ARCTIC
VOL. 51, NO. 2 (JUNE 1998) P. 94–104

Abundance of Selected Fish Species in Relation to Temperature and Salinity Patterns in the Sagavanirktok Delta, Alaska, Following Construction of the Endicott Causeway

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(*Received 9 July 1997; accepted in revised form 23 October 1997*)

ABSTRACT. Hydrography data from 1985 to 1993 in the vicinity of the Endicott Causeway near Prudhoe Bay, Alaska, were analyzed to determine if the trend in yearly post-causeway construction temperature and salinity was toward colder and more saline conditions. No significant ($p \leq 0.05$) relationship was found for temperature; however, salinity levels significantly decreased with time following construction. Intra-year variations in hydrographic conditions appeared to be due to coast-wide meteorological and oceanographic events rather than causeway-induced. We analyzed abundance indices, as $\log_e$ transformed catch-per-unit-effort (CPUE), of four marine species (arctic cod, *Boreogadus saida*; fourhorn sculpin, *Myoxocephalus quadricornis*; arctic flounder, *Pleuronectes glacialis*; saffron cod, *Eleginus gracilis*); two freshwater species (round whitefish, *Prosopium cylindraceum*; arctic grayling, *Thymallus arcticus*); and the anadromous rainbow smelt, *Osmerus mordax*, to determine whether there were increases in the abundances of marine species and declines in anadromous and freshwater species. We developed the "best-fit" regression models, based on the criterion of maximized regression F-ratio (i.e., minimized regression p-values), using year, temperature, salinity, and all possible interactions. Results suggested that all species exhibited changes in abundance levels over the period of record. In particular, arctic flounder and rainbow smelt both showed sharp increases in abundance five years after construction. For all species, the observed changes in abundance levels appeared to be due to naturally occurring events in the species' life histories or changes in coast-wide meteorological conditions rather than to causeway-induced alterations in local hydrographic conditions.

Key words: Alaska, Sagavanirktok Delta, causeway, arctic fishes, abundance, temperature, salinity

RÉSUMÉ. On a analysé les données hydrographiques obtenues de 1985 à 1993 dans le voisinage immédiat du pont-jetée Endicott situé près de Prudhoe Bay en Alaska, en vue de déterminer si, après la construction du pont, la température annuelle avait tendance à être plus froide et l'eau plus saline. On n'a trouvé aucun rapport significatif ($p \leq 0{,}05$) pour la température. Le niveau de salinité, par contre, a considérablement baissé à mesure que le temps passait après la construction. Les variations intra-annuelles dans les conditions hydrographiques semblaient être dues à des phénomènes météorologiques et océanographiques affectant le littoral tout entier plutôt qu'au pont-jetée lui-même. On a analysé les indices d'abondance, exprimés en $\log_e$ des prises par unité d'effort (PPUE), de quatre espèces marines (morue arctique, *Boreogadus saida*; chaboisseau à quatre cornes, *Myoxocephalus quadricornis*; plie arctique, *Pleuronectes glacialis*; navaga jaune, *Eleginus gracilis*); deux espèces d'eau douce (ménomini rond, *Prosopium cylindraceum*, et ombre arctique, *Thymallus arcticus*); ainsi qu'une espèce anadrome (éperlan arc-en-ciel, *Osmerus mordax*), afin de déterminer s'il y avait une augmentation dans l'abondance des espèces marines et une diminution dans les espèces anadromes et d'eau douce. On a développé des modèles de régression de meilleur ajustement, fondés sur le critère de maximisation du F de régression (c.-à-d. minimum des valeurs p de régression), en utilisant l'année, la température, la salinité et toutes les interactions possibles. Les résultats suggéraient que toutes les espèces montraient des changements dans les niveaux d'abondance durant la période de relevés. La plie arctique et l'éperlan arc-en-ciel en particulier affichaient tous deux un accroissement très net dans leur abondance cinq ans après la construction. Pour toutes les espèces, les changements observés dans les niveaux d'abondance semblent être dûs à des phénomènes qui se produisent naturellement dans le cycle biologique de l'espèce ou à des changements dans les conditions météorologiques affectant le littoral tout entier plutôt qu'à des transformations causées par le pont-jetée dans les conditions hydrographiques locales.

Mots clés: Alaska, delta du Sagavanirktok, pont-jetée, poissons de l'Arctique, abondance, température, salinité

Traduit pour la revue *Arctic* par Nésida Loyer.

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INTRODUCTION

For over 15 years, fish and hydrographic studies have been conducted in the Prudhoe Bay region, Alaska, to monitor the effects of nearshore oil and gas developments on fish populations. The studies have resulted in several publications about the distribution, movement patterns, and growth rates of various fish species (Craig et al., 1982, 1985; Craig, 1984, 1989; Fechhelm et al., 1989, 1992, 1995; Griffiths et al., 1992). In addition, there have been studies of the effects of nearshore developments on the local hydrography and fish populations (Niedoroda and Colonell, 1990; Cannon et al., 1991; Gallaway et al., 1991; Hachmeister et al., 1991), and methods have been developed for synthesizing available data to address specific fish-related development issues (Wilson and Gallaway, 1997).

A common concern expressed in these studies has been the potential for nearshore developments to disrupt a biologically important feature of the Beaufort Sea: a band of relatively warm, brackish water (5–10˚C, 10–25‰) that lies adjacent to the shore (Craig, 1984). This nearshore band, which results from a combination of river discharge and solar heating of shallow nearshore waters during summer, constitutes the main feeding habitat of anadromous, amphidromous, and some marine and freshwater fishes that disperse along the coastline. Its importance relates, with minor exceptions, to the limited time available for feeding, from mid-June to mid-September, during which fish must accomplish most of their annual growth and accumulate food reserves before the onset of the nine-month winter (Craig, 1989).

