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# Estimating the Hydrographic Effects of Prudhoe Bay Causeway Breaches Using the Before-After Control-Impact (BACI) Analysis

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ABSTRACT. A Before-After Control-Impact (BACI) analysis was used to test the effects of new breaches constructed in two Prudhoe Bay causeways on hydrographic conditions during the open-water summer season. At West Dock, under east wind conditions, significant cross-causeway differentials in salinity and temperature at the surface (1 m depth or less) were observed in all eight pre-breach cases tested. In the years following construction of the breach, there were no significant cross-causeway differentials in seven of those eight cases. At Endicott Causeway, under east wind conditions, significant cross-causeway differentials in surface salinity and temperature were observed in all eight pre-breach cases tested. Significant cross-causeway differentials continued in all eight cases following construction of the new breach. Results suggest that the new breach at West Dock has successfully mitigated cross-causeway hydrographic differentials, and that the new breach at the Endicott Causeway has had no observable effect. The possible reasons for this disparity include different hydrographic dynamics in the vicinity of each causeway.

Key words: breaching, causeways, hydrography, mitigation, Prudhoe Bay, water quality

RÉSUMÉ. On a procédé à une analyse de contrôle-incidence avant-après pour tester les effets de nouvelles brèches aménagées dans deux ponts-jetées de la baie Prudhoe sur les conditions hydrographiques durant la saison estivale d'eau libre. Au West Dock, par vent d'est, on a observé des écarts notables de part et d'autre du pont-jetée dans la salinité et la température de surface (jusqu'à 1 m de profondeur) dans les huit tests effectués avant l'aménagement de la brèche. Au cours des années suivantes, on n'a relevé aucun écart notable de part et d'autre du pont-jetée dans sept de ces huit cas. Au pont-jetée Endicott, par vent d'est, on a relevé d'importants écarts dans la salinité et la température de surface dans les huit tests datant d'avant la brèche. D'importants écarts de part et d'autre ont continué à se manifester dans les huit cas, après la construction de la nouvelle brèche. Les résultats suggèrent qu'au West Dock, la nouvelle brèche a réussi à atténuer les écarts hydrographiques, et qu'au pont-jetée Endicott, elle n'a pas causé d'effet observable. Parmi les raisons possibles de cette disparité, il faut compter une différence dans la dynamique hydrographique au voisinage de chaque pont-jetée.

Mots clés: aménagement de brèches, ponts-jetées, hydrographie, atténuation, baie Prudhoe, qualité de l'eau

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## INTRODUCTION

Oceanography and fishery studies have been conducted in the Prudhoe Bay region of Alaska since the late 1970s to evaluate possible effects of oil and gas development in the Beaufort Sea (e.g., Craig and Haldorson, 1981; Mangarella et al., 1982; Gallaway et al., 1983, 1991; Savoie and Wilson, 1983, 1986; Moulton et al., 1986; Hachmeister et al., 1987, 1991; Fechhelm et al., 1989; Niedoroda and Colonell, 1990; Short et al., 1990; Robertson, 1991; Griffiths et al., 1992, 1998; Morehead et al., 1992a, b, 1993). A major issue has been the construction of solid-fill, breached causeways along the coast and the effect they might have on the coastal habitats and feeding dispersals of diadromous fishes in the region (U.S. Army Corp of Engineers, 1980, 1984). Diadromous fishes overwinter beneath the ice in the rivers of Alaska's North Slope; during the ice-free summer season, they disperse out into brackish coastal waters to feed (Craig, 1989). Most species remain close to the coast and do not venture offshore into colder, marine waters. The concern is that causeways might impede alongshore dispersals either by directly blocking fish movements and migrations or by modifying nearshore water conditions to the point where they might become too cold and saline for these species (U.S. Army Corp of Engineers, 1980, 1984; Hale et al., 1989, Thorsteinson et al., 1991; Thorsteinson and Wilson, 1995).

The two major causeways in the Prudhoe Bay area are West Dock and the Endicott Causeway (Fig. 1). West

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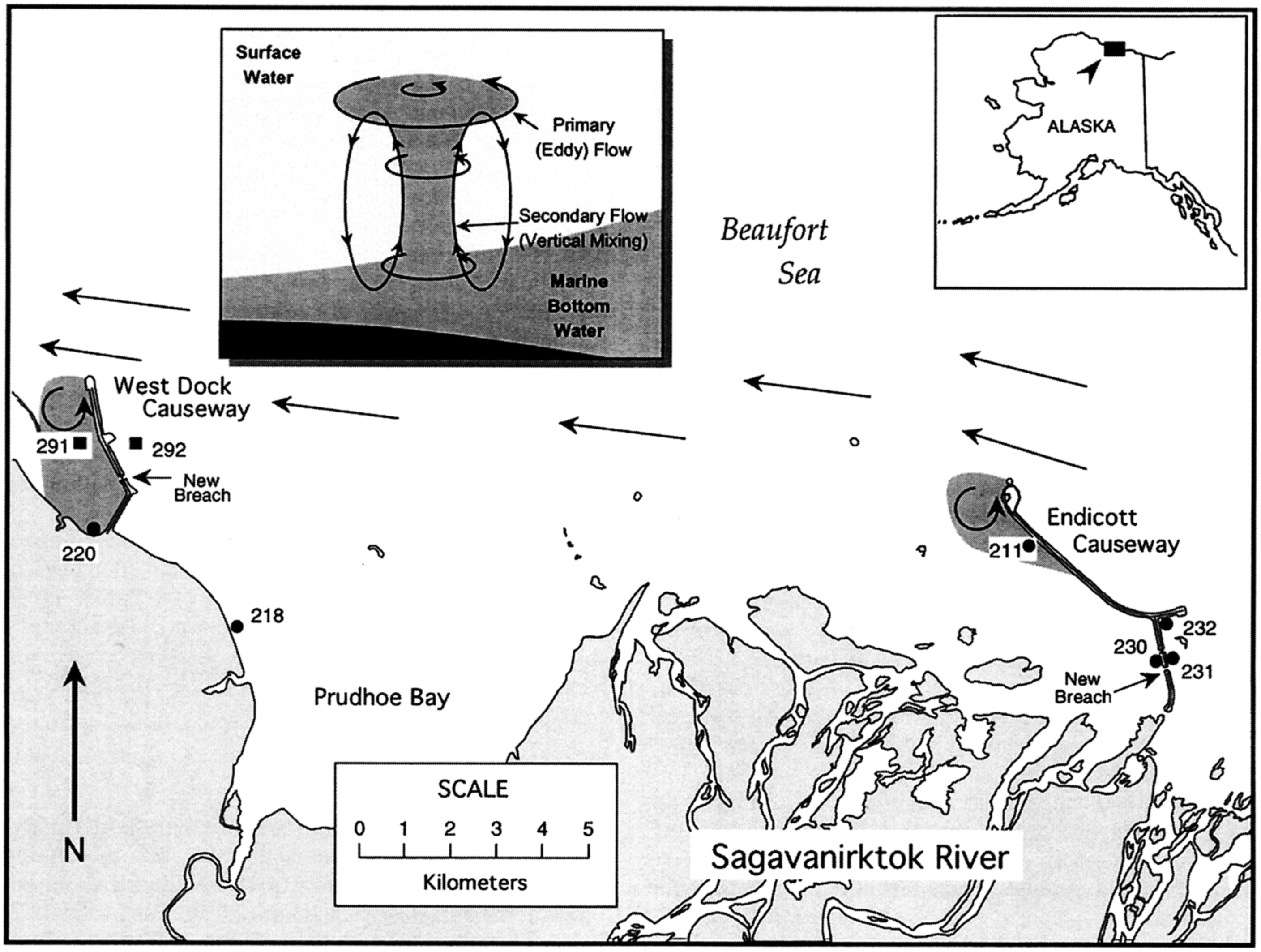


