ARCTIC
VOL. 52, NO. 2 (JUNE 1999) P. 139–151

Prudhoe Bay Causeways and the Summer Coastal Movements of Arctic Cisco and Least Cisco

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(*Received 5 December 1997; accepted in revised form 15 October 1998*)

ABSTRACT. Catch-per-unit-effort and mark-recapture data collected by fyke net during the summers of 1985–93 near Prudhoe Bay, Alaska, were analyzed to determine whether two oil industry causeways constructed perpendicular to the Beaufort Sea coast, West Dock and the Endicott Causeway, affected the feeding and migratory patterns of least cisco (*Coregonus sardinella*) and arctic cisco (*C. autumnalis*). During two of the four years in which juvenile least cisco were abundant in the study area, catch rates were significantly lower ($p \leq 0.0005$) east of West Dock, which suggested that small fish traveling eastward along the coast failed to bypass the causeway. Hydrographic conditions were generally consistent with the hypothesis that causeway-induced upwellings of saline marine water immediately west of West Dock may affect alongshore movement. No such disparities in catch were observed at the Endicott Causeway. We studied rates of return for subadult and adult (≥ 250 mm) arctic cisco and least cisco tagged in the Prudhoe Bay area and recovered in a commercial fishery that operates in the Colville River, Alaska. The expected rate of return was compared with actual rates of return over five years (for least cisco) and six years (for arctic cisco). Rates of return were based upon three areas of release: east of the easternmost causeway, west of the westernmost causeway, and between the two causeways. For both species, across the three regions and all years, there was no significant difference ($p = 0.25$ for least cisco; $p = 0.30$ for arctic cisco) between the expected and actual rates of tag returns. The contrasting effects of the two causeways are discussed in terms of their design and location.

Key words: *Coregonus sardinella*, least cisco, *Coregonus autumnalis*, arctic cisco, Beaufort Sea, causeways, Arctic oil, impacts

RÉSUMÉ. Les données de prises par unité d'effort et de marquage-recapture, recueillies par des verveux au cours des étés de 1985 à 1993 près de Prudhoe Bay en Alaska, ont été analysées afin de déterminer si deux ponts-jetées construits pour l'industrie pétrolière perpendiculairement au rivage de la mer de Beaufort (le pont-jetée West Dock et le pont-jetée Endicott) affectaient les schémas de nutrition et de migration du cisco sardinelle (*Coregonus sardinella*) et du cisco arctique (*C. autumnalis*). Durant deux des quatre années au cours desquelles le cisco sardinelle juvénile était abondant dans la zone de l'étude, les taux de prises étaient sensiblement inférieurs ($p \leq 0{,}0005$) à l'est du West Dock, ce qui suggérait que les poissons de petite taille se dirigeant vers l'est le long de la côte ne réussissaient pas à contourner le pont-jetée. En général, les conditions hydrographiques concordaient avec l'hypothèse que les remontées d'eau marine salée provoquées par le pont-jetée juste à l'ouest du West Dock peuvent affecter le mouvement le long du rivage. On n'a observé aucun écart de ce genre dans les prises au pont-jetée Endicott. On a étudié les taux de retour pour les jeunes adultes et les adultes (≥ 250 mm) du cisco arctique et du cisco sardinelle, marqués dans la région de la baie de Prudhoe et recapturés dans une pêcherie commerciale en exploitation sur la rivière Colville en Alaska. On a comparé le taux de retour escompté aux taux de retour réels sur cinq ans (pour le cisco sardinelle) et sur six ans (pour le cisco arctique). Les taux de retour s'appuyaient sur trois zones de remise à l'eau: à l'est du pont-jetée le plus oriental, à l'ouest du plus occidental et entre les deux. En tenant compte des trois emplacements et de toutes les années, il n'y avait pas de différence marquante pour les deux espèces ($p = 0{,}25$ pour le cisco sardinelle; $p = 0{,}30$ pour le cisco arctique) entre les taux de retour prévus et les taux réels des individus marqués. On discute les effets opposés des deux ponts-jetées en considérant leur design et leur emplacement.

Mots clés: *Coregonus sardinella,* cisco sardinelle, *Coregonus autumnalis,* cisco arctique, mer de Beaufort, ponts-jetées, pétrole arctique, retombées

Traduit pour la revue *Arctic* par Násida Loyer.

INTRODUCTION

Since the late 1970s, summer fish surveys have been conducted regularly in the coastal waters of the Beaufort Sea near Prudhoe Bay, Alaska, to monitor the effects of local oil and gas development on regional fishery resources (e.g., Craig and Haldorson, 1981; Griffiths and Gallaway, 1982; Moulton et al., 1986; Cannon et al., 1987;

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Glass et al., 1990; Reub et al., 1991; LGL, 1992; Griffiths et al., 1996). Development has included the construction of solid-fill, breached, gravel causeways that extend seaward from the coast. These structures are used as platforms in recovering offshore petroleum reserves and extracting seawater that is injected into subsurface oil reservoirs. A primary concern has been whether these causeways adversely affect summer coastal feeding dispersals and migrations of diadromous species that are important to commercial and Native subsistence fisheries (U.S. Army Corps of Engineers, 1980, 1984).

Two fish species that have been studied extensively over the years are least cisco (*Coregonus sardinella*) and arctic cisco (*C. autumnalis*). Least cisco spawn and overwinter in the Colville River, located approximately 90 km west of Prudhoe Bay, but are not normally found in any Alaskan river to the east (Craig, 1984, 1989). The nearest population is 600 km away in the Mackenzie River, Canada. Arctic cisco found in the Alaskan Beaufort Sea are believed to originate from spawning grounds in the Mackenzie River system (Gallaway et al., 1983). In spring, newly hatched young-of-the-year are flushed downriver, and some are transported westward to Alaska by wind-driven coastal currents (Gallaway et al., 1983; Fechhelm and Fissel, 1988, Moulton, 1989; Fechhelm and Griffiths, 1990; Schmidt et al., 1991; Underwood et al., 1995; Colonell and Gallaway, 1997). In summers with strong and persistent east winds, enhanced westward transport can carry fish to Alaska's Colville River, where they take up winter residence. They remain in the Colville River until the onset of sexual maturity at about age seven; then they migrate back to the Mackenzie River to spawn (Gallaway et al., 1983). The Colville River appears to be the only Alaskan river large enough to support substantial numbers of subadult and adult fish (Schmidt et al., 1989).

During the ice-free summer, arctic and least cisco disperse out of the Colville River to forage in coastal waters. Some fish move eastward through Simpson Lagoon to the Prudhoe Bay/Sagavanirktok Delta area and beyond (Cannon et al., 1987; Fechhelm et al., 1989, 1994; Glass et al., 1990; Reub et al., 1991; LGL, 1992). Summer is the primary feeding and growth period for most fishes of northern Alaska (Craig, 1989). Fish eventually migrate back to overwintering grounds in the Colville River before the onset of freeze-up. The exceptions are arctic cisco that have reached reproductive maturity and return to Canada to spawn.

This paper analyzes the possible effects that Prudhoe Bay causeways have on the alongshore dispersal of least cisco and arctic cisco from their overwintering grounds in the Colville River. Part 1 analyzes catch data for juvenile least cisco collected during the summers from 1985 to 1993. On the basis of studies conducted from 1981 to 1984, it has been suggested that West Dock, a 4.3 km long causeway built at the western margin of Prudhoe Bay, may disrupt the west-to-east alongshore movements of juvenile least cisco (Fechhelm et al., 1989). East winds cause an eddy to form on the western (lee) side of the causeway, enhancing the vertical mixing of cold, saline marine water into an otherwise brackish nearshore zone (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986; Niedoroda and Colonell, 1990). Because juvenile fish are (presumably) intolerant of high-salinity water, the cell of marine water may occasionally block their eastward dispersal. This potential for blockage is assessed through the expanded database.

