intense development activities in the summer feeding area.

Methods: We modeled survival anomalies for age-0 to age-5 survival (Surv.age5; Chapter 4–Biological Indicators, Survival from Age-0 to Age-5), as well as adult survival anomalies (Surv.567; Chapter 4–Biological Indicators, Survival from Age-5 to Age-7) as a function of development indicators for the central and western portions of the Beaufort Sea from the Sagavanirktok River to Cape Halkett during summer. In particular, we examined potential effects of the total disturbance potential in the central and western sections during the open water season and the total amount of seismic line surveyed in the western Beaufort Sea, which included both our central and western sections. In addition, we specifically tested for potential effects of offshore activities (outside state waters) on survival anomalies. Survival anomalies from age-0 to age-5 may be affected at any stage from the arrival of juveniles at Prudhoe Bay to their capture in the fishery 5 years later. Therefore, we also modeled age-0–5 survival anomalies as a function of development indicators averaged over the 6-year period corresponding to the first six summers of a given age class. We used a Generalized Additive Modeling (GAM) approach to test for non-linear or threshold relationships. Simple linear regressions were used if there was no evidence of non-linearity. Because most of the development indicators have positive values for a few years only and offer relatively little contrast, we were only able to examine the effects of one variable at a time.

Results: Because of the large number of hypothesis tests conducted, we summarize results in table form for each dependent variable and each explanatory variable with the type of model, overall significance (P-value for testing a given model against the Null model), and AIC_c values indicated (Table 17). Effects on age-0 to age-5 survival were tested at lag 0 (i.e., effects occurring during the first summer—no significant effects at any other lag were found) and as an average effect across all six summers between age-0 and age-5. Models that minimize the AIC_c value for each combination of explanatory and dependent variable are highlighted in bold. Model degrees of freedom (d.f.) denotes the order of the model with estimated degrees of freedom for the "best" GAM model, 1 for simple linear regression models, and 0 for the Null model (intercept only). GAM model results are only shown where the optimal degrees of freedom for smoothing was larger than 1.

Table 17. Models of two indicators of survival of Arctic cisco as a function of various annual measures of development activities during summer

Response variable	Explanatory variable	Model d.f.	Adjusted R^2	P-value	AIC_c
Surv.age5	Central.open	1	-0.01	0.379	63.0
	West.open	1	-0.02	0.450	63.2
	Seismic.West	1	-0.03	0.551	63.5
	Offshore.open	1	-0.06	0.948	63.9
	Drilling.central	1	-0.05	0.835	63.8
	None	**0**			**61.1**
Surv.567	Central.open	1.2	0.00	0.578	57.5
		1	-0.02	0.440	57.4
	West.open	1	-0.03	0.503	57.5
	Seismic.West	2.5	0.08	0.229	58.4
		1	0.001	0.864	58.0
	Offshore.open	1.6	0.02	0.375	57.8
		1	-0.05	0.716	57.9
	Drilling.central*	**1.7**	**0.28**	**0.034**	**51.4**
		1	0.24	0.023	52.2
	None	0			55.3

* See Appendix L, Model VII.2.1

There was no evidence that survival from age-0 to age-5 was affected by development activities during the first summer, as quantified by our indicators of disturbance potential. The AIC_c-best model was a simple mean model and none of the disturbance indicators explained a significant proportion of the variance in Surv.age5. Survival anomalies from age-0 to age-5 were significantly related to the amount of seismic activity in the western Beaufort Sea over the previous 6 years (Table 18; Appendix L, Model VII.2.2). However, the sign of the relationship was positive, implying higher survival in years with more seismic activity. This result is not consistent with the hypothesized detrimental effect of seismic activity on survival and we, therefore, conclude that the observed effect was spurious. Survival of adult Arctic cisco (Surv.567) was significantly related to the number of drilling operations in the Prudhoe Bay region during summer (Drilling.central; Appendix L, Model VII.2.1). However, the relationship was entirely driven by one unusually high survival anomaly and implies higher survival at the highest level of disturbance (Figure 125). With this outlier removed, the effect was no longer significant (Adj. $R^2 = 0.016$, $p = 0.599$), again suggesting a spurious relationship.

Table 18. Models of age-0 to age-5 survival anomalies of Arctic cisco as a function of 6-year averages of various measures of development activities during summer.

Response variable	Explanatory variable (6-year means)	Model d.f.	Adjusted R^2	P-value	AIC_c
Surv.age5	Central.open	1	0.03	0.221	62.2
	West.open	1	0.01	0.293	62.6
	Seismic.West*	**1**	**0.13**	**0.067**	**60.0**
	Offshore.open	1	0.12	0.078	60.3
	Central.drilling	1	0.10	0.243	62.2
	None	0			61.1

* See Appendix L, Model VII.2.2

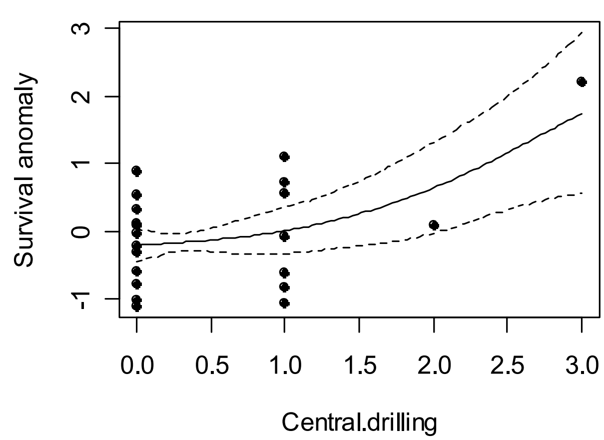

Figure 125. Scatterplot of survival anomalies of adult Arctic cisco (age 5 to 6 and age 6 to 7) against number of drilling activities in the Prudhoe Bay region.

Conclusions: Based on our coarse measures of disturbance potential for development activities, there was no evidence that survival of Arctic cisco has been negatively affected by development activities occurring during the summer in the coastal or offshore areas of the central and western Beaufort Sea.

WINTER DEVELOPMENT ACTIVITIES IN WESTERN BEAUFORT SEA AND ARCTIC CISCO SURVIVAL

Background and Hypotheses: Most Arctic cisco, at least those 2 years old or older, are believed to overwinter in the Colville delta and may be affected by recent oil development activities occurring in and around the delta. Specifically, the local Panel of Experts identified drilling operations and ice bridges, as well as several spills, as factors that may displace or harm Arctic cisco. Exploratory analyses revealed a negative correlation between survival anomalies of subadult Arctic cisco and an indicator of "disturbance potential" based on the summed disturbance potential across all development activities in the Colville delta.

Methods: We modeled survival anomalies for age-0 to age-5 survival (Surv.age5), as well as adult survival anomalies (Surv.567) as a function of development indicators for the western portion of the Beaufort Sea from Oliktok Point to Cape Halkett during winter. In particular, we estimated effects of the total disturbance potential in the western section during the frozen season, the number of ice bridges across the Colville River, and the number of drilling operations in the Colville delta on survival anomalies. We used a Generalized Additive Modeling approach to test for non-linear or threshold relationships. Simple linear regressions were used if there was no evidence of non-linearity. Because most of the development indicators have positive values for a few years only and offer relatively little contrast, we were only able to examine the effects of one variable at a time.

Results: We summarized results in table form for each dependent variable and each explanatory variable with the type of model, overall significance (P-value for testing model against Null model), and AIC_c values (smaller value indicates better model). We found no evidence that survival from age-0 to age-5 was affected by development activities as quantified by our indicators of disturbance potential (Tables 19 and 20). The AIC_c-best model was a simple mean model, and none of the disturbance indicators explained a significant proportion of the variance in Surv.age5. Survival of adult Arctic cisco (Surv.567) was related to the total disturbance potential indicator for the entire western region (Oliktok Point to Cape Halkett), as well as for the Colville region only. A simple linear regression model on these variables provided a better fit, based on the small-sample AIC, than the Null model, although the estimated effect was not significant at the 95% level (Appendix L, Model VII.3.1). The regression suggests that survival tends to be lower in years with intense development activities (Figure 126). The best fit was obtained by a threshold model, which indicated that survival was substantially lower in most years with a disturbance potential larger than 15 (Figure 126; Appendix L, Model VII.3.2). A

Table 19. Models of two indicators of survival of Arctic cisco as a function of various annual measures of development activities during winter

Response variable	Explanatory variable	Model d.f.	Adjusted R^2	P-value	AICc
Surv.age5	West.frozen	1	-0.04	0.559	63.5
	Colville.frozen	1	-0.05	0.781	63.8
	Channel.crossings	1	-0.06	0.931	63.9
	Drilling	1	-0.05	0.702	63.7
	None	**0**			**61.1**
Surv.567	West.frozen	**2***	**0.18**	**0.033**	**53.9**
		1.6	0.17	0.122	54.4
		1	0.16	0.074	54.4
	Colville.frozen	1	0.15	0.078	54.5
	Channel.crossings	1	-0.03	0.545	57.6
	Drilling	1	-0.04	0.684	57.9
	None	0			55.3

* Threshold model

Table 20. Models of age-0 to age-5 survival anomalies of Arctic cisco as a function of 6-year averages of various measures of development activities during winter

Response variable	Explanatory variable (6-year means)	Model d.f.	Adjusted R^2	P-value	AIC_c
Surv.age5	West.frozen	1	-0.05	0.913	63.9
	Colville.frozen	1.7	0.04	0.369	63.3
		1	-0.06	0.970	63.9
	Channel.crossings	1	0.02	0.262	62.4
	Drilling	1.9	0.08	0.244	62.9
		1	-0.05	0.737	63.7
	None	**0**			**61.1**

disturbance potential of 15 during winter in the western area implies a large number of drilling operations, ice roads, and/or other activities such as those recorded in 1993 and 1994, 1997–2001, and 2003 (Figure 70). Survival anomalies were particularly low from 1997 through 2000, which coincided with the period of most intense activity as measured by our index of disturbance potential (Figure 127).

Conclusions: We tentatively conclude that development activities in the Colville delta may have reduced the survival of subadult Arctic cisco during years with the most intense activity.

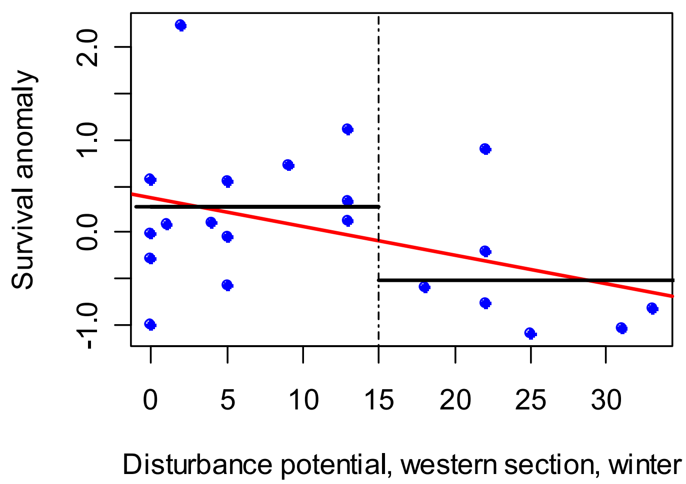

Figure 126. Scatterplot of survival anomalies of adult Arctic cisco (age 5 to 6 and age 6 to 7) against total "disturbance potential" from all development activities in the western section (Oliktok Pt to Cape Halkett) with linear regression model (red) and threshold model (black).

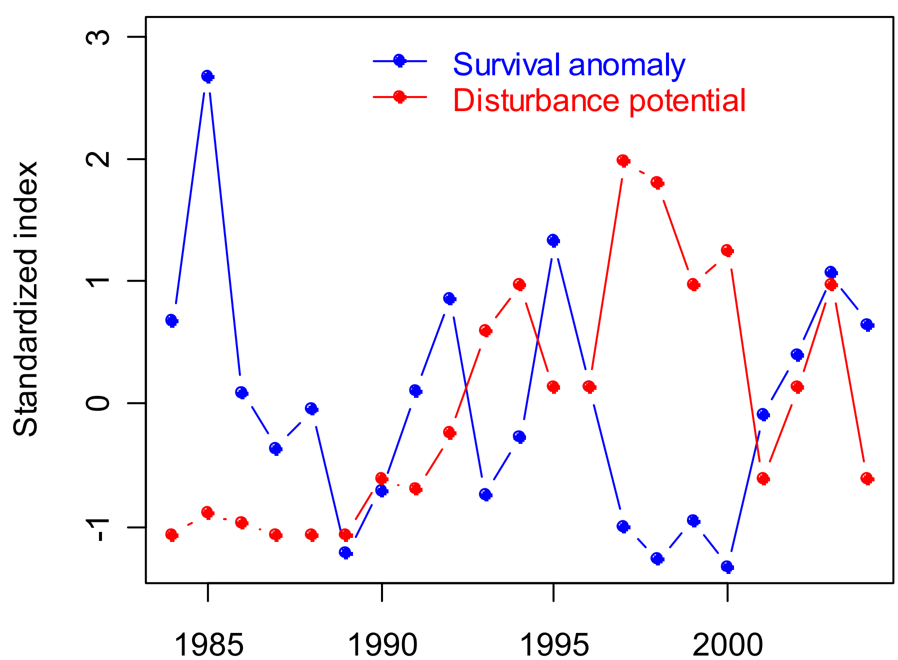

Figure 127. Time series of survival anomalies of adult Arctic cisco (age 5 to 6 and age 6 to 7) and total "disturbance potential" from all development activities in the western section (Oliktok Point to Cape Halkett).

WINTER DEVELOPMENT ACTIVITIES IN THE COLVILLE DELTA AND ARCTIC CISCO CATCH RATES

Background and Hypotheses: The fishery for Arctic cisco in the Colville River takes place following freeze-up in October and November. At least some development activities occur during this period and potentially impact catch rates in the river by disturbing and displacing Arctic cisco from areas of high activity. For example, noise and vibration from drilling operations may affect the distribution of fish in the river. However, the temporal and spatial overlaps between measures of catch rates and our measures of development activity are likely to be poor and unknown because we did not have exact time periods for many activities. Therefore, we cannot test for local impacts of activities on catch rates in the fishery but only for potential effects of the total amount of activity on average catch rates in the fishery.

Methods: We modeled catch rates (Col.ARCS, 1967–2005) and catch rate anomalies (deviations from expected catch rates based on recruitment to Prudhoe Bay: CPUE.unexpl, 1988–2005) as a function of disturbance potential indicators that quantify the amount of development activity taking place in the Colville delta during winter. In particular, we estimated effects of the total disturbance potential, the number of ice bridges across the Colville River, and the number of drilling operations in the Colville delta on catch rates. We used a Generalized Additive Modeling approach to test for non-linear or threshold relationships. Simple linear regressions were used if there was no evidence of non-linearity. Because most of the development indicators have positive values for a few years only and offer relatively little contrast, we were only able to examine the effects of one variable at a time.

Results: None of the annual measures of development activity explained a significant proportion of the variance in catch rates (Table 21). However, the disturbance potential of all development activities in the western section or in the Colville delta, when averaged over the previous 6 years, was significantly related to catch rates and catch rate anomalies (Table 22). The linear model, although indicating a decrease in catch rate with increasing development activities,

Table 21. Models of two indicators of Arctic cisco catch rate in the Colville River as a function of various annual measures of development activities during winter.

Response variable	Explanatory variable	Model d.f.	Adjusted R^2	P-value	AIC_c
Col.ARCS	West.frozen	1	-0.03	0.980	271.5
	Colville.frozen	1	-0.03	0.808	271.5
	Channel.crossings	1	-0.01	0.498	271.4
	Drilling	1	-0.01	0.497	271.0
	None	**0**			**269.2**
CPUE.unexpl	West.frozen	1	0.05	0.188	119.6
	Colville.frozen	1	0.02	0.254	120.1
	Channel.crossings	1	0.05	0.199	119.9
	Drilling	1.8	0.07	0.313	120.8
		1	-0.06	0.848	121.6
	None	**0**			**118.7**

Table 22. Models of two indicators of Arctic cisco catch rate in the Colville River as a function of 6-year averages of various measures of development activities during winter.

Response variable	Explanatory variable	Model d.f.	Adjusted R^2	P-value	AIC_c
Col.ARCS	**West.frozen**	2	0.10	0.089	267.9
		1	-0.02	0.610	271.3
		1*	**0.09**	**0.035**	**266.8**
	Colville.frozen	1.9	0.09	0.129	268.1
		1	-0.02	0.633	271.3
		1*	**0.09**	**0.035**	**266.8**
	Channel.crossings	1	-0.03	0.900	271.5
	Drilling	1.5	0.00	0.351	271.1
		1	-0.02	0.625	271.3
	None	0			269.2
CPUE.unexpl	**West.frozen**	2.8	0.36	0.026	116.7
		1	0.18	0.078	118.0
		1*	**0.37**	**0.004**	**112.2**
	Colville.frozen	2	0.23	0.075	117.9
		1	0.19	0.067	117.7
		1*	**0.37**	**0.004**	**112.2**
	Channel.crossings	2.7	0.20	0.109	120.4
		1	-0.06	0.947	121.6
	Drilling	1	0.06	0.160	119.3
	None	0			118.7

* Threshold model,; Appnedix L, Model VII.4.1 (a-d)

was generally not significant at the 95% level. The best model in all cases was a threshold model, indicating a significant decrease in catch rates when development activities during the previous 6 years reached a certain threshold (Figure 128). Development activities were highest during the mid- to late-1990s and were associated with lower than expected catch rates from 1998–2002 (Figure 129). While the relationship was statistically significant, this result depends on the choice of model. The threshold for the threshold model was chosen subjectively after examination of the data, and we did not adjust p-values and AIC_c values for the additional parameter implied by choosing a threshold. Therefore, p-values and AIC_c values are somewhat lower than they should be for the threshold models, and there is an unknown probability that the relationship between high development activity and reduced catch rates from 1998–2002 was due to chance.

Conclusions: Average annual catch rates of Arctic cisco in the Colville River appeared to be significantly reduced following several years with intense development activity. The reduced catch rates in the late 1990s and early 2000s are likely due to reduced survival of adult stages of Arctic cisco in the late 1990s (e.g., Figure 127). It is not clear at present whether this relationship is a coincidence or reflects a causal relationship between development activities and reduced survival of Arctic cisco and subsequent lower catch rates.

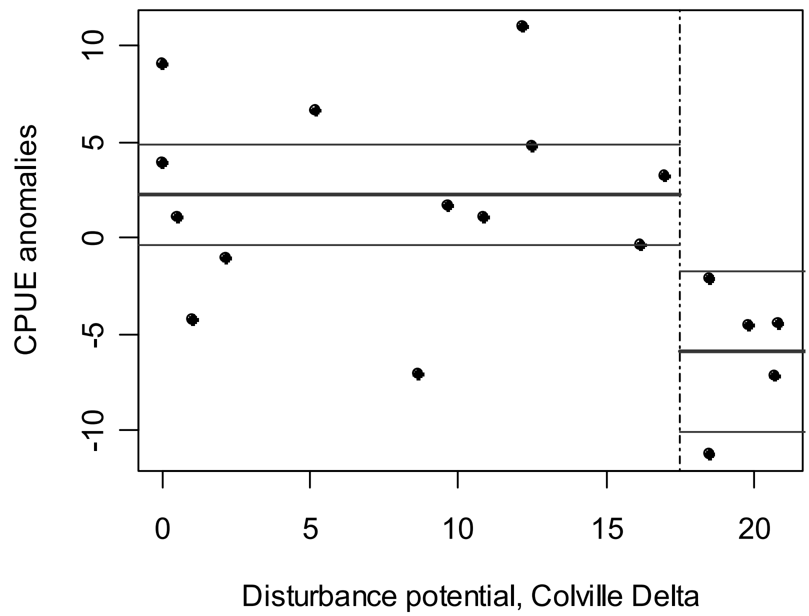

Figure 128. Scatterplot of catch rates (CPUE) anomalies of Arctic cisco in the Colville River against “disturbance potential” of all winter development activities in the Colville delta averaged over previous 6 years.

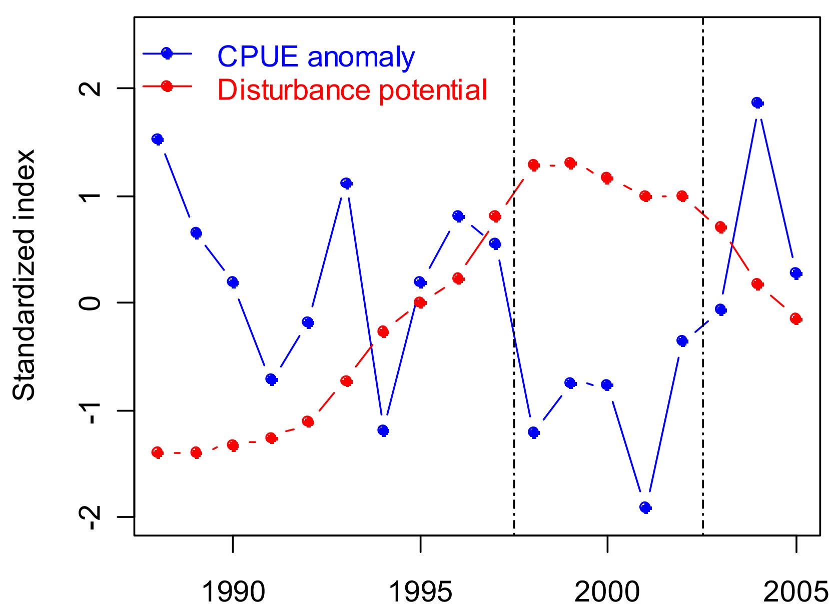

Figure 129. Time series of catch rate (CPUE) anomalies of Arctic cisco in the Colville River and total “disturbance potential” from all development activities in the Colville River and delta. The indicated period corresponds to levels of the disturbance potential that exceed the threshold in Figure 22.

EFFECTS OF FISHING ON ARCTIC CISCO

Background: Arctic cisco in the Colville delta are harvested in both the commercial and subsistence fisheries. Catches in both fisheries have fluctuated substantially, but the subsistence fishery has been monitored only since 1985 (Figure 130). Commercial catches were highest in the 1970s, intermediate in the 1980s and early 1990s, and have been very low in recent years. Subsistence catches have been more variable and display an apparent cyclic trend with relatively high catches occurring approximately every 5–6 years. These cycles are reminiscent of similar cycles in average Colville River salinity and were in phase with salinity fluctuations after about 1992 ($r = 0.79$, $p < 0.001$), but not in earlier years. Because we know very little about the spawning population of Arctic cisco, it is not clear if the historical or current catches are sustainable. Catches have been higher in the past than in the last decade, suggesting that current exploitation rates are relatively low, if the population has remained stable. Estimated catch rates (CPUE) in the fishery are assumed to reflect population abundance and do not suggest a declining trend.