FIG. 1. The Prudhoe Bay region of the Alaskan Beaufort Sea. Hydrographic sampling sites are denoted by solid symbols. Circles are sites associated with fyke nets (≤ 0.5 m depth); squares were strictly water quality stations (≤ 2.0 m depth). BACI stations pairings are 211–232 and 230–231 at Endicott and 220–218 and 291–292 at West Dock. Approximate dimensions of the depicted marine cells are from Hachmeister et al. (1991) and Gallaway et al. (1991).

Dock, located at the western edge of Prudhoe Bay, was constructed incrementally during the winters 1974–75, 1975–76, and 1980–81. Its final configuration was 4.3 km long with a 15 m wide breach located 2.8 km offshore. Although the original breach was built as a passageway for fish, few fish actually used the breach because of its small size and location (Fechhelm et al., 1989). In recent years that breach has silted in, and no attempts have been made to dredge it open. In the winter of 1995–96, a new breach 61 m (200 ft) wide was constructed 1.5 km from the base of the causeway.

The Endicott Causeway was constructed east of Prudhoe Bay in the middle of the Sagavanirktok Delta during the winter 1984–85. The mainland segment of the causeway was initially built with a nearshore breach 152 m (500 ft) wide and an offshore breach 61 m wide to aid in fish passage and to maintain hydrographic continuity across the delta. A third breach, also 61 m wide, was added in the winter 1993–94 approximately midway between the two existing breaches.

Hydrographic conditions that develop in the vicinity of the Prudhoe Bay causeways during summer are the result of regional meteorological and oceanographic processes coupled with local bathymetric and river discharge features that are unique for each causeway (Neidoroda and Colonell, 1990). In early summer, river runoff and the melting of sea ice create brackish conditions (low to moderate salinities) in nearshore areas, particularly near the mouths of rivers. The relatively warm river discharges and heating by solar radiation elevate nearshore water temperatures. The resultant nearshore band of warm, low-salinity water is used by many diadromous fishes to move up and down the coast (Craig, 1984). As the summer progresses, mixing with cold ocean water causes the nearshore band to dissipate.

Nearshore coastal currents along the Beaufort Sea coast are governed primarily by winds. East winds generate westerly flowing surface currents that are deflected offshore in response to Coriolis forces (Niedoroda and Colonell, 1990). The offshore deflection of surface waters causes a depression in sea level (negative storm surge), which is partially compensated for by an onshore movement of underlying marine water. This marine layer is sometimes referred to as the "marine wedge." Conversely, west winds cause surface currents to flow eastward with a resultant onshore Coriolis deflection. The onshore transport of surface waters is balanced by a seaward movement of the marine wedge, resulting in regional downwelling along the coast.

At West Dock, easterly winds (westward flowing currents) generate a wake-eddy (i.e., gyre) on the lee (west) side of the causeway near its tip (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986) (Fig. 1). As the "marine wedge" moves onshore and encroaches on the distal part of the causeway, secondary circulation patterns within the wake-eddy draw colder marine water up to the surface, where it mixes with nearshore water. As a result, a cell of marine water (i.e., cold and saline) forms in the otherwise warm and brackish nearshore area immediately west of West Dock. At the same time, the surface plume of warm, low-salinity water from the Sagavanirktok River is transported to the west. West Dock diverts the plume seaward and prevents it from mixing with the marine water in its lee (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986). The net result is the development of cross-causeway hydrographic differentials in which waters on the west side of West Dock are colder and more saline than waters on the east side.

There is evidence that the marine cell that develops west of West Dock, in conjunction with the physical presence of the causeway itself, can block the coastal movements of some diadromous fishes (Fechhelm et al., 1989). With the new breach in place, it was hypothesized that easterly winds would transport the warmer, less saline water of the Sagavanirktok River plume through the breach from east to west, where it would mix with the cell of marine water, thereby diluting it and eliminating cross-causeway hydrographic differences. Dissolution of the marine cell and the presence of the breach could also allow fish to move unimpeded along the coast.

At the Endicott Causeway, upwelling and wake-eddy processes also occur under east winds. However, the spatial extent of the marine cell is largely limited to the inside western leg of the inter-island causeway segment extending several kilometers eastward (see Fig. 1). Freshwater discharge from the Sagavanirktok River prevents the cell from moving shoreward into the delta, so marine water does not reach the shore as it can under conditions that develop at West Dock.

The development of marine cells occurs only under east wind conditions. Under west winds, gyres develop on the east (lee) sides of the causeways; however, the winds also cause the "marine wedge" to move offshore, seaward of the causeways. Gyres thus mix warm, low-salinity surface water with warm, low-salinity bottom water and no marine cell develops.