Part 2 of this paper uses data from several mark-recapture studies to analyze rates of tag recovery in a Colville River commercial gill net fishery for subadult and adult least and arctic cisco. Substantial numbers of fish ≥ 250 mm tagged as part of the Prudhoe Bay monitoring studies are recaptured in October and November in a commercial gill net fishery operated in the lower Colville Delta (Moulton and Field, 1994; Moulton, 1995). This commercial fishery produces annual harvests ranging from 9000 to 70 000 arctic cisco and from 6000 to 38 000 least cisco, depending on the year (Moulton, 1995). Our analysis compares expected and observed rates of tag returns in the commercial fishery for both species to determine whether the two major Prudhoe Bay causeways, either singly or jointly, appear to affect the late-summer return migration of fish to the Colville River.

STUDY AREA

The study area covers 120 km of coastline running from the Colville River eastward through Prudhoe Bay to the delta of the Sagavanirktok River (Fig. 1). Much of the coastline between the Colville River and Prudhoe Bay is bounded by a chain of barrier islands, which encloses Simpson Lagoon. West Dock is located at the eastern end of Simpson Lagoon and the western edge of Prudhoe Bay. Approximately 4.3 km long, it was constructed with a breach 15 m wide located 2.8 km offshore. Although the breach was built as a passageway for fish moving along the coast, virtually everyone that has studied the dynamics of the causeway has agreed that few fish actually use the breach because of its small size and its location (Fechhelm et al., 1989). In recent years the breach has silted in, and no attempt has been made to dredge it open. In the winter of 1995–96, another breach 200 m wide was constructed at the base of West Dock, where water depths are generally less than 2.5 m.

The Sagavanirktok Delta is located immediately east of Prudhoe Bay, approximately 12 km east of West Dock. It is fronted by a shallow shelf (≤ 1.5 m deep) approximately 16 km wide that extends seaward for 3–4 km. The Endicott Causeway was constructed in the middle of the delta shelf during the winter of 1984–85. The mainland segment of the causeway was built with a nearshore breach 152 m wide and an offshore breach 61 m wide; both were designed to serve as fish passageways and to maintain hydrographic continuity between the two sides of the delta.

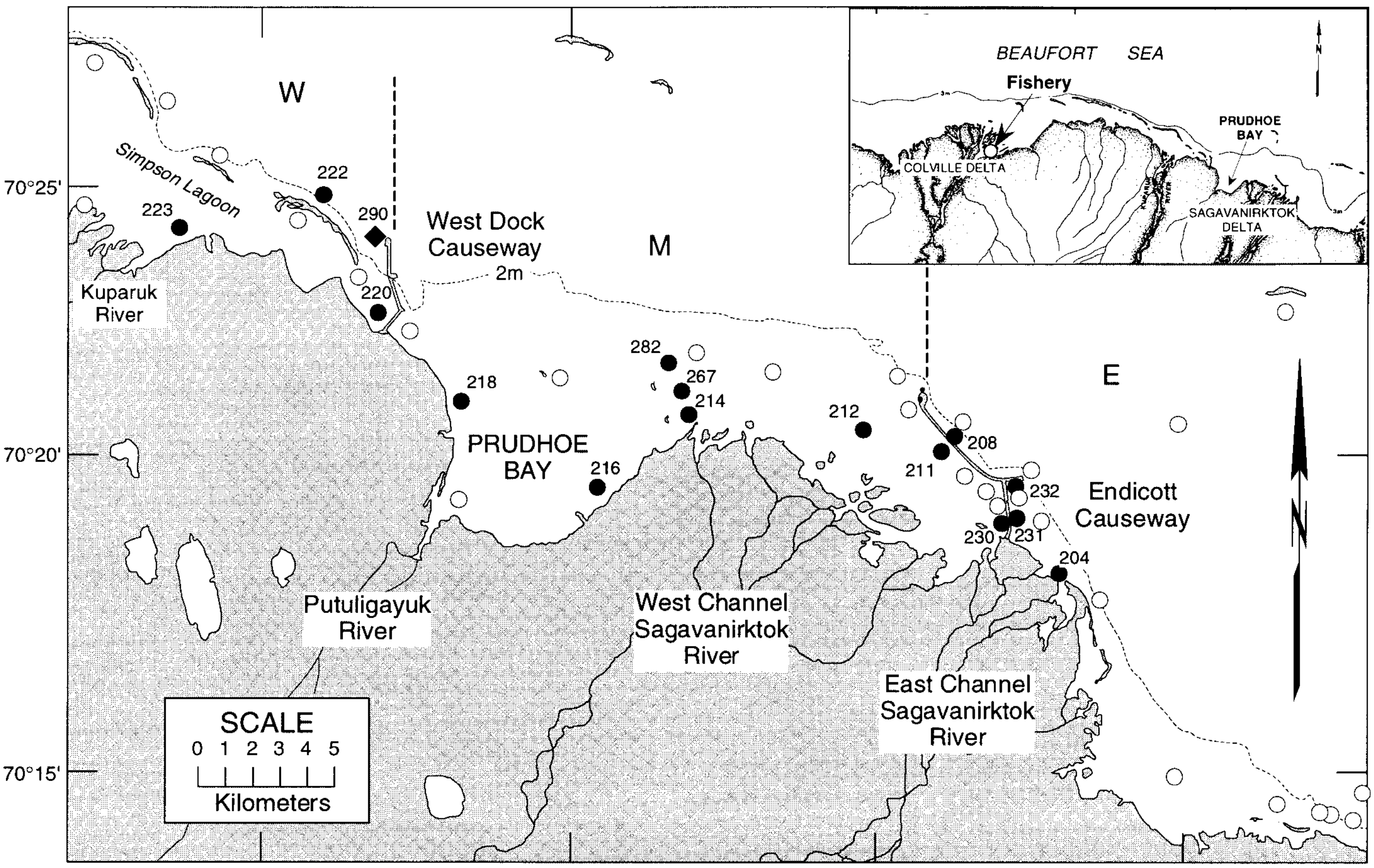

FIG. 1. The Prudhoe Bay region of the Alaskan Beaufort Sea. Fyke net sampling locations are indicated by hollow and solid circles. Solid circles denoted by station number are discussed in detail within the text. Station 290 (diamond) is a hydrographic station. The inset shows the location of the Colville River commercial fishery.

MATERIAL AND METHODS

Fish were collected in fyke nets located in the vicinity of Prudhoe Bay and the Sagavanirktok River delta during the summers of 1985–93 (Fig. 1). Although not all sites were sampled each year, net arrays did extend along the coast from Station 223 in the west to Station 204 in the east in all years, thereby providing reasonable geographical cross-sections of the study area. Surveys were conducted during the open-water season, which typically lasted from late June to late August-mid September. Except during periods of inclement weather, sampling continued 24 hours a day throughout the summer, and nets were emptied at approximately the same time each day. Captured fish were placed in floating holding pens, anaesthetized in a dilute solution of tricaine (MS-222), measured (fork length in mm, or FL), and then released after the effects of the anaesthetic had worn off. During the summers of 1985, 1988 (arctic cisco only), and 1990–93, large (≥250 mm) least cisco and arctic cisco were marked prior to release. We used coded anchor tags, which were inserted into the epaxial muscle mass lateral to the posterior margin of the dorsal fin. Each code was unique, so that the release date and location were documented for every fish.