Interest has centered on the Endicott Development, a gravel-filled breached causeway constructed during the winter of 1984–85 in the delta of the Sagavanirktok River as a platform for developing offshore petroleum reserves (Fig. 1). Oceanographic studies have shown that under persistent east winds, a condition that promotes coast-wide upwelling of cold marine bottom water, the presence of the causeway induces the formation of a wake-eddy in the lee of its western tip (Gallaway et al., 1991). The circulation pattern within the eddy transports marine bottom water, if present, to the surface, where it is advected a short distance along the shoreward side of the causeway's western leg. Some investigators expressed concern that this causeway-induced transport of cold marine water would alter the nearshore band of warm, brackish water and cause the habitat to become marine. Such alteration would make the post-construction years similar to a naturally occurring harsh year by extending the period when cold, salty water was present (Ross, 1988), and could lead to domination of the nearshore fish community by euryhaline species at the expense of stenohaline fish (Ross, 1988). Conversely, other investigators hypothesized that the frequency and intensity of the wake-eddy events that induce cold marine water to reach the surface and the extent of the area affected would be insufficient to alter either the hydrographic character of the delta or the structure of the fish community (Gallaway et al., 1991).

Few pre-development hydrographic and fish data are available from the vicinity of the Endicott Causeway. In fact, the environmental impact statement (USACE, 1984) issued prior to the construction of the causeway was based on studies from several years of monitoring of the nearby West Dock Causeway (Fig. 1) and on a single summer's data (1982) from four stations located across the Sagavanirktok Delta (Griffiths et al., 1983). Since construction of the Endicott Causeway, fish and oceanographic monitoring studies have been conducted at the four original 1982 baseline stations, providing a large database on species abundance and water temperature and salinity in the Sagavanirktok Delta (Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991; Griffiths et al., 1995).

The Endicott monitoring studies have concentrated on four fish species of importance to Native subsistence and/or sport fisheries: arctic cisco (*Coregonus autumnalis*), broad whitefish (*C. nasus*), Dolly Varden (*Salvelinus malma*), and least cisco (*C. sardinella*). The abundance levels, distribution patterns, and growth rates of these four species in the Prudhoe Bay and Endicott Causeway region have been described in detail in numerous publications (Craig and Haldorson, 1981; Gallaway et al., 1983, 1989, 1997; Craig, 1984, 1989; Craig et al., 1985; Fechhelm and Fissel, 1988; Fechhelm et al., 1989, 1991, 1992, 1993, 1994, 1995, 1997; Moulton, 1989; Fechhelm and Griffiths, 1990; English, 1991; Moulton et al., 1991; Schmidt et al., 1991; Griffiths et al., 1992; Bryan and Fechhelm, 1997; Colonell and Gallaway, 1997). These studies collectively indicate that the variations in abundance levels of these anadromous and amphidromous species observed in the Prudhoe Bay region from 1985 to 1993 are the result of coastal winds (for small arctic and least cisco), a possible density-dependent mechanism (for broad whitefish), and summer feeding dispersals (for large arctic and least cisco and Dolly Varden).

Little information, however, has been published on the so-called "minor species," those not targeted by subsistence or sport fishers. This group includes the anadromous rainbow smelt (*Osmerus mordax*); freshwater species, arctic grayling (*Thymallus arcticus*) and round whitefish (*Prosopium cylindraceum*); and marine species, arctic cod (*Boreogadus saida*), saffron cod (*Eleginus gracilis*), fourhorn sculpin (*Myoxocephalus quadricornis*), and arctic flounder (*Pleuronectes glacialis*). Ross (1988) suggested that these species would be most affected by causeway-induced changes in temperature and salinity levels that shift local hydrographic conditions to a more marine state. Hypothetically, marine species would become more abundant, and less salinity tolerant or freshwater species would become less abundant.

We first analyzed the temperature and salinity data from 1985 to 1993 to determine if the hydrographic environment in the post-causeway years has shifted to a more marine state. We then analyzed the patterns of relative abundance of the various fish species to test the hypothesis that there have not been any changes in abundance directly related to causeway effects. We discuss the results of these analyses in terms of causeway-induced factors versus naturally occurring events.