Local hydrographic conditions in the Sagavanirktok Delta during east winds are determined by a different process. Westward and seaward deflection of the Sagavanirktok River plume contributes to the lowering of water levels in the delta, which is partially offset by the onshore movement of subsurface marine water into the eastern delta (Hachmeister et al., 1987; Short et al., 1990; Morehead et al., 1992a, b, 1993). Because the wake-eddy effect at the northwest tip of the causeway does not extend into the inner delta, the only marine influence within the delta is from ocean water moving in from the east. Typically, coastal waters to the east of the mainland segment of the Endicott Causeway are colder and more saline than waters to the west (Short et al., 1990; Morehead et al., 1992a, b, 1993). These conditions are the exact opposite of hydrographic differentials resulting from a wake-eddy. As was the case with West Dock, the new Endicott breach was installed to eliminate cross-causeway hydrographic differentials and protect essential fish habitat within the delta.

In this paper, we use a Before-After Control-Impact (BACI) model, described by Stewart-Oaten et al. (1986), and modified by Osenberg et al. (1994), Thrush et al. (1994), and Underwood (1994), to determine the effects of the newest West Dock and Endicott Causeway breaches on local hydrography in the vicinities of the causeways.

## METHODS

Much of the hydrographic data used in the BACI analyses were collected as part of summer fish monitoring surveys (see Fig. 1). Fyke nets, live-capture fishing devices, were operated each summer from 1985 to 1998 at various locations throughout the Prudhoe Bay area. Temperature and salinity data were recorded daily at each site at 0.5 m depth intervals. Yellow Springs Instruments® salinity/temperature meters were used from 1985 to 1988. From 1991 to 1998, data were collected using Hydrolab Surveyor III conductivity/temperature/depth meters. Meters were checked daily throughout each sampling season against salinity standards and standardized in-glass mercury thermometers. Meters that deviated by more than 2‰ or 1˚C from standard were removed from service.

Because fyke nets are set in shallow water, measurements were generally available at the surface (0.0 m) and at a depth of 0.5 m. During periods of high water (storm surges), measurements could be taken as deep as 1.0 m. In addition to the normal suite of fyke net stations, two hydrographic stations were monitored in deeper waters around West Dock in the summers of 1993 to 1998 (Stations 291 and 292; see Fig. 1). Vertical temperature and salinity profiles were measured daily at these sites at depths of 0.0, 0.5, 1.0, 1.5, and 2.0 m.

### *BACI Analysis*

The basic premise of the BACI model is that paired observations for a given parameter are collected at two

TABLE 1. Years in which stations were in operation.

| Area | Station | Year 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| West Dock | 218 | • | • | • | • | • | • | • | • | • | • | • | • | • | • |
| | 220 | • | • | | • | • | • | • | • | • | • | • | • | • | • |
| | 291 | | | | | | | | | • | • | • | • | • | • |
| | 292 | | | | | | | | | • | • | • | • | • | • |
| Endicott | 211 | | | | | | | • | • | • | • | • | • | | |
| | 230 | | | | | | | • | • | • | • | • | • | | |
| | 231 | | | | | | | • | • | • | • | • | • | | |
| | 232 | | | | | | | • | • | • | • | • | • | | |

sites prior to an expected environmental event (Stewart-Oaten et al., 1986; Osenberg et al., 1994; Thrush et al., 1994; Underwood, 1994). One site is located beyond the influence of the expected impact (control site), the other within its influence (impact site). The difference in parameter values between the two sites provides an index of their relationship. A priori paired measurements are taken to first establish the intra-site association. If there is no change in the interactive relationship between the two sites after the "impact" event occurs, it is concluded that no effect occurred.

The standard index value for our BACI analyses was calculated by subtracting the daily value of the parameter in question (i.e., temperature or salinity) for a station located east of the causeway (control) from the daily value recorded at the complementary station west (impact) of the causeway. For example, for any station pair, if salinity on a given day was 15.6‰ for the station west of a causeway and 23.4‰ for the complementary station east of the causeway, the index value for that day would be 15.6 - 23.4 = -7.8. Similar values were calculated daily for all station pairings for both temperature and salinity. Locations west of the causeways were considered impact sites because of the dynamics of the wake-eddy effect in which marine water cells develop west of the causeways.

For hydrographic data collected at fyke net sites, depth-averaged values of temperature or salinity were used. Stratification at these sites was nominal because of their location in shallow water (1.0 m deep or less): e.g., of 2279 paired (surface versus bottom) salinity measurements recorded over the period of record, salinity differentials of less than ± 0.5‰ occurred nearly 70% of the time, and temperature differentials of less than ± 0.5˚C nearly 86% of the time. At hydrographic stations 291 and 292, water depth was greater (2.0 m), and incidences of stratification were more common: e.g., surface to bottom salinity differentials were greater than 1‰ nearly 70% of the time and greater than 5‰ more than 25% of the time. Temperature differentials were greater than ± 1.0°C about 30% of the time. For these reasons, we analyzed surface and bottom values of temperature and salinity independently at the two deepwater sites.

Given the available stations and the underlying premise, the following pairings were used for the BACI analysis. At West Dock, the two onshore stations (220 [impact] and 218 [control]) yielded one pairing, while the two offshore stations (291 [impact] and 292 [control]) yielded two others, one at the surface and the other at the bottom. At the Endicott Causeway, the two most seaward stations (211 [impact] and 232 [control]) yielded one pairing, while the two interior delta stations (230 [impact] and 231 [control]) represented another. Because station pairings were in operation for different periods of time throughout 1985–98, BACI analyses were conducted across different time intervals depending upon the sampling history of each pairing (Table 1).

*Autocorrelation Analysis*

Pseudoreplication is a potential problem in repetitive sampling, with concurrent observations sometimes not being independent of each other (Stewart-Oaten et al., 1986). In general, repetitive samplings must be far enough apart in time for the dynamics of the system to shift within its normal range of variability. Although the nearshore waters of the Beaufort Sea can undergo rapid changes in temperature and salinity in conjunction with wind-driven coastal mixing processes, we questioned whether daily temperature and salinity conditions at our paired stations were truly independent.

Autocorrelation analysis (Wilkinson, 1989) was used to test for independence in temperature and salinity. A time series analysis of temperature or salinity measurements recorded at a single site during the summer was correlated against itself for differing periods of lag. Lag represents the number of days that a time series is offset from itself. For example, a time series correlated directly against itself (lag = 0) would have a perfect correlation of r = 1.0. Correlation coefficients (r) were calculated for the time series offset by lags of 1 day, 2 days, etc. through 20 days. Results from numerous time series were then combined. The underlying premise was to determine the lag needed for a mean r to approximate 0. Zero correlation was interpreted as independence in repetitive sampling, and the associated lag time was considered to be the sample interval required for independent observations.