Juvenile Least Cisco

Catch data for juvenile least cisco were designated as catch-per-unit-effort (CPUE). CPUE = $\text{fish}\cdot\text{net}^{-1}\cdot 24\ \text{h}^{-1}$, or the number of fish caught per fyke net per 24 h of fishing effort. Least cisco have historically been segregated into two size cohorts: small ≤180 mm FL) and large (>180 mm FL) (Griffiths et al., 1996). This delineation is based on the age structure of the population: the smaller size cohort generally comprises fish age three and younger. This portion of the paper adheres to the same cohort designations and deals exclusively with fish < 180 mm in length (i.e., juveniles). The *t*-test (Ostle and Mensing, 1975), applied to $\log_e$-t ransformed catch data (i.e., $\log_e$ [CPUE + 1]), was used for comparing catch among groups of nets.

Mark-Recapture Studies

Analytical methods employed in this paper were originally used in a single-year study by Craig and Griffiths (1981) to assess fish movement around an early and shorter configuration of West Dock. For our analyses, the summer fyke net study area was divided into three regions. Region W (west) consisted of all nets located west of West Dock; Region M (middle) comprised all nets located between

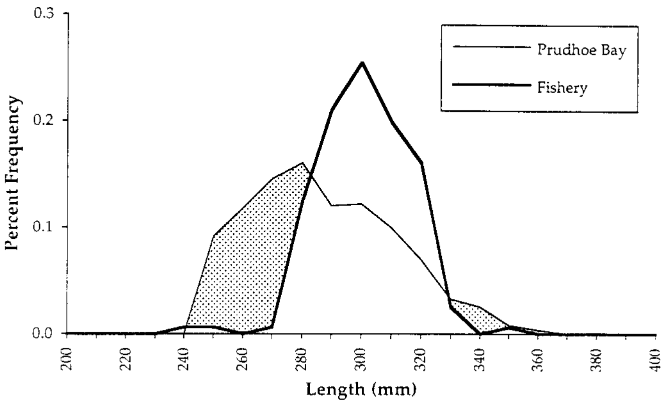

FIG. 2. Length-frequency distributions of least cisco tagged in Prudhoe Bay fyke nets (Region E) compared to those of all least cisco taken in the Colville River commercial gill net fishery for 1993. Shaded area represents the tagged fish that were deemed not susceptible to the size-selective gill net fishery. Similar adjustments were made for all year-region-species combinations.

West Dock and the Endicott causeway; and Region E (east) included all net sites east of Endicott (see Fig. 1). Because none of the Alaskan rivers that lie to the east of the Colville River are known to support substantial overwintering populations of large fish (≥ 250 mm) of either species (Craig, 1984), the operating premise is that most of the arctic and least ciscoes found in the Prudhoe Bay area originate from and return to the Colville River system.

For each species, the expected number of tag returns in the commercial fishery was calculated as

$$E_{ij} = (M_{ij}/M_{Tj}) * R_{Tj}$$

where E_{ij} is the expected number of tag returns in the commercial fishery for fish released in region *i* in year *j*, M_{ij} is the number of fish tagged in region *i* in year *j*, M_{Tj} is the total number of fish tagged from all regions in year *j*, and R_{Tj} is the total number of tagged fish recaptured in the commercial fishery in year *j*.

Before calculating the expected number of tag returns, we adjusted recapture data to correct for the size selectivity of the commercial gill nets (76 mm stretched mesh), using the methods described by Ricker (1975). Length-frequency distributions (in 10 mm intervals) were calculated for all fish of a species taken in the fishery in any given year. That distribution was then compared to the length-frequency distributions of all fish tagged in each region that same year (Fig. 2). For each size interval, the difference in percent composition was calculated in cases where fyke net frequency exceeded gill net frequency. These values were then summed across all size intervals to yield the adjustment factor. The number of tagged fish was then reduced by this factor to yield the effective number tagged (i.e., the number susceptible to recapture).

The chi-square (χ^2) test statistic (Ostle and Mensing, 1975) was used to calculate the goodness-of-fit between the predicted and observed number of recaptures in the commercial fishery for each species over all regions and years:

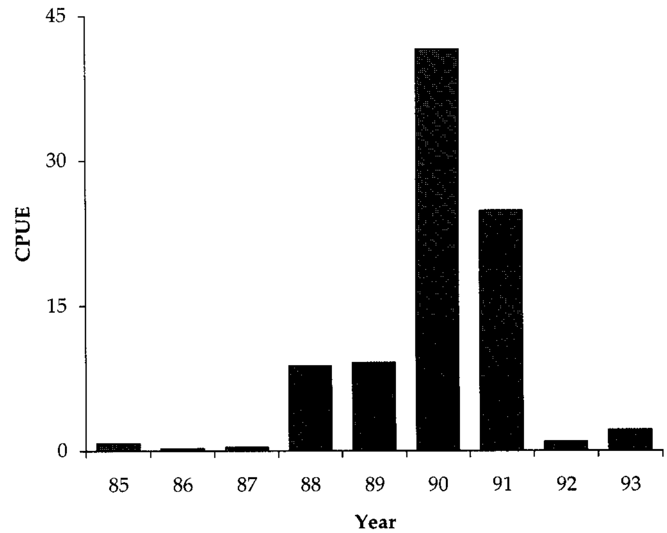

FIG. 3. Seasonal catch-per-unit-effort (CPUE: fish·net^{-1}·24 h^{-1}) of small (<180 mm) least cisco for 1985–93.

$$\chi^2 = S_i S_j((O_{ij} - E_{ij})/E_{ij})$$

where O_{ij} is the number of observed recaptures from region *i* in year *j* and E_{ij} is the expected number of recaptures from region *i* in year *j*. The underlying assumption is that within a given year, and assuming no causeway effect, all fish released at Prudhoe Bay have an equal probability of being recaptured in the commercial fishery. Fish from a particular region should comprise the same proportion of recaptures as they did of releases for that year: e.g., if during 1985 least cisco from Region E comprised 31% of all releases, they should also comprise 31% of all recaptures in the fishery that same year.

RESULTS AND DISCUSSIO

Juvenile Least Cisco

Over the nine-year study, yearly variation in the summer catch rates of small least cisco was considerable (Fig. 3). During the summers of 1985–87 and 1992–93, CPUE was nominal, ranging from 0.3 to 2.2 fish·net^{-1}·24 h^{-1}. These catch rates contrasted sharply with those recorded during the summers of 1988–91, when CPUE ranged from 8.8 to 41.5 fish·net^{-1}·24 h^{-1}. This inter-year pattern appears to be linked to wind-governed transport processes within Simpson Lagoon (Fechhelm et al., 1994). West winds in early summer (primarily July) create easterly flowing currents within the lagoon, and this flow enhances the eastward dispersal of small least cisco into the Prudhoe Bay area. Few small least cisco reach the eastern end of Simpson Lagoon in summers devoid of strong west wind events. The yearly catch patterns depicted in Figure 3 are consistent with regional wind patterns over the nine-year period of record (Fechhelm et al., 1994). However, the