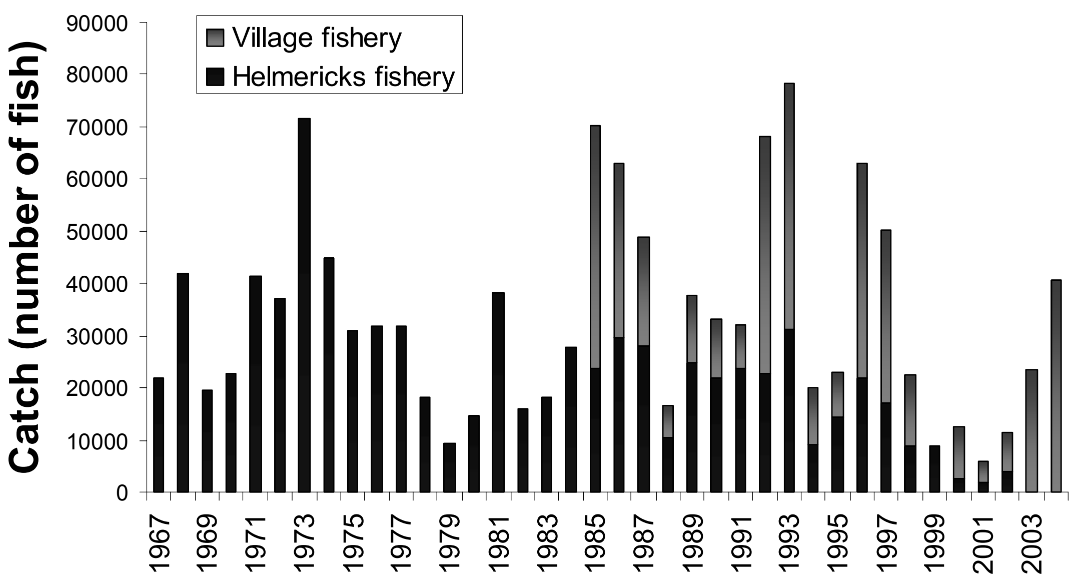

Figure 130. Estimated catches of Arctic cisco in the Colville River in commercial fishery (Helmericks) and subsistence fishery (Village). Catches in commercial fishery were estimated 1967–2002, catches in subsistence fishery were monitored 1985–2004 (except 1999).

Hypothesis: One of the concerns expressed by the Panel of Experts was that high combined catches (subsistence + commercial) may have reduced the spawning population to unsustainable levels. Therefore, we hypothesize that fishing has depleted the Arctic cisco population to a level that has resulted in a reduction in spawning and subsequent recruitment to the Colville region.

Methods: To examine the effects of fishing and to estimate fishing mortalities, we attempted to fit an age-structured model to the Arctic cisco population. However, because of the relative paucity of reliable age data and the number of different mesh sizes used in the fishery, we were unable to obtain a reliable model fit. Therefore, we examined potential fishering effects by relating recruitment and recruitment anomalies in a given year to fishing effort and total catches in the fishery several years earlier. If catches reduce the spawning population sufficiently to affect recruitment, such effects should become apparent approximately 5 years later. This lag is because the fishery catches primarily 5–8 year old fish, which make up the bulk of the spawning population some 4 years later (ages 9–12) and produce offspring in the following year. We tested for effects of effort or catch rates in the fishery on recruitment by regressing recruitment on average summer wind speeds (because of the known effects of winds) and on total catch or effort in the fishery 5 years earlier. Because Arctic cisco spawn repeatedly and because a number of different age groups make up the catches as well as the spawning population, we also substituted 3-year and 5-year averages of catch and effort as explanatory variables in these regressions.

Results: We found no evidence that recruitment was related to total catches or total effort in the fishery 5 years earlier (Figure 131). Similarly, there was little evidence for a relationship if we used 3-year or 5-year averages of catches and effort. The only significant relationship was a positive relationship between catches averaged over 5 years (t-2 to t+2), and recruitment 5 years later (year t). This relationship was driven by two overlapping periods of low catches (1997–

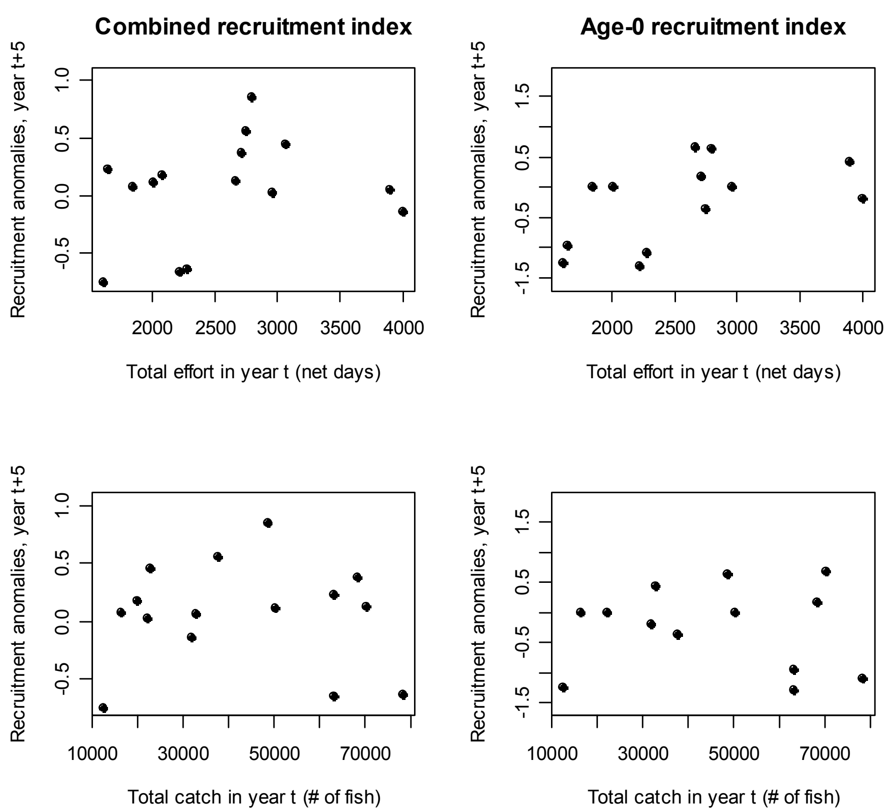

Figure 131. Scatterplots of recruitment anomalies of Arctic cisco, based on combined recruitment index (left) or age-0 recruitment index (right), on total effort (top) and total catches in the Colville fishery (bottom) 5 years earlier.

2001 and 1998–2002), that were followed by lower than expected recruitment anomalies in 2004 and 2005. While these low catches may reflect low abundances of Arctic cisco and subsequent low recruitment, they are not likely to be the cause, but rather a consequence, of low abundances of Arctic cisco.

If we assume that catch rates (CPUE) in the fishery reflect abundances and that fishing mortalities are low enough to not affect future spawner abundances, average CPUE in the fishery may be considered a proxy for spawner abundances some 2–5 years later, when all of the age-classes caught in the fishery have returned to the Mackenzie River to spawn. Because the spawning population consists of multiple age-classes and because several age-classes are caught in the fishery, we averaged CPUE over 4 years (year t-5 to year t-1) to obtain a proxy for the spawning abundance of Arctic cisco in year t (including age-classes 6–13), which gives rise to the cohort recruiting as age-0 fish in year t+1. Using this proxy, we can examine the relationship between presumed spawner abundance and recruitment. Under the above assumptions, the relationship shows some evidence that negative recruitment anomalies occurred more often when spawner abundances were low (Figure 132). In particular, the low recruitments in the early 1980s and in the most recent years were generally preceded by a period of relatively low catches in the fishery, which may indicate reduced spawner abundances. However, there was no statistically significant linear or non-linear relationship. A non-parametric regression of the recruitment index on both average summer winds (to account for known effects of wind) and the index of spawner abundance suggested a possible dome-shaped relationship between recruitment and spawner abundance, implying that highest recruitment occurs at intermediate spawner abundances. Most importantly, years with apparent low levels of abundance tend to result in low recruitment in future years. However, the effect of apparent spawner abundance on recruitment was not significant ($p = 0.254$).

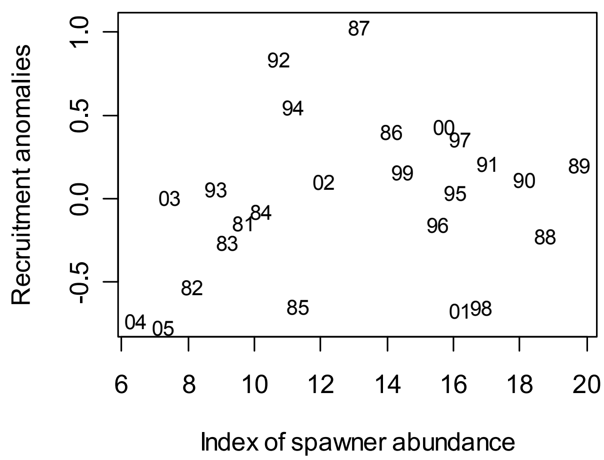

Figure 132. Scatterplot of recruitment anomalies of Arctic cisco in a given year against a proxy for the corresponding spawner abundance that gave rise to the indicated year classes.

Conclusions: While there is some evidence for a dome-shaped relationship between spawner abundance and recruitment, which might be expected on theoretical grounds, the index of spawner abundance is highly uncertain and the relationship was not significant. We conclude that there is little evidence that would suggest that spawner abundances over the past 25 years have been low enough to result in reduced recruitment. However, the two most recent years had very low recruitment anomalies, following several years with low spawner abundances (based on the proxy). Future recruitment and, if possible, spawner abundances should be closely monitored to assess whether this trend continues and reflects a declining trend in the abundance of Arctic cisco.

6. SENSITIVITY ANALYSIS

INTRODUCTION

To help determine which factors are most critical in improving our understanding of variability of the Arctic cisco population in the Colville River, we assessed the sensitivity of our results to uncertainty and gaps in the data. These sensitivity analyses include qualitative assessments as well as formal sensitivity analyses. Here, we briefly summarize results of the analyses and discuss which aspects of human activity, the environment, and of the life history of Arctic cisco need to be better understood to improve our overall understanding of Arctic cisco variability.

We conducted formal sensitivity analyses to quantify the effects of a given explanatory variable on a given response variable and to assess the relative importance of different explanatory variables (Saltelli et al. 2004). For example, we would like to know by how much Arctic cisco recruitment changes as a result of a given change in easterly wind speeds compared to a given change in river discharge rates. In Chapter 5 we tested various hypotheses to determine whether an explanatory variable is likely to have an effect on Arctic cisco, whereas here we quantify and compare the magnitude of these effects.

A comparison of the effects of different explanatory variables is complicated by the fact that each explanatory variable may be measured on a different scale. In the above example, wind speed is measured in m/s and discharge is measured in m^3/s, so how do we compare the estimated effects of, for example, a change in wind speed of 2 m/s to a change in discharge of 500 m^3/s? One way to approach the problem is to standardize explanatory variables by putting all variables on a common scale. For continuous variables, a reasonable standardization would be to remove the mean and divide by the standard deviation:

$$x_i' = \frac{x_i - \bar{x}}{\sqrt{Var(x_i)}}$$

The resulting standardized variable has a mean of zero and a standard deviation of one. Returning to the example, we may now compare the estimated change in recruitment resulting from a change in the explanatory variables corresponding to 1 “unit” (i.e., one standard deviation, which may be considered a typical change in wind speed and discharge).

In addition to quantifying the magnitude of the estimated effect, we also quantify its uncertainty to assess the consequences of being wrong (i.e., uncertain) about the true values that describe the relationship between the explanatory and response variables. An important explanatory variable is one that has both a large estimated effect and whose effect is highly uncertain. Variables with an uncertain effect are considered important because reducing this uncertainty can have large benefits in terms of improving our understanding and reducing uncertainty about the response.

METHODS

We evaluated the sensitivity of each of the main response variables to variability in explanatory variables by quantifying the magnitude of estimated effects and their uncertainty. To allow for comparisons of different explanatory variables, across different models, and across response variables, we standardized all variables to have a mean of zero and a standard deviation of one. For each of the response variables, we fit a “full” model that included all of the explanatory variables that were identified earlier as having a significant relationship with the response variable. Coefficients of determination for each of the full models are summarized to provide a measure of the amount of variability in the response variables that can be accounted for by the explanatory variables. These should be considered maximum estimates because the full models are likely to over-fit the data because they may include redundant and non-significant variables. “Local” sensitivity of each response to variability in the explanatory variables was then evaluated for linear model fits based on the standardized regression coefficients and their uncertainty (Saltelli et al. 2004). This measure is not appropriate for non-linear model fits, but we limited the analyses to the best linear versions of all of the models that were examined. We summarized the full probability distribution of each coefficient graphically to facilitate comparisons. In addition, we evaluated the full probability distribution of each coefficient based on a model that included each variable one at a time.

RESULTS

SENSITIVITY OF RECRUITMENT TO NATURAL AND HUMAN INFLUENCES

Recruitment of Arctic cisco to the Prudhoe Bay region is most sensitive to environmental influences and does not appear to be significantly affected by variability in development activities, at least as measured by our development indicators. The full model including 5 explanatory variables (easterly wind, Sagavanirktok discharge, coregonid abundance, temperature index, and combined development index) had 16 years with data for all variables and explained 85% of the variability in recruitment. The most important variable determining recruitment variability of Arctic cisco is wind speed, followed by discharge rate and the abundance of other coregonids in the region (Figure 133). In addition, temperature may have a small effect on Arctic cisco recruitment, but the estimated effects of both temperature and discharge on recruitment were highly uncertain and were only significant if all variables were included in the model. Therefore, because neither temperature nor discharge had a large estimated effect, and the effects they did have were fairly uncertain, they are not considered important.

All of the estimated effects on recruitment were linear, therefore, the value of the standardized regression coefficients are sufficient to assess sensitivity. However, there was considerable collinearity among variables. In particular, the temperature index (first principal component of several climate variables) was strongly correlated with discharge rate ($r = 0.71$); therefore, the relative effects of discharge and temperature conditions are difficult to assess. In addition, there were moderate correlations between easterly winds and coregonid abundance ($r = -0.45$), as well as between discharge and coregonid abundance (0.40). The high degree of collinearity was the main reason for the large difference in the estimated effects of some of the environmental variables between models (compare solid lines and dashed lines in Figure 133).

Although we found no significant effects of any of the disturbance indicators on Arctic cisco, we included an indicator of overall development activities in the eastern Beaufort Sea in our analysis for comparison (Figure 133, bottom panel). In contrast to the environmental variables, the apparent effect of development activities on recruitment, as captured by our

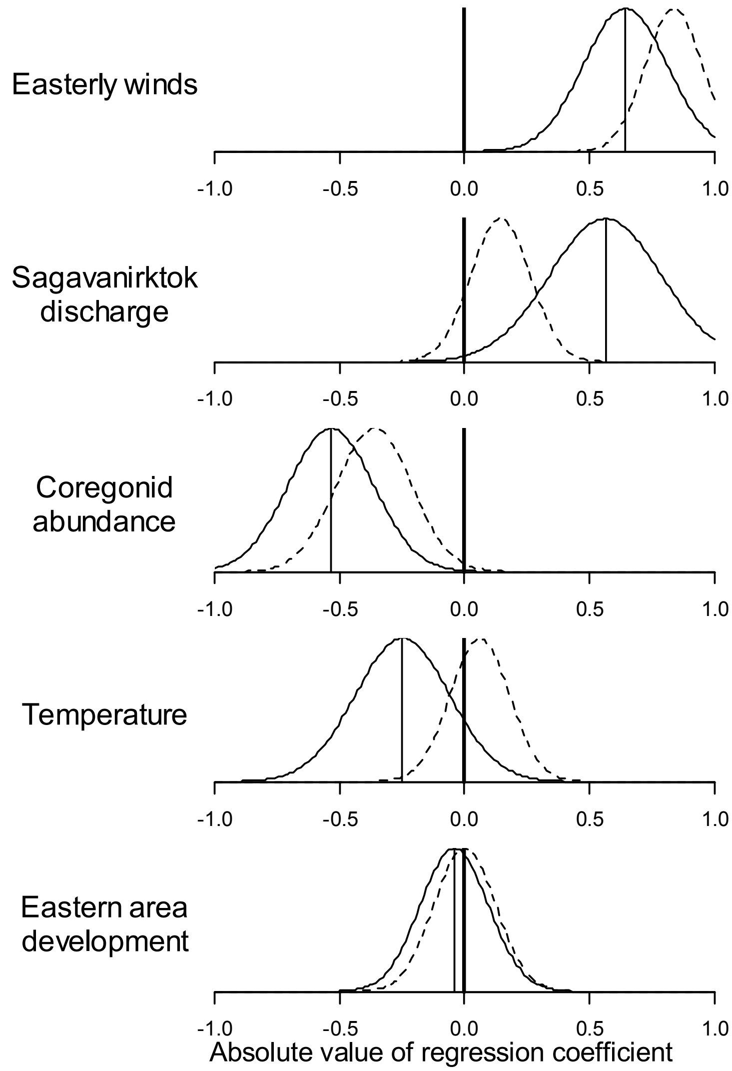

Figure 133. Sensitivity of Arctic cisco young-of-year recruitment to environmental indicators and one development indicator. Solid lines denote probability distribution (relative scale) of regression coefficients based on the "full" model (i.e. a multiple linear regression including all 5 variables), whereas dashed lines denote probability distributions based on a model that include the wind effect plus the variable specified on the left.

indicator of disturbance potential was centered on zero regardless of the model used. Therefore, we conclude that recruitment is insensitive to variability in the overall level of disturbance from oil development in the eastern Beaufort Sea, at least at the coarse level of the available disturbance data. Because these data are relatively coarse, the power to detect significant effects is likely to be low. Disturbance indicators could be refined by tracking the exact location and time of disturbance and by developing quantitative measures of the "magnitude" of specific disturbance events.

SENSITIVITY OF YEAR-TO-YEAR SURVIVAL TO NATURAL AND HUMAN INFLUENCES

We examined two indices of survival in our analysis, including age-0 to age-5 survival anomalies and survival anomalies at subadult stages (ages 5–6 and ages 6–7). We found only a single environmental variable (temperature conditions at age-0, as measured by first principal component of several climate variables) that had a possible (and counterintuitive) effect on age-0 to age-5 survival. None of the development indicators appeared to negatively affect age-0 to age-5 survival, although some appeared to affect survival positively. The model of age-0 to age-5 survival had 19 years of survival and temperature estimates and a coefficient of determination of 30%. Survival at subadult stages was related to both temperature conditions and to development activities in the Colville delta. Therefore, we examined the sensitivity of survival anomalies at the subadult stages to these two variables. A multiple linear regression based on 21 years of data had a coefficient of determination of only 26%; thus, much of the variability in survival remains unexplained and/or measurement errors are large.

Survival anomalies at juvenile and subadult stages were sensitive to temperature variations, but the effects were highly uncertain (Figure 134). The estimated effect of development activities in the Colville delta on the survival of subadult stages (ages 5–6 to ages 6–7) was somewhat smaller than the temperature effect and had similar uncertainty. Our development indicator and the temperature index were positively correlated with each other (r = 0.42). As a result, their

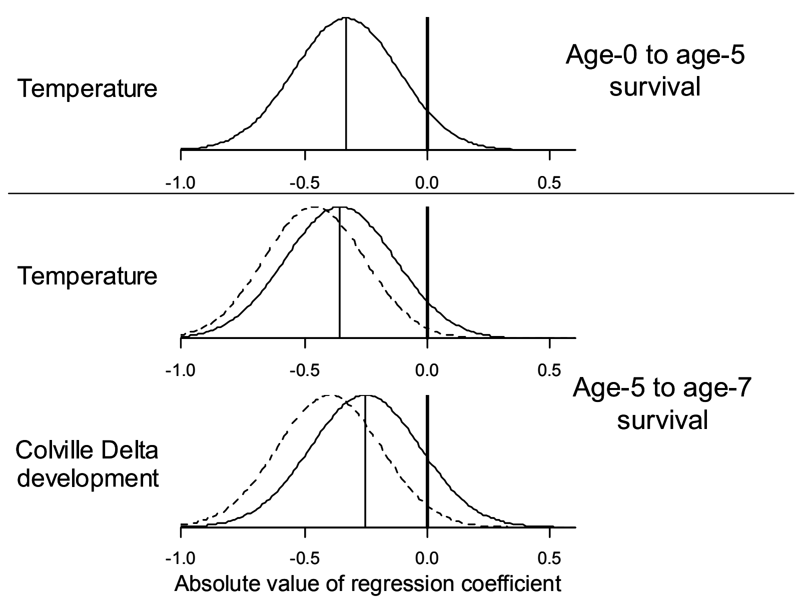

Figure 134. Sensitivity of Arctic cisco survival to temperature conditions and development activity in and around the Colville delta. Top panel denotes probability distribution of the effect of temperature conditions during the first summer on age-0 to age-5 survival. Bottom panels summarize estimated effects on survival of subadults (age 5 to 6 and 6 to 7). Solid lines denote probability distribution (relative scale) of regression coefficients based on the “full” model (i.e., a multiple linear regression including both the temperature and development variable), whereas dashed lines denote probability distributions based on a model that includes only the variable specified on the left.

effects are difficult to separate, and each explains a larger proportion of the variability in survival when used as a single explanatory variable (larger regression coefficients, see dashed lines in Figure 134). Our measures of survival are highly variable and are likely to be affected by many unknown factors. Furthermore, it is unclear what types of development are most relevant to overwintering survival, making it difficult to define an appropriate development indicator. Therefore, we consider it unlikely that uncertainty in the effects of development activities on survival can be reduced without a much improved understanding of the overwintering ecology of Arctic cisco and considerable effort to develop more specific development indicators.