Time series data included the daily depth-averaged values of temperature and salinity recorded at every fyke net and hydrographic station for every summer of sampling (Table 1). Missing data comprising two days or less in any time series were estimated assuming a linear relationship between nearest preceding and following data points. If temperature and salinity data were missing from three or more consecutive days, the time series was not analyzed.

Because the hydrographic character of coastal waters in the Beaufort Sea undergoes a pronounced change during the course of a summer as the nearshore band of warm brackish water mixes with Arctic Ocean water, we ran autocorrelation analyses for data collected both early (first 40 days of sampling) and late (last 40 days of sampling) in the season. Data collected in early and late seasons were analyzed to determine whether the seasonal cycle might affect the independence of the repetitive sampling.

*Wind Periodicity*

Because the wake-eddy phenomenon, upwelling, and the resultant cross-causeway hydrographic differentials are a function of prevailing winds, BACI values are likewise a function of meteorological conditions. Plots of BACI values versus corresponding mean daily wind speeds for the three station pairings at West Dock and the two pairings at Endicott are depicted in Figure 3. Hourly wind data collected at the Deadhorse Airport, Deadhorse, Alaska, were obtained from the National Climatic Data Center of the National Weather Service, Asheville, North Carolina. Wind data are recorded in terms of compass bearing and speed. These polar coordinates ($x$, Ø) were converted to linear coordinates ($x$, $y$), the ordinate ($x$) thus representing the east/west wind component in km•h$^{-1}$. Negative values represent winds from the west, positive values winds from the east. Hourly values of $x$ were averaged (1200 h to 1200 h) to yield net daily wind components.

The greatest cross-causeway hydrographic differentials developed during periods of east winds (see Fig. 2). (Results for the station 230–231 pairing were indeterminate.) The higher differentials were expected, given the dynamics of the upwelling and wake-eddy phenomena, which occur under east winds but not west winds.

Because of this meteorological disparity, we analyzed data collected during periods of east winds separately from data collected during west winds. Consider a summer in which pooled data for a given station pair were analyzed and yielded no significant cross-causeway differential in salinity. The conclusion would be that there was no causeway effect. Yet there might be a very real causeway effect: it's just that it occurs only under east winds. Pooling of the data could obscure such an effect by diluting the database with west wind (i.e., no effect) data.

At West Dock, there was also evidence of greater hydrographic differentials developing during periods of strong east winds (see Fig. 2). This trend was somewhat less evident at the Endicott Causeway. So as not to obscure any possible effects of either the wake eddies or the breaches by a preponderance of "weak" east wind events, we also conducted analyses on data collected solely during periods of strong east winds (> 10 km/h). If the breaches were going to negate the effects of the wake eddies, the effectiveness of this mitigation would be most severely tested during periods of strong east winds.

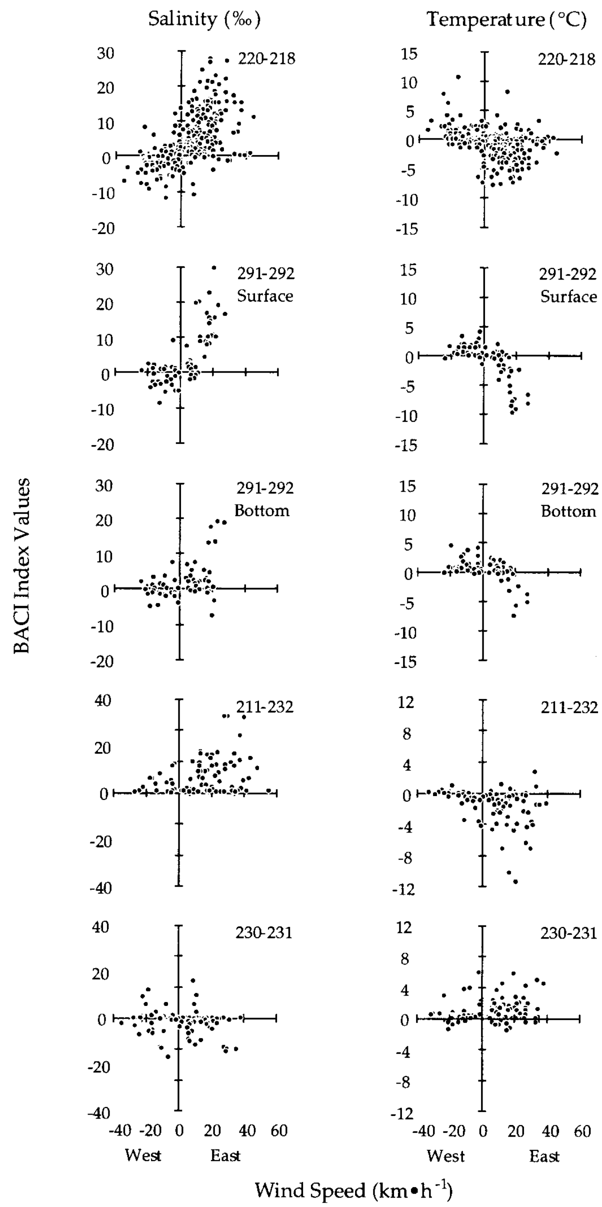


FIG. 2. Pre-breach salinity and temperature BACI values versus corresponding mean daily east/west wind speed for the five station pairings.