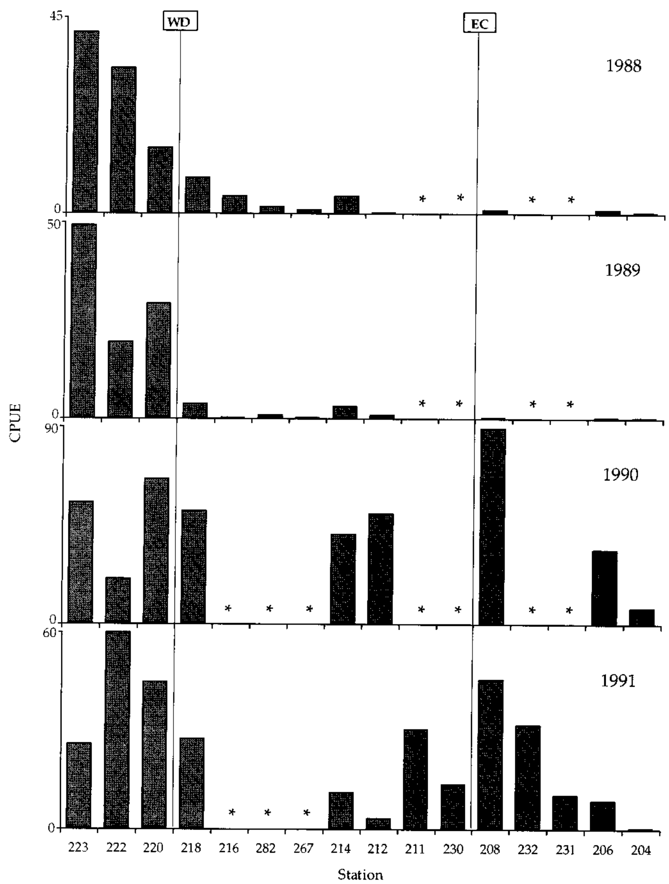

FIG. 4. Catch-per-unit-effort (CPUE: fish·net^{-1}·24 h^{-1}) of small (<180 mm) least cisco by net site for 1988–91. Left to right order of stations represents their west-to-east distribution along the Beaufort Sea coast. Vertical lines indicate the relative locations of West Dock (WD) and the Endicott Causeway (EC). Asterisks denote nets that were not operational in the designated year.

analysis of localized movement had to be limited to the four years in which small least cisco reached the Prudhoe Bay study area in meaningful numbers: 1988 to 1991.

In the four years of high CPUE, the geographical distribution of catch along the coast conformed to two distinct patterns (Fig. 4). In 1990 and 1991, CPUE, although variable, was relatively evenly distributed along the 40 km of coastline that was sampled. There was no significant difference in CPUE recorded at nets east (versus west) of West Dock in either 1990 ($p = 0.66$) or 1991 ($p = 0.10$), nor was there any significant difference in CPUE recorded east (versus west) of the Endicott Causeway in either 1990 ($p = 0.46$) or 1991 ($p = 0.37$) (Table 1). This distribution would be consistent with fish arriving from the west, dispersing through the study area, and bypassing both causeways in substantial numbers. In both 1988 and 1989, in contrast, catch rates east of West Dock were significantly ($p < 0.0005$) lower than levels recorded west of the causeway. The sharp disparity in the coastal distribution of CPUE suggests that fish arriving in the study area from the west failed to bypass West Dock in large numbers: their eastward dispersal essentially stopped at the causeway. No comparisons were made for 1988 and 1989 relative to the

TABLE 1. Summary statistics comparing catch ($\log_e$[CPUE + 1]) for fyke nets located east and west of West Dock and for nets located east and west of the Endicott Causeway. Comparisons of CPUE for Endicott were inapplicable for 1988 and 1989, since few small least cisco reached the Sagavanirktok Delta during those years.

Causeway	Year	Side	Mean	SD	t-statistic	df	*p*
West Dock	1988	East	1.09	0.69	-5.07	10	<0.0005
		West	3.80	0.40			
	1989	East	0.69	0.50	-8.40	10	<0.0005
		West	3.45	0.45			
	1990	East	3.50	0.75	-0.45	10	0.66
		West	3.80	0.60			
	1991	East	2.70	1.01	-1.77	11	0.10
		West	3.70	0.41			
Endicott	1988	na	na	na			
	1989	na	na	na			
	1990	East	3.21	1.35	-0.79	7	0.46
		West	3.66	0.43			
	1991	East	2.37	1.63	-1.01	11	0.37
		West	3.05	0.88			

Endicott Causeway because few fish reached the Sagavanirktok Delta in those years.

Some intuitive evidence supports the premise that high salinity in the vicinity of West Dock may have contributed to the cessation of eastward movement in 1988 and 1989. In 1990, small least cisco arrived west of West Dock on 14 July and within three to four days CPUE east of the structure began to rise, eventually peaking at nearly 250 fish·net^{-1}·24 h^{-1} by 23 July (Fig. 5). Throughout that time, salinities immediately west of the causeway at Station 220 (see Fig. 1) remained below 10‰. Similarly, in 1991, fish passed eastward of the causeway before salinities rose above 10‰ on 31 July. In contrast, the fish arriving west of the causeway in 1989 encountered a sharp increase in salinity to 19.5‰ several days later. From that point onward, salinities never dropped below 9.5‰, and by 25 July salinity at the western base of the causeway had reached 30‰. Negligible CPUE east of West Dock indicated that few fish bypassed the structure. Few small least cisco were observed anywhere in the study area after 25 July, and we suspect they retreated westward. In 1988, small increases in CPUE east of West Dock suggested that there was some passage; however, the area west of the causeway experienced a salinity increase from 3.0 to 15.0‰ from 24 to 25 July. Relatively few fish were collected east of West Dock for the remainder of that year. Collectively, these data are consistent with the hypothesis that if salinities near West Dock are relatively low in the absence of a wake-eddy effect, small least cisco can pass eastward of the causeway, but when high salinity water is encountered in the lee of the structure, eastward dispersal is hampered.

As discussed previously, simulation models of juvenile least cisco movement from the Colville River to Prudhoe Bay indicate that eastward dispersal is a function of wind-driven coastal currents in early summer: extended periods of east winds prevent fish from reaching the eastern end of