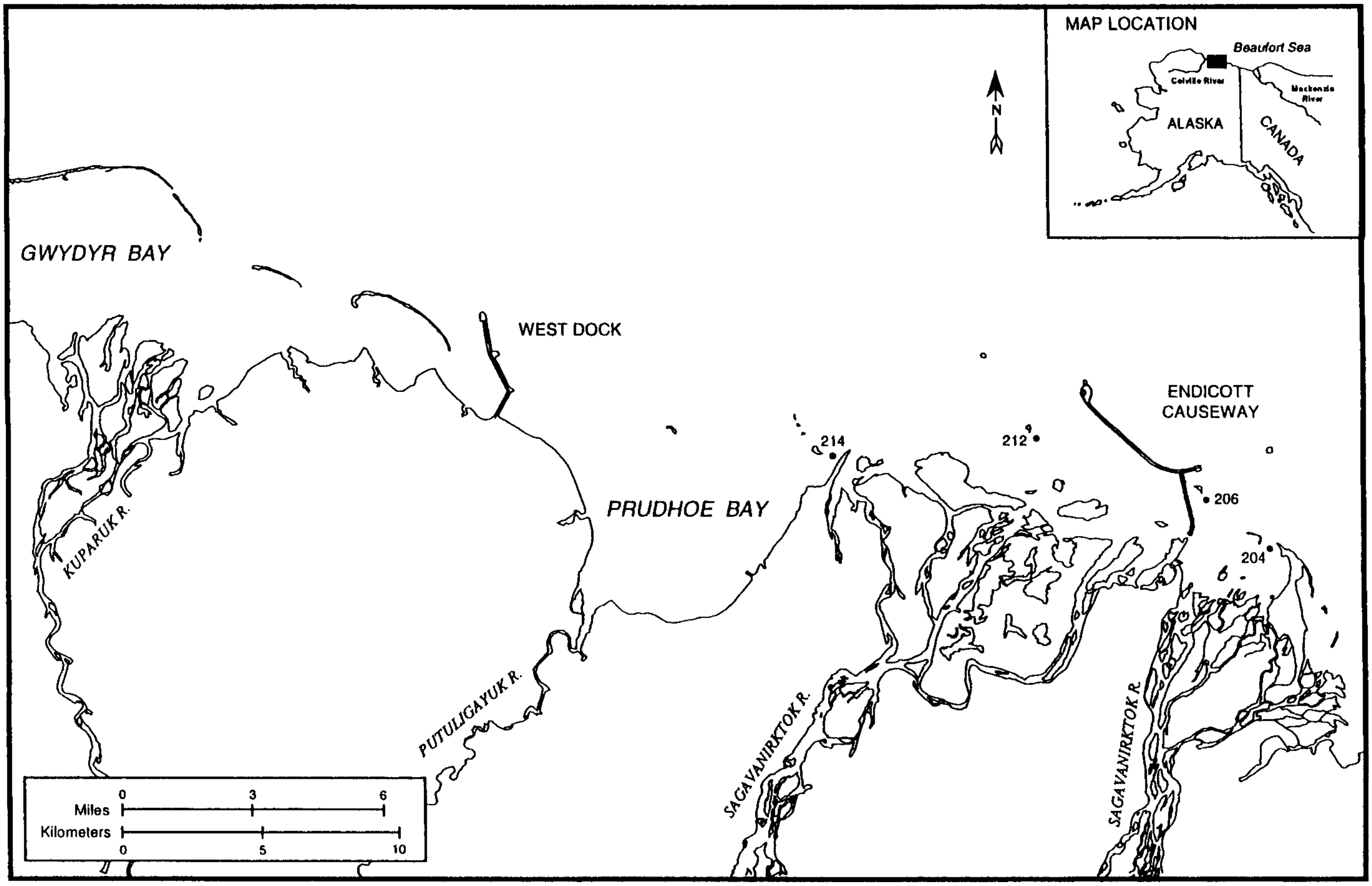

FIG. 1. Map of the Prudhoe Bay region showing the Endicott and West Dock causeways and the locations of the four baseline fish and hydrographic sampling stations (204, 206, 212, 214).

METHODS

Fish were collected at four fyke net stations in the Sagavanirktok Delta (Fig. 1) during the open water seasons from 1985 to 1993. Nets were in place continuously over 24 h and were emptied once a day, weather permitting. The four major fish species were placed in holding pens, anesthetized in a dilute solution of tricaine (MS-222), identified, measured (fork length, mm) and released after they had recovered from the effects of the anesthetic. The minor species were counted and released. Between 1985 and 1990, YSI® salinity/temperature meters were used to measure daily surface temperature (˚C) and salinity (‰) at each fyke net station. From 1991 to 1993, similar measurements were taken using Hydrolab Surveyor III conductivity/temperature/depth meters. Since most of the delta is quite shallow (less than 2 m deep) and hydrographic stratification is minimal (Fechhelm et al., 1991), we considered surface hydrographic measurements to be representative of the water column at each sampling site.

Numerous sites have been sampled over the years, but only the original four 1982 stations depicted in Figure 1 have been sampled in every year, except 1987, for which there are no data (Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991; Griffiths et al., 1995). For consistency among years, we used only the common sampling dates 7 July to 31 August. This eight-week period covers most of the ice-free feeding season of the fish.

The basic unit in our analyses was catch per unit effort (CPUE), standardized as the mean number of fish collected at a given net per 24 h (i.e., fish·24 h^{-1}). We assumed, on the basis of mark-recapture and tagging data, that CPUE was an index to abundance, i.e., that CPUE changed proportionally with change in abundance. Gallaway et al. (1997) showed that fyke-net CPUE was an index to abundance for small, broad whitefish in the Sagavanirktok Delta by correlating mark-recapture population estimates to net CPUE. In addition, tagging studies in Prudhoe Bay between 1981 and 1993 showed that fish did not re-enter nets immediately after release, since only 0.06% of the large anadromous fish and 0.26% of the small anadromous fish were recaptured the following day in the same net from which they had originally been released.

To avoid the problems associated with "pseudoreplication," we used the seasonal mean CPUE for each net: individual daily fyke-net CPUEs and hydrographic measurements are not truly independent samples, since they are usually strongly correlated with the previous day's and the next day's values (Stewart-Oaten et al., 1986). Our method provided four estimates of abundance (from four nets) for each year and species. The daily catch data were $\log_e$-transformed

($\log_e$ [CPUE + 1]) before calculation of seasonal means. Non-transformed seasonal mean surface temperatures and salinities were used for the four baseline stations.