*Statistical Tests*

Preliminary analysis of BACI index values for all station pairings, either for single years or pooled over several years, indicated that, in most cases, the distributions of data (either raw or log$_e$-transformed) were significantly different from normal ($P \leq 0.05$; Lilliefors' test [Sprent, 1993]). Under the assumption of a symmetrical distribu-

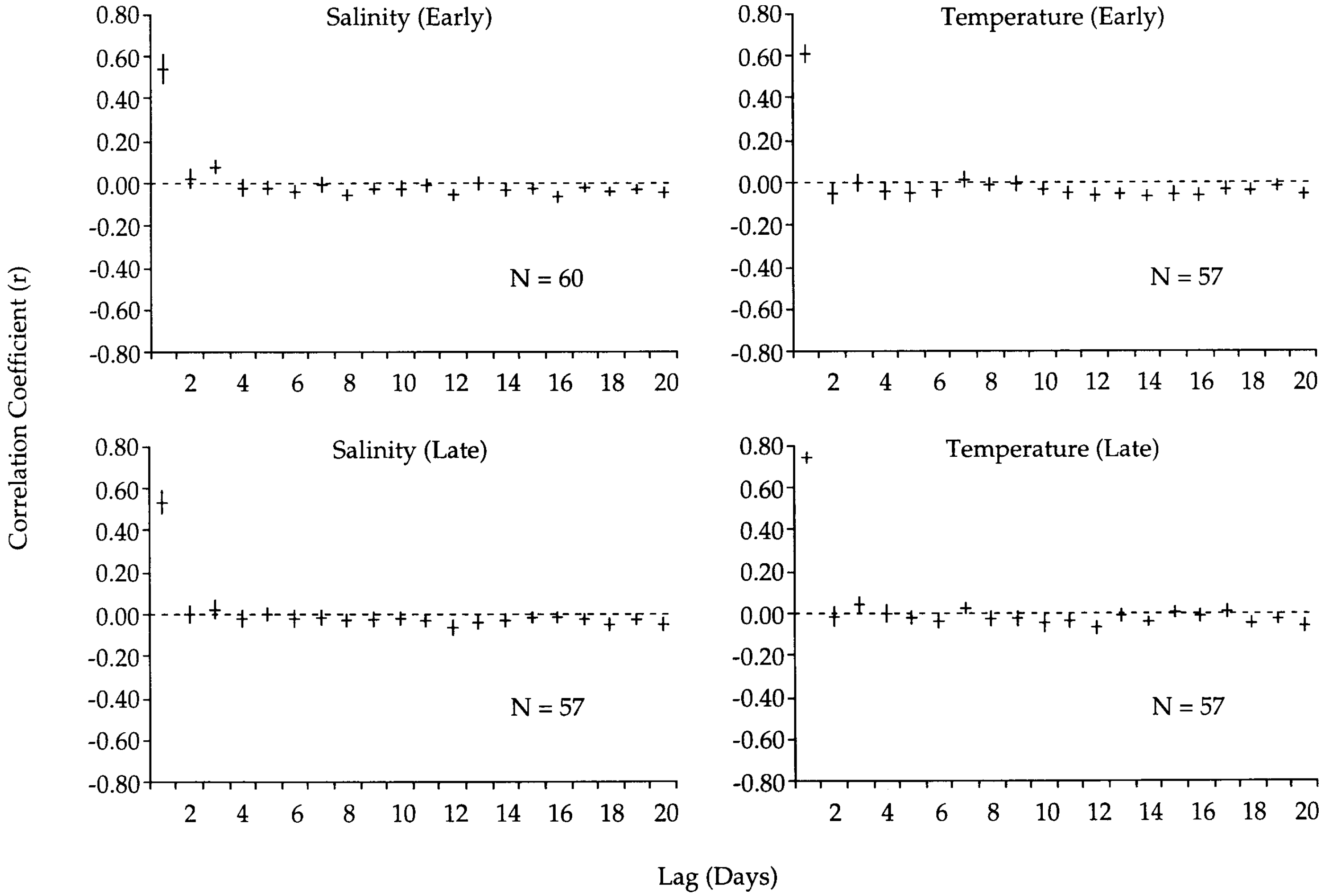


FIG. 3. Partial autocorrelation coefficients (mean ± 95 % CI) for temperature and salinity time series. Lag indicates the number of days between correlated observations. Each mean (± 95 % CI) is based upon N number of time series (i.e., all suitable station by year combinations recorded from 1993 to 1998).

tion, the nonparametric Wilcoxon signed-rank test (Sprent, 1993) was used to test the hypothesis $H_o$: $\mu = 0$ (against $H_A$: $\mu \neq 0$); that is, whether BACI index values for a given station pairing were different from zero. Rejection of $H_o$: implies that there was a significant cross-causeway differential for the case in question. A total of 60 BACI analyses (i.e., 60 Wilcoxon signed rank tests) were required to address all possible independent variable combinations: two physical variables, temperature (T) and salinity (S), by five station pairings, by two periods (before and after breaching), by three wind patterns (west winds, east winds, and strong east winds).

Note that statistical analyses were not designed to identify a significant change in cross-causeway T/S differentials before and after construction of the breaches; i.e., $H_o$: $\mu_{BEFORE} = \mu_{AFTER}$. Rather, statistical hypotheses were considered in terms of the intended effect of mitigation. Did the breaches eliminate cross-causeway differentials, not merely significantly alter those differentials? Thus the use of $H_o$: $\mu = 0$ (against $H_A$: $\mu \neq 0$) before and after breach construction.

The use of multiple statistical tests inflates the overall probability of committing a type-1 error; i.e., of incorrectly rejecting a null hypothesis within the entire group of tests. To correct for multiple test probabilities, we used the sequential Bonferroni adjustment (Holm, 1979; Rice, 1989) to establish a tabular level of statistical probability. In the sequential Bonferroni, the initial probability ($P$) of significance at the $\alpha = 0.05$ level is

$$P_1 = \alpha/\mathrm{k} \quad (1)$$

where k is the number of statistical tests. As described above, k = 60 for this study. Thus, the initial probability of rejecting the null hypothesis was $P_1$ = 8.33 E-4. If the test that yields the lowest $P$ (of the 60 Wilcoxon signed-rank test results) is less than $P_1$ = 8.33 E-4, it is considered significant. $P_2$ is then calculated as

$$P_2 = \alpha/\mathrm{k}\text{-}1 \quad (2)$$

(e.g., 0.05/59 = 8.47 E-4) and used to test for significance of the test with the second lowest $P$. If that value is less then 8.47 E-4, the result is considered significant. This process is iteratively applied to all 60 Wilcoxon $P$-values proceeding from lowest to highest until the next test in the