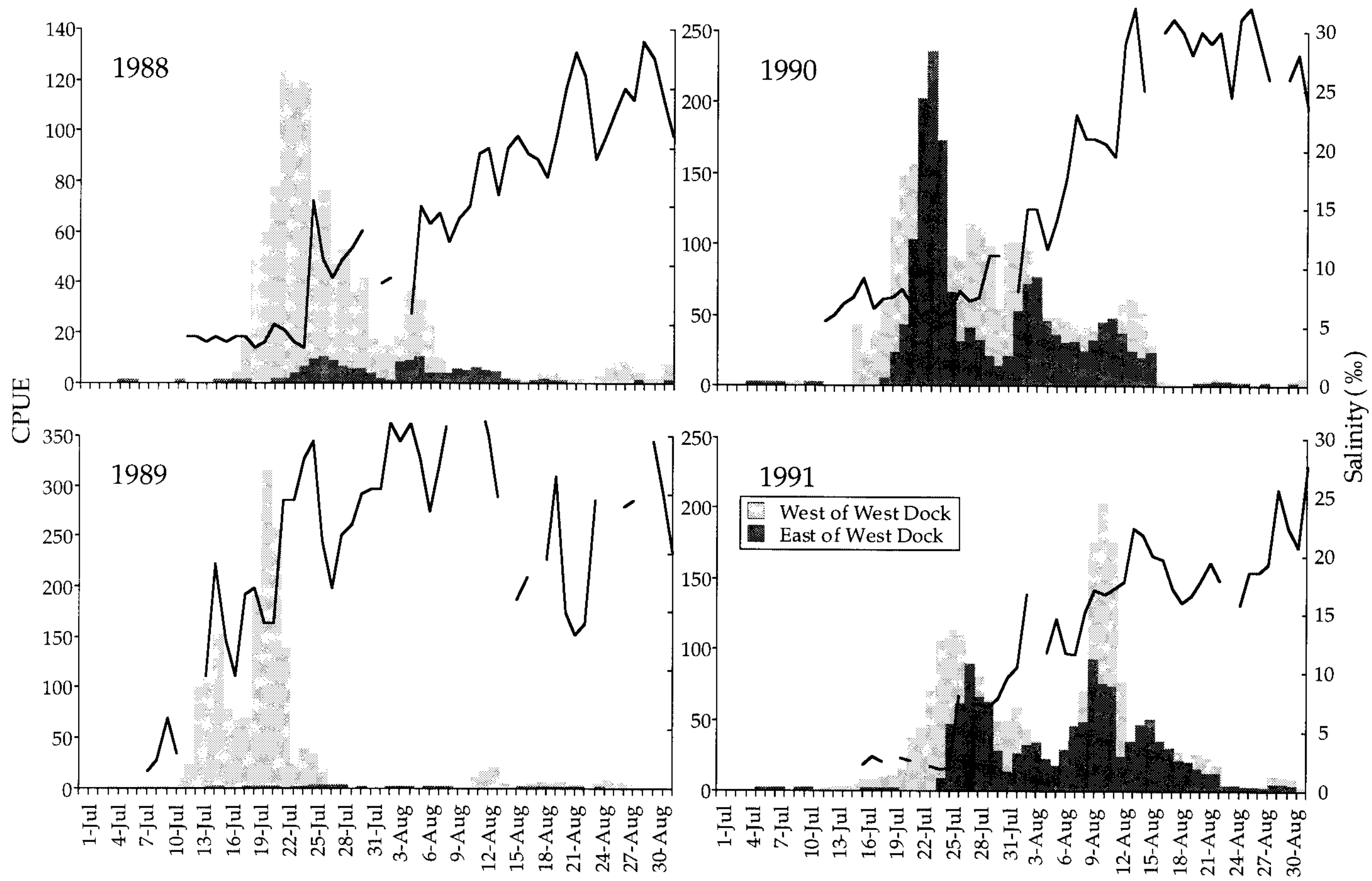

FIG. 5. Daily catch-per-unit-effort (CPUE: fish·net^{-1}·24 h^{-1}) of small (<180 mm) least cisco at stations located west and east of West Dock for 1988–91. To identify major trends, CPUE data were smoothed, using a three-point average. The superimposed black lines show real-time daily bottom salinities recorded at Station 220 (at western base of West Dock). Scaling of the CPUE axis is not consistent for all years because the figure is designed to illustrate comparative catch within each year, not between years.

Simpson Lagoon (Fechhelm et al., 1994). Using the model described by Fechhelm et al. (1994), we tested whether the apparent inability of least cisco to bypass West Dock in 1988 and 1989 may have been more a function of wind direction and transport, as opposed to suspected hydrographic conditions at West Dock.

On the basis of hourly wind patterns for the month of July, the simulation model predicted patterns of arrival of small least cisco at West Dock for 1988 and 1989 that were reasonably consistent with catch patterns observed west of the causeway in both years (Fig. 6). In both 1988 and 1989, CPUE began to increase during the third week in July, as fish arrived in the area from the west. When the model simulations were allowed to continue beyond the arrival date, results suggested that overall wind patterns were more than sufficient to allow fish to continue much farther east of West Dock (Fig. 7). There were no indications that east wind events per se may have prevented fish from moving east of West Dock.

One of the caveats in deciphering event-based scenarios such as those depicted in Figure 5 is that salinity levels recorded at the western base of West Dock may not always mirror the hydrographic conditions that fish would face when attempting to bypass the causeway. West Dock extends seaward for 4.3 km, and water depth at its tip is over 4 m. Under east winds, bottom marine water may move to the 2 m isobath, well within the area influenced by the causeway-induced wake eddy (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986; Niedoroda and Colonell, 1990). Conditions at the tip of West Dock would therefore be expected to become saline before conditions at its western base. This phenomenon was exemplified in the summer of 1993.

In 1993, vertical temperature and salinity profiles were recorded daily at Station 290, located at the western tip of West Dock (see Fig. 1). Figure 8 (top panel) shows hourly east/west wind conditions from 4 July through 16 July. Superimposed are daily bottom salinity measurements recorded at stations 220 and 290. Data show that brief periods of east winds on 6–7 and 8–9 July coincided with sharp increases in salinity at the tip of West Dock. These salinity increases were probably caused by the onshore movement of bottom marine water. Yet conditions at the western base of the causeway at Station 220 remained nearly fresh, which suggests that the upwelling event was of insufficient magnitude and duration to affect nearshore water conditions. It wasn't until 11 July that salinity at the base of West Dock began to increase. Persistent marine

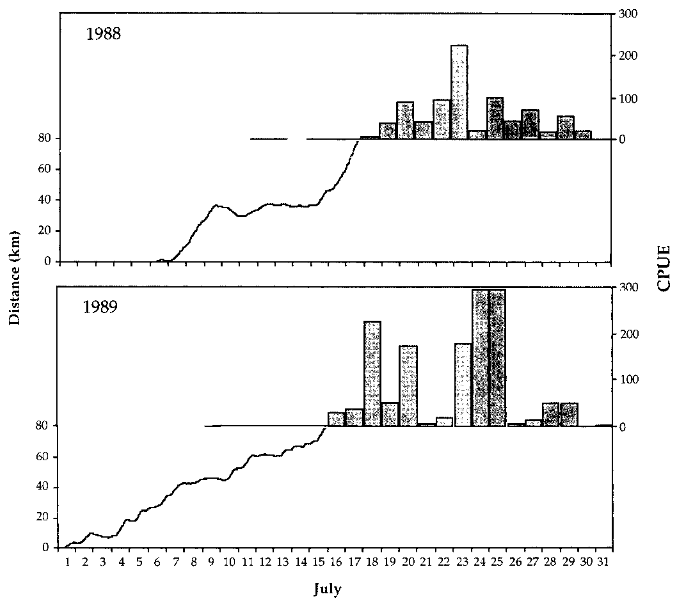

FIG. 6. Simulated distances traveled by small (<180 mm) least cisco from the Colville River to West Dock (~80 km) for 1988 and 1989. The distance line terminates if the net distance traveled reaches 80 km before 31 July. Histograms represent observed daily CPUE (fish·net^{-1}·24 h^{-1}) at fyke nets located west of West Dock. Absence of a CPUE baseline indicates no sampling effort. Data indicate that the arrival of fish at the eastern end of Simpson Lagoon was reasonably consistent with the wind transport model of Fechhelm et al. (1994) in both years.

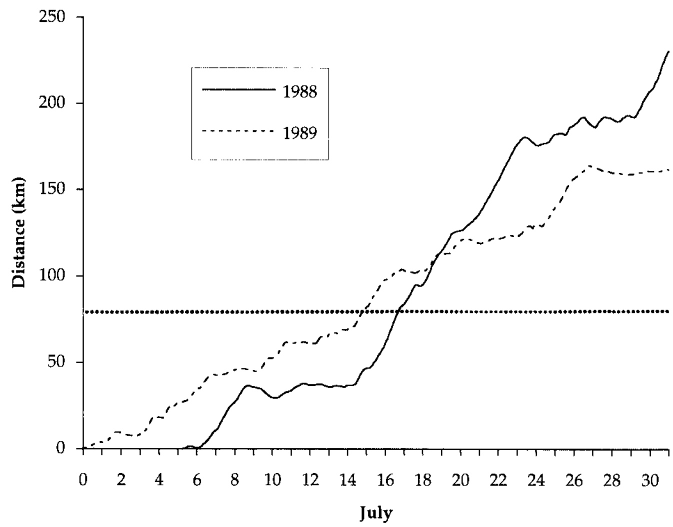

FIG. 7. Simulated distances traveled by small (<180 mm) least cisco from the Colville River through the end of July in 1988 and 1989, based upon the wind transport model of Fechhelm et al. (1994). The horizontal line at 80 km represents the distance to West Dock. Data suggest that wind conditions were sufficient to carry juvenile least cisco far beyond West Dock in both years and that their inability to bypass the causeway was probably not a result of east wind events.

conditions did not occur until the 12 July onset of sustained east winds.