Using the multiple general linear hypothesis (MGLH) provided by SYSTAT (Wilkinson, 1987), we conducted multiple regression and residual analyses to determine if post-causeway changes in the temperature and salinity levels were related to year or to the other hydrographic variable or to their interaction. Similarly, we looked for significant models that could explain the observed changes in fish abundance using post-causeway year, temperature and salinity levels, and their interactions. We used the Lillifores Test to determine if the CPUE data were normally distributed. The temperature and salinity data were normally distributed, as were the transformed CPUE data for arctic cod, fourhorn sculpin, and round whitefish. However, similar data for arctic flounder, arctic grayling, rainbow smelt, and saffron cod were not normally distributed.

In cases where the data were normally distributed, we developed the "best-fit" models based on the criterion of maximized regression F-ratio (i.e., minimized regression p-values) using the all-possible-regression model. For the temperature and salinity data, we ran separate regression models, using temperature or salinity as the independent variable, against year and the remaining variable (temperature or salinity) as the dependent variables, along with the interaction term. We then removed nonsignificant interaction terms and independent variables to arrive at the "best-fit" model. Separate multiple regression models were developed for each fish species. In all cases, the independent factor CPUE was regressed against the dependent factors (year, temperature, salinity) and all possible interaction terms. We then sequentially removed the nonsignificant interaction terms and independent variables to produce the "best-fit" model.

Non-normal distributions in the transformed CPUE data for arctic flounder, arctic grayling, rainbow smelt, and saffron cod precluded parametric statistical analysis; nonparametric methods were not used, because they are inappropriate for analysis of interaction terms. We inspected these data visually, described the abundance levels, and made some generalizations about the temperature-salinity-abundance relationships in the post-causeway environment.

RESULTS

The "best-fit" model for explaining temperature was a simple regression with year after excluding all other variables and interactions (Table 1; Fig. 2). However, the model was not significant and explained only 6% of the variation. The best model for salinity contained year, temperature, and their interaction. This model was significant but accounted for only 17% of the observed variation (Table 1, Fig. 2). Although there was a significant year effect, the negative coefficient implies a slight decline in delta salinities since the causeway's construction. This trend was in the opposite direction to that hypothesized, namely, that the nearshore waters would become more marine as a result of the causeway's presence.

Mean temperatures varied over the nine years of record, but there was no obvious trend toward a colder, more saline condition. Two years that differed substantially from the other years (1989, with high temperatures, and 1991, with low temperatures), were both post-construction years. The high 1989 temperatures resulted from extensive periods of solar radiation that warmed the shallow nearshore waters of the Alaskan Beaufort Sea. The low 1991 temperatures were due to extensive ice cover that remained in the nearshore region for much of that summer. Both cases represented coast-wide events that affected temperatures along the Alaskan Beaufort Sea coast as far east as Barter Island, approximately 200 km away (Underwood et al., 1995).

Mean yearly salinities also varied over the same post-construction period but did not show a sequential trend toward higher salinity levels. Both high (1993) and low (1991) salinity years were recorded in post-construction years. The high 1993 salinities resulted from numerous wind-generated coastal upwelling events that occurred in July and early August of that year (LGL, Alaska, unpubl. data). The low 1991 salinities were due to the extensive ice cover that persisted in the nearshore region and prevented wind-mixing of the more marine offshore waters with the brackish nearshore waters (LGL, Alaska, unpubl. data). The low 1991 salinity pattern was also observed near Barter Island and also resulted from extensive ice cover in that area (Underwood et al., 1995). There were no comparable 1993 data from Barter Island.

Arctic cod abundance varied widely among years in the post-causeway environment (Fig. 2). There were, however, no significant regression models for arctic cod abundance and year, temperature, salinity, or their interactions (Table 1), suggesting that the changes were probably independent of year and hydrographic conditions.

The "best-fit" model for fourhorn sculpin was a simple regression on salinity, after excluding all other variables and their interactions (Table 1; Fig. 2). A plot of CPUE vs. salinity showed that the significant relationship was primarily due to the four lowest abundance levels, which occurred when salinities were less than 4‰, and the highest, which occurred when salinities were greater than 12‰ (Fig. 3).

The "best-fit" model for round whitefish was based on year, temperature, and their interaction; however, the model was not significant and accounted for only 15% of the observed variation (Table 1; Fig. 4). The significant interaction term year*temperature within the model confounded the analysis of these variables. In the end, we were left with significant factors within a nonsignificant model (Table 1). Biologically, this suggests that round whitefish abundance has not been strongly affected by temperature or salinity but that temperature may play a role in conjunction with year.

Arctic flounder and rainbow smelt both exhibited dramatic stepwise increases in abundance levels approximately five years after construction of the causeway, and these high levels persisted through 1993 (Fig. 4). No corresponding

TABLE 1. Results of multiple regression analyses for mean seasonal temperature and salinity and year, and for mean seasonal abundance as CPUE ($\log_e$ [CPUE+1]) for selected species. Listed models are "best-fit" models based on the criterion of maximized regression F-ratio (minimized P-value).

Variable or Species	Source	Coefficient	SS	df	MSE	F-ratio	P	Adjusted r^2
	Year	0.146						
Temperature	Regression		4.714	1	4.710	2.992	0.094	0.060
	Residual		47.265	30	1.575			
Salinity	Year	-5.034		1			0.009[1]	
	Temperature	-3.437		1			0.015[1]	
	Year*Temperature	0.719		1			0.007[1]	
	Regression		76.172	3	25.391	3.127	0.042[1]	0.171
	Residual		227.367	28	8.120			
Arctic cod	Year	-0.312		1			0.138	
	Salinity	-0.214		1			0.229	
	Year*Salinity	0.042		1			0.125	
	Regression		3.856	3	1.285	0.957	0.427	0.000
	Residual		37.607	28	1.343			
Fourhorn sculpin	Salinity	0.126		1			<0.001[1]	
	Regression		4.844	1	4.844	26.164	<0.001[1]	0.448
	Residual		5.554	30	0.019			
Round whitefish	Year	0.677		1			0.025[1]	
	Temperature	0.508		1			0.023[1]	
	Year*Temperature	-0.089		1			0.033[1]	
	Regression		1.734	3	0.578	2.809	0.058	0.149
	Residual		5.761	28	0.206			

[1] Indicates significant difference at the 0.05 level.