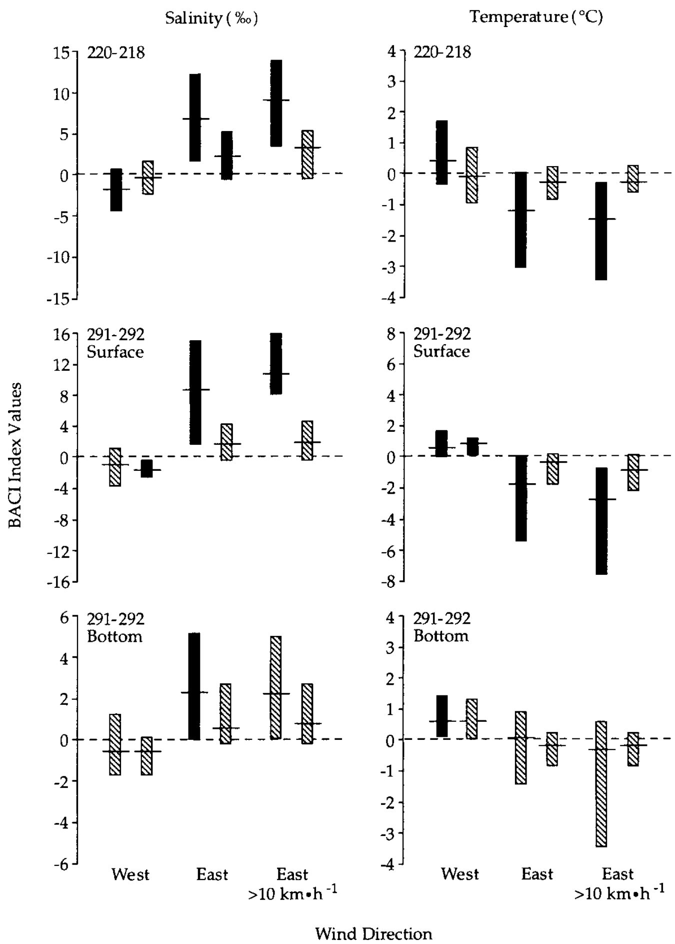


FIG. 4. Median and interquartile range of BACI index values for West Dock pairings under different wind conditions. Adjacent histogram pairs represent data before and after breach construction. Black bars denote data sets significantly different from zero (i.e., significant cross-causeway differential); cross-hatched bars denote data sets not significantly different from zero (i.e., no significant cross-causeway differential).

progression exceeds $P_l$. It and all other remaining tests with higher $P$ values are considered nonsignificant at the table-wide $\alpha$ level of 0.05. The advantage of the sequential Bonferroni is that it has greater statistical power than the standard Bonferroni method (e.g., $\alpha$/k for all tests).

## RESULTS

### *Autocorrelation*

Results of the autocorrelation analysis for all temperature and salinity time series are depicted in Figure 3. Each data point represents the mean r (± 95% CI) of N time series (all station-by-year combinations depicted in Table 1 minus several time series in which there were too many missing days to perform the analysis). The results of the autocorrelation analysis indicated that for all cases, the times series reached independence (i.e., began oscillating around a r = 0) in about two days. The same patterns were observed when West Dock data (stations 218, 220, 291, 292) and Endicott Causeway data (stations 211, 230, 231, and 232) were analyzed independently. Hydrographic data for all analyses were therefore limited to observations made at least two days apart.

### *West Dock*

Significant cross-causeway salinity and temperature differentials were observed under east wind conditions at station pairs 220–218 and 291–292 (surface) prior to construction of the breach (Fig. 4, Table 2). These results were consistent with the wake-eddy model; i.e., waters were more saline (positive differentials) and colder (negative differentials) west of the causeway during periods of east winds. These significant cross-causeway differentials were not observed after construction of the West Dock breach in seven of the eight cases tested.

For the station 220–218 pairing under west winds, there were significant salinity and temperature differentials prior to construction of the breach but none in the years following its installation (see Fig. 4, top panels). For station pairing 291–292 (surface), statistical tests provided no clear evidence of a breach effect. Surface waters at Station 291 were significantly warmer than at 292 prior to and following construction of the breach (see Fig. 4, middle panels). There was actually a significant negative salinity differential after construction of the breach where none had been observed before.

Bottom waters at the 291–292 (bottom) station pairing were less indicative of either a wake-eddy effect or a breach effect. Under east winds, there were no significant cross-causeway salinity or temperature differentials either before or after construction of the breach, with the exception of salinity in the east-wind, pre-breach case (see Fig. 4 [bottom panels], Table 2). Under west winds, there was no significant salinity differential either before or after installation of the breach. There was a significant positive temperature differential during west winds prior to construction of the breach and none afterward.

### *Endicott Causeway*

Under east wind conditions, there were significant pre-breach, cross-causeway salinity and temperature differentials at both the 211–232 and 230–231 station pairings (Fig. 5, Table 3). In every case, the same significant differentials were observed in the years following construction of the new Endicott breach. Hydrographic conditions under west winds were less clear and somewhat inconsistent with the underlying theory. There were no significant pre-breach cross-causeway salinity differentials at stations 211–232, but there were significant differentials after construction of the breach. At pairing 211–232, there was a significant temperature differential prior to breach construction and no differential afterward. At pairing 230–231, there was no significant temperature differential either before or after construction of the breach.

TABLE 2. Results of Wilcoxon signed-rank tests of BACI index values before and after construction of the new West Dock breach for different station pairings and depths. Probabilities denoted by asterisks indicate a significant difference subsequent to sequential Bonferroni adjustments to all test probabilities under the $\alpha = 0.05$ level criterion.