Data for 1993 illustrate the subtle (and at times undetectable) scope of the wake-eddy effect and its potential to influence least cisco dispersal. For example, it was asked why in 1988 least cisco arrived west of West Dock six to seven days prior to the sharp increase in salinity, yet few managed to move east of the causeway (see Fig. 5). This is in contrast to 1990 and 1991, when it took the fish only two or three days to move east of West Dock under conditions of low salinity. One possibility is that brief east wind events in 1988 (Fig. 8, lower panel) may have resulted in higher salinities at the tip of West Dock—conditions that could have prevented juvenile least cisco from moving east of the causeway.

Certainly, factors other than those addressed in our "wake-eddy" conceptual model play a role in the overall dynamics of the least cisco feeding dispersal, and some may affect the ability of juvenile fish to move east of West Dock. However, collectively, the events and conditions that occurred in the summers of 1988–91 provide a reasonable argument for the idea that the high-salinity conditions that develop west of West Dock under east winds block juvenile least cisco from dispersing eastward along the coast.

Although the data for the Endicott Causeway are based on only two years, they give no indication that small least cisco were being prevented from dispersing east of the Endicott Causeway in 1990 and 1991. The reason for this may be threefold. First, two breaches in the mainland segment of the causeway would have allowed cross-delta passage of fish. Second, the entire Endicott Causeway was constructed inside the 2 m isobath, thereby providing fish with a shallow-water passage around its seaward side. Movement around the seaward side of the Endicott Causeway is evident from the high catch rates at Station 208 (see Figs. 1 and 3). Third, although a wake eddy does occur at Endicott, its spatial scope is much less than at West Dock. Also, it does not occlude the nearshore migration/dispersal corridor, largely because of freshwater discharge from the Sagavanirktok River (Gallaway et al. 1991; Hachmeister et al. 1991).

Mark-Recapture Studies

There was no significant difference between the expected and observed number of tag returns in the Colville River commercial fishery for either least cisco ($p = 0.25$, Table 2) or arctic cisco ($p = 0.30$, Table 3). The six-year study of arctic cisco was based upon a total of 20391 tagged fish released in the Prudhoe Bay area against 355 recaptures. Correction for gear selectivity yielded an effective release number of 12028 fish, which translated into an overall recapture rate of 3.0%. Yearly recapture rates ranged from 2.3% in 1988 to 5.6% in 1990. In five years, 41251 (28209 corrected) tagged least cisco were released in Prudhoe Bay and 903 were recaptured in the fall fishery, for an overall recapture rate of 3.2%. Yearly recapture rates ranged from a low of 1.7% in 1991 to a high of 5.6% in 1988.

For arctic cisco, the yearly recapture rates in this study were notably higher than the recapture rates of ≤ 1.1% that are typically reported for the summer monitoring studies at

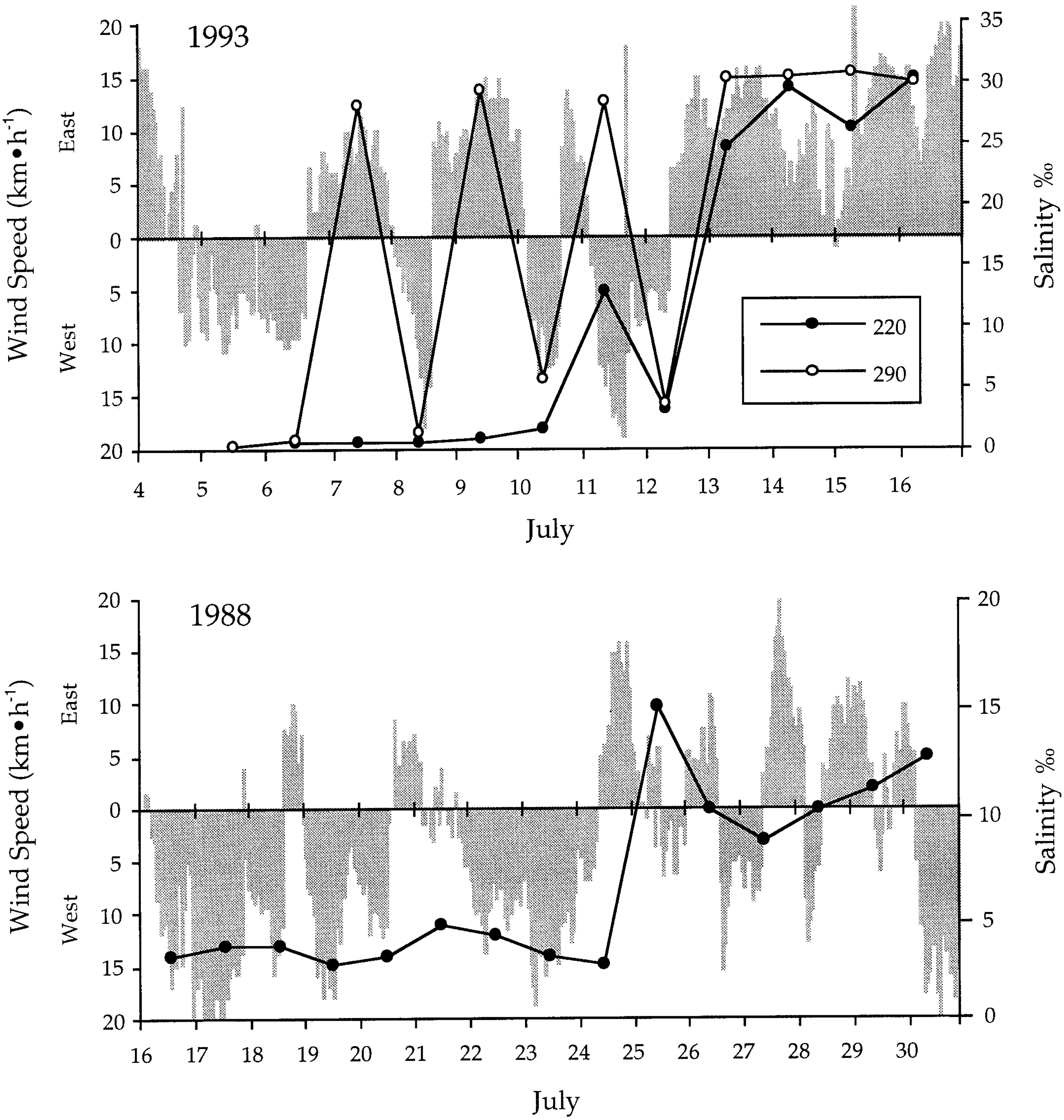

FIG. 8. Hourly east/west wind conditions for selected time frames, recorded during July 1993 and 1988. Superimposed are daily bottom salinity measurements recorded at stations 220 and 290 (1993 only). Hash marks represent 0000 h on the designated date. Salinity values are positioned at about 0900–1100 h, the approximate time of day when measurements were taken. Data for 1993 show that limited periods of easterly winds can cause salinity to increase sharply at the tip of the causeway (station 290) yet not influence nearly freshwater conditions at the western base of West Dock (station 220).