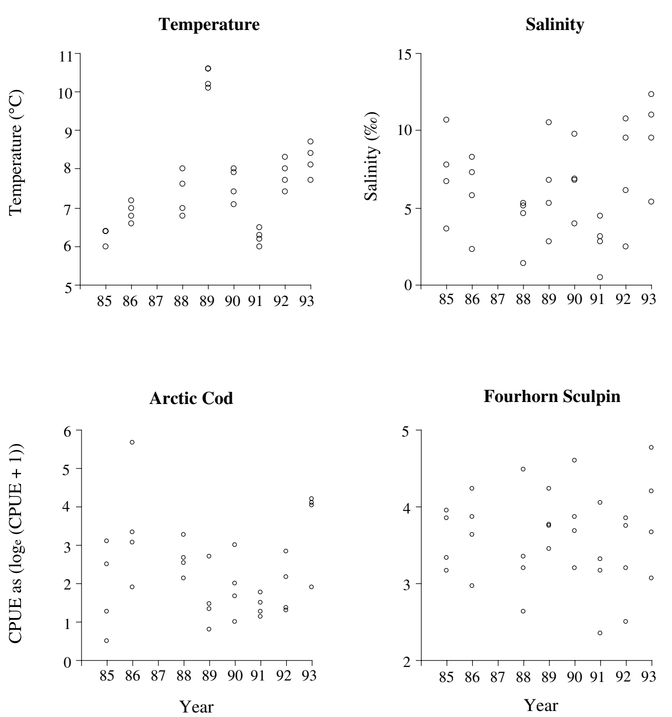

FIG. 2. Plots of mean seasonal surface temperature and salinity and mean seasonal abundance as catch per unit effort (CPUE) for arctic cod and fourhorn sculpin collected at the four baseline stations in the Prudhoe Bay region, Alaska, 1985–93. Actual CPUE data have been transformed to $\log_e$ (CPUE+1).

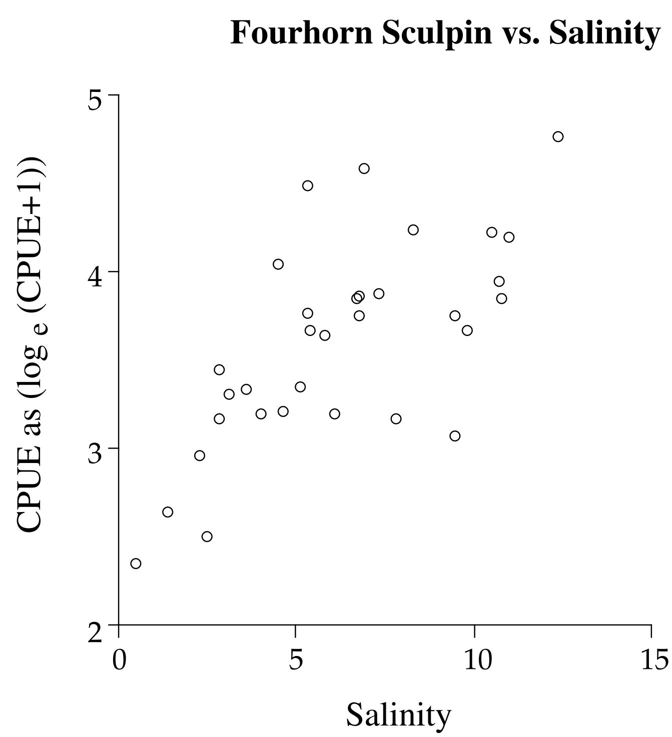

FIG. 3. Plot of fourhorn sculpin CPUE vs. salinity levels for 1985–93.

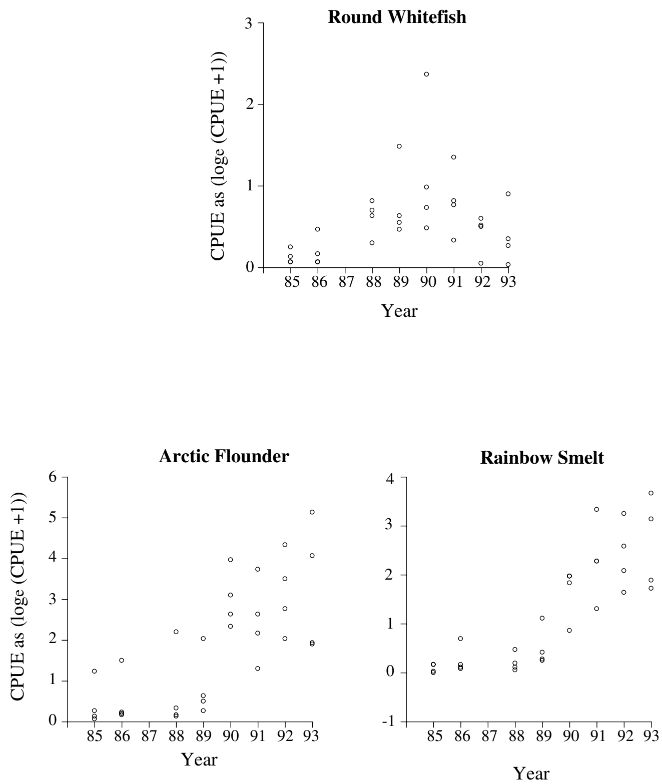

FIG. 4. Plots of mean seasonal abundance as catch per unit effort (CPUE) for round whitefish, arctic flounder, and rainbow smelt collected at the four baseline stations in the Prudhoe Bay region, Alaska, 1985–93. Actual CPUE data have been transformed to $\log_e$ (CPUE+1).