SENSITIVITY OF CATCH RATES TO NATURAL AND HUMAN INFLUENCES

Catch rates in a given year may be impacted by environmental or human influences during the current year or during earlier years, because Arctic cisco are not caught until they are 5 to 8 years old. Based on the well-established effect of wind-driven transport on recruitment and hence on catch rates 5–8 years later, we estimated and removed this effect prior to examining effects of other variables. For the period from 1984 through 2005, the effect of easterly winds explained 24% of the variability in catch rates, with the other variables (in-river salinities, temperature and wind conditions during the preceding six summers, and development activities during the preceding six winters) explaining 55% of the remaining variability (42% of total), together explaining 66% of the total.

The magnitude of the estimated effect of easterly winds on catch rates (Figure 135, top panel) is smaller than the effect on recruitment (Figure 133, top panel). Presumably, this difference is because many other factors affect catch rates between the time of recruitment and the time fish are caught in the fishery. After catch rates were adjusted for the effect of easterly winds on recruitment, the remaining variability appeared to be most sensitive to temperature and wind conditions during the preceding summers, followed by in-river salinities during the time of the fall fishery (dashed lines in Fig. 135).

The effect of development activities on catch rates, averaged over the preceding winters, was highly uncertain, and the estimated coefficient was very sensitive to the inclusion of other variables. If all variables were included in a single model, the magnitude of the estimated effect was very small, positive, and had a very large variance (Figure 135, bottom panel, solid line). If other explanatory variables were not included in the model (dashed line), the magnitude of the effect was very large but highly uncertain. The difference in the results was a consequence of collinearity in the variables, which makes it impossible to distinguish effects of the environmental variables from those of the development variables. For example, there were strong positive correlations between the time-averaged development indicator and the time-averaged measures of temperature ($r = 0.65$) and easterly winds ($r = 0.51$) during summer.

Uncertainty in the effects of environmental variability and development activities on catch rates is high in part because the catch rate index itself has considerable uncertainty. Because catch rates are the primary response variable for monitoring variations in in-river abundance, efforts to improve catch rate estimates in cooperation with local fishers (e.g. through improved harvest monitoring, gear standardization, and recording of auxiliary information) will be most useful in further improving our understanding of variability in the Arctic cisco population.

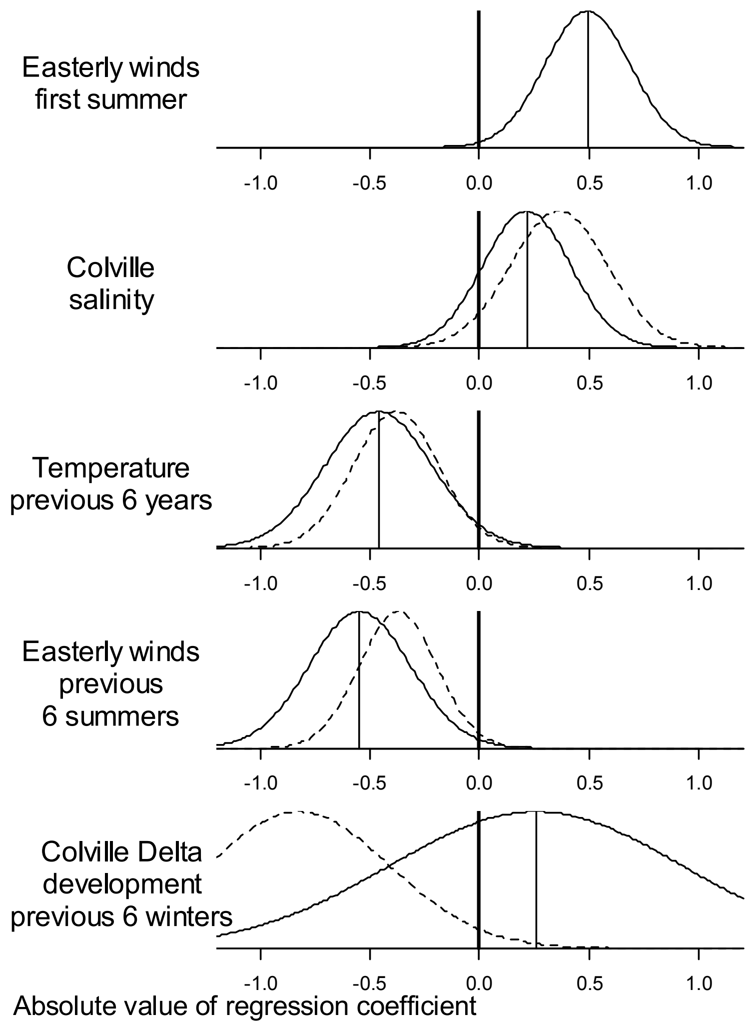

Figure 135. Sensitivity of Arctic cisco catch rates in the Colville River to environmental indicators and one development indicator. The effect of wind speed was estimated using a model including only wind speed. Solid lines in other panels denote probability distribution (relative scale) of regression coefficients based on a "full" model of residuals from the wind model on all other variables (multiple linear regression), whereas dashed lines denote probability distributions based on a model that include the wind effect plus the variable specified on the left.

SENSITIVITY OF SIZE-AT-AGE TO NATURAL AND HUMAN INFLUENCES

We examined time series for the approximate final size at age-0 and an index of relative size-at-age across age-2–6 in the Prudhoe Bay region. Final size-at-age-0 was significantly related to both temperature conditions and alongshore winds, which explained 72% of the variability in final size (based on 13 years of data). Relative size-at-age of juvenile and subadult Arctic cisco (age-2–6) in Prudhoe Bay was related to alongshore winds and to the abundance of other species in the region. A model including a categorical "dummy" variable for wind (westerly winds = 0, easterly winds = 1) had 12 years of data and explained 94% of the variability in relative size-at-age because of the large difference in size-at-age between years with easterly winds and those with westerly winds (see Chapter 5–Hypothesis Testing). We did not include any development activities in models of size-at-age because the exploratory analysis did not suggest any relationships between size-at-age and any of the indicators of disturbance potential. Furthermore, there is little *a priori* reason to believe that development activities will have discernable effects on relatively coarse measures of size-at-age. Better measures of size-at-age and condition have been collected (e.g., Fechhelm et al. 2006), but only summary data were available for this study. However, we consider the summary measures used here adequate for examining interannual variability in average size at age and it is unlikely that more refined measures of size-at-age or condition would show effects of development activities on size.

Summer temperature conditions had a stronger effect on final size at age-0 than easterly winds during summer (Figure 136, top panels). The estimated effects changed only slightly if they were estimated separately using simple linear regressions on temperature and easterly winds, respectively (dashed lines). This result was not surprising because temperature and easterly winds were completely uncorrelated (r = 0.01).

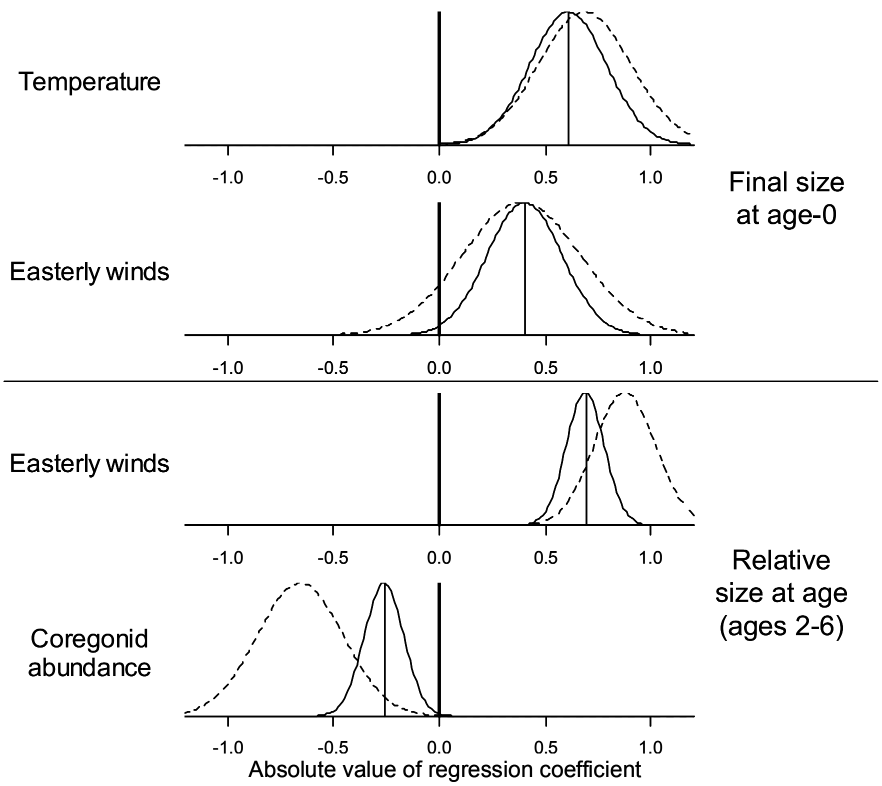

Figure 136. Sensitivity of Arctic cisco size-at-age (final size-at-age-0 or relative size of older age classes) in Prudhoe Bay to environmental indicators and coregonid abundance. Solid lines in each panel denote probability distribution (relative scale) of regression coefficients based on a "full" model of the response variable on both explanatory variables (multiple linear regression), whereas dashed lines denote probability distributions based on a model that includes only the variable specified on the left.

Relative size-at-age of older Arctic cisco in Prudhoe Bay was most sensitive to the direction of easterly winds, and less sensitive to the total abundance of coregonids (Figure 136, bottom panels). However, coregonid abundance was strongly correlated with easterly winds ($r = -0.55$) and was highest during the 2 years of westerly winds. Therefore, the model that included only abundance of coregonids attributed much of the variability in relative size at age to this abundance, but with very large uncertainty (Figure 136, bottom panel, dashed line). Because of the strong collinearity, we cannot separate the effects of coregonid abundance and easterly winds. Improved data on coregonid abundance alone would not help resolve the issue, only direct evidence for competition effects on Arctic cisco (e.g., dietary overlap and food limitation) would be able to refute or support the hypothesis that competition with other species affects Arctic cisco.

DISCUSSION

Understanding variability in abundance of Arctic cisco in the Colville River is a key goal for MMS, as well as for Nuiqsut fishers and other stakeholders. The main sources of variability that determine the abundance of Arctic cisco in the Colville River and the availability of the fish to subsistence fishers include the following:

- Variability in the number of young-of-year Arctic cisco recruiting to Prudhoe Bay by the fall of each year;
- Variability in the cumulative survival of Arctic cisco from the time they recruit to Prudhoe Bay as age-0 fish to the time they are caught in the fishery at ages ranging from 4–9 years (primarily ages 5–8); and
- Variability in in-river conditions during the fall that determine the local abundance of Arctic cisco available to the fishery. While local abundances are obviously most important to local fishers that depend on harvesting Arctic cisco, they are affected by other large scale factors and, therefore, the total abundance of the Colville River population of Arctic cisco may be more important from a long-term conservation perspective, regardless of whether they are available to be caught in the subsistence fishery or whether they reside elsewhere during a given year.

These three sources of variability (recruitment, survival, catch rates) were used in our analyses as the main response variables. Each of these variables is affected not only by environmental factors, but also potentially by human factors, and our analyses sought to parse out the most important factors affecting the observed variation. In most cases, however, there was considerable uncertainty in the response variables, which greatly affected our ability to detect significant relationships. In addition, there may be considerable uncertainty, and possibly bias, in some of the explanatory variables (for example our indicators of development activity), which could lead to spurious results. Therefore, statistical results without independent confirmation should be interpreted with caution. For most of the models, a *post-hoc* power analysis could have helped to quantify the power to detect an effect of a specified magnitude. However, because of the exploratory nature of the analyses and the large number of hypotheses tested, we were much more concerned about Type I errors (detecting a significant effect when there actually is no effect) than about Type II errors (failing to detect a significant effect, which is related to the power of a test). Therefore, we focus on the plausibility of the statistically significant relationships that we did identify, rather than focusing on cases where we might have missed a significant relationship (power analysis).

Large uncertainty about the explanatory variables may violate regression assumptions (because the independent variables are rarely known "without error"), but will generally not affect the nature (sign or magnitude) of an estimated effect. Uncertainty in explanatory variables could be incorporated in Bayesian analyses, but in most cases we lack adequate measures of variance to do so formally. Therefore, we focused on assessing whether individual explanatory variables are reasonable proxies for the mechanisms they were designed to capture and whether they provide unbiased measures. We discuss these issues and some ways to improve our understanding of each of the components of variability.

RECRUITMENT VARIABILITY

The observed variability in recruitment of age-0 fish to Prudhoe Bay is to a large extent explained by variability in summer winds (70–80%). This relationship has held up for over 20 years of subsequent monitoring since it was first postulated and presumably reflects variability in wind-driven transport. This result is very robust and holds for several different wind indices. In spite of our attempts to develop a wind index that more closely reflects alongshore winds during summer (Chapter 4), measured winds at Deadhorse consistently explained more of the variability in recruitment than other indices, suggesting that they may provide the best available proxy for alongshore transport. We consider it unlikely that more refined wind indices or a more complex model of alongshore transport would provide better predictors of recruitment. Moreover, because we have direct estimates of recruitment that can be used to predict future catch rates in the Colville River, there is little reason to improve wind indices for the purpose of explaining variability in Arctic cisco abundance or catch rates in the Colville River. Therefore, reducing uncertainty about the effect of wind-driven transport on recruitment may by of little practical value.

Recruitment estimates (CPUE of ages 0–2) in the Prudhoe Bay region appear to be sensitive to variations in Sagavanirktok River discharge and to the total abundance of coregonids. The effect of river discharge is highly uncertain (large variance of the estimated effect and large difference in the estimated effect between models; Figure 133) and may be due to a long-term decreasing trend in discharge that parallels a similar trend in the abundance of new recruits in Prudhoe Bay. Whether the relationship is real or coincidental can only be resolved through detailed, long-term studies of the effects of salinity on the distribution and/or abundance of juvenile Arctic cisco in the Prudhoe Bay region. Given the complexities of such a study, the benefits are likely to be small compared to the expense, and little would be lost if we attribute the apparent effect of discharge to other, unknown factors.

Our results suggest that the abundance of large coregonids in Prudhoe Bay had a negative effect on the number of recruits. The number of coregonids displayed a long-term increasing trend (opposite to a decreasing trend in recruitment), but unlike the estimated relationship with discharge this relationship was relatively precise (small confidence interval) and was consistent between models (Figure 133). Therefore, we consider it likely that the relationship represents a true interaction between large coregonids and young-of-year Arctic cisco. Along with apparent effects of large coregonids in Prudhoe Bay on the size of Arctic cisco (Figure 136), this represents a potentially important interaction between other species and Arctic cisco that is poorly understood at present. Our index of coregonid abundance is highly uncertain, but measures of uncertainty (variance of estimates) are available from various LGL reports. Including this uncertainty in the model (e.g., as Bayesian priors on coregonid abundance) would increase the uncertainty in the estimated effects. Therefore, both the index and our understanding of interaction effects could be greatly improved through a short-term (one or two summers) study of trophic interactions. These studies should determine (1) the dietary overlap between other fishes in the Prudhoe Bay region and Arctic cisco, and (2) the extent to which other fishes in the Prudhoe Bay region prey on Arctic cisco. Results from such a study, together with estimates of abundance, would allow us to better quantify the potential effects of competition and predation on juvenile and subadult Arctic cisco.

Our results suggest that recruitment was not affected by the overall level of development activities in the eastern Beaufort Sea. The estimated effect was centered on zero and had a relatively small confidence interval (Figure 133). However, our index of development activities simply enumerates activities that occurred in the coastal areas, which may not adequately reflect their potential impact. We judged the sensitivity of our results to uncertainty in our measures of human activity by estimating effects based on a number of different measures of activity and by changing the relative weights given to different activities in the overall index of "disturbance potential." Activities in the eastern area consisted primarily of drilling and seismic exploration (Figure 137). Recruitment to Prudhoe Bay was not related to either the number of drilling

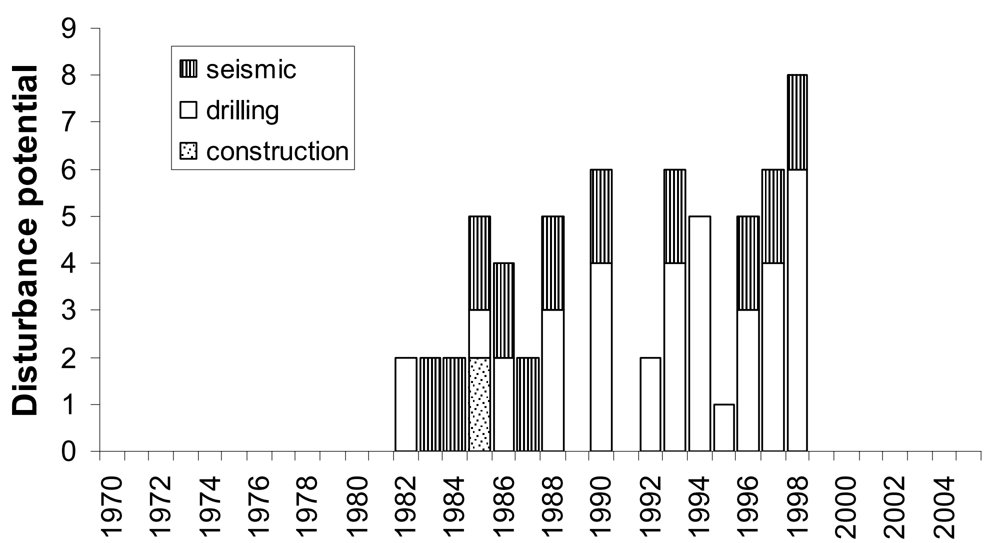

Figure 137. Disturbance potential of all documented human exploration activities in the coastal Beaufort Sea between the Canadian Border and the Sagavanirktok River during summer by major activity. Each occurrence of an activity was rated on a scale from 0 to 3 and ratings were summed by year.

operations, the amount of seismic line surveyed, or the total disturbance potential. This conclusion and the magnitude of the estimated effect did not change when all activities were equally weighted (instead of using weights from 1–3 based on duration of activity or subjective assessments; see Chapter 4). Therefore, as long as our index reflects at least relative differences in activities among years, our findings of no significant effect appears to be robust. If our index missed substantial activity occurring in some years or periods, our conclusions could change. There was some concern that activities during the 1980s were not fully accounted for in these analyses. We examined how our results changed if activities in the 1980s were underestimated, and we redid the analyses using a modified indicator of disturbance potential that doubles the value of the indicator during the 1980s while leaving the values in the 1990s unchanged. In addition, the disturbance potential for 3 years in the 1980s with no reported activity in our database was set equal to the average of the other years in the 1980s. The modified indicator had considerably higher activity in the 1980s compared to the 1990s (average value of 6.2 compared to 3.9 in the 1990s). The estimated effect of the modified indicator on recruitment was very similar to that depicted in Figure 133 and was not significant. This relationship suggests that our results are not very sensitive to the magnitude of the disturbance potential in the 1980s and our conclusions are robust, even if there is considerable bias and uncertainty in our indicator during the 1980s.

Our conclusions imply that total recruitment has not been affected by the overall level of activity in the region, but does not exclude localized effects of seismic or drilling activity on juvenile Arctic cisco. With regard to seismic activities, a considerably body of research exists (e.g. Turnpenny and Nedwell 1994) that could be used to evaluate the likelihood that seismic activities in the Beaufort Sea impact Arctic cisco during their migration. Effects of seismic surveys on catch rates of (adult) Pacific cod and haddock have been documented over considerable distances (10s of miles), but these effects are likely to be transient (Turnpenny and Nedwell 1994). Moreover, impacts on fishes in nearshore areas are likely to be much less because of the species commonly found there and because of much greater sound attenuation in nearshore waters (Turnpenny and Nedwell 1994). These and similar studies, combined with our analytical results, suggest that seismic activity in the offshore region is unlikely to have affected juvenile Arctic cisco in the Beaufort Sea during their coastal migration.

With regard to drilling operations, effects are likely to be much more localized and can only be fully evaluated through intensive sampling that occurs prior to and in conjunction with drilling. However, because of the lack of an apparent effect of drilling operations on overall recruitment, we do not consider such studies to be a high priority for evaluating offshore development with regard to young-of-the-year fishes during their coastal migration. Such studies may be more relevant to development activities inshore, where the State of Alaska manages development in waters within three miles of shore, and on land, where resources are managed by the State of Alaska and federal agencies (e.g., BLM).

Recruitment of young-of-year Arctic cisco to Prudhoe Bay is an important determinant of future catch rates and annual estimates of recruitment can be used directly to predict future catch rates (Figures 56 and 57). Monitoring and understanding recruitment variability can provide an early indicator of changes in abundance and a recent downward trend in recruitment (Figure 45) is a cause of concern. Our analyses suggest a potential effect of other coregonids in the Prudhoe Bay area on the numbers of new recruits. Understanding the relationship between juvenile Arctic cisco and other nearshore species, therefore, should be a priority. However, the trend could also be caused by changes in the source population in the Mackenzie River (for example a decrease in spawner abundances), about which very little is known. To better understand the population dynamics of Arctic cisco in Alaska, improving our understanding of the spawning population in the Mackenzie River is of critical importance.

VARIABILITY IN JUVENILE SURVIVAL

Survival of Arctic cisco from the time they recruit as young-of-year fish to Prudhoe Bay to the time they are first caught in the fishery is highly variable (Figures 56–62). Survival appears to be affected by temperature conditions and was reduced when temperatures were low (Figures 98 and 134). The estimated relationship and its uncertainty (confidence interval in Figure 134) assume that temperatures are measured accurately and reflect conditions experienced by Arctic cisco. However, the temperature index we used was a multivariate index (first principal component) based on air temperatures, NOAA reconstructed sea-surface temperatures, and ice condition in the Colville region. The index is likely to reflect overall climate conditions on a regional and larger scale, rather than actual temperature conditions experienced by Arctic cisco. The thermal environment experienced by Arctic cisco is poorly known because of the lack of direct temperature measurements and the unknown spatial distribution of Arctic cisco.

The estimated temperature effect was very sensitive to the temperature measure that we used for analysis and was statistically significant only when the first principal component was used or, in trying to explain adult (age 5–7) survival, when a direct measure of nearshore SST was used. Other indices (summer average SST from NOAA, summer air temperature at Barrow, spring ice concentration, fall ice concentration) had weaker and non-significant relationships with survival. Moreover, uncertainty in the first principal component (which cannot easily be quantified) increases the uncertainty about the estimated effect. There is no intuitive interpretation of the magnitude of the effect because both the explanatory variable (first principal component) and the response variable (survival anomaly) are relative indices. In general, survival tended to be above average when temperature conditions were below average (Figure 111).