Prudhoe Bay (e.g., Griffiths and Gallaway, 1982; Griffiths et al., 1983; Moulton et al., 1986; Cannon et al., 1987; LGL, 1992). Low return rates at Prudhoe Bay are probably influenced by the migratory and dispersal behavior of this species. Tagging studies have demonstrated that large arctic cisco can range along the Beaufort Sea coast for considerable distances during summer (Craig and Mann, 1974; Griffiths et al., 1975, 1977; Craig and Haldorson, 1981; Griffiths and Gallaway, 1982; Griffiths, 1983; West and Wiswar, 1985; Cannon et al., 1987; Wiswar and West, 1987; Fruge et al., 1989; Underwood et al., 1995). Fish that disperse eastward from the Colville River and are marked

TABLE 2. Summary data for least cisco tagged in the Prudhoe Bay study area and recaptured the same year in the Colville River commercial fishery. Regions are designated as stations west of West Dock (W); between West Dock and the Endicott Causeway (M); and east of the Endicott Causeway (E).

Year	Region	Total Number Tagged	Adjustment Factor	Effective Number Tagged	Predicted Recaptures	Observed Recaptures	Chi-square
1985	W	3,203	0.657	2,104	117	91	5.77
	M	3,522	0.884	3,113	173	172	0.01
	E	2,645	0.850	2,248	125	152	5.85
1990	W	2,185	0.639	1,396	54	53	0.02
	M	1,502	0.711	1,068	41	39	0.12
	E	2,117	0.805	1,704	66	69	0.15
1991	W	4,119	0.614	2,529	43	37	0.92
	M	4,129	0.586	2,420	41	49	1.37
	E	2,576	0.662	1,705	29	28	0.05
1992	W	3,037	0.762	2,314	52	45	1.03
	M	2,562	0.677	1,734	39	48	1.96
	E	1,141	0.715	816	18	17	0.11
1993	W	2,811	0.582	1,636	33	33	0.00
	M	4,122	0.599	2,469	50	51	0.01
	E	1,580	0.602	951	19	19	0.01
						Total Chi-square	17.39
						df	14
						P =	0.25

TABLE 3. Summary data for arctic cisco tagged in the Prudhoe Bay study area and recaptured the same year in the Colville River commercial fishery. Regions are designated as stations west of West Dock (W); between West Dock and the Endicott Causeway (M); and east of the Endicott Causeway (E).

Year	Region	Total Number Tagged	Adjustment Factor	Effective Number Tagged	Predicted Recaptures	Observed Recaptures	Chi-square
1985	W	4,507	0.541	2,439	56	65	1.56
	M	3,756	0.542	2,034	46	44	0.13
	E	2,900	0.557	1,615	37	30	1.28
1988	W	366	0.440	161	6	3	1.38
	M	209	0.440	92	3	6	2.13
	E	324	0.496	161	6	6	0.01
1990	W	345	0.427	147	7	8	0.08
	M	180	0.403	73	4	3	0.09
	E	189	0.555	105	5	5	0.01
1991	W	950	0.468	445	17	15	0.22
	M	589	0.489	288	11	8	0.81
	E	864	0.427	369	14	19	1.73
1992	W	1,981	0.721	1,428	35	29	1.02
	M	1,135	0.797	905	22	20	0.21
	E	507	0.794	403	10	18	6.72
1993	W	631	0.830	524	29	34	0.80
	M	783	0.892	698	39	33	0.90
	E	175	0.811	142	8	9	0.15
						Total Chi-square	19.22
						df	17
						P =	0.30

and released in the Prudhoe Bay area most likely continue moving eastward along the coast. Those fish that have reached sexual maturity may even be returning to Canada to spawn. Emigration from the tagging area would contribute to lower return rates. Many of the non-spawning cisco might be susceptible to recapture as they move through the Prudhoe Bay area on their return migration to the Colville River. However, most summer monitoring programs end by late August to early September, more than a month before the start of the Colville River commercial fishery. Large arctic cisco migrating eastward during the intervening period would be able to pass through Prudhoe Bay undetected. By comparison, the commercial fishery is specifically timed and located to intercept the principal return migration of these fish.

For least cisco, yearly recapture rates of 0.9 to 5.7% in the Prudhoe Bay area were more in line with the 1.7 to 5.4% return rates observed in the fishery. This trend may also reflect the dispersal characteristics of this coregonid. Whereas large arctic cisco are common all along the Beaufort Sea coast during summer, large least cisco are relatively rare in eastern Alaska (Roguski and Komarek, 1972; Griffiths et al., 1975, 1977; Griffiths, 1983; Wiswar and West, 1987; Fruge et al., 1989; Underwood et al., 1995). The implication is that the coastal foraging range of least cisco is more restricted than that of arctic cisco. A more spatially restricted coastal habitat increases the probability that least cisco forage in closer proximity to the Prudhoe Bay study area, thereby increasing residency time and, in turn, the likelihood of being recaptured within the summer. There is some indication of greater residency time, in that the daily catch rates of large least cisco in the Prudhoe Bay area are typically much higher and more persistent throughout the summer than those of large arctic cisco. It should be noted, however, that although the dispersal range of adult least cisco appears to be more restricted than that of arctic cisco, least cisco can still migrate considerable distances along the Beaufort Sea coast during the open-water season. They have been reported, albeit in relatively small numbers, as far east as Camden Bay, 120 km east of Prudhoe Bay (Underwood et al., 1995).

To determine the amount of loss that would be required for the chi-square test to register a significant difference in tag returns at $\alpha = 0.05$, given the available data, we considered the initial premise of the analysis. Fish disperse from the Colville River in early summer, when nearshore temperatures are highest and salinities lowest. They return in late summer, when coastal conditions have become considerably more marine. If causeways did block the return migration, the ratio of actual to expected returns would be lower for fish released east of any causeway. Under this premise, we began with the assumption that each causeway would result in a 1% loss of fish (i.e., tag returns). That is, the actual number of tag returns was reduced by 1% for fish released in region M and by 2% for fish released in region E. We made this adjustment for every study year and recalculated the subsequent chi-square probability. This process was repeated, progressively increasing the percent loss by 1% at each iteration.

The plot of chi-square p-values versus assumed percent loss indicates that, for both species and given the available data, a causeway would have to result in about a 24–25% loss for the test to register a significant difference at $p \leq 0.05$ (Fig. 9). Given this estimate, overall results suggest that while there is no indication of a major causeway effect, population losses of 10–20%, losses that could affect population structure, would go undetected. On the other hand, the actual total return rates for fish released farthest from the Colville River, east of the Endicott Causeway, were higher than expected for arctic cisco (80 expected versus 87 observed) and nearly neutral for least cisco (187 expected versus 186 observed). Neither set of values suggests a loss of fish related to the locations of the two causeways. Further, if losses of 10–20% did occur,

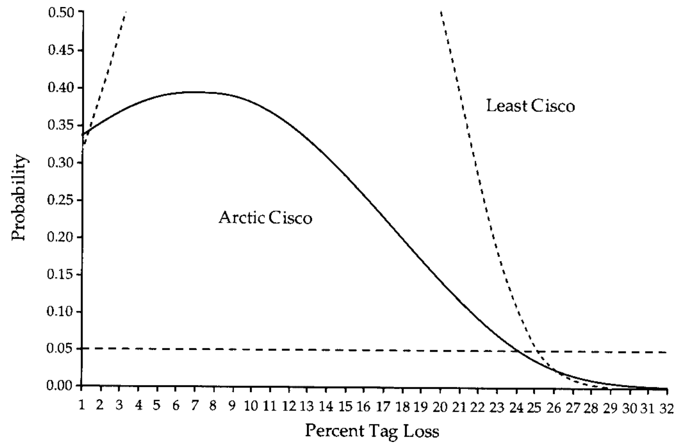

FIG. 9. Distribution of chi-square probabilities under the assumption that causeways result in the indicated percentage loss of tagged fish. Data suggest that, for both Arctic and least cisco, losses of 24–25% would be required for the chi-square test to detect a significance at the $\alpha = 0.05$ level.

there would almost certainly be some tangible impact to the commercial fishery. Yet, through 30 consecutive years of monitoring the fishery, there has been no discernible change in the annual harvests of least or arctic cisco related to the construction of either West Dock or the Endicott Causeway (Moulton and Helmericks, 1997).