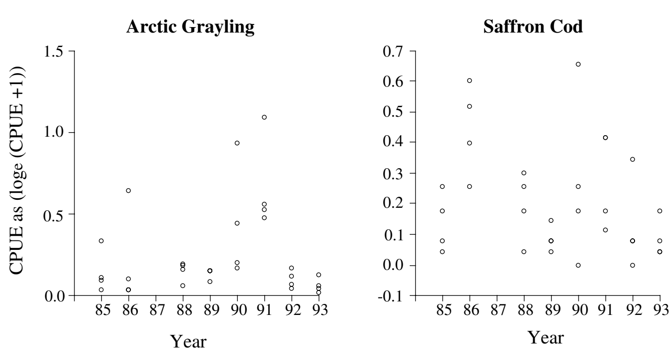

FIG. 5. Plots of mean seasonal abundance as catch per unit effort (CPUE) for arctic grayling and saffron cod collected at the four baseline stations in the Prudhoe Bay region, Alaska, 1985–93. Actual CPUE data have been transformed to $\log_e$ (CPUE+1).

shifts in temperature and salinity levels occurred over the same time period (see Fig. 2). The CPUE for saffron cod has shown yearly oscillations during the study period, which probably account for the non-normal CPUE data distribution for this species (Fig. 5). As with arctic flounder and rainbow smelt, no corresponding changes in the temperature and salinity levels occurred over the same time period. These results suggest that the observed changes in abundance levels for these species were independent of hydrography.

The non-normal distribution of the arctic grayling abundance data reflects the generally low levels between 1985 and 1989, followed by two years of high catches and a return to lower levels in 1992 and 1993 (Fig. 5). The high catches in 1990 appeared unrelated to temperature and salinity, since during this year neither was substantially different than in the years with low catches. However, in 1991, when catches were the highest, salinities were the lowest recorded (see above).

DISCUSSION

Wind is the primary factor governing open-water nearshore currents and temperature and salinity patterns along the Beaufort sea coast (Hufford and Bowman, 1974; Kozo, 1984; Niedoroda and Colonell, 1990; Gallaway et al., 1991; Hachmeister et al., 1991). Wind direction is primarily from the northeast and secondarily from the northwest. The prevailing east-west direction of the winds, along with river discharge and solar warming, creates a nearshore band of low-salinity or brackish water that is, on average, markedly warmer than water further offshore (Craig, 1984; Gallaway et al., 1991). The construction of the Endicott Causeway in the winter of 1984–85 caused concern that the new structure would alter the hydrographic characteristics of the nearshore band of water, in turn affecting its suitability for fish, and as a result changing the composition of the fish community.

The "causeway effect" is the result of a combination of wind-induced, coast-wide events and the local bathymetry around the causeway (Gallaway et al., 1991). Under persistent and strong east winds, coastal surface Beaufort Sea waters are transported offshore and are replaced by a return flow of cold, salty, bottom water (temperature $< 2.0^{\circ}$C; salinity $\geq 25‰$). These periodic upwellings bring marine bottom water to the surface along the coast where depths are 2 to 3 m or less (Gallaway et al., 1991). In the vicinity of the causeway, these events typically reach the surface for 3–5 days four to five times per open-water season, accounting for about 30% of that season (Niedoroda and Colonell, 1990; Gallaway et al., 1991).

Because its orientation is perpendicular to the currents generated by east winds, the causeway acts as a barrier to water movement, causing an eddy to form in the wake of its western tip (Gallaway et al., 1991). The circulation within this wake-eddy transports bottom water to the surface, where it is advected a short distance along the inside of the causeway. During upwelling events, the water column in the wake-eddy is nonstratified and consists entirely of the cold, salty, upwelled water that reached the surface naturally. The impact of the Endicott Causeway occurs only when the water mass in the area of the wake-eddy exhibits strong vertical stratification, an event caused by the warmer, fresher water from the Sagavanirktok River overlying the cold, marine bottom layer (Niedoroda and Colonell, 1990). In these cases, the wake-eddy transports the cold marine bottom water to the surface, where it is advected along the inside of the causeway. This situation occurs in about 4% of the upwelling events, and this low frequency provides some index of the magnitude of the effects from the Endicott Causeway (Gallaway et al., 1991).

Under west winds, surface waters are transported onshore; cold marine bottom water is downwelled away from shore and is not available for transport to the surface (Gallaway et al., 1991; Hachmeister et al., 1991).

On the basis of the 1985–87 Endicott oceanographic studies, it was hypothesized that this causeway-induced impact would displace the nearshore band of warm, brackish water in this area, causing the habitat to become marine (Ross, 1988). Thus, each post-construction year would be hydrographically similar to a naturally occurring harsh year, with an extended period when cold, salty water was present. Presumably, stenohaline fish would be excluded from this important feeding habitat and replaced by euryhaline species, thus altering the species community in the area. However, continued monitoring studies (from 1988 to 1993) showed that high salinity waters (> 25‰) rarely reached the surface, and for most of the season, high-salinity bottom water was not present in the lee of the causeway (Gallaway et al., 1991). Although the temperature and salinity patterns in the post-causeway period have varied, we found no significant relationship with year for temperature, and the significant relationship for year with salinity was in the opposite direction to that hypothesized by Ross (1988). In the case of temperature, despite the lack of a statistically significant difference, there appears to be a trend towards increasing temperatures with time. This trend, if real, is also opposite to that hypothesized by Ross (1988). What is clear is that the waters of the Sagavanirktok Delta have not become colder and more saline since the causeway was built, but rather have reflected coast-wide meteorological and oceanographic events that vary naturally among years.