A negative effect of warm temperature conditions on survival would be expected to reduce future catch rates following warm years, and we did indeed find a negative effect of temperature conditions (averaged over several years) on Arctic cisco catch rates in the Colville fishery (Figure 135). No obvious mechanism would explain why survival is lower during warmer years, and it is possible that the effect is due to other unrelated factors that happen to be correlated with temperature conditions. To reduce uncertainty about the potential temperature effect a better characterization of the thermal environment experienced by Arctic cisco during summer would be useful. However, this assumes that the effect is a direct temperature effect (which is doubtful) and would require a long-term monitoring program, as well as a better understanding of Arctic cisco distribution.

Survival of Arctic cisco apparently was lower during years with intense development activity in the Colville delta region, which suggest that these activities may reduce overwintering survival. However, the effect was highly uncertain, as evident in relatively large confidence intervals (Figure 134), and was sensitive to uncertainty in the development index. It was not possible to evaluate sensitivity to uncertainty in the development index (e.g., in the form of a Bayesian prior) because the uncertainty in the index cannot be quantified. Therefore, we examined the sensitivity of our results (apparent detrimental effect of development activities on survival) by comparing responses to a number of different development indicators in the analysis, in addition to the combined index, and by changing the weights for different activities in the combined index.

Our analyses suggest that onshore construction activities were the critical component of the apparent effect of total development activities on Arctic cisco survival. Reported development activities in the Colville delta that may affect Arctic cisco include ice bridges (channel crossings), drilling activities, construction (and associated traffic), and drilling mud spills (Figure 138). When individual activities were evaluated one at a time and in different combinations, a negative effect on survival only was apparent when construction activities (roads, ice pads, gravel pads, facilities) were included in the index, but not without construction included. In contrast, channel crossings and drilling activities alone or in combination displayed no apparent relationship with survival. It is noteworthy, however, that the Panel of Experts cited ice bridges at channel crossings and drilling activities (noise and vibration) as being likely sources of human

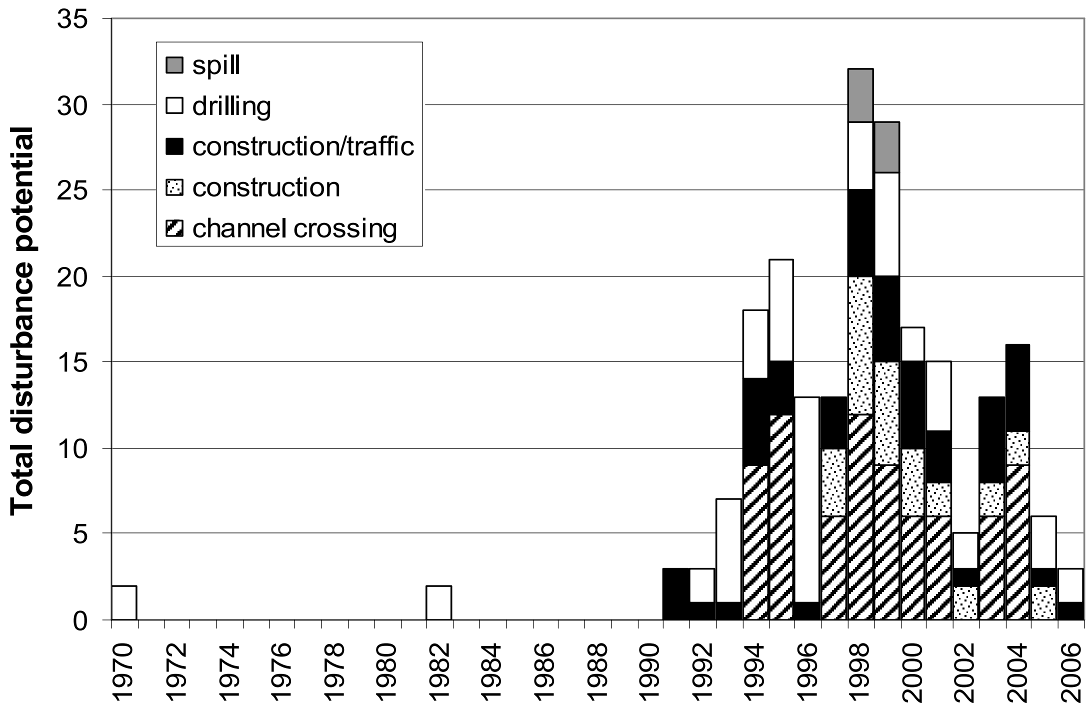

Figure 138. Disturbance potential of all documented human exploration activities in the Colville delta during winter. Each occurrence of an activity was rated on a scale from 0 to 3 and ratings were summed by year.

disturbance that could adversely effect Arctic cisco. Nevertheless, our finding of a potential detrimental effect of development activities on Arctic cisco suggests that a more precise quantification of potential disturbances in the Colville region and fish responses to disturbance are warranted. Industry could be required to submit more detailed records of their activities, and small-scale field studies could be designed to examine potential effects of development activities on Arctic cisco. Clearly, winter development activities in the Colville delta have the potential to adversely affect Arctic cisco survival and should be closely monitored to evaluate their effect on overwintering mortality.

Other development activities that may affect Arctic cisco survival during the summer in Prudhoe Bay or in other coastal feeding areas (western and central areas; Figure 4) were examined as well but did not show any significant effects. In all cases, the estimated effects of development indicators, as subjectively measured by disturbance potential, were close to zero or positive (i.e., implying a positive effect of development activities on survival). Therefore, any failure to find significant effects was not due to lack of power, and reducing uncertainty in the values of the indicators would not change our conclusions regarding no significant effects. However, because of the simple enumeration of development activities and the large uncertainty in survival indices, these results to not exclude the possibility that specific activities affect the survival of Arctic cisco at local scales.

VARIABILITY IN ABUNDANCE OF ARCTIC CISCO IN THE COLVILLE RIVER

Catch rates of Arctic cisco in the Colville River, and presumably fish abundance, appear to be strongly affected by local and regional environmental conditions and potentially by winter development activities in the Colville region as well. The positive effect of easterly winds during the juvenile stages on catch rates 5–7 years later (Figure 135) was expected and has a well-established mechanistic explanation. Nevertheless, the effect was fairly sensitive to the kind of wind index that was used in the analysis (NCEP/NCAR winds vs. measured winds; Chapter 4). As for recruitment, the best relationship was achieved with measured Deadhorse winds and, therefore, we assumed that Deadhorse winds provide a good proxy for alongshore transport. Given the already tight relationship between Deadhorse winds and young-of-year recruitment (R^2 = 70–80%), it is unlikely that any improvement in the wind index could be achieved that would result in a much better relationship between winds and catch rates than the one estimated (R^2 = 24%; Figure 135). Therefore, efforts to improve our understanding of variability in abundance may better be focused elsewhere (i.e., at processes that affect Arctic cisco after initial recruitment to Prudhoe Bay).

Effects of in-river salinities on Arctic cisco catches also are reasonably well estimated, as indicated by a relatively narrow confidence interval (Figure 135). This effect likely reflects a preference of Arctic cisco for medium-to-high salinities, as indicated by the effects of salinity at the local scale (i.e., among nets) on CPUE (see Chapter 5). This local effect translates into an overall effect on average catch rates at the scale of the entire fishery (Figure 135). Salinities have been consistently monitored at fixed locations within the river and throughout the fishing season and, therefore, should provide a reliable indicator of the salinity experienced by Arctic cisco. However, considerable variability occurs in the vertical profiles of the salinity data (Moulton et al. 2006), and this variability may not be adequately reflected in our salinity index, which averaged salinities between 3 and 4 m depth only (subsurface layer, nets typically fish the surface layer and the upper part of this subsurface layer). To examine the sensitivity of our results to the choice of depth range over which salinities were averaged, we also used average salinity over the entire water column, as well as average salinity over the surface layer only (upper 2 m) as explanatory variable in models of CPUE. The resulting salinity effects were very similar, but using surface-layer salinities resulted in larger variability and, hence, larger uncertainty in the effect of salinity on catch rates. The high variability resulted from the frequent presence of a shallow freshwater lens at the monitoring stations, which caused lower average salinities in the upper 2 m compared to the subsurface layer (3–4 m). Nevertheless, our conclusions with regard to the effect of salinity are not strongly affected by the depth range over which salinities were averaged. A more objective choice of this depth range could be obtained by examining the depth distribution of Arctic cisco during the fall fishery. This evaluation could easily be done by noting the vertical location of Arctic cisco in gillnets over a number of sets and comparing it to the salinity profiles.

In contrast to the effects of in-river salinities and winds during the first summer, which have a sound rationale, we consider the effects of average temperature conditions and average easterly winds during the summer feeding season on subsequent catch rates of Arctic cisco (Figure 135) to be highly uncertain. Although the confidence intervals for the estimated effects are relatively narrow, we lack a mechanistic explanation for the observed relationships and, therefore, do not know whether the temperature and wind measures, averaged over several summers, provide a meaningful measure of environmental variability. Nevertheless, the estimated effects are consistent between models (compare dashed and solid lines in Figure 135) and are statistically significant. In combination, these effects account for a considerable portion of the variability in catch rates that is not explained by the effects of easterly winds on recruitment or local salinities (49%), or as much as 35% of overall variability in catch rates. A better understanding of oceanographic influences during the summer feeding season on Arctic cisco could greatly enhance our understanding of variability in fish abundance in the Colville River. Changes in temperature conditions and easterly (upwelling) winds may be associated with differences in spatial distribution, prey availability, and predator abundance. Therefore, field studies of Arctic cisco distribution, trophic relationships, and prey abundances during summer in relation to temperature and wind forcing would be very useful. However, lacking specific hypotheses, an extensive field sampling program to address such general issues may be prohibitively expensive. A more thorough examination of existing oceanographic data from the nearshore areas in Prudhoe Bay and elsewhere, not all of which were available to us, could help in developing more specific hypotheses to be tested in future field studies. These include temperature and salinity profiles obtained during various monitoring programs in the Prudhoe Bay region, oceanographic sampling during OCSEAP studies, NOAA studies (e.g., Thorsteinson et al. 1991), and studies by the U.S. Fish and Wildlife Service (Tevis Underwood, USFWS, pers. comm.), as well as more recent sampling conducted by the University of Alaska, including numerous current meter moorings (Tom Weingartner, UAF, pers. comm.) and radar-based estimates of surface currents (http://www.ims.uaf.edu/salmon/).

Although we found strong evidence of environmental effects on Arctic cisco catch rates, effects of development activities were less certain (very large confidence intervals) and were not consistent between different models (Figure 135, bottom panel). The large difference in the estimated effects between a model that included only the disturbance potential (dashed line in Figure 135) and a model that included other covariates was a result of strong confounding between the temperature variable and the indicator of disturbance potential. The 6 years with the largest disturbance potential (1998–2002) coincided with the warmest period in the time series. Therefore, it is not possible to statistically distinguish the effects of temperature and development activities based on the existing indices. However, the estimated effect of development activities was inconsistent between models and had an extremely wide confidence interval, whereas the temperature effect was relatively consistent. These results suggest that the effects of development activities may be spurious. Moreover, our results suggest that development activities did not cause fluctuations in the Arctic cisco population outside the range of natural variability that was observed prior to the onset of development activities in the Colville delta. Nevertheless, as noted above, winter development activities in the Colville delta clearly have the potential to adversely affect Arctic cisco survival. Hence, both catch rates and development activity should be closely monitored.

Because development activities in the Colville delta started relatively recently, we assume that our database includes all of the major activities that occurred. To further examine the sensitivity of our results to uncertainty in the development indicator, we compared responses to a number of development indicators for specific activities, in addition to the combined index, and by changing the weights for different activities in the combined index. Apparent responses to individual activities ranged from moderately negative effects to moderately positive effects, depending on the index, and were generally not statistically significant. Construction activities and drilling had apparent negative effects, but both were strongly confounded with temperature. The estimated effect of the number of channel crossings on catch rates was small and non-significant. If the relative weights of different activities contributing to the total disturbance indicator were all set equal to 1, results were similar and did not alter the overall conclusion of a potential, but highly uncertain, detrimental effect of development activities in the Colville delta on catch rates. Clearly, as for effects on survival, improved indices of development activities could be developed to more accurately define potential impacts of specific activities. Because of the confounding between temperature trends and development activities, a better understanding of potential temperature effects would help in ascertaining whether development activities contributed to the low survival rates and catch rates observed in the late 1990s and early 2000s.

UNCERTAINTY ABOUT DEVELOPMENT INDICATORS

Our analysis of effects of development on Arctic cisco recruitment, survival, and catch rates assumes that the indicators are a meaningful representation of development activities and are not biased. Here, we examined only one potential source of bias, namely the possibility that development activities in the 1980s were underestimated. Our conclusions with regard to potential effects of development activities on Arctic cisco were not very sensitive to potential biases in the 1980s. Lacking information on other potential sources of bias or uncertainty in our indicators of “disturbance potential,” we were unable to further quantify the sensitivity of our results to these sources of error. We also reiterate that we only examined coarse measures of overall development activity in relation to interannual variability in recruitment, survival, or catch rates. A lack of significant effects at the overall population level does not exclude the possibility that development activities affect the local abundances of Arctic cisco in the Prudhoe Bay region or within the Colville delta. Such effects can only be tested through detailed field studies in conjunction with specific development activities.

SUMMARY OF MAIN EFFECTS

Recruitment, survival, catch rates, and size-at-age of the Arctic cisco population in the Colville River were shown to be related to environmental variability in the coastal Beaufort Sea and in the Colville River, as well as to development activities in the Colville delta. In general, interannual variability in the Arctic cisco population appears to be more sensitive to environmental variability than to development activities. We briefly summarize the main effects that were identified in this study with a subjective evaluation of our confidence in each effect.

- Consistent easterly (alongshore) winds are crucial to the recruitment of young Arctic cisco to the Prudhoe Bay region and, thereby, affect catch rates in the Colville River 5–8 years later. Because of considerable variability in subadult survival, the effect of easterly winds on catch rates is greatly attenuated compared to the direct effect on recruitment.
- Convincing evidence shows that variations in salinity in the Colville delta affects local catch rates of individual fishers, as well as the annual average catch rate in the subsistence fishery (no salinity data are available for the commercial fishery). This component of variability in catch rates (which may explain as much as 32% of observed variability in catch rates in the past) is likely to be independent of changes in abundance and simply reflects variability in the availability of Arctic cisco to the fishery.
- Reasonable evidence indicates that the total abundance of other coregonids in the Prudhoe Bay region affects the abundance of recruits and the growth of Arctic cisco, presumably through predation and/or competition.
- Westerly winds during summer not only result in recruitment failures, but may also result in poor growth of juvenile and subadult Arctic cisco (as reflected in small size-at-age). Presumably, reduced growth results from reduced productivity, possibly due to lack of upwelling of nutrient rich waters onto the shelf.
- Some evidence supports the conclusion that warm conditions and strong easterly winds during summer negatively affect subadult and adult survival and subsequent catch rates of Arctic cisco, although we do not have plausible mechanism to explain this apparent relationship.
- Some evidence indicated that survival and catch rates of Arctic cisco were negatively affected by winter development activities in the Colville delta. However, these estimated effects are either smaller and/or much more uncertain than the effects of environmental variability. While our results suggest that development activities did not cause fluctuations in the Arctic cisco population outside the range of natural variability, the large uncertainty in the effects of winter development activities on Arctic cisco underline the need for precaution. Winter development activities in the Colville delta clearly have the potential to adversely affect Arctic cisco survival and should be closely monitored to evaluate whether they lead to increased overwintering mortality.

ISSUES RAISED BY SUBSISTENCE FISHERS

Our findings were able to shed light on some of the questions that were raised in the 2003 *qaaktaq* workshop and by the Pane of Experts. Issues identified by the panel that we were able to address include the following:

Fewer fish available to subsistence fishery in recent years: Our results suggest that the reduced catch rates in 2000–2002, and particularly in 2001, resulted from a combination of relatively poor recruitment 5–7 years prior (as a result of unfavorable winds), changes in in-river distribution of fish in 2001 associated with unusually low salinities, and reduced survival in the late 1990s and 2000, possibly as a consequence of increased development activities.

Reduced size and/or weight of fish in recent years: The two years with greatly reduced sizes (and weights) at age coincided with the relatively rare occurrence of predominantly westerly winds during summer, suggesting an oceanographic effect on growth of Arctic cisco.

We hypothesize that reduced upwelling during those years resulted in poor feeding conditions for Arctic cisco.

Changes in distribution of fish in the Colville River: We found that the preference of Arctic cisco for brackish water results in reduced catch rates at very low and very high salinities. Thus, very low average salinity in the Niġliq channel in 2001 almost certainly contributed to the low catch rates observed that year.

Changes in quality of fish (taste, texture, color): Although no data are available to quantify taste, texture, or color, size data clearly indicate the poor condition (size-at-age) of Arctic cisco in some recent years, most notably in 2002 and 2003.

Obstructions (e.g., causeways): We were able to rule out short-term detrimental effects of causeways on the recruitment, survival, and overall catch rates of Arctic cisco at the population level.

Noise from drilling and dredging / vibration from seismic surveys and drilling: Although we cannot attribute any effects to noise, vibration, or other specific disturbances associated with drilling and dredging on catch rates, we found that over-wintering survival may have been reduced during the years with the most intense development activities in the Colville delta, in particular activities associated with construction. In contrast, we found no obvious effects of offshore seismic activity on total recruitment levels or catch rates.

Over-harvesting by the commercial fishery: Although we were unable to fully investigate the effects of fishing because fishing mortality rates are unknown, there is some concern that the recent decrease in recruitment levels may be a result of reduced spawner abundances (and hence reduced numbers of offspring) in the Mackenzie River. These trends could have resulted from over-harvesting. We emphasize that there is no direct evidence for a decrease in spawner abundance because of the lack of monitoring in the Mackenzie River. However, considering the lack of any other explanation and the apparent decrease in a proxy index for spawner abundance (Chapter 5), a decrease in spawner abundance provides a reasonable explanation for recent decreases in recruitment. Whether the decrease in spawner abundance is a result of over-harvesting cannot be answered with the available data, but we found no evidence in the time series of total catch and effort (subsistence + commercial fishery) that would suggest over harvesting by the Colville fisheries. Over-harvesting at the population level cannot be attributed to either the subsistence or commercial fishery but can only be evaluated on the basis of total catch and effort.

Contaminants (bio-uptake): A recent study (Moulton et al. 2006) suggests that the levels of polycyclic aromatic hydrocarbons in Arctic cisco are below detectable limits. Other contaminants, such as other organic compounds or trace metals, have not been examined to our knowledge.

We were unable to examine any of the other concerns that were identified by the Panel of Experts (deformed fish; food chain effects, i.e. changes in prey availability and prey types; energetic stress associated with navigating obstructions; upstream gravel extraction; siltation in nearshore waters from causeways and dredging) because of a lack of biological samples on deformities, diet composition, or energetic condition and because of a lack of data on gravel extraction and siltation.

The *qaaktaq* workshop in 2003 identified additional issues, including (1) genetic issues regarding the stock of origin of Colville River Arctic cisco; (2) Arctic cisco life history; (3) Colville River dynamics; (4) climate change; and (5) socio-economic issues (see Chapter 7 for a full list). Genetic issues and socio-economic issues were not addressed by this study, but we included a brief discussion of the stock of origin controversy in Chapter 7. The life history of Arctic cisco was reviewed in Chapter 1 (Table 1), and some aspects of their life history were confirmed by our analyses (recruitment dynamics, age composition in the Colville River and Mackenzie River, etc.). There remain some obvious gaps in our understanding of Arctic cisco life history with respect to their spawning and early life history, as noted above. Although we did not explicitly address climate change, we noted a change in nearshore species composition associated with a shift in the large-scale atmospheric circulation in the Arctic, potential effects of sea-surface temperature on growth and survival, and the detrimental effect of a reversal in the direction of summer winds along the Beaufort Sea coast, all of which may be related to changes in the global climate.

RECOMMENDATIONS FOR FUTURE MONITORING AND RESEARCH

Based on results from the exploratory analyses, hypotheses testing, and sensitivity analyses, we provide a table summarizing the present level of monitoring, the cost and complexity of maintaining, improving, or initiating monitoring, and the long-term value of various indicator variables for improving our understanding of variability in Arctic cisco dynamics (Table 23). We grouped indicator variables into several categories and identified the highest priority studies within each category. We offer our overall recommendations for issues that should receive priority in Chapter 7.

Climate: Most relevant climate indicators are either adequately monitored or are not particularly useful indicators of conditions experienced by Arctic cisco. We consider river discharge to be the highest priority for monitoring in this category, although other biological variables should receive first priority. Discharge into the summer feeding grounds along the Beaufort Sea coast have some potential for predicting coastal feeding conditions and/or overwintering survival and could be obtained at relatively moderate costs. Monitoring has improved in recent years (addition of a USGS gauge on the Colville River) and estimates of runoff could be obtained from new hydrographic models (Jia Wang, IARC, UAF, pers. comm.).

Oceanography: Our understanding of the role and importance of oceanographic conditions to Arctic cisco is still limited, and we consider both better temperature measures and a suitable upwelling index to be priorities for future studies and monitoring. Our results suggest that temperature conditions are important to Arctic cisco growth and survival and that temperature also is correlated with other potentially important variables (e.g., ice conditions). Current temperature measures do not adequately reflect the spatial distribution of Arctic cisco, which range from the coast up to at least 12 km offshore. We therefore consider improving the spatial coverage of temperature measures, either through remote sensing or *in-situ* measurements, a high priority among the oceanographic indices. Second, our findings suggest that westerly winds and the associated lack of upwelling may be very important to the growth of Arctic cisco. An upwelling index could be estimated from existing wind data at low cost, and a comparison with available oceanographic data will help determine whether it provides an adequate measure of interannual differences in upwelling onto the shelf. Given the relatively low cost, such an index also should receive high priority.

Table 23. Summary of present level of monitoring, cost and complexity of maintaining, improving, or initiating monitoring, long-term value, and data required to improve measurement of various indicator variables for understanding variability in Arctic cisco abundance. Indicator variables that were identified as a priority for monitoring are denoted by an asterisk (*).