| Station Pair | Parameter | Period | Year | Wind Direction | N | $H_o$: $\mu = 0$ Probability |
|---|---|---|---|---|---|---|
| 220–218 | Salinity | Before | (1985–1995) | West | 86 | 1.20 E-3* |
| | | | | East | 170 | < 1.00 E-9* |
| | | | | East (>10 km•h$^{-1}$) | 112 | < 1.00 E-9* |
| | | After | (1996–1998) | West | 34 | 5.16 E-1 ns |
| | | | | East | 37 | 2.61 E-4* |
| | | | | East (>10 km•h$^{-1}$) | 24 | 6.36 E-3 ns |
| | Temperature | Before | (1985–1995) | West | 87 | 1.57 E-3* |
| | | | | East | 173 | < 1.00 E-9* |
| | | | | East (>10 km•h$^{-1}$) | 114 | < 1.00 E-9* |
| | | After | (1996–1998) | West | 35 | 6.13 E-1 ns |
| | | | | East | 36 | 1.27 E-2 ns |
| | | | | East (>10 km•h$^{-1}$) | 23 | 7.13 E-2 ns |
| 291–292 Surface | Salinity | Before | (1993–1995) | West | 27 | 6.32 E-2 ns |
| | | | | East | 36 | 1.72 E-6* |
| | | | | East (>10 km•h$^{-1}$) | 22 | 4.60 E-5* |
| | | After | (1996–1998) | West | 32 | 2.38 E-4* |
| | | | | East | 35 | 6.55 E-3 ns |
| | | | | East (>10 km•h$^{-1}$) | 21 | 7.36 E-2 ns |
| | Temperature | Before | (1993–1995) | West | 27 | 9.04 E-4* |
| | | | | East | 33 | 2.85 E-4* |
| | | | | East (>10 km•h$^{-1}$) | 22 | 2.00 E-4* |
| | | After | (1996–1998) | West | 32 | 3.67 E-5* |
| | | | | East | 35 | 5.00 E-3 ns |
| | | | | East (>10 km•h$^{-1}$) | 22 | 3.92 E-2 ns |
| 291–292 Bottom | Salinity | Before | (1993–1995) | West | 27 | 3.74 E-1 ns |
| | | | | East | 34 | 3.12 E-4* |
| | | | | East (>10 km•h$^{-1}$) | 23 | 6.38 E-3 ns |
| | | After | (1996–1998) | West | 32 | 1.63 E-2 ns |
| | | | | East | 32 | 1.10 E-2 ns |
| | | | | East (>10 km•h$^{-1}$) | 18 | 4.28 E-2 ns |
| | Temperature | Before | (1993–1995) | West | 30 | 4.30 E-5* |
| | | | | East | 29 | 7.16 E-1 ns |
| | | | | East (>10 km•h$^{-1}$) | 18 | 7.58 E-2 ns |
| | | After | (1996–1998) | West | 23 | 9.07 E-3 ns |
| | | | | East | 29 | 6.71 E-2 ns |
| | | | | East (>10 km•h$^{-1}$) | 16 | 2.00 E-1 ns |

## DISCUSSION

Results of the BACI analysis at West Dock were generally consistent with the wind-driven mechanisms of the wake-eddy phenomenon and flow dynamics in the vicinity of the causeway. The most consistent patterns in cross-causeway salinity and temperature differentials occurred during periods of east winds. Among station pairings 220–218 and 291–292 (surface), there were significant pre-breach cross-causeway differentials in temperature and salinity in all eight cases examined. These differentials were eliminated in seven of the eight cases following construction of the breach, including all four of the "strong" east wind cases. Although test results for west wind cases were varied and showed no clear pattern, they were not inconsistent with underlying theory, since the wake-eddy marine cell does not develop during periods of west winds. In the absence of east winds, the principal force driving the cross-causeway hydrographic differentials is eliminated. Water conditions would then be influenced to a greater degree by other natural factors, such as solar heating, freshwater runoff, and localized currents.

Analysis of bottom water differentials at West Dock station pairing 291–292 (bottom) provided no clear indication of either a wake-eddy or breach effect. These results are likely attributable to the fact that part of the cross-causeway hydrographic differential that develops at West Dock is caused by the low-salinity, warm-water surface plume from the Sagavanirktok River, which flows into the eastern face of the causeway during periods of east winds (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986). Deeper water, including the marine wedge moving shoreward along the eastern face of West Dock, would be less affected by these surface conditions.

Even with the new breach at West Dock, waters west of the causeway are still slightly colder and more saline during east winds (see Fig. 4). This pattern may reflect a residual wake-eddy effect; i.e., upwellings still occur, and substantial portions of the freshwater plume approaching from the east are deflected around the seaward tip of the causeway. East-west differentials may also be caused by natural influences unrelated to the causeway. In the complete absence of West Dock, Station 218 might be warmer and less saline relative to Station 220 simply because it is located closer to the plumes of the Putuligayuk and Sagavanirktok Rivers (see Fig. 1). This argument is less compelling for stations 291 and 292 because of their closer

TABLE 3. Results of Wilcoxon signed-rank tests of BACI index values before and after construction of the new Endicott breach for the two station pairings. Probabilities denoted by asterisks indicate a significant difference subsequent to sequential Bonferroni adjustments to all test probabilities under the $\alpha = 0.05$ level criterion.

| Station Pair | Parameter | Period | Year | Wind Direction | N | $H_o$: $\mu = 0$ Probability |
|---|---|---|---|---|---|---|
| 211–232 | Salinity | Before | (1991–1993) | West | 26 | 7.35 E-3 ns |
| | | | | East | 64 | < 1.00 E-9* |
| | | | | East (>10 km•h$^{-1}$) | 37 | 6.76 E-7* |
| | | After | (1994–1996) | West | 37 | 4.78 E-7* |
| | | | | East | 51 | < 1.00 E-9* |
| | | | | East (>10 km•h$^{-1}$) | 34 | 3.64 E-7* |
| | Temperature | Before | (1991–1993) | West | 30 | 1.39 E-3* |
| | | | | East | 57 | 8.00 E-9* |
| | | | | East (>10 km•h$^{-1}$) | 33 | 1.66 E-5* |
| | | After | (1994–1996) | West | 38 | 7.22 E-3 ns |
| | | | | East | 49 | 4.29 E-8* |
| | | | | East (>10 km•h$^{-1}$) | 32 | 7.19 E-5* |
| 230–231 | Salinity | Before | (1991–1993) | West | 28 | 9.1 E-2 ns |
| | | | | East | 64 | 3.84 E-7* |
| | | | | East (>10 km•h$^{-1}$) | 35 | 4.23 E-6* |
| | | After | (1994–1996) | West | 34 | 7.01 E-5* |
| | | | | East | 42 | 1.14 E-6* |
| | | | | East (>10 km•h$^{-1}$) | 32 | 3.79 E-6* |
| | Temperature | Before | (1991–1993) | West | 34 | 1.41 E-1 ns |
| | | | | East | 59 | 5.81 E-6* |
| | | | | East (>10 km•h$^{-1}$) | 37 | 7.35 E-4* |
| | | After | (1994–1996) | West | 33 | 3.26 E-3 ns |
| | | | | East | 41 | 9.97 E-7* |
| | | | | East (>10 km•h$^{-1}$) | 29.000 | 2.16 E-5* |

proximity. Nevertheless, the fact that significant cross-causeway hydrographic differentials were almost entirely eliminated indicates that the new breach is effective mitigation and reaffirms that the causeway was responsible for the cross-causeway differentials in the first place.