Although post-construction trends in hydrography were nonsignificant for temperature and in the opposite direction for salinity, selected fish species abundance levels varied, sometimes showing dramatic increases with time. Ross (1988) hypothesized that site-specific changes in temperature and salinity at a given time, rather than average regional or seasonal changes, are of most immediate importance to the fish and may result in detrimental impacts over the years. Such changes could reduce the abundance of amphidromous and freshwater species and increase that of marine and brackish water species. The 1985–93 results do not show these patterns. The following species accounts discuss the available data in light of known life histories and measured hydrographic events.

Arctic Cod Abundance

Arctic cod is a widely distributed and abundant species in northern North American waters, occurring from the Bering Sea in the west, across the Arctic and down to the Labrador Sea in the east (Craig et al., 1982; Bradstreet et al., 1986). It is a key trophic species because of its importance in the diets of marine mammals, birds, and other fish species (Craig et al., 1982; Bradstreet et al., 1986). In the Beaufort Sea, the importance of nearshore habitats for young-of-the-year and juvenile arctic cod has been the subject of debate. Some authors have suggested that the warmer, lower-salinity nearshore waters are essential for arctic cod productivity (Cannon et al., 1991); others have found young-of-the-year, juvenile, and adult arctic cod in cold marine waters from 50–150 km offshore during the open-water season (Hunter, 1979; Lowry and Frost, 1981) and at least 175 km offshore during winter (Craig et al., 1982), which suggests a preference for offshore marine waters. Craig et al. (1982) suggested that arctic cod were infrequent visitors to nearshore habitats early in the open-water season, but that late in the summer some migrate into coastal waters. Arctic cod appear able to utilize a variety of habitats, a characteristic reflected by their wide distribution.

The abundance of arctic cod increased in the first three years after construction of the Endicott Causeway (Cannon et al., 1991), leading some to think that because of causeway-induced changes in local hydrography, arctic cod were moving into the nearshore habitat around the causeway and displacing other species (Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991). Although arctic cod abundance varied between 1985 and 1993, it did not increase over time (Fig. 2). Arctic cod abundance has also been highly variable at other Beaufort Sea locations (Craig et al., 1982; Underwood et al., 1995). Craig et al. (1982) reported an almost 200-fold increase in the numbers of arctic cod between 1977 and 1978 (767 vs. 139 790) in Simpson Lagoon, about 40 km west of Endicott. They also reported that this increase was not restricted to Simpson Lagoon but was observed elsewhere along the Beaufort Sea coastline. Arctic cod were also reported to be common in the Prudhoe Bay region in 1975 and 1976 (Bendock, 1977). In the Barter Island region, approximately 200 km east of Prudhoe Bay, there were significant differences in the among-year comparisons of arctic cod abundance between 1988 and 1991 (Underwood et al., 1995). These results suggested that the arctic cod abundance varies widely along the Beaufort Sea coast, and this same variability was evident in the Prudhoe Bay region both before and after construction of the causeway. Arctic cod do not appear to have exhibited a shift in habitat use as a result of causeway-induced changes in the temperature and salinity levels in the Sagavanirktok Delta area.

Fourhorn Sculpin Abundance

Fourhorn sculpin have a circumpolar distribution (Morrow, 1980). They are ubiquitous in virtually all Alaskan Beaufort Sea nearshore habitats, including the deeper waters not frequented by anadromous and amphidromous species (Craig et al., 1985; Cannon et al., 1987; Underwood et al., 1995). Fourhorn sculpin are not a valued subsistence or recreational resource and are considered a minor species despite their widespread distribution and abundance. Most studies provide only abundance-level data for this species. However, as they are a marine species, there was concern that causeway-induced changes in local hydrography could enhance conditions for fourhorn sculpin at the expense of stenohaline species (Ross, 1988).

Fourhorn sculpin abundance was significantly and positively related to salinity (Table 1). If the water in each post-construction year had tended to be more marine, then we would have expected consistently high abundance levels for this species. However, as reported, post-construction salinity patterns and fourhorn sculpin abundances have varied synchronously (Fig. 2), suggesting that causeway-induced effects do not appear to have altered the fourhorn sculpin abundance in the area.

Round Whitefish Abundance

Round whitefish is a freshwater species found throughout mainland Alaska from the panhandle north to the Arctic coast (Morrow, 1980). It occasionally ventures into nearshore coastal waters if salinities are very low (Craig, 1984). The Sagavanirktok River supports a population of round whitefish, and they are typically captured in low numbers at stations near the delta (Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991; Griffiths et al., 1995). If causeway-related or natural salinity levels had increased, we would have expected the abundance of round whitefish to decrease to the advantage of the more marine species. In this study, round whitefish abundance was significantly correlated with year and temperature, but this result was confounded by a significant year*temperature interaction (Table 1). A possible explanation is that the number of round whitefish entering nearshore waters varies each year, but once they are in nearshore waters, temperature is a major factor in determining their distribution and abundance. The important fact is that this species has not been excluded from the nearshore region, although its abundance has varied with time (Fig. 4). Round whitefish abundance did not show a continuous decrease in the post-construction years and appears to be independent of any causeway-induced hydrographic changes.