Indicator variables	Present level / quality[a]	Cost / Complexity[b]	Long-term value[b]	Data needs / variables & scales
Climate				
Easterly winds at Deadhorse	Excellent	Low	High	
Average alongshore winds	Poor[c]	High	Low[d]	Improved global model, more weather stations
Air temperature	Excellent	Low	Low	
River discharge – Mackenzie	Poor[e]	Medium	U / Medium	Gauges on major tribute. OR hydrographic model
*River discharge – North Slope	Poor	Medium	Medium	Gauges on major rivers OR hydrographic model
Oceanography				
*Nearshore (~0–5km) water temperature	Poor[f]	Med / High	Medium	Cross-shelf line of moorings (summer)
Coastal ice / timing of breakup	Poor	Medium	U / Medium	High-res SAR images (e.g., Eicken et al. 2006)
Nearshore (~0-5km) salinity	Poor	Med / High	U / Medium	Cross-shelf line of moorings (summer)
Current speed and direction	Poor[g]	Med / High	Unknown	Cross-shelf line of moorings (summer)
Alongshore transport	N/A	High	Medium[d]	High-res ocean model
*Upwelling	N/A	Low[h]	U / Medium	High—quality modeled wind fields
Nutrient concentrations	N/A	High[i]	Unknown	*In-situ* profiles, summer feeding area, 0–5 km
Fluorescence (Chl. A)	N/A	High	Unknown	Cross-shelf line of moorings (summer)
Prudhoe Bay fish monitoring				
*Prudhoe Bay YOY	Good	High	High	
*Size-at-age / condition	Poor[j]	Low [k]	Medium	Age / length / weight samples (available?)
*Coregonid abundance in Prudhoe Bay	Good	Low [k]	Medium	
Abundance of other species	Good	Low[k]	U / Low	
Nearshore temperature	Good	Low[k]	Low[l]	
Nearshore salinity	Good	Low[k]	Low[l]	
Harvest monitoring				
*Fishing effort	Good	High	High	
*Subsistence catches	Good	High	High	
(*) *Derived:* Total CPUE	Adequate	Low[k]	High	
Catch location	Adequate	Low	Medium	

Table 23. Continued.

Indicator variables	Present level / quality[a]	Cost / Complexity[b]	Long-term value[b]	Data needs / variables & scales
Harvest monitoring (cont.)				
Catch date	Adequate	Low	Medium	
*Size composition of catches	Adequate	Low[k]	High	
*Age composition of catches	Poor[m]	Medium[k]	High	Larger sample for aging
(*) *Derived:* Age-specific CPUE	Poor	Low[n]	High	Larger sample for aging
(*) *Derived:* Overwintering Survival	Poor	Medium	U / High	Larger sample for aging
Catches of other species	Adequate	Medium[k]	Low	
In-river salinities	Good	Low[k]	Medium	Expanded study of habitat distribution
Other biological data				
Prey availability – nearshore	N/A	High	U / Medium	Cross-shelf sampling with plankton nets
*Diet composition / overlap	N/A[o]	Medium[p]	High	Stomach samples by species & size class
Predator abundance – Nearshore Beaufort Sea	Poor	Medium	U / Medium	Stomach samples by species & size class
*Spawner abundance – Mackenzie tributaries	N/A	High	High	Sonar / counting towers on major tributaries
Egg / fry densities – Mackenzie tributaries	N/A	High	U / Medium	Need to find spawning areas first
Abundance of outmigrating YOY – Mackenzie	N/A	High	U / Medium	Sonar on tributaries?
Stock structure based on otolith chemistry	N/A	Med / High[q]	High	Water samples from rearing areas & otolith samples (Colville)
Stock structure based on genetic markers	Poor	High	High	New genetic tools?
Fish energetics: lipid content, condition	N/A	High	Medium[r]	Annual samples by size for lipid analysis
Oil development				
*Disturbance: drilling	Poor	Medium	High	Require reporting: dates, location, duration
*Disturbance: construction	Poor	High[s]	High	Require reporting: dates, location, duration
Disturbance: seismic	Adequate	Low	High	
Disturbance: ice bridges	Adequate	Low	High	
*Pollution / water quality (river & nearshore)	Poor (N/A?)[t]	Medium	High	Time series of water samples from Colville, nearshore areas
Siltation	N/A	Medium	U / High	Monitor water depth at a few fixed locations, anecdotal info (LTK)?

Notes: N/A = Not available (not currently measured), U = Unknown

Table 23 (footnotes). Continued.

[a] Rankings are: poor < adequate < good < excellent
[b] Rankings are: low < medium < high
[c] Quality of NCEP / NCAR winds in the Arctic may be questionable (few measurements)
[d] Although valuable, may offer little improvement over simpler Deadhorse wind index
[e] Although main channel is gauged, spawning tributaries are not (and are poorly known)
[f] Available SST indices do not reflect Arctic cisco distribution in nearshore waters (from coast to ~12 km)
[g] High quality data available at selected location over limited time periods (T. Weingartner, UAF, pers. comm.)
[h] Can be estimated from wind data, provided good wind data are available.
[i] Costs of acquiring spatially adequate data and determining importance to upper trophic levels
[j] Size-at-age is adequately monitored by LGL, but only summary data was available for this study
[k] When done in conjunction with existing monitoring programs and assuming these programs continue
[l] Temperature and salinities unlikely to be representative of "average" habitat of Arctic cisco
[m] Larger sample size may be needed to adequately describe age-structure
[n] Given that catch data and adequate age composition data are collected
[o] No recent data
[p] One-time study, if done in conjunction with monitoring (2-3 years)
[q] Medium if done in conjunction with existing monitoring, but high cost of establishing baseline for water samples
[r] Unclear whether it would provide advantage over simpler condition indices
[s] Difficult to quantify, may require understanding of mechanisms
[t] Baseline studies on trace metal and hydrocarbon concentrations in shelf sediments are available (Naidu et al. 2001)

Prudhoe Bay fish monitoring: The existing monitoring program at Prudhoe Bay provides good relative indices of recruitment of Arctic cisco to the region and has proved indispensable in estimating the strength of incoming year classes and of future catch rates. Continuing this sampling program should therefore receive a very high priority. In addition, the sampling program has provided other biological indices, such as size-at-age of Arctic cisco and the abundance of other coregonids, at low additional cost. Because of the relatively low cost and the potential utility of these indices (as suggested by our results), continuing this aspect of the sampling program and making the raw size-at-age data available to other researchers are considered high priorities as well.

Harvest monitoring: Given the focus of this research effort on Arctic cisco as an important subsistence resource for the residents of Nuiqsut, the continuation (and potentially improvement) of the harvest monitoring program obviously should be the highest priority. In particular, good estimates of fishing effort and catch are essential to any fishery sampling program and are the highest priority. In addition, estimates of size and age-composition of the catch are critical for predicting future catch rates, and we recommend improving age-composition estimates as a high priority for this purpose and for developing an age-structured model. In the past, otoliths for age composition have been collected in the commercial fishery and sample sizes have been relatively low. To adequately resolve the age composition of the Arctic cisco catches, which will greatly facilitate the development of an age-structured population dynamics model, we recommend that representative samples (n = 400+) from the subsistence fishery be obtained for each major gear type. Improved age composition data also can greatly improve age-specific estimates of catch rates and survival.

Other biological data: In our view, some of the highest priorities for improving the collection of other biological data relevant to the population dynamics of Arctic cisco are: (1) the estimation of spawner abundances in the Mackenzie River tributaries where Colville River Arctic cisco are believed to originate. The Mackenzie River system likely is another important source of recruitment variability and quantifying this variability is a critical component for assessing the sustainability of current fishing levels; and (2) the collection of diet composition data of Arctic cisco and other co-occurring species to assess the degree of overlap and the potential for food limitation. This will help resolve the potential importance of competition between Arctic cisco and other species. With regard to spawner abundances, a long-term commitment to monitoring is essential because at least 10 years of data will be required to assess potential harvest impacts on the population.

Development Activities: Based on available databases, we constructed relatively coarse indices of potential disturbance that could be greatly improved with better reporting requirements. In particular, we recommend improving the characterization and quantification of drilling and construction activities as a high priority. To adequately describe potential impacts from these activities, at a minimum, exact location information and the duration of activities should be recorded. In addition, small-scale studies to determine short-term impacts of such activities on local abundances would be extremely valuable to address the concerns of Nuiqsut fishers regarding such activities. Understanding the mechanisms by which such activities may affect Arctic cisco will in turn help in determining how to adequately quantifying the activities. Given the concerns of local fishers over contaminants, evaluating the adequacy of existing pollution monitoring programs should be a high priority.

In addition to the above priorities, we recommend improving the measurement of any of the indicators that are currently poorly measured, to the extent that improvements can be accomplished at a relatively low cost and where the potential value is unknown (Table 23).

7. SYNTHESIS

PANEL OF EXPERTS

It was important to include the community of Nuiqsut in this project because of their extensive local knowledge of Arctic cisco, their experience as subsistence fishers, and their status as stakeholders in the management of this resource. Ten Nuiqsut residents with experience and knowledge about Arctic cisco and a willingness to work with scientists were selected to be on a Panel of Experts. The primary roles of the panel were to identify sources of information, including traditional knowledge, that would help the scientific team understand the observed annual changes in Arctic cisco abundance and to evaluate (i.e., validate) the findings of the scientific team. Five meeting were held in Nuiqsut to accomplish these goals. During these meetings the panel identified these issues**:**

1. Fewer fish available to subsistence fishery in recent years (+)
2. Reduced size and/or weight of fish in recent years (+)
3. Changes in distribution of fish in the Colville River (+)
4. Changes in quality of fish (taste, texture, color) (-)
5. Deformed fish (-)
6. Food chain effects (changes in prey availability and prey types) (+)
7. Energetic stress (cost of navigating obstructions) (-)
8. Obstructions (e.g., causeways) (+)
9. Noise from drilling and dredging (+)
10. Vibration from seismic surveys and drilling (+)
11. Contaminants (bio-uptake) (-)
12. Upstream gravel extraction (-)
13. Over-harvesting by the commercial fishery (-)
14. Siltation in nearshore waters from causeways and dredging (+)

Due to data limitations, we only were able to address approximately half of these issues during our analyses (note: issues above identified with a "+" were addressed, whereas no data were available to address issues identified with a "-"). Most of our efforts were focused on Issue 1 regarding annual variability in the abundance of fish, but we also were able to at least indirectly assess Issues 2, 3, 6, 8, 9, 10, and 13. Some recent data are available on Issue 11, but no data were available to assess the other issues.

The panel provided the scientific team with insight into the history of the subsistence and commercial fisheries on the delta, the effects of wind, ice, and salinity on fishing success, and their assessments of the effects of various types of development activity on Arctic cisco. This information led directly to the formulation of hypotheses, some of which we were able to address in our analyses. For example, the panel's observations regarding the appearance of "skinny fish" during 2002 and 2003 led to further analysis by the scientists, who found a relationship between fish quality and environmental factors. Other hypotheses based on local knowledge that could not be analyzed because of a lack of data contributed directly to our assessment of data gaps and recommendations for future research. For example, one panel member remarked that the causeways not only were a potential barrier to fish movements but also that they had changed patterns of sedimentation and that the waters west of the causeway had become shallower in recent years. We had not considered habitat change in the marine environment as a potential influence on Arctic cisco, and we had no data to evaluate this issue. Nevertheless, we were able to identify this as an area of concern that might warrant study in the future.

The strengths of the collaboration between the scientists and the local experts were that we were able to build a relationship of trust, which in turn facilitated effective information transfer. An informal poll of the panel members present at the last meeting indicated that they thought this collaboration with the scientists was worthwhile and that they particularly valued learning more about the biology of this important resource. The scientific team felt welcome in Nuiqsut and privileged to have had the opportunity to work with and learn from these local experts. Additional detail about the success of the panel process from the viewpoints of the scientists and the panel members can be found in Appendices E and F.

ANALYTICAL RESULTS

Based on a literature review, exploratory analyses, and input from the Nuiqsut community (through an Arctic cisco workshop held in 2003 and through the Panel of Experts), we identified a suite of at least 26 overarching, testable hypotheses (Table 24). These hypotheses corresponded to one or more of the following generalized *a priori* null hypotheses:

- Changes in oceanographic or hydrographic processes do not significantly affect the recruitment, survival, or abundances of Arctic cisco in the Colville River at any stage in their life history.
- Ecological processes and other species do not significantly affect recruitment, survival, or abundance of Arctic cisco in the Colville River.
- Human activities related to oil development or fishing do not significantly affect the recruitment, survival, or abundance of Arctic cisco in the Colville River.

Hypotheses H1–H15 (Table 24) examined the effects of environmental variability on Arctic cisco recruitment, survival, catch rates, and size-at-age. Our analyses confirmed the pronounced effect of easterly winds during summer on recruitment (H1) and subsequent catch rates (H2). A number of new hypotheses regarding environmental effects emerged in the exploratory analyses, several of which were supported by the statistical evidence. Specifically, we found:

- Weak statistical evidence that freshwater discharge is positively related to recruitment anomalies (H4), but we did not identify a plausible biological mechanism for this apparent relationship.
- Strong evidence that fishery catch rates at a given location decline over the course of the fishing season (H9) and a detailed analysis of daily catch rates suggested that the relationship may result from local depletion (reduction in fish density because of fishery removals).

Table 24. Main hypotheses tested in this study, strength of evidence that the hypothesized effects are biologically and statistically significant (‘0’ = no evidence for an effect; ‘+’ = weak evidence; + + = strong evidence).

Hypothesis	Description	Strength of Evidence
H1	Consistent easterly winds during summer increase the recruitment of juvenile (age-0) Arctic cisco to Prudhoe Bay	+ +
H2	Consistent easterly winds during summer increase catch rates of Arctic cisco in the Colville River 5–8 years later	+ +
H3	Warmer temperatures (and reduced ice) in the coastal Beaufort Sea are associated with higher recruitment of young-of-year Arctic cisco to Prudhoe Bay	0
H4	Freshwater discharge into the coastal Beaufort Sea affects the number of young-of-year Arctic cisco caught in Prudhoe Bay	(+)
H5	Environmental conditions (temperature and discharge) in the Mackenzie River affect young Arctic cisco prior to and during outmigration and modify the recruitment of young-of-year Arctic cisco to Prudhoe Bay	0
H6	Warm temperatures in the coastal Beaufort Sea enhance the survival of Arctic cisco	(+)
H7	Upwelling-favorable winds in the coastal Beaufort Sea enhance the survival of Arctic cisco	0
H8	Local salinities in the Niġliq channel of the Colville River affect catch rates (CPUE) of Arctic cisco (dome-shaped relationship)	+ +
H9	The time of fishing (day of year) affects catch rates (CPUE) of Arctic cisco in the Colville River	+ +
H10	Average salinities in the Niġliq channel during the fall affect the average catch rate (CPUE) of Arctic cisco	(+)
H11	Summer temperature conditions in the coastal Beaufort Sea affect catch rates in the Colville River fall fishery during subsequent years	(+)
H12	Summer upwelling conditions (upwelling-favorable, easterly winds) in the coastal Beaufort Sea affect catch rates in the Colville River fall fishery during subsequent years	(+)
H13	Summer temperature conditions in the coastal Beaufort Sea affect the size-at-age of Arctic cisco in the Prudhoe Bay region	0

Table 24. Continued.

Hypothesis	Description	Strength of Evidence
H14	Summer upwelling conditions (upwelling-favorable, easterly winds) in the coastal Beaufort Sea affect the size-at-age of Arctic cisco in the Prudhoe Bay region	(+)
H15	A climatic shift in the Arctic in the late 1980s / early 1990s has affected the recruitment of Arctic cisco and the abundance of Arctic cisco and other nearshore fish species in the coastal Beaufort Sea	(+)
H16	The abundance of other species in the Prudhoe Bay region affects the number of juvenile Arctic cisco	(+)
H17	The abundance of other species in the Prudhoe Bay region affects the size-at-age of Arctic cisco	(+)
H18	Construction of major causeways decreases the long-term average recruitment of Arctic cisco to Prudhoe Bay (while breaching increases average recruitment)	0
H19	Construction of major causeways decreases the long-term average survival of Arctic cisco in the Colville River / Prudhoe Bay region (while breaching increases average survival)	0
H20	Construction of major causeways decreases the long-term average catch rate of Arctic cisco in the fall fishery (while breaching increases average catch rates)	0
H21	The intensity of seismic activity, the number of drilling operation, or the sum of all development activities in the eastern Beaufort Sea affects the recruitment of young-of-year Arctic cisco to Prudhoe Bay	0
H22	The intensity of development activities in the summer feeding area of Arctic cisco (western Beaufort Sea) affects survival of juveniles and subadults	0
H23	The number of drilling operations, the number of ice roads, construction activities, or the sum of all development activities in the Colville River affects the overwintering survival of subadult Arctic cisco	(+)
H24	The number of drilling operations, the number of ice roads, construction activities, or the sum of all development activities in the Colville River affects the catch rates of Arctic cisco in subsequent years	(+)
H25	Fishing affects the long-term average level of recruitment of Arctic cisco to the Prudhoe Bay region	0
H26	Fishing affects the long-term average catch rates of Arctic cisco in the Colville River fall fishery	0

- A significant dome-shaped relationship between local salinities and catch rates of Arctic cisco in the fishery. We showed that this relationship results in a weak, but statistically significant and biologically plausible increase in annual average catch rates with increasing average salinities in the river (H10).
- Statistically significant effects of temperature on survival (H6). However, the estimated effects suggested decreased survival with increasing temperature, which was contrary to our expectations. We do not have a biological explanation for this apparent relationship, and it is possible that the relationship is due to other underlying variables that were not examined here.
- Low catch rates in the Colville River fishery following warm temperature conditions during summer (H11). The effect was statistically significant and its estimated magnitude was as large as the effect of easterly winds during the first year. We currently lack an explanation for this apparent relationship; hence, other variables related to temperature fluctuations in the coastal waters should be examined for their effects on Arctic cisco.
- A strong positive effect of easterly winds on size-at-age (H14), which may reflect the importance of upwelling-favorable winds to the growth of Arctic cisco. While it is unclear whether reduced size decreases survival and future catch rates of Arctic cisco, this apparent effect on size is important because it affects the size and quality of fish caught in the fishery, as evident in concerns over “skinny” fish in 2002 and 2003.
- In contrast, a statistically significant, but non-intuitive negative effect of upwelling-favorable winds during summer on lowering catch rates in the next fall fishery (H12). Although highly uncertain, this effect also deserves further scrutiny.
- Changes in recruitment of Arctic cisco to Prudhoe Bay and abrupt changes in the abundance of other nearshore fishes in the late 1980s that were associated with changes in large-scale atmospheric circulation in the Arctic, as measured by the Arctic Oscillation index (H15).

Hypotheses H16 and H17 examined the effects of other coregonids on the number (H16) and size (H17) of Arctic cisco in Prudhoe Bay. Both relationships were statistically significant and biologically plausible (i.e., competition and/or predation), suggesting a negative effect of high coregonid abundances on the number of juvenile Arctic cisco and on the size-at-age of Arctic cisco in the Prudhoe Bay region. A long-term increasing trend in the abundance of adult whitefishes may in part account for a decreasing trend in recruitment of Arctic cisco, and this relationship should be examined in more detail. There is strong potential for competition between Arctic cisco and least cisco due to a high degree of diet overlap (Craig 1984), but diet overlap between Arctic cisco and other coregonids is unknown.

The remaining hypotheses (H18–H26) examined effects of development activities on Arctic cisco. Key hypotheses centered on the effect of causeways on recruitment or survival and on the effects of winter activities in the Colville delta on over-wintering survival. Although the potential effects of causeways on Arctic cisco have been examined in the past, the effects of development activities in the Colville delta associated with drilling, ice bridges, and construction are a much more recent concern. In summary, we found no statistical evidence that causeways had a negative impact on average recruitment levels, survival, or average catch rates in the fishery (H18–H20). However, we did find weak evidence that intense development activity, specifically construction activities and traffic in the Colville delta region, was associated with a reduction in survival (H23) and subsequent catch rates (H24) in the fishery.

2003 *QAAKTAQ* WORKSHOP REVISITED

As previously described, much of the impetus for this study was derived from the MMS-sponsored workshop held in Nuiqsut in 2003 (MBC Applied Environmental Sciences 2004). At the time of that workshop, catch rates were at historical lows and the quality of the fish appeared to be deteriorating. Subsistence fishers were describing “skinny” fish that tasted “earthy.” Because the decline in harvest in the early 2000s coincided with increased industrial activity in the area, it was not surprising that the subsistence community thought that there was a link between development and both the quality and quantity of fish. In addition to presentations and testimony from subsistence fishers, the workshop also included panel discussions. Participants were divided into two groups, each with a mix of elders, local experts, and scientists. The groups were tasked with developing a list of issues that needed to be addressed in future studies. MMS then took the results of the two groups and developed a ranking system and a list of the issues most important to the participants. In rank order, these issues were as follows:

1. Effects of development and human activities
2. Review previously collected Canada and Alaska data, including Elders’ information
3. Arctic cisco life history
4. Migration of young-of-the-year from the Mackenzie River
5. Water quality, contaminants
6. Genetics, source stocks
7. Colville River dynamics
8. Ice roads and bridges
9. Seismic, noise
10. Climate change
11. Socio-economics

Although this study was focused primarily on addressing Issue 2, we also addressed, at least in part, Issues 1, 3, 4, 8, and 9.

Community members at the workshop also expressed some specific concerns and opinions (MBC Applied Environmental Sciences 2004), some of which we were able to address in this study. What follows are specific comments followed by what was learned from this study:

- Leonard Lampe: “ Some people believe that the closer you are to the mouth of the river the greater the catch.” This observation is consistent with our finding that CPUE increases toward the mouth of the river, probably as a result of higher average salinities near the mouth of the river. These higher salinities appear to be preferred by Arctic cisco.
- Leonard Lampe: “The first person out is generally the most successful.” This observation is consistent with our finding that CPUE tends to decrease over the course of the season, probably as a result of local depletion.