In summary, results of the BACI analyses for West Dock indicate that the breach has mitigated cross-causeway hydrographic differentials that develop during periods of east winds. This mitigation likely results from warm, low-salinity water flowing westward through the breach and diluting the marine cell located just west of the causeway. Although hydrographic differentials have not been completely eliminated, they are no longer statistically significant. Mitigation appears to have been successful in its primary goal by eliminating conditions that block the alongshore migrations of diadromous fishes. Less severe hydrographic conditions, coupled with the new breach serving as a nearshore passageway, could enable more unrestricted fish movement along the coast. There is evidence that one species of fish has already extended its coastal distribution subsequent to installation of the breach (Fechhelm, 1999).

Results of the BACI analysis at the Endicott Causeway suggest that installation of the new breach had no discernible effect on local hydrography. Among station pairings 211–232 and 230–231, there were significant pre-breach cross-causeway differentials in temperature and salinity in all eight east-wind cases examined. None of these differentials were eliminated following construction of that causeway's breach. However, the situation at the Endicott Causeway is different from that at West Dock. The Endicott wake-eddy phenomenon is limited to the seaward tip of the

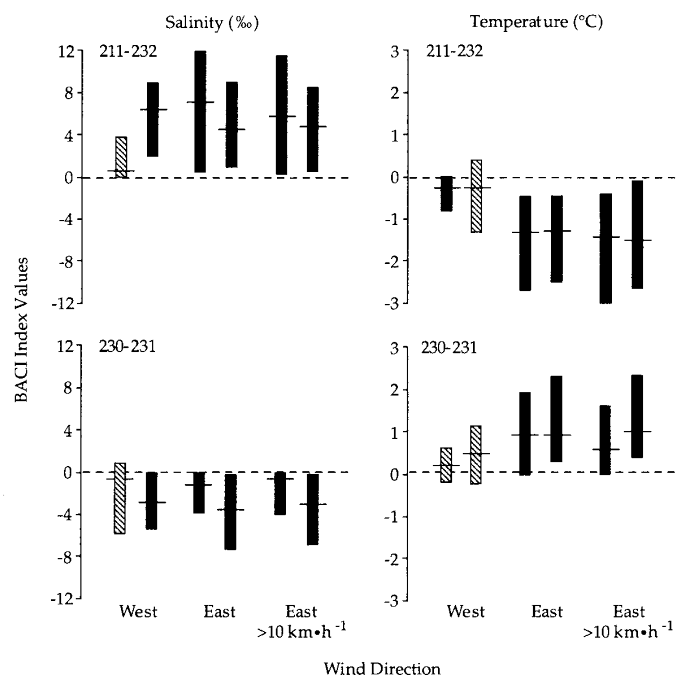


FIG. 5. Median and interquartile range of BACI index values for Endicott pairings under different wind conditions. Adjacent histogram pairs represent data before and after breach construction. Black bars denote data sets significantly different from zero (i.e., significant cross-causeway differential); cross-hatched bars denote data sets not significantly different from zero (i.e., no significant cross-causeway differential).

western leg of the inter-island causeway, isolated more than 2 km from any of the breaches. Breach effectiveness, relative to dilution of the marine cell, would be compromised by distance. It is even reasonable to argue that the

211–232 comparison is not an adequate measure of breach effectiveness at the Endicott Causeway, since the effects of mitigation would be limited to the inner areas of the delta and would not be expected to affect conditions at 211 and thus the 211–232 BACI analyses. (Station 211 was specifically positioned to sample within the localized marine cell.)

It is uncertain why the hydrographic differentials at stations 230–231 continued after construction of the new breach. Of all the station pairings, stations 230 and 231 are physically the closest, separated by a distance of approximately 300 m. Their proximity suggests that the significant hydrographic differentials recorded at this pairing are causeway-related. One possible reason for the continued differentials, despite a total of 264 m of breaching, may be station location. Station 230 is located against the western face of the causeway between the two 61 m breaches and is partially sheltered from marine water flowing westward through the breaches. By contrast, Station 231 would be fully exposed to marine waters entering the delta from the east.

The contrasting results of the BACI analyses at West Dock and the Endicott Causeway indicate that the underlying hydrographic characteristics of specific coastal regions may be a crucial element in monitoring water quality conditions in the vicinity of causeways. The wake-eddy phenomenon and the unidirectional influence of the Sagavanirktok River plume are the dominant factors in determining T/S conditions at West Dock during periods of east winds (Mangarella et al., 1982; Savoie and Wilson, 1983, 1986; Niedoroda and Colonell, 1990). The spatial extent and the contrasting hydrographic character of these two forces create distinct east/west discontinuities that are quite pronounced in the area around West Dock and allow for considerable flexibility in the location of sampling sites. The West Dock breach is able to mitigate T/S differentials because of the configuration and location of the marine cell. The breach is positioned so that water flowing westward through it empties directly into the marine cell, thereby maximizing the potential for diluting the cold, saline water with warmer freshwater from the Sagavanirktok River plume.

Conditions at the Endicott causeway are different. The marine cell that develops along the western leg of the causeway is localized and does not dominate the area east of the causeway, even under extreme east wind conditions. Further, the diluting influence of river discharge affects waters on both sides of the causeway. Thus, the two unidirectional forces (marine water to the west; river plume to the east) that dominate conditions at West Dock do not occur with the same intensity around the Endicott Causeway. In the absence of these two major forces, hydrography within the Sagavanirktok Delta is influenced by more subtle determinants, including solar heating, localized currents, disproportionate freshwater runoff, and bathymetry. Unlike the area around West Dock, which can be overwhelmed by the wake-eddy/plume phenomenon, the more subtle hydrographic dynamics of the Sagavanirktok Delta are more likely to create fine-scale spatial T/S discontinuities. Hydrographic measurements taken in a deepwater channel versus those from a nearby mud flat could result in substantial T/S differentials regardless of the presence of a causeway.

The contrasting results of the BACI analyses at West Dock and the Endicott Causeway mirror the contrasting hydrographic dynamics associated with each causeway. Results at West Dock appear consistent with underlying theory, but this may have occurred merely because of the overwhelming intensity of conditions that develop around the causeway under east winds. Areas characterized by more subtle hydrographic forces could make sample site location a more critical issue in designing oceanographic studies of future causeways and could even preclude side-of-causeway analyses unless the dynamics of the system are reasonably understood.

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