Arctic Flounder Abundance

The arctic flounder is a marine species that has a near circumpolar distribution (Morrow, 1980). Typically found in shallow coastal waters during the open-water season, it commonly enters low-salinity habitats (Walters, 1955; Morrow, 1980). Between the Colville River and Prudhoe Bay, abundance levels have been low compared to other marine, amphidromous, and anadromous species (Craig and Haldorson, 1981; Moulton et al., 1986; Cannon et al., 1987; Glass et al., 1990; Reub et al., 1991). We also found arctic flounder catch rates were relatively low during the first five post-construction years.

Starting in 1990, there was a step-change increase in CPUE that continued through 1993 (Fig. 4). A similar abrupt increase in abundance also occurred in 1990 near Barter Island, Alaska (Underwood et al., 1995). The length-frequency and age data from both areas suggest that the abundance increases resulted from a single, coast-wide event that was possibly linked to a high overwinter survival rate of the strong 1989 year-class. Most of the arctic flounder in the Endicott area in 1990 and thereafter are representatives of this year-class (LGL Alaska, unpubl. data).

The dramatic coast-wide increase in arctic flounder abundance five years after construction of the Endicott Causeway suggests that the increase was not caused by localized hydrographic patterns.

Rainbow Smelt Abundance

In Alaska, rainbow smelt are distributed from the Bering Sea north into the Arctic Ocean (Morrow, 1980). Little information on this species is available for the central Alaskan Beaufort Sea. Craig and Haldorson (1981) reported that rainbow smelt in this region are slow-growing and long-lived, reaching maximum sizes of 300 mm at ages 13 to 15. Earlier studies in the Prudhoe Bay area suggested that most of the rainbow smelt in the nearshore waters during the open-water season are small, immature fish (Craig et al., 1985).

The abundance patterns of rainbow smelt between 1985 and 1993 were similar to those of arctic flounder (Fig. 4). Catch rates were relatively low in the first five post-construction years, but abundance increased sharply in 1990 and remained high thereafter. This increase in abundance appears to have been a coast-wide event, as catch data from the Barter Island area also showed a trend of increasing abundance levels starting in 1990 (Underwood et al., 1995).

As with arctic flounder, rainbow smelt population increases appear to have been due to coast-wide phenomena, and were probably not correlated with causeway construction in the Prudhoe Bay region.

Saffron Cod Abundance

The Beaufort Sea is the northern limit of saffron cod distribution (Morrow, 1980; Craig and Haldorson, 1981). Although saffron cod are widespread along the Alaskan Beaufort Sea coast, two earlier studies in our study region had reported only low numbers, typically small fish 80–220 mm in length (Bendock, 1977; Craig and Haldorson, 1981). Our results showed that saffron cod abundance varied (Fig. 5), but numbers remained relatively low in all years compared to other marine species. No comparable data on the abundance of saffron cod are available for the Barter Island region. There are no obvious relationships between the abundance of this species and temperature or salinity levels (Figs. 2 and 5) in the Prudhoe Bay region.

Arctic Grayling Abundance

The arctic grayling is a freshwater species that inhabits most Alaskan North Slope rivers (Craig and McCart, 1975). In summer, they periodically enter brackish lagoons along the Beaufort Sea coast where salinities are 4‰ or less, presumably to feed and to migrate from one river system to another (West et al., 1992). Because the species is stenohaline, most of these forays occur early in the open-water season, when nearshore salinity levels are low.

As with round whitefish, if salinity levels had increased we would have expected grayling to be displaced from nearshore waters and replaced by more euryhaline species. During the 1985–93 monitoring program, grayling abundance levels varied with time, with low abundance from 1985 to 1989, followed by two years of increased abundance and then two more years of low abundance (Fig. 5). These fluctuations in arctic grayling abundance do not appear to be related to any causeway-induced hydrography changes.

SUMMARY

The nine-year time series of post-construction fish species composition and hydrographic conditions suggests that there has not been a shift in the abundance of the marine or freshwater species in the Prudhoe Bay region. There was no significant relationship between temperature and year within this period, while the significant salinity model suggested that salinities had moved in the direction opposite to that hypothesized. Several fish species showed changes in abundance levels in the post-causeway construction environment. The two clear cases involve the increased abundance of arctic flounder, a marine species, and rainbow smelt, an anadromous species. Both species appear to have undergone a sharp increase in abundance around 1989–90, and catch levels have remained high since then. Age data for arctic flounder and catch data for both species from other surveys in the Beaufort Sea suggest that the increases in abundance were broad-scale events along the Alaskan Beaufort Sea coast.

Fluctuations in fish species abundance in the Prudhoe Bay region over the period 1985–93 do not appear to have led to the hypothesized, causeway-induced shift toward dominance by marine species and a displacement of the less salt-tolerant species. Stenohaline freshwater species are still present in the area. Our data suggest that the year-to-year changes in abundance levels of fish are most likely the result of either naturally occurring events in the species' life histories or changes in coast-wide meteorological conditions, rather than a response to causeway-induced changes in the local temperature and salinity patterns.

ACKNOWLEDGEMENTS

We thank Dr. Kirk Lolman, Mike Link, and Jean Erwin for critically reviewing the manuscript. We also thank Dr. James Reynolds and two anonymous reviewers who provided many useful comments that greatly improved the manuscript. Monitoring studies were funded by the Endicott Development owners; Endicott is operated by BP Exploration (Alaska) Inc. We thank BP Exploration (Alaska) Inc. and the North Slope Borough for their continuing interest in determining the effects of coastal developments in northern Alaska. The conclusions and opinions expressed in this paper do not necessarily represent those of any of the above organizations.

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