- Carl Brower and others: “In the 1970s the fish were very large. Compared to the 1970s when we had large fish, last year we had small ones. They’ve grown smaller every year.” There are no data to evaluate size during 1970s, but recent size-at-age data show a pronounced drop in size-at-age during 2001 to 2002.
- Ruth Nukapigak: “Once the causeway was built, the seawater treatment plant (STP), changes began to occur. These changes affected the size and abundance of fish.” Causeways do not appear to have affected long-term trends in abundance (catch rates), recruitment, or survival of Arctic cisco. Effects on size cannot be fully evaluated because size-at-age data only are available since 1985. We were not able to evaluate the direct effects of the STP.
- Several residents commented that North Star development turned water muddy as a result of dredging. No data are available to test this directly, but North Star activities are part of the database and contribute to the “disturbance potential” indicator. Our results suggest a possible connection between disturbance potential and Arctic cisco survival.
- Gordon Brown: “I think that the constant noise from the development disturbed the fish.” Noise has not been quantified but is associated with drilling activity, which is included in the “disturbance potential” indicator.
- Gordon Brown: “We have always thought that the west winds brought in the cisco for us along with the salinity of water.” Our analyses found no evidence that interannual salinity differences in the Colville River were related to differences in average wind forcing off the mouth of the Colville River during the fishing season. However, we did not analyze daily catch rates in the fishery as a function of wind direction because of uncertainties about the lag time between westerly winds and effects on in-river conditions.
- Elders at the workshop thought that some of the most dramatic changes in catches began in the 1970s, when catches reportedly decreased from 100s of fish per day to 10s of fish per day. Because these changes occurred at a time when there was little or no monitoring of Arctic cisco, there are no data to verify the reported changes. The only long-term record going back to before the 1970s are catch rates reported in the Helmericks’ fishery. While these catch rates show a declining trend from 1973 through 1979, average catch rates in the late 1960s and early 1970s were very similar to those in the 1980s and 1990s.
- A number of residents expressed concerns over ice bridges blocking the up-river or down-river movement of Arctic cisco. To assess the effects of ice bridges on Arctic cisco would require more detailed process studies because there may be local effects that are not evident in the annual indices included in this study. We did include ice bridges (channel crossings) in the “disturbance potential” indicator and compared catch rates and survival anomalies between years with and without ice bridges. The analysis did not reveal any apparent effects of ice bridges, but the sum of all activities in the delta, including ice bridges, was highest during the years that had the lowest observed survival anomalies, suggesting a potential effect of the overall level of development activity on Arctic cisco survival.
- Whalers have observed that the river delta is getting shallower over time due to sedimentation. This may affect Arctic cisco migration but sedimentation has not been quantified and its effect cannot be assessed at present.

- A number of residents expressed concern about pollutants. A recent study of the levels of polycyclic aromatic hydrocarbons (PAH) in fish tissues (liver, muscle, and whole fish) of Arctic cisco caught in the 2005 fishery found non-detectable levels of PAH in any samples (Moulton et al. 2006); thus, it appears at present there is little exposure to these compounds.
- During discussions of genetic stock and population source issues at the workshop, Craig George (North Slope Borough) mentioned that Warren Matumeak (Barrow elder) thinks there is a source of spawning Arctic cisco in the rivers emptying into Dease Inlet (i.e., west of the Colville River). Several biologists also speculated that there may be more than the Mackenzie River stock of Arctic cisco present in the Colville River, citing that there has never been a complete absence of a year class even when summer winds are predominantly west. They theorized that the strong Siberian current coupled with westerly winds could be responsible for bringing fish from Russian stocks from the west. Our review of data collected at Prudhoe Bay indicates that at least some recruitment occurs even during years with unfavorable wind conditions. However, during both 2002 and 2003, when winds during the summer blew from the west on average, no age-0 Arctic cisco were captured in Prudhoe Bay and very few specimens of these year classes were sampled in subsequent years. Moreover, we note that fish of Russian origin would have to cross high-salinity waters in the southern Chukchi Sea (which are outside the preferred salinity range of Arctic cisco) and would have to overcome northward currents in the Chukchi Sea that would tend to transport juveniles away from the coast into the central Arctic Ocean (Seth Danielson, UAF, pers. comm.). An alternate explanation to the western spawning stock hypothesis is that juvenile Arctic cisco are capable of some degree of active behaviors, such as actively swimming towards the west or vertical / horizontal movements to stay in surface waters during periods of westward transport, while descending to the bottom or into nearshore areas during periods of eastward transport. Current meter measurements from mooring sites near Prudhoe Bay suggest that currents during the open-water season generally are swift but highly variable. Current speed and direction are significantly correlated with alongshore winds but typically exceed 10 cm/sec with speeds up to 100 cm/s (Okkonen and Weingartner, p. 24 in MBC Applied Environmental Sciences 2003). Moorings deployed in nearshore areas along the Beaufort Sea coast in recent years suggest that more than 50% of measured current speeds exceeded 15 cm/s and that drifting particles were transported an average distance of ~13 km/day eastward during the open-water seasons of 2003/2004 (Seth Danielson, UAF, pers. comm.). Therefore, if currents of this magnitude are typical for other locations along the coast, juvenile Arctic cisco would have been passively transported over a distance of 780 km during July/August of these years (13 km/day for 60 days). Similarly, Thorsteinson et al. (1991) estimated passive and directed migration rates of 15–18 km/day for YOY Arctic cisco. This is more than enough to cover the distance from the Mackenzie River to Prudhoe Bay (~500 km). If frequent flow reversals occur during summers when westerly winds are common, active behavior may be required to prevent juveniles from being transported back to the east. Of course, this theory is not mutually exclusive of the western stock theory and, in fact, may enhance it if juvenile fish are indeed capable of some degree of active behavior. Genetic stock assessments of Arctic cisco clearly are warranted.

DATA GAPS

One critical limitation to understanding the population dynamics of Arctic cisco in the Colville River is the lack of information on adult abundances. Because maturing Arctic cisco (ages 6–9) from the Colville River return to the Mackenzie River to spawn, and because maturation rates (which are equivalent to emigration rates in this case) may vary from year-to-year, catch rates of subadults in the Colville River hold little information about the size of the adult spawning population. Moreover, adult Arctic cisco experience variable (and unknown) rates of mortality during their return migration and in other fisheries (Barter Island, Tuktoyaktuk), which increases uncertainty about the size of the adult population. Finally, Arctic cisco may spawn repeatedly and reach ages of up to at least 19 years (reported from the Peel River), which further increases uncertainty about the size of the effective spawning population. No reliable measures of adult abundance or effective spawner abundance are available. Therefore fishing mortality rates and the impact of fishing on the population are unknown at present.

The lack of data on spawner abundance did not affect most of our analyses because we had a direct measure of Arctic cisco recruitment to Prudhoe Bay from the long-term monitoring program. These estimates of relative recruitment were used to compute indices of survival that are independent of any changes in spawner abundance. However, understanding variability in recruitment, such as the recent declining trend, is severely hampered by a lack of spawner abundance data. Furthermore, effective management of anadromous fish species generally focuses on ensuring that enough spawners reach their spawning grounds. Without any information on spawner abundances, effective management is difficult.

There is continuing uncertainty about stock structure of Arctic cisco in Alaskan waters. For our analyses, we assumed that all or most young Arctic cisco recruiting to the Prudhoe Bay region originate from the Mackenzie River, although the existence of other source populations has not been ruled out. For example, there was continuing speculation that some Arctic cisco originate from spawning grounds west of the Colville River (e.g., testimony at the 2003 Arctic cisco workshop). To resolve stock structure issues, genetic studies have been conducted in the past (Bickham et al. 1989, 1993, 1997), and results were consistent with a Mackenzie River origin. However, distinct spawning populations exist within the Mackenzie River (Bickham et al 1989), and the tributary that is the main source population for Colville River Arctic cisco has not been identified. If Arctic cisco in the Colville River primarily originate from a single Mackenzie River tributary, identifying this tributary would greatly facilitate monitoring of the appropriate spawning population. As an alternative to or to supplement genetic analyses, elemental composition of otoliths may provide a valuable tool in identifying spawning locations.

Our analysis of environmental effects on Arctic cisco recruitment and survival was limited by the lack of direct measures of coastal environmental conditions in Arctic cisco summer habitat. In particular, few long-term measures of water temperature and salinity are available to adequately characterize summer feeding areas. The only time series of direct measurements are nearshore salinities and sea-surface temperatures sampled in conjunction with the fish monitoring program. To obtain a time series of sufficient length for our analyses, we resorted to the use of interpolated sea-surface temperature estimates (NOAA Extended Reconstructed SST) that are averaged over relatively large regions (on a 1 degree grid) and are based on satellite measurements and very sparse *in-situ* data. A comparison of these two data sources showed reasonable agreement, but a full assessment of all existing temperature and salinity data in the coastal Beaufort Sea in relation to the distribution of Arctic cisco was beyond the scope of this project. Such an analysis may reveal that existing measures are adequate to describe Arctic cisco habitat or may suggest suitable sites for a long-term monitoring program.

Environmental conditions experienced by young Arctic cisco in the eastern Beaufort Sea after outmigration also are poorly measured and may have affected our analyses if biases and uncertainties in the available data are high. Our only source of information for the analysis were NOAA Extended Reconstructed SSTs from this area. A time series of measured SST was not available to us. However, oceanographic sampling has been conducted in the area (e.g., Carmack and MacDonald 2002) and may provide an opportunity for assessing the adequacy of reconstructed SSTs to characterize likely habitat for outmigrating Arctic cisco.

Another important factor affecting Arctic cisco in the coastal Beaufort Sea during spring and early summer is the timing of ice breakup, which may not be adequately captured by the NOAA reconstructed ice indices used in our analyses. Ice conditions are important to the transport of juveniles through their effect on wind-driven coastal transport and to the summer habitat of adult Arctic cisco through their effect on temperature and productivity. Better indicators of the timing of break-up may be available from direct observations or other sources such as weekly or bi-weekly ice charts from the Arctic Climatology Project (National Ice Center, available at http://www.natice.noaa.gov) or daily and monthly observations from the National Snow and Ice Data Center (NSIDC, available at http://nsidc.org/data/seaice/alpha.html). Breakup data for North Slope rivers are limited at present, but will be useful for analyzing the effects of the timing of breakup when longer time series become available.

A major limitation for analyzing factors that may affect overwintering survival of Arctic cisco is the lack of data on the quantity and quality of overwintering habitat. We have shown that salinity affects the distribution and abundance of Arctic cisco within the river and that interannual variability in average salinity affects average catch rates. However, the salinity distribution and the availability and extent of suitable overwintering habitat during most of the winter is unknown. Understanding the distribution of preferred habitat of Arctic cisco is also critical for understanding the potential effects of development activities on Arctic cisco, because the effects of development will vary if the distribution of Arctic cisco relative to the locations where development occurs varies from year-to-year. We were unable to address this potentially important interaction.

We were unable to address concerns over the quality of food for Arctic cisco because prey organisms (primarily mysids and amphipods; Craig 1984) have not been monitored in the coastal Beaufort Sea. While Craig (1984) stated that food generally is not limiting in summer, the poor growth of Arctic cisco during 2002 and 2003 (as reflected in small size-at-age) suggest that food may be limiting during summers with westerly winds. No data on prey availability are currently available to test this hypothesis. Similarly, we were unable to accurately quantify the abundance of potential competitors and predators of Arctic cisco because the degree of diet overlap and predation is unknown for many other species that co-occur with Arctic cisco.

Our analysis of the effects of development on Arctic cisco is limited by the availability of quantitative measures of development activities. Our indices of "disturbance potential" relied on subjective assessments of disturbances and, in most cases, simply enumerating the number of times a specific activity occurred. While quantitative measures were available in some cases (e.g., seismic activity), and others could potentially be quantified (e.g., duration of drilling activities), it is unlikely that suitable quantitative measures of such activities can be developed without first understanding the nature of potential impacts. This understanding can only be gained through process studies that monitor Arctic cisco before, during, and after potential disturbances.

RECOMMENDATIONS

HIGH PRIORITY

For optimal understanding and management of the Arctic cisco population, it is critical to monitor trends in spawner abundance, in recruitment, and in overall abundance of fish available to the fishery on the Colville delta. Unfortunately, there is virtually no information available on spawner abundances in the Mackenzie River. Establishing a monitoring program for spawners should, therefore, be a high priority from a fisheries biology perspective. This recommendation was made at the 2003 workshop as well, but no progress has been made on the Canadian side to our knowledge.

Recruitment trends of juvenile fish to Prudhoe Bay have been monitored since 1981 by oil industry-sponsored studies. These data have been invaluable for deciphering life history characteristics, monitoring recruitment strength, monitoring demographic patterns, predicting future harvest success, and assessing development impacts. We strongly recommend that these studies be continued.

Since 1985, the oil industry also has funded studies for monitoring the subsistence harvest of Arctic cisco on the Colville delta. Data from these studies have been critical for monitoring the status of the fishery, plus they have been critical for deciphering life-history traits, habitat use, and age-class survival rates, and for assessing development impacts. Improved data from these studies would also help fishery scientists develop a state-of-the-art age-structured model of the population dynamics of Arctic cisco.

We recommend that the population dynamics of Arctic cisco be comprehensively examined through a modeling effort, which would benefit our understanding of Arctic cisco as well as the management of the fishery. In principle, sufficient data exist to develop a full age-structured model of the Arctic cisco population. We experienced difficulties fitting such a model but we believe that these difficulties could be resolved with a dedicated effort. The benefits of developing an age-structured model include obtaining better estimates of abundance over time than simple CPUE indices, estimates of fishing mortality and exploitation rates, as well as improved estimates of recruitment. These could be used to determine the impact of the fishery on the population and set biologically acceptable and sustainable catch levels. However, this requires an estimate of natural mortality (percentage of fish dying of natural causes each year), some assumption about how mortality varies across ages, and some assumption about the vulnerability of different age classes to the fishing gear (selectivity). Unfortunately, all of these factors affecting numbers at age are generally difficult to separate, and are particularly difficult to evaluate and separate for Arctic cisco. For example, natural mortality in older age-classes of Arctic cisco cannot be separated from emigration as older fish mature and return to the Mackenzie River for spawning. Both natural mortality and emigration act simultaneously to reduce the number of older age classes in the fishery. Because of this confounding between emigration and natural mortality, because of the small number of age classes routinely caught in the fishery (ages 5–8), and because of the small sample size for age composition, we were not able to fit an age-structured model to the available data. If independent and reliable estimates of either natural mortality or emigration rates by age (presumably reflecting maturity-at-age), as well as reliable age and/or size compositions for major gear types used in the fishery could be obtained, an age-structured model could provide improved estimates of recruitment and abundance, as well as estimates of fishing mortality rates. However, the development of an age-structured model would still be hampered by the total lack of data on the abundance of older age classes in the Mackenzie River.

MODERATE PRIORITY

The Panel of Experts contends that the nearshore environment west of the causeways in Prudhoe Bay has changed since construction of the offshore oil facilities. In addition to thinking that causeways are obstructions to fish, they believe that the waters west of the causeways are more turbid and that siltation has adversely affected navigability and seal hunting. In turn, they suspect that the decline in seal numbers is a reflection of fewer fish in this area. Several panel members also expressed concern about impacts to fish associated with the Saltwater Treatment Plant (STP) at Oliktok Point. Although we were able to address the issue of obstruction of fish by the causeways on overall population trends, there were no data available to address these other concerns related to offshore facilities. Without a stronger signal from scientific studies linking offshore developments to adverse impacts on Arctic cisco, however, we do not assign a high priority to committing limited research money to disturbance studies in the marine environment.

Subsistence fishers also are concerned about the effects of onshore oil and gas development on the Colville delta, and these concerns were expressed at the 2003 workshop and during our meetings with the Panel of Experts. Although we detected a few significant relationships between development activity on the delta and population-level trends in recruitment and abundance, the weight of evidence from all of our analyses suggests that development activities have not had a noticeable detrimental effect on the overall population of Arctic cisco in the Colville River. Our conclusions apply to variability in the Colville population as a whole and evidence against (or for) population-level effects do not exclude (or imply) the possibility of short-term, local effects. For example, the results of our retrospective analysis cannot address potential effects of development activities on local catch rates in specific sections of the Niġliq channel. Such local effects on Arctic cisco in areas like the Niġliq channel can only be resolved by detailed studies in conjunction with specific activities that may impact catch rates. We recommend that such studies be undertaken before additional development is permitted on the delta, and that these studies include real-time monitoring of fish responses to potential disturbances.

Ice bridges that cross the channels of the Colville River were cited as another concern for their potential to negatively affect overwintering populations of Arctic cisco. Our analyses were not able to explicitly evaluate the effects of ice roads, but they indicated that the overall effects of winter development activities on the Colville delta on Arctic cisco survival warrant further scrutiny. We recommend studies to evaluate the effects of ice bridges on local catch rates in the Colville River through a controlled experiment (e.g., using a Before/After–Control/Impact design).

Noise and vibration from drilling operations both offshore and on the Colville delta also have been cited by subsistence fishers as major concerns. We did not detect any effects from offshore drilling operations on Arctic cisco recruitment or survival. But, as previously described, our analyses of development activity on the Colville delta during winter, which included drilling under and adjacent to the Colville River, indicated that focused studies on fish responses to noise and vibration from drilling probably are warranted. We suspect that impacts associated with drilling operations are likely to be localized and, therefore, can only be evaluated through intensive sampling that occurs prior to and in conjunction with drilling. However, because of the lack of an apparent effect of drilling operations on overall recruitment, we do not consider such studies to be a high priority with regard to juvenile and subadult fishes in the marine environment.

Contaminants finding their way into the food chain are a concern that is heard from the subsistence community in almost any discussion of development impacts and, indeed, this concern was repeatedly communicated to us during discussions with the Panel of Experts. Although bowhead whales and caribou, which are staples of the Iñupiat diet have been tested for contaminants, until recently little has been done to assess contaminant loads in fish. In 2006, Moulton et al. (2006) collected tissue samples from broad whitefish in the Colville River and had those analyzed for polycyclic aromatic hydrocarbons (PAH). None of the 11 samples analyzed showed detectable levels of PAHs. Baseline data on trace metal concentrations and hydrocarbon components in shelf sediments have been collected in some nearshore areas in the 1970s and in the late 1990s (Naidu et al. 2001) and show very low concentrations of trace metals and hydrocarbons compared to other regions around the world. We recommend monitoring water quality in the Colville River and measuring trace metal concentrations and hydrocarbon compounds in fish tissue on a regular basis.

The basic stock structure of Arctic cisco remains unresolved. At present, we do not know the importance of the Colville River population to the overall Arctic cisco population. For example, what proportion of total young-of-year Arctic cisco originating in the Mackenzie River system recruit to the Colville River population during an average or good year? If the Colville population experiences recruitment failure during years with westerly winds, do juveniles experience much higher mortalities or do they simply recruit to other areas? Does the Colville River population originate from a defined subpopulation within the Mackenzie River? To begin to address these issues, a closer working relationship with Canadian scientists and Tuktoyaktuk residents needs to be established. A simple reconnaissance trip to Tuktoyaktuk and to regional DFO offices may be able to unearth a wealth of anecdotal and scientific data on Arctic cisco in the Mackenzie River. While it is unlikely that sufficient data will be available to resolve any of these issues, existing data and knowledge will help identify potential problems and focus future studies.

Otolith chemistry (elemental composition) offers an alternative to genetic studies to examine the origin of Colville River Arctic cisco. This approach probably would be more cost effective than establishing a genetic baseline and could be used to assign Arctic cisco to source waters within the Mackenzie River drainage, because each major drainage is likely to have a distinct chemical signature. We recommend that the feasibility of such studies be explored.

Concerns over decreases in size or condition of fish were voiced by panel members, despite recent increases in size-at-age, and factors that affect size and condition are poorly understood. Our results suggest that westerly winds during summer, which clearly adversely affect recruitment, may also have contributed to reduced size and condition of Arctic cisco in 2002 and 2003. We hypothesize that westerly winds may have prevented the upwelling of nutrient-rich waters along the coast and reduced prey availability in the nearshore environment. To test this hypothesized relationship, we recommend that both the abundance of prey in summer feeding areas and the diet composition of Arctic cisco during summer be examined over several years with contrasting wind conditions to resolve differences between years with easterly and westerly winds. For example, copepods (mysids and amphipods), which are primary prey in marine waters, could be monitored at a few coastal locations for several years to examine differences in prey abundance under different wind conditions. Historical measurements of weight-at-length to assess condition have been collected in the Prudhoe Bay region, but were not examined here because we were unable to obtain the data. These data could be used to construct an improved condition index to examine past changes in condition over time. Alternatively, archived scales or otoliths could be used to examine changes in growth increments over time. However, assessing growth potential in the field under variable wind conditions should take precedent over improving historical estimates of condition.

Our analyses provided some indirect evidence for effects of competition and predation. We recommend that these mechanisms be explored in limited field studies. For example, a short-term study of trophic interactions over one or two summers could determine 1) the dietary overlap between other fishes in the Prudhoe Bay region and Arctic cisco and 2) the extent to which other fishes in the Prudhoe Bay region prey on Arctic cisco. Results from such a study, together with estimates of abundance, would allow us to better quantify the potential effects of competition and predation on juvenile and subadult Arctic cisco.

LOW PRIORITY

MMS is particularly concerned about potential effects of offshore activities on Arctic cisco. However, Arctic cisco primarily are distributed in the nearshore environment, and analyses based on an index of offshore activities showed no evidence of a detrimental effect on Arctic cisco recruitment or survival during the open-water season. Nevertheless, our coarse index of combined offshore activities, primarily derived from the MMS report on "GIS Geospatial Database of Oil-Industry and Other Human Activity (1979–1999) in the Alaskan Beaufort Sea" (Wainwright 2002), could be refined to better quantify potential disturbance. For example, a large proportion of offshore activities consisted of drilling, and we were able to obtain the duration of drilling activities for some but not all drilling operations. We recommend that drilling records could be examined in more detail to establish the duration and timing of these operations to develop an indicator that is proportional to the actual duration of drilling. In addition, requirements for recordkeeping could be strengthened to allow better quantification of activities. Hence, we strongly recommend that MMS and resource agencies with management responsibilities for nearshore waters in the Beaufort Sea (e.g., Alaska Department of Natural Resource) require that industry maintain and submit detailed documentation of seismic and drilling activities, undersea pipeline construction, and ice management activity.

Because of the difficulties of obtaining estimates of spawner abundance in the Mackenzie River, a monitoring program to estimate spawner abundances during the Barter Island fall fishery could be established. A reliable index of catch-per-unit-effort in the Barter Island fishery is likely to reflect the number of maturing fish returning to the Mackenzie River. However, the index would not reflect total spawner abundance because Arctic cisco spawn repeatedly and are subject to another fishery at the mouth of the Mackenzie River.