GENERAL DISCUSSION

Spatial patterns in catch and hydrographic data are generally consistent with the idea that causeway-induced changes in local salinity can disrupt the eastward foraging dispersal of juvenile least cisco emanating from the Colville River. Analysis of commercial fishery tag recaptures indicated no significant difference in the return rates of subadult and adult least and arctic cisco based upon the location of release relative to either the West Dock or Endicott causeways. Although the tag recapture analysis has its limitations in sensitivity, even the trend in tag losses was inconsistent with the underlying hypothesis that the Prudhoe Bay causeways prevented fish from returning to the Colville River in late summer. Results of the mark-recapture analysis agree with those reported by Craig and Griffiths (1981) and Cannon and Hachmeister (1987), each of which was based on a single-year study, and with those of Fechhelm et al. (1989), who analyzed tag returns relative to West Dock alone covering the pre-Endicott years 1981–84.

The results of both analyses tend to support the idea that large fish appear to be able to bypass the Prudhoe Bay area causeways, but juvenile fish can encounter causeway-induced conditions that can block alongshore dispersal. It seems reasonable that large fish are able to bypass area causeways, given their swimming capacities. Summer feeding dispersals may take adults hundreds of kilometres from their overwintering sites, along an irregular coastline characterized by diverse bathymetic and topographical features. Unlike juveniles, large least cisco are present throughout the Prudhoe Bay study area every summer (e.g., Griffiths and Gallaway, 1982; Griffiths et al., 1983; Moulton et al., 1986; Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991; LGL, 1992; Griffiths et al., 1996). They have been taken in substantial numbers as far east as Mikkelsen Bay, some 40 km east of West Dock (Fechhelm et al., 1996). Large arctic cisco are common in the coastal waters of eastern Alaska near the Arctic National Wildlife Refuge (West and Wiswar, 1985; Wiswar and West, 1987; Fruge et al., 1989; Underwood et al., 1995). Upon reaching sexual maturity, arctic cisco are believed to migrate over 600 km from the Colville River back to their natal drainages in the Mackenzie River system, Canada (Gallaway et al., 1983). Given the distances involved, the Prudhoe Bay causeways would appear to be a minor obstacle to dispersal and migration.

If the events of 1988 and 1989 do indicate blockage at West Dock for juvenile least cisco, the long-term repercussions of this phenomenon for the least cisco population remain unclear. Fish monitoring studies have been conducted in the Prudhoe Bay area each summer since 1981, yet over those 16 years (through 1996) blockage at West Dock has been evident only twice. Because of summer wind/transport conditions, juvenile least cisco do not even reach West Dock in one of every two years (Fechhelm et al., 1994). If blockage were more chronic, it would heighten concern that disruptions to the summer feeding dispersals of the Colville River least cisco were placing the population at risk over the long term. The history of study suggests that blockage is a rare event and, as such, probably does not constitute an appreciable effect on summer feeding dispersals (Wilson and Gallaway, 1997). On the other hand, the mere fact that there is evidence of blockage, no matter how rarely that might occur, evokes the possibility that more subtle and undetectable disruptions to dispersal could be occurring.

Comparisons of side-of-causeway CPUE, as was done for juvenile least cisco in this paper, are not applicable to adults, nor do they apply to the other key diadromous species of the region—Dolly Varden (*Salvelinus malma*), broad whitefish (*C. nasus*), and arctic cisco (as identified by U.S. Army Corps of Engineers, 1980, 1984). Resident populations of all three species either spawn or overwinter in both the Sagavanirktok and Colville Rivers (e.g., Griffiths et al., 1983; Craig, 1984; Moulton et al., 1986; Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991; LGL, 1992; Griffiths et al., 1996). The effort to identify movement patterns of these three species is confounded by the mixing of stocks and the inability to distinguish fish of a purely Colville River or Sagavanirktok River origin. Further, once fish are distributed throughout the study area, daily variation in CPUE is large enough to preclude side-of-causeway statistical comparisons. Because they overwinter in the Sagavanirktok River, all three species are common throughout the Prudhoe Bay area as soon as sampling can begin, which is shortly after breakup. Juvenile least cisco are the only group that is completely absent from Prudhoe Bay waters in very early summer and arrives in the area only from the west. Subadult and adult arctic cisco also originate from the Colville River. These large fish do not overwinter extensively in the Sagavanirktok River (Schmidt et al., 1989); however, they disperse out into coastal waters very early and are typically present throughout the Prudhoe Bay area when sampling begins each summer.

Although we continually refer to the water quality issue at West Dock in terms of salinity, there is, in fact, a more than occasional correlation between the wake-eddy effect and temperature: salinity and temperature are often inversely related. However, high-salinity water that moves into nearshore shallow areas can heat up quite rapidly, particularly on warm, sunny days. This leads to "numerous anomalies" in the wake eddy/salinity/temperature association. It is quite feasible that the cold temperatures and high salinities that characterize marine water can act together in influencing the movements of juvenile fish. It is just that, quantitatively, the most convincing trends in the vicinity of West Dock are evident in salinity patterns.

If the interpretations and conclusions expressed in this paper are correct, the implications are that the potential impacts of a causeway on Beaufort Sea fish populations are strongly related to the locations of the causeway itself and the size of the fish encountering it. West Dock was constructed within the dispersal range of a diadromous species, at the eastern terminus of an extensive brackish-water lagoon system through which fish disperse and migrate, and seaward enough into the marine system to exacerbate coastal mixing processes. The Endicott Causeway, on the other hand, was constructed entirely on a shallow-water shelf, was fitted with breaches, and is constantly bathed in freshwater discharge from the Sagavanirktok River. Fish movement around and through the Endicott Causeway is less restricted. Given such differences, factors such as location, bathymetry, and coastal topography should be major considerations in the planning of any future developments along the Beaufort Sea coast.

As mentioned previously, a 200 m wide breach was installed in the base of West Dock during the winter 1995–96. The extent to which this breach may alleviate the apparent blockage of juvenile least cisco remains to be determined. If historical records are any indication, one would have to wait, on average, eight years to find out.

ACKNOWLEDGEMENTS

We thank J. Erwin and G. Hubbard for critically reviewing the manuscript. We are also grateful to field managers D. Schmidt and R. Dillinger; senior field crew leaders B. Seavey, K. Waggoner, and Don Campbell; field team leaders G. Colonell, B. Colthorp, G. Lawley, and D. Malone; field technicians T. Akpik, R. Basi, M. Bingham, J. Bush, M. Cole, S. Davis, L. Dugan, P. Fitzgerald, D. Gerkin, T. Green, B. Haley, A. Herrera, D. Hopler, J. Itta, S. Kilmowski, E. Parsons, B. Pierson, D. Rentenaar, D. Rosenau, and E. Westlien; and, expediter D. Roche for their superb efforts during the 1988–94 studies. Environmental monitoring programs were funded by the owners of the Endicott Development, which is operated by BP Exploration (Alaska) Inc. Programs conducted from 1985 to 1987 were under the joint supervision of the Alaska Department of Fish and Game, the U.S. Environmental Protection Agency, the National Marine Fisheries Service, the North Slope Borough (NSB), the U.S. Army Corps of Engineers, and the U.S. Fish and Wildlife Service. Environmental monitoring programs from 1988 to 1996 were conducted under permit requirements and supervision of the NSB and the NSB Science Advisory Committee. The conclusions and opinions expressed in this paper do not necessarily represent those of any of the above-mentioned organizations.

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