A better understanding of oceanographic influences during the summer feeding season on Arctic cisco could greatly enhance our understanding of variability in abundance in the Colville River. Changes in temperature conditions and easterly (upwelling) winds may be associated with differences in spatial distribution, prey availability, and predator abundance. Therefore, field studies of Arctic cisco distribution, trophic relationships, and prey abundances during summer in relation to temperature and wind forcing would be very useful. However, lacking specific hypotheses, an extensive field sampling program to address such general issues may be prohibitively expensive. A more thorough examination of existing oceanographic data from the nearshore areas in Prudhoe Bay and elsewhere, not all of which were available to us, could help in developing more specific hypotheses to be tested in future field studies.

To better understand the small-scale distribution of Arctic cisco in the Colville delta during winter, salinities could be monitored throughout the main channels, for example, by using probes fixed on the river bottom during winter. In conjunction with satellite-based estimates of potential overwintering habitat (Claude Duguay, UAF, pers. comm.), this would provide a good description of the spatial extent and location of suitable habitat and may allow quantification of the volume of suitable habitat.

A summary of these recommendations is provided in Table 25.

Table 25. Summary of major recommendations for future studies to improve our understanding of variability in the Colville River Arctic cisco population.

Highest priority

- Monitor trends in spawner abundance in the Mackenzie River
- Continue fish monitoring studies in Prudhoe Bay to estimate YOY recruitment, abundance of Arctic cisco and other coregonids in Colville delta region, and size- and age composition
- Continue harvest monitoring at Prudhoe Bay to obtain estimates of effort, catches, and age composition

Moderate priority

- Small-scale process studies of the effects of specific development activities in the Colville delta, such as ice bridges and drilling operations, on catch rates of Arctic cisco (Before / After studies)
- Monitoring water quality in the Colville River and measuring trace metal concentrations and hydrocarbon compounds in fish tissue on a regular basis
- Resolve stock structure and river of origin issues for Arctic cisco through short-term studies based on otolith chemistry and/or modern genetic approaches
- Short-term study of prey abundances and diet composition in years of contrasting wind conditions
- Develop improved historical condition index based on available data or samples (detailed weight-length data, growth increments from archived otoliths)
- Short-term study of distribution of suitable Arctic cisco habitat (and its variability) in the Colville River based on salinity and river morphology

Table 25. Continued.

Low priority
• Develop better quantitative indices of development activity and improve record keeping such activities on the North Slope
• Monitor catches and catch rates of Arctic cisco in the Barter Island subsistence fishery
• Revisit existing oceanographic and biological samples of fish distribution to improve understanding of oceanographic influences on distribution and condition of Arctic cisco

SUMMARY

This study brought together local experts from Nuiqsut, social scientists, and fishery scientists to enhance our understanding of variability in the Colville River population of Arctic cisco. Local knowledge was combined with results from previous research and with new analyses in an iterative approach to develop a shared understanding of the most important factors affecting changes in this subsistence resource. We achieved general agreement on the basic life cycle of Arctic cisco, confirmed the importance of environmental variability on Arctic cisco recruitment and survival, and found limited support for the commonly held belief by local fishers that development activities in and around the Colville delta have affected the Arctic cisco fishery. A summary of new findings and validations of previous findings are provided in Table 26.

Nearly 25 years of fish monitoring programs in Prudhoe Bay and over 20 years of harvest data from the Colville River, in combination with short-term studies off the Arctic National Wildlife Refuge and in the Mackenzie delta region, have provided a reasonably clear picture of the basic life history characteristics of the Colville River population of Arctic cisco. One of the more remarkable features of this life history is the relatively tight coupling between easterly winds along the Beaufort Sea shelf and the number of young Arctic cisco recruiting to the Prudhoe Bay region. This relationship continues to hold more than 20 years after it was first described. Furthermore, the recruitment index for young Arctic cisco in Prudhoe Bay provides a good predictor for catch rates of the corresponding age classes in the Colville fishery 5–8 years later and, therefore, can be used as a predictor of future catch rates. This is a rare example in the fisheries literature of a survey-based juvenile index that provides a good indicator of future abundances.

Variability in the Colville River Arctic cisco population is potentially affected by human and environmental influences at local-to-regional spatial scales and at daily-to-interannual or longer time scales. This study focused primarily on interannual variability at the scale of the entire population, which consists of all Arctic cisco that overwinter in (or in the vicinity of) the Colville delta. We suspect, however, that many of the environmental and human factors we examined may affect Arctic cisco at local scales over the course of days. For example, the effects of salinity on local catch rates in the fishery likely vary daily and on a very localized scale.

Table 26. Summary of new understandings and validation of previous findings.

Confirmation of previously reported observations

Environmental trends

- After several years of strong easterly winds at Deadhorse in the late 1990s, a sharp and significant decrease (to negative, i.e. westerly winds) was apparent in 2002–2003.
- There was a highly significant increase in coastal air temperatures over time at Barrow and Inuvik from 1950–2004, implying a substantial warming trend in the Alaskan and Canadian Arctic
- There was a significant increase in freshwater discharge from the Sagavanirktok River over time, similar to reported trends for numerous Arctic rivers

Biological trends

- We found strong increasing trends in the abundances of Arctic cisco, least cisco, broad whitefish, Arctic flounder, and rainbow smelt in Prudhoe Bay as reported in Fechhelm et al. (2006)
- We confirmed a strong decrease in the size of all age classes of Arctic cisco in Prudhoe Bay as reported in Fechhelm et al. (2006)
- Age-0 recruitment is positively correlated with age-1 and age-2 abundances in the following year and two years later, as well as with catch rates in the Colville fishery 5-8 years later, confirming previous conclusions that recruitment to Prudhoe Bay provides a reasonable proxy for year-class strength of Arctic cisco

Environmental effects on Arctic cisco

- We found positive correlations between easterly wind speed and year-class strength that reflect previously reported effects of wind-driven transport on recruitment of Arctic cisco

Human impacts on Arctic cisco

- Fishing effort in the commercial fishery is negatively correlated with the CPUE of Arctic cisco and least cisco, possibly reflecting the effect of local depletion on CPUE indices as suggested by Moulton and Seavey (2005)
- Our relative index of disturbance potential for the West Dock causeway is negatively correlated with the abundance of least cisco in the Prudhoe Bay area, supporting previous results that West Dock, prior to breaching, provided a barrier to the migration of this species from the Colville delta into the Prudhoe Bay region (Fechhelm et al. 1999)

Confirmation of previously stated hypotheses and conclusions

Environmental effects on Arctic cisco

- Much of the variability in recruitment of Arctic cisco to Prudhoe Bay is determined by the prevalence of favorable easterly winds, as hypothesizes by various authors
- Local salinities significantly affect daily catch rates of Arctic cisco in the Colville River, which tended to be lower when the salinity was low and also decreased at very high levels of salinity, consistent with expectations. Therefore, variability in local salinities, which may be related to variability in alongshore wind direction, affects overall catch rates of Arctic cisco in the Colville River as suggested by Moulton (1994)

Human impacts on Arctic cisco

- We found no evidence of any effect of causeways on total recruitment, survival, or catch rates of Arcitic cisco, supporting previous results that causeways do not appear to have a detrimental effect on Arctic cisco

New conclusions from tests of newly developed hypotheses

Environmental effects on Arctic cisco

- Recruitment of Arctic cisco is not strongly affected by temperature conditions in the coastal Beaufort Sea or by river discharge in the Mackenzie R. or on the North Slope
- Winter and spring temperatures, discharge, and ice conditions in the Mackenzie River and delta have no discernible effect on the recruitment of Arctic cisco to the Prudhoe Bay region, after accounting for the effects of wind-driven transport

Table 26. Continued.

New conclusions from tests of newly developed hypotheses (continued)

- Warm conditions in the coastal Beaufort Sea are associated with enhanced catch rates in the fishery in the following year
- The size of young-of-year Arctic cisco at the end of the first summer increases with higher temperatures

Human impacts on Arctic cisco

- We found evidence for a negative correlation between winter development activities in the Colville delta and the overwintering survival of older (Age 5–7) Arctic cisco. In particular, the lowest survival anomalies in the years 1997–2000 corresponded to the 4 years with the most development activity in the delta
- We found no other effects of development activities, as captured by our subjective development indicators, on Arctic cisco recruitment, survival, or catch rates in the Colville fishery
- We found no evidence of over-harvesting in the Colville River fishery

New conclusions from exploratory analysis (not based on a priori hypotheses)

Environmental trends

- When Mackenzie River discharge is large, average spring ice concentrations in the coastal Beaufort Sea tend to be lower
- Discharge rates in the Sagavanirktok River tend to be higher during warm years (air temperature and SST) with less ice
- Cold winters tend to be followed by stronger easterly winds, which should enhance coastal salinities (through offshore Ekman transport and upwelling) in the coastal Beuafort Sea. Yet, easterly winds are uncorrelated with summer salinities in Prudhoe Bay
- Both nearshore salinities in the Prudhoe Bay region and river discharge from the Sagavanirktok River increased substantially after 1991, resulting in a counterintuitive, positive correlation between discharge and salinity
- Flow through the Bering Strait displays significant decadal-scale variability, which may be related to the AO. Coincident with an increase in Bering Strait flow, the AO changed sign in 1988/89.
- Average salinity in the Colville River during the fall fishery undergoes significant cyclic fluctuations with a period of approximately 6 years

Biological trends

- We found a strong decreasing trend in recruitment anomalies of Arctic cisco (after adjusting for wind effects) from 1987 through 2005
- A strong increasing time trend in least cisco and broad whitefish coincides with a decreasing trend in Arctic cisco recruitment. This inverse relationship between the abundance of other coregonids in the Prudhoe Bay region and Arctic cisco recruitment may result from competition or predation, or from other sources of variability that affect YOY Arctic cisco and other coregonids in opposite ways
- The abundance of age-2+ Arctic cisco in Prudhoe Bay is negatively correlated with recruitment of Arctic cisco, suggesting a possible negative effect of older Arctic cisco on the survival of new recruits (e.g. competition for food), or another factor that affects older Arctic cisco and YOY Arcitc cisco in opposite ways.
- The abundance of age-2+ Arctic cisco in Prudhoe Bay is strongly negatively correlated with the size of most age classes of Arcitc cisco, suggesting competition effects
- The abundance of least cisco and broad whitefish were negatively correlated with size-at-age of Arctic cisco, suggesting possible inter-specific competition
- A number of species whose abundances in Prudhoe Bay were monitored from 1985–2005 showed highly significant step-increases in the late 1980s or early 1990s (Dolly varden, Arctic flounder, rainbow smelt, broad whitefish, and least cisco), resulting in a relatively abrupt change in relative species composition that coincides with the well known shift in the Arctic Oscillation Index between 1988 and 1989

Table 26. Continued.

New conclusions from exploratory analysis (continued)

Environmental effects on Arctic cisco and other species:

- The change in relative species composition in the late 1980s was related to both the Arctic Oscillation and to the flow through Bering Strait
- Age-0 and age-1 fishes tend to grow to a larger size in warm years with low ice concentrations, suggesting that warm conditions may improve growth of young-of-the-year Arctic cisco
- Strong positive correlation between the Arctic Oscillation and our combined recruitment index after the 1989–1990 regime shift, but not prior to the shift
- Years with low salinities in the nearshore area of Prudhoe Bay, such as 1995 and 2001, tend to be characterized by high abundances of burbot and humpback whitefish, while years with high salinity tend to be characterized by rainbow smelt, Arctic cisco, and round whitefish

Where possible, we estimated and accounted for such effects to obtain better measures of interannual variability in abundance. Nevertheless, data constraints did not allow an in-depth investigation of spatial or temporal patterns in Arctic cisco abundance at seasonal or shorter time scales or at smaller than regional spatial scales (e.g., spatial patterns within Prudhoe Bay). Therefore, our primary objective was to test for population-level effects of human and environmental factors on interannual differences in Arctic cisco. Our conclusions apply to variability in the Colville population as a whole and evidence against (or for) population-level effects do not exclude (or imply) the possibility of short-term, local effects. For example, the results of our retrospective analysis cannot address potential effects of development activities on local catch rates in specific sections of the Niġliq channel. These local effects can only be resolved by detailed process studies in conjunction with specific activities that may impact catch rates. Such studies should estimate catch rates of Arctic cisco immediately prior to, during, and after specific activities and monitor changes in salinity, turbidity, and other relevant variables that may be affected by the activity.

Consistent with previous studies (e.g., Fechhelm and Griffiths 1990, Fechhelm et al. 2006), our analyses confirmed that much of the variability in recruitment of Arctic cisco to Prudhoe Bay and subsequent catch rates in the Colville River are driven by variability in wind-driven transport of juvenile fish along the Beaufort Sea coast. We found little evidence that any of the other regional or large-scale environmental variables were related to the recruitment or survival of Arctic cisco. The decreasing trend in recruitment anomalies to values below the long-term average (normal) recruitment since 1987 is a potential concern, but recent negative recruitment anomalies (1998, 2001, 2004, 2005) are not unprecedented and were similar to some anomalies in the early 1980s. The declining trend did not correlate with any of our measures of development activities in the eastern and central Beaufort Sea. This suggests that the number of young-of-year Arctic cisco entering the Beaufort Sea from the Mackenzie River has declined since the mid-1980s, resulting in fewer young fish arriving in Prudhoe Bay. The number of age-0 recruits in Prudhoe Bay decreased from an average of 102 fish per net per day in the 5-year period from 1986–1990 to 2.3 fish per net per day in 2001–2005. However, much of the decline was explained by poor wind conditions in the latter period; hence, the decline in the source population is likely to be less extreme.

Based on our analyses of interannual variability in Arctic cisco in relation to development activities, we found little evidence that recruitment, survival, or average catch rates were lower than "normal" during or after years when many development-related activities were occurring in coastal areas or on the Colville delta. A possible exception is the period of below average survival of Arctic cisco from 1997–2000. This period of low year-to-year survival coincided with a period of development (drilling, construction, and ice bridges) in the Colville delta and was followed by a period of below average catches. However, the relationship was only marginally significant, and cause and effect can not be inferred from these limited data without more detailed process studies conducted concurrently with potential disturbances. Arctic cisco had unusually high overwintering survival in 1985 (fall 1984 to fall 1985), which could not be explained by any of the variables we considered. The unusually high survival may simply reflect random variability in the index, which is computed from age-specific CPUE values that have a high degree of uncertainty.

Catch rates in the fishery have been highly variable from year-to-year, but the low catch rate in 2001 was highly unusual in the context of the entire 1967–2005 time series. Reduced catch rates in 2000–2002, and particularly in 2001, resulted from a combination of relatively poor recruitment some 5–7 years earlier (as a result of unfavorable winds), changes in in-river distribution in 2001 associated with unusually low salinities, and reduced survival in the late 1990s and 2000, possibly as a consequence of increased development activities. Members of the Panel of Experts also suggested that high amounts of slushy ice at the mouth of the river in 2001 may have blocked the channel for Arctic cisco returning from marine habitats used for summer feeding. Catch rates increased in 2003–2005 because of strong age-0 recruitment in 1997–2000. However, recruitment failures in 2002–2003, resulting from westerly winds, combined with unexpectedly low recruitment in 2001, 2004, and 2005 are likely to greatly reduce catch rates in 2007–2010.

Catch rates in individual sets were strongly related to local salinity conditions in the Colville River (at 3-4 m depth), as well as to the time of year. Sub-surface salinities appear to affect the distribution of Arctic cisco within the river and, hence, the number of fish available to the fishery. This implies that fishers in the Niġliq channel can maintain higher catch rates by fishing near the mouth of the channel where salinities (and catch rates) generally are higher (but also more variable). The fishery itself appears to reduce the number of available fish because catch rates typically decrease as the fishing season progresses.

At the scale we were able to measure, out findings suggest that the Arctic cisco population is not very sensitive to oil and gas development activities that have occurred to date, but may be very sensitive to climate change, particularly if such changes affect the direction and magnitude of alongshore winds in the Beaufort Sea. Two recent years (2002 and 2003) were characterized by highly unusual westerly winds during the summer (1981 is the only other year since 1976 with westerly winds on average). Westerly winds evidently led to near-complete recruitment failures and may have contributed to the exceptionally poor growth and reduced size of subadult fish during the same two years.

The Arctic cisco population may be sensitive to fishing, but the effects cannot be determined because we were unable to estimate fishing mortality rates due to the unknown status of the spawning population. This emphasizes the importance of better information on the spawning population of Arctic cisco in the Mackenzie River.

Environmental factors also may affect growth rates of subadult fish. For example, the markedly lower size-at-age fish observed in 2002 and 2003 were associated with predominantly westerly winds during summer in those years. We hypothesize that normal transport of nutrients into nearshore marine waters may have been disrupted by these wind conditions, which in turn may have resulted in poor feeding conditions and low growth rates of the fish. This hypothesis was not testable with available data, although the link between prevailing winds and size-at-age was fairly compelling.

LITERATURE CITED

Alt, K. T., and D.R. Kogl. 1973. Notes on the Whitefish of the Colville River, Alaska. *Journal of the Fisheries Research Board of Canada* 30:554–56.

Barber, W. E., R. L. Smith, M. Vallarino, and R. M. Meyer. 1997. Demersal Fish Assemblages of the Northeastern Chukchi Sea, Alaska. Fisheries Bulletin 95:195–209.

Bendock, Terrence N. 1979. Beaufort Sea Estuarine Fishery Study. In: *Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators*, Vol. IV. Boulder, CO: USDOC, NOAA, OCSEAP, pp. 670–729.

Bickham, J. W., S.M. Carr, B.G. Hanks, D.W. Burton, and B.J. Gallaway. 1989. Genetic Analysis of Population Variation in the Arctic Cisco (*Coregonus autumnalis*) Using Electrophoretic, Flow Cytometric, and Mitochondrial DNA Restriction Analyses. In: *Research Advances on Anadromous Fish in Arctic Alaska and Canada: Nine Papers Contributing to an Ecological Synthesis*, David W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks, AK: Institute of Arctic Biology, pp. 112–122.

Bickham, J.W., J.C. Patton, B.J. Gallaway and J.C. Morales. 1993. Biogeography, phylogeny, and relative rates of evolution of mitochondrial DNA in arctic and Bering ciscoes from the Western Arctic of North America. Volume IV *in* 1991 Endicott Fish Monitoring Program. Prepared for BP Exploration (Alaska) Inc., Anchorage, AK, and the North Slope, Borough, Barrow, AK, by LGL Alaska Research Associates, Inc., Anchorage, AK.

Bickham, J.W., J.C. Patton, S. Minzenmayer, L.L. Moulton and B.J. Gallaway. 1997. Identification of arctic and Bering ciscoes in the Colville River delta, Beaufort Sea coast, Alaska. Pages 224–228 *in* J. Reynolds, ed. Fish ecology in arctic North America. American Fisheries Society Symposium 19. Bethesda, MD.

Bjerklie, D. 1994. The 1993 Endicott Development Fish Monitoring Program. Volume III: Sagavanirktok River Discharge. Anchorage, AK: BPXA.

Bond, W.A. 1982. A Study of the Fishery Resources of Tuktoyaktuk Harbour, Southern Beaufort Sea Coast, with Special Reference to Life Histories of Anadromous Coregonids. Canadian Technical Report of Fisheries and Aquatic Sciences 1119. Winnipeg, Manitoba: Fisheries and Oceans Canada.

Bond, W.A. and R.N. Erickson. 1985. Life History Studies of Anadromous Coregonid Fishes in Two Freshwater Lake Systems on the Tuktoyaktuk Peninsula, Northwest Territories. Canadian Technical Report of Fisheries and Aquatic Sciences 1336. Winnipeg, Manitoba: Fisheries and Oceans Canada.

Bond, W.A., and R.N. Erickson. 1987. Fishery Data from Phillips Bay, Yukon, 1985. Report, 0706–6465. Winnipeg, MB: Fisheries and Oceans Canada, Central and Arctic Region, Department of Fisheries and Oceans.

Bond, W.A. and R.N. Erickson. 1989. Summer Studies of the Nearshore Fish Community at Phillips Bay, Beaufort Sea Coast, Yukon. Canadian Technical Report of Fisheries and Aquatic Sciences 1676. Winnipeg, Manitoba: Department of Fisheries and Oceans, Central and Arctic Region.

Bond, W.A., and R.N. Erickson. 1997. Coastal Migrations of Arctic Ciscoes in the Eastern Beaufort Sea. *In: Fish Ecology in Arctic North America. Proceedings of the Symposium, Fairbanks, AK, 19-21 May 1992*, James B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society, pp. 155-64.

BP Exploration (Alaska) Inc. 2001. History and Marine Studies of Causeways. Technical Brief: Alaska's North Slope Oilfields. Anchorage, AK: BPXA

Burnham, K.P., and Anderson, D.R. 2002. Model Selection and Multi-model Inference: A Practical Information-Theoretic Approach. Springer-Verlag, New York.

Cannon, T.C., J.A. Knutzen, and B. Adams. 1987. Mark-Recapture Study. *In: 1985 Endicott Environmental Monitoring Program Final Report, Vol. VI.* Anchorage, AK: U.S. Army Corps of Engineers, pp. 1–38.

Carmack, E.C., and R.W. MacDonald. 2002. Oceanography of the Canadian shelf of the Beaufort Sea: A setting for marine life. Arctic 55 (Suppl. 1): 29–45.

Chadwick, E.M.P. 1982. Stock-Recruitment Relationship for Atlantic Salmon (*Salmo salar*) in Newfoundland Rivers. *Canadian Journal of Fisheries and Aquatic Sciences* 39:1496–1501.

Colonell, J.M., and B.J. Gallaway. 1997. Wind-Driven Transport and Dispersion of Age-0 Arctic Ciscoes along the Alaskan Beaufort Coast. *In: Fish Ecology in Arctic North America. Proceedings of the Symposium, Fairbanks, AK, 19-21 May 1992*, J. B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society, pp. 90–103.

Craig, P.C. 1984. Fish use of coastal waters of the Alaskan Beaufort Sea: a review. *Transactions of the American Fisheries Society* 113:265–82.

Craig, P.C. 1989. An Introduction to Anadromous Fishes in the Alaskan Arctic. *In: Research Advances on Anadromous Fish in Arctic Alaska and Canada: Nine Papers Contributing to an Ecological Synthesis*, D.W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks, AK: Institute of Arctic Biology, pp. 27-54.

Craig, P.C. and W.B. Griffiths. 1981. Passage of Large Fish around a Causeway in Prudhoe Bay, Alaska. *Arctic* 34(4):314-17.

Craig, P.C. and L. Haldorson. 1981. Beaufort Sea Barrier Island-Lagoon Ecological Processes Studies: Final Report, Simpson Lagoon. *In: Environmental Assessment of the Alaskan Continental Shelf, Final Reports of Principal Investigators,* Vol. VII. Boulder, CO: USDOC, NOAA, OCSEAP, pp. 384-678.

Craig, P. C., and G. J. Mann. 1974. Life History and Distribution of Arctic Cisco (*Coregonus autumnalis*) along the Beaufort Sea Coastline in Alaska and the Yukon Territory. *In: Life Histories of Anadromous and Freshwater Fish in the Western Arctic,* P.J. McCart, ed. Arctic Gas Biological Report Series 20. Calgary: Canadian Arctic Gas Study Limited and Alaskan Arctic Gas Study Company, pp. 1-27.

Craig, P.C., W.B. Griffiths, L. Haldorson, and H. McElderry. 1985. Distributional Patterns of Fishes in an Alaskan Arctic Lagoon. *Polar Biology* 4(1):9–18.

Deegan, L.A. 1990. Effects of Estuarine Environmental Conditions on Population Dynamics of Young-Of-The-Year Gulf Menhaden. *Marine Ecology Progress Series* 68:195–205.

Dillinger, R.E. 1989. An Analysis of Taxonomic Status of the *Coregonus autumnalis* Species Complex in North America, and an Investigation of the Life History of Whitefishes and Ciscoes (Pisces; Corgoninae) in North America and Eurasia. Ph.D. Dissertation. St. John's, Newfoundland: Memorial University of Newfoundland.Dillinger, R.E., Jr., T. P. Birt, and J. M. Green. 1992. Arctic Cisco, *Coregonus autumnalis*, Distribution, Migration and Spawning in the Mackenzie River. *Canadian Field-Naturalist* 106:175–80.

Doxey, M.R. 1977. Fishery Impact Survey of the Arco Causeway at Prudhoe Bay. Fairbanks, AK: Alaska Department of Fish and Game, Division of Sport Fish. 37 pp.

Fechhelm, R.G. 1999. The Effect of New Breaching in a Prudhoe Bay Causeway on the Coastal Distribution of Humpback Whitefish. *Arctic* 52:386–94.

Fechhelm, R.G., and D.B. Fissel. 1988. Wind-aided Recruitment of Canadian Arctic Cisco (*Coregonus autumnalis*) into Alaskan Waters. *Canadian Journal of Fisheries and Aquatic Sciences* 45:906–10.

Fechhelm, R.G., and W.B. Griffiths. 1990. Effect of Wind on the Recruitment of Canadian Arctic Cisco (*Coregonus autumnalis*) into the Central Alaskan Beaufort Sea. *Canadian Journal of Fisheries and Aquatic Sciences* 47:2164–2171.

Fechhelm, R.G., P.S. Fitzgerald, J.D. Bryan, and B.J. Gallaway. 1993. Effect of Salinity and Temperature on the Growth of Yearling Arctic Cisco (*Coregonus autumnalis*) of the Alaskan Beaufort Sea. *Journal of Fisheries Biology* 43:463–74.

Fechhelm, R.G., W.B. Griffiths, B. E. Haley, and M.R. Link. 2004. Nearshore Beaufort Sea Fish Monitoring in the Prudhoe Bay Region, 2003. Anchorage, AK: BPXA

Fechhelm, R.G., W.B. Griffiths, B. E. Haley, and W.J. Wilson. 2003. Nearshore Beaufort Sea Fish Monitoring in the Prudhoe Bay Region, 2002. Anchorage, AK: BPXA

Fechhelm, R.G., B.E. Haley, G.B. Buck, G.D. Wade, and M.R. Link. 2005. Nearshore Beaufort Sea Fish Monitoring in the Prudhoe Bay Region, 2004. Anchorage, AK: BPXA

Fechhelm, R.G., L.R. Martin, B.J. Gallaway, W.J. Wilson, and W.B. Griffiths. 1999. Prudhoe Bay Causeways and the Summer Coastal Movements of Arctic Cisco and Least Cisco. *Arctic* 52:139–51.

Fechhelm, R.G., L.R. Martin, B. J. Gallaway, W. J. Wilson, and W. B. Griffiths. 2001. Estimating the Hydrographic Effects of Prudhoe Bay Causeway Breaches Using the Before-After Control-Impact (BACI) Analysis. *Arctic* 54:162–73.

Fechhelm, R.G., G.D. Wade, and M. R. Link. 2006. Nearshore Beaufort Sea Fish Monitoring in the Prudhoe Bay region, 2005. Report for BP Exploration (Alaska) Inc.by LGL Alaska Research Associates, Inc., Anchorage, Alaska.

Ford, J. and B.L. Bedford. 1987. The Hydrology of Alaskan Wetlands, U.S.A.: A Review. *Arctic and Alpine Research* 19(3): 209-29.

Fruge, D.J., D.W. Wiswar, L.J. Dugan, and D.E. Palmer. 1989. Fish Population Characteristics of Arctic National Wildlife Refuge Coastal Waters, Summer 1988. U.S. Fish and Wildlife Service, Fairbanks, Alaska. 69 pp.

Gallaway, B.J., and J.M. Colonell. 1990. The 1988 Endicott Development Fish Monitoring Program: Final Report, Vol. I: Executive Summary and Synthesis. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

Gallaway, B.J. and R.G. Fechhelm. 2000. Anadromous and Amphidromous Fishes. *In: The Natural History of an Arctic Oilfield: Development and the Biota*, J.C. Truett and S.R. Johnson, eds. New York: Academic Press, pp. 349-69.

Gallaway, B.J., W.J. Gazey, and L.L. Moulton. 1989. Population Trends for the Arctic Cisco (*Coregonus autumnalis*) in the Colville River of Alaska as Reflected by the Commercial Fishery. *In: Research Advances on Anadromous Fish in Arctic Alaska and Canada: Nine Papers Contributing to an Ecological Synthesis*, David W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks, AK: Institute of Arctic Biology, pp. 153–65.

Gallaway, B.J., W.B. Griffiths, P.C. Craig, W.J. Gazey, and J.W. Helmericks. 1983. An Assessment of the Colville River delta Stock of Arctic Cisco: Migrants from Canada? *In: Contributions to the Science of Environmental Impact Assessment: Three Papers on the Arctic Cisco (*Coregonus autumnalis*) of Northern Alaska*. Biological Papers of the University of Alaska 21. Fairbanks, AK: Institute of Arctic Biology, pp. 4–23.

George, J.C. and R. Kovalsky. 1986. Observations on the Kupigruak Channel (Colville River) Subsistence Fishery, October 1985. Barrow, AK: North Slope Borough, Department of Wildlife Management, 60 pp.

Gibson, R.J. and Myers, R.A. 1988. Influence of Seasonal River Discharge on Survival of Juvenile Atlantic Salmon, Salmo salar. Can. J. Fish. Aquat. Sci. 45(2): 344–348.

Griffiths, W. B., B. J. Gallaway, W.G. Gazey, and R.E. Dillinger, Jr. 1992. Growth and Condition of Arctic Cisco and Broad Whitefish as Indicators of Causeway-Induced Effects in the Prudhoe Bay Region, Alaska. Transactions of the American Fisheries Society 121:557–577.

Hare, S.R. and Mantua, N.J. 2000. Empirical Evidence for North Pacific Regime Shifts in 1977 and 1989. Prog. Oceanogr. 47: 103–145.

Hastie, T.J. and Tibshirani, R.J. 1990. Generalized Additive Models. Monogr. Stat. Appl. Probab. 43. London: Chapman and Hall.

Hatfield, C.T., J.N. Stein, M.R. Falk, and C.S. Jessop. 1972. Fish Resources of the Mackenzie River Valley, Interim Report 1, Vol. 1. Winnipeg, MB: Department of the Environment, Fisheries Service. 247 pp.

Hoefler Consulting Group. 2006. Study Final Report for the Beaufort Sea Meteorological Monitoring and Data Synthesis Project. OCS Study, MMS 2005-069. Anchorage, AK: USDOI, MMS, Alaska OCS Region, 73 pp.

Irvine, J.R. 1986. Effects of Varying Discharge on the Downstream Movement of Salmon Fry, *Oncorhynchus tshawytscha* Walbaum. J. Fish. Biol. 28(1): 17–8.

Jonsson, N., Hansen, L.P., and Jonsson, B. 1991. Variation in Age, Size and Repeat Spawning of Adult Atlantic Salmon in Relation to River Discharge. J. Animal Ecology 60(3): 937–947.

Jarvela, L.E. and L.K. Thorsteinson. 1997. Movements and Temperature Occupancy of Sonically Tracked Dolly Varden and Arctic Ciscoes in Camden Bay, Alaska. *In: Fish Ecology in Arctic North America. Proceedings of the Symposium, Fairbanks, AK, 19-21 May 1992*, James B. Reynolds, ed. American Fisheries Society Symposium 19. Bethesda, MD: American Fisheries Society, pp. 165–74.

Keefer, M.L., Peery, C.A., Jepson, M.A., Tolotti, K.R., Bjornn, T.C., and Stuehrenberg, L.C. 2004. Stock-Specific Migration Timing of Adult Spring-Summer Chinook Salmon in the Columbia River Basin. N. Am. J. Fish. Manag. 24(4): 1145–1162.

Legendre, P. and L. Legendre. 1998. Numerical Ecology. Amsterdam: Elsevier Science.

LGL Alaska Research Associates, Inc. 1990. The 1988 Endicott Development Fish Monitoring Program. 5 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1991. The 1989 Endicott Development Fish Monitoring Program. 4 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1992. The 1990 Endicott Development Fish Monitoring Program. 4 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1993. The 1991 Endicott Development Fish Monitoring Program. 4 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1994a. The 1992 Endicott Development Fish Monitoring Program. 4 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1994b. The 1993 Endicott Development Fish Monitoring Program. 4 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1995. The 1994 Endicott Development Fish Monitoring Program. 3 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1996. The 1995 Endicott Development Fish Monitoring Program. 3 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1997. The 1996 Endicott Development Fish Monitoring Program. 2 v. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

LGL Alaska Research Associates, Inc. 1999a. The 1997 Beaufort Sea Fish Monitoring Program. Anchorage, AK: BPXA.

LGL Alaska Research Associates, Inc. 1999b. The 1998 Beaufort Sea Fish Monitoring Program. Anchorage, AK: BPXA.

MBC Applied Environmental Sciences. 2003. Physical Oceanography of the Beaufort Sea: Workshop Proceedings. OCS Study MMS 2003-045. Minerals Management Service, Alaska OCS Region, Anchorage, 26 pp + appendices.

MBC Applied Environmental Sciences. 2004. Proceedings of a Workshop on the Variability of Arctic Cisco (*Qaaktaq*) in the Colville River. OCS Study MMS 2004-033. Minerals Management Service, Alaska OCS Region, Anchorage, 60 pp + appendices.

McPhail, J.D., and C.C. Linsey. 1970. Freshwater Fishes of Northwestern Canada and Alaska. Fisheries Research Board of Canada. Bulletin of the Fisheries Research Board of Canada No. 173. Winnipeg, Manitoba: Fisheries Research Board of Canada.

MMS (Minerals Management Service, Alaska OCS Region). 2003. Beaufort Sea Planning Area Oil and Gas Lease Sales 186,195, and 202: Final Environmental Impact Statement, Vol. 1: Executive Summary, Sections I through VI. OCS EIS/EA, MMS 2003-001. Anchorage, AK: USDOI, MMS, Alaska OCS Region, pp. III-13 to18.

Mortensen, D., Wertheimer, A., Taylor, S., and Landingham, J. 2000. The Relation Between Early Marine Growth of Pink Salmon, *Oncorhynchus gorbuscha*, and Marine Water Temperature, Secondary Production, and Survival to Adulthood. Fish. Bull. 98: 319–35.

Moulton, L.L. 1989. Recruitment of Arctic Cisco (*Coregonus autumnalis*) into the Colville Delta, Alaska, in 1985. *In: Research Advances on Anadromous Fish in Arctic Alaska and Canada: Nine Papers Contributing to an Ecological Synthesis*, D. W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks, AK: Institute of Arctic Biology, pp. 107–11.

Moulton, L.L. 1994. The 1993 Colville River Fishery. *In: The 1993 Endicott Development Fish Monitoring Program, Vol. II*. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough, 60 pp. plus appendices.

Moulton, L.L., and J.C. George. 2000. Freshwater Fishes in the Arctic Oil-Field Region and Coastal Plain of Alaska. *In: The Natural History of an Arctic Oil Field: Development and the Biota,* J. C. Truett and S. R. Johnson, eds. San Diego, CA: Academic Press, pp. 327–48.

Moulton, L.L., and B. T. Seavey. 2003. Harvest Estimate and Associated Information for the 2003 Colville River Fall Fishery. Anchorage, AK: ConocoPhillips Alaska, Inc.

Moulton, L.L. and B.T. Seavey. 2004. Harvest Estimate and Associated Information for the 2003 Colville River Fall Fishery. Anchorage, AK: ConocoPhillips Alaska, Inc.

Moulton, L.L., and B. T. Seavey. 2005. Harvest Estimate and Associated Information for the 2004 Colville River Fall Fishery. Anchorage, AK: ConocoPhillips Alaska, Inc.

Moulton, L.L., L.J. Field, and R. Kovalsky. 1990. The 1988 fall gill net fisheries for ciscoes in the Colville River, Alaska. Chapter 2 *In: The 1989 Endicott Development Fish Monitoring Program, Vol. : a Monograph of Project Papers.* Anchorage, AK: BPXA; Barrow, AK: North Slope Borough, 35 pp. plus appendices.

Moulton, L.L., B.J. Gallaway, M.H. Fawcett, W.B. Griffiths, K.R. Critchlow, R.G. Fechhelm, D.R. Schmidt, and J.S. Baker. 1986. 1984 Central Beaufort Sea Fish Study. Chapter 3 *In: Prudhoe Bay Waterflood Project Environmental Monitoring Program 1984*. Anchorage, AK: U.S. Army Corps of Engineers, 322 pp.

Moulton, L.L., B.T. Seavey, and J. Pausanna. 2006. Harvest Rates for the 2005 Colville River Fall Fishery. Anchorage, AK: ConocoPhillips Alaska, Inc.

Mueter, F.J. and Norcross, B.L. 1999. Linking community structure of small demersal fishes around Kodiak Island, Alaska, to environmental variables. Mar. Ecol. Prog. Ser. 190: 37–51.

Mueter, F.J., R.M. Peterman, and B.J. Pyper. 2002. Opposite Effects of Ocean Temperature on Survival Rates of 120 stocks of Pacific Salmon (*Oncorhynchus* spp.) in Northern and Southern Areas. *Canadian Journal of Fisheries and Aquatic Sciences* 59:456–63.

Mueter, F.J., Ladd, C., Palmer, M.C., and Norcross, B.L. 2006. Bottom-up and Top-down Controls of Walleye Pollock (*Theragra chalcogramma*) on the Eastern Bering Sea Shelf. Prog. Oceanogr. 68(2-4): 152–183.

Murray, C.B., and Beacham, T.D. 1986. Effect of Varying Temperature Regimes on the Development of Pink Salmon (*Oncorhynchus gorbuscha*) Eggs and Alevins. Canadian Journal of Zoology 64(3): 670–676.

Myers, R.A. 1998. When do Environment-Recruitment Correlations Work? Rev. Fish Biol. Fish. 8: 285–305.

Naesje, T.F., B. Jonsson, and O.T. Sandlund. 1986. Drift of Cisco and Whitefish Larvae in a Norwegian river. Trans. Am. Fish. Soc. 115: 89–92.

Naidu, A.S., Goering, J.J., Kelley, J.J., and Venkatesan, M.I. 2001. Historical Changes in Trace Metals and Hydrocarbons in the Inner Shelf Sediments, Beaufort Sea: Prior and Subsequent to Petroleum-related Industrial Developments OCS Study MMS 2001-061, University of Alaska, Coastal Marine Institute.

Niedoroda, A.W. and J.C. Colonell. 1990. The 1988 Endicott Development Fish Monitoring Program Analysis of 1985–1987 Data, Volume 1: Endicott Area Oceanographic Processes. Anchorage, AK: BPXA; Barrow, AK: North Slope Borough.

Palmer, D.E., and L.J. Dugan. 1990. Fish Population Characteristics of Arctic National Wildlife Refuge Coastal Waters, Summer 1989. Fairbanks, AK: USDOI, FWS, 83 pp.

Percy, R.J. 1975. Fishes of the Outer Mackenzie Delta. Beaufort Sea Technical Report 8. Freshwater Institute, Fisheries and Marine Service, Environment Canada, 114 pp.

Peterman, R.M. 1987. Review of the components of recruitment of Pacific salmon. American Fisheries Society Symposium 1: 417–429.

Peterson, B.J., R.M. Holmes, J.W. McClelland, C.J. Vörösmarty, R.B. Lammers, A.I. Shiklomanov, and S. Rahmstorf. 2002. Increasing River Discharge to the Arctic Ocean. *Science* 298: 2171–73.

Reub, G.S., J.D. Durst, and D.R. Glass. 1991. Fish Distribution and Abundance. Chapter 1 *In: 1987 Endicott Environmental Monitoring Program,* Vol. VI. Anchorage, AK: U.S. Army Corps of Engineers, Alaska District, pp. 1–60.

Roach A.T., K. Aagaard, C.H, Pease, S.A. Salo, T. Weingartner, V. Pavlov, and M. Kulakov. 1995. Direct Measurements of Transport and Water Properties through the Bering Strait. *Journal Geophysical Research* 100(C9):18443–58.

Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M. 2004. Sensitivity Analysis in Practice. Chichester: John Wiley & Sons.

Schmidt, D.R., W B. Griffiths, and L.R. Martin. 1989. Overwintering Biology of Anadromous Fish in the Sagavanirktok River Delta, Alaska. *In: Research Advances on Anadromous Fish in Arctic Alaska and Canada: Nine Papers Contributing to an Ecological Synthesis*, D.W. Norton, ed. Biological Papers of the University of Alaska 24. Fairbanks, AK: Institute of Arctic Biology, pp. 55–74.

Schmidt, D.R., W. B. Griffiths, D.K. Beaubien, and C.J. Herlugson. 1991. Movement of Young-of-the-Year Arctic Ciscoes across the Beaufort Sea Coast, 1985–1988. *In: Fisheries and Oil Development on the Continental Shelf,* C.S. Benner and R.W. Middleton, eds. American Fisheries Society Symposium 11. Bethesda, MD: American Fisheries Society, pp. 132–44.

Smith, S.G., Muir, W.D., Hockersmith, E.E., Zabel, R.W., Graves, R.J., Ross, C.V., Connor, W.P., and Arnsberg, B.D. 2003. Influence of River Conditions on Survival and Travel Time of Snake River Subyearling Fall Chinook Salmon. N. Am. J. Fish. Manag. 23(3): 939–961.

Stephenson, S.A. 2004. Harvest Studies in the Inuvialuit Settlement Region, Northwest Territories, Canada: 1999 and 2001-2003. Resource Management and Aboriginal Affairs, Central and Arctic Region, Fisheries and Oceans Canada, Winnipeg, Manitoba.

Ter Braak, C.J.F. 1986. Canonical Correspondence Analysis: A New Eigenvector Technique for Multivariate Direct Gradient Analysis. *Ecology* 67:1167–79.

Ter Braak, C.J.F. 1995. Ordination. In: Data Analysis in Community and Landscape Ecology. R.H.G. Jongman, C.J. F. Ter Braak and O.F.R. Van Tongeren, eds. Cambridge: Cambridge University Press. pp. 91–173.

Thompson, D.W.J., and Wallace, J.M. 1998). The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical Research Letters, 25: 297–1300.

Thorsteinson, Lyman K., Laurie E. Jarvela, and David A. Hale. 1991. Arctic Fish Habitat Use Investigations: Nearshore Studies in the Alaskan Beaufort Sea, Summer 1990. OCS Study, MMS 92-0011. Anchorage, AK: NOAA, National Ocean Service, Office of Ocean Resources Conservation and Assessment, 78 pp.

Turnpenny, A.W.H., and Nedwell, J.R. 1994. The Effects on Marine Fish, Diving Mammals and Birds of Underwater Sound Generated by Seismic Surveys. Fawley Aquatic Research Laboratories, Ltd., Consultancy Report, FCR 089/94.

Underwood, T. J., J. A. Gordon, and B. M. Osborne. 1992. Fish Population Characteristics of Arctic National Wildlife Refuge Coastal Waters, Summer 1990. Alaska Fisheries Progress Report no. 92-3. Fairbanks, AK: USDOI, FWS, Fishery Assistance Office.

Underwood, T. J., J. A. Gordon, L.A. Thorpe, and B. M. Osborne. 1994. Fish Population Characteristics of Arctic National Wildlife Refuge Coastal Waters, Summer 1991. Alaska Fisheries Progress Report no. 94-1. Fairbanks, AK: USDOI, FWS, Fishery Resource Office.

VanGerwen-Toyne, M. and J. Walker-Larsen. 2004. Monitoring Spawning Populations of Migratory Inconnu and Coregonids in the Peel River, NWT: the Peel River Fish Study. Under review at Canadian Manuscript Report of Fisheries and Aquatic Sciences.

Wainwright, P. 2002. GIS Geospatial Database of Oil-industry and other Human Activity (1979–1999) in the Alaskan Beaufort Sea. OCS Study MMS 2002-071, U.S. Department of the Interior, Minerals Management Service, Alaska)CS Region, Anchorage, AK.

Wilderbuer, T. K., A. B. Hollowed, W. J. Ingraham, Jr., P. D. Spencer, M. E. Conners, N. A. Bond, and G. E. Walters. 2002. Flatfish Recruitment Response to Decadal Climate Variability and Ocean Conditions in the Eastern Bering Sea. *Progress in Oceanography* 55:235–47.

Wood, S.N. 2000. Modeling and Smoothing Parameter Estimation with Multiple Quadratic Penalties. *Journal of the Royal Statistical Society B* 62:413–28.

Youngson, A.F., Buck, R.J.G., Simpson, T.H., and Hay, D.W. 1983. The Autumn and Spring Emigrations of Juvenile Atlantic Salmon, *Salmo salar L.*, from the Girnock Burn, Aberdeenshire, Scotland: Environmental release of migration. J. Fish. Biol. 23(6): 625–639.