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Regime Shift in the Gulf of Maine

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Abstract.—Conventional wisdom, based on observations spanning two and a half decades (1975–2000), asserts that inflow to the Gulf of Maine (GoM) occurs primarily in two areas: inshore on the Scotian Shelf off Cape Sable, Nova Scotia and on the eastern side of the Northeast Channel (NEC). In particular, the monthly mean currents in the eastern NEC have shown persistent inflow at all depths and in all seasons, except for the occasional, but brief, reversals near the bottom (~200 m). Conversely, the flow on the western side of the NEC is normally directed out of the gulf in the surface layer and at mid-depth, consistent with the clockwise gyre over Georges Bank, but those currents do show relatively frequent reversals to inflow in the deeper layers (150–200 m), in sympathy with the flow on the eastern side. At some point between the year 2000, when the last Bedford Institute of Oceanography (BIO)/U.S. GLOBEC mooring was removed from the eastern NEC, and 2004, when a new mooring was placed there as part of the U.S. ocean observing array, a transformation occurred. The recent data, collected from a representative location in the eastern NEC, show a strongly seasonal current signal marked by persistent periods of outflow in the deep layers (>100 m), particularly in winter. This observation was first reported by Pettigrew et al. (2008), where the outflow currents occasionally extend to the surface layers as well, most notably in the winters of 2004–2005 and 2006–2007. Additional data and analyses reported here suggest that this new mode of behavior in the NEC currents could have important consequences for the GoM ecosystem. Possible causes for this "regime shift" in the NEC circulation and implications for the GoM deepwater nutrient fields and ecosystem are discussed.

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Introduction

Background

Studies of the circulation in the GoM during the 1970s and 1980s suggest that the primary inflows were located in the nearshore region of the Scotian Shelf off Cape Sable (CS; Smith 1983, 1989) and in the deep and shallow layers on the eastern side of the Northeast Channel (NEC; Ramp et al. 1985; Smith et al. 2001; see Figure 1). These results, along with other historical hydrographic surveys (e.g., Bigelow 1927; Brooks 1985) led to the conception of a three-component mechanism for the exchange of shelf and offshore waters in the NEC (Brooks 1992). According to this model, the bottom layer consists of warm, saline, nutrient-rich slope water, which hugs the eastern side of the NEC as it moves into Georges basin but intermittently extends across the channel, causing deep inflow there as well. On average, the top of the deep inflow layer (as indicated by the 34 g/kg isohaline contour) generally lies between 75 and 100 m on the eastern side of the NEC and descends to 125–150 m on the west. Occasional reversals of the deep inflow appear to be associated with wind forcing and/or events in the slope water (e.g., impingement of Gulf Stream warm core rings; Bisagni and Smith 1998; Smith et al. 2001) and can have significant impacts on both the heat and salt budgets, as well as plankton bloom timing and dynamics (Townsend and

General Circulation During Stratified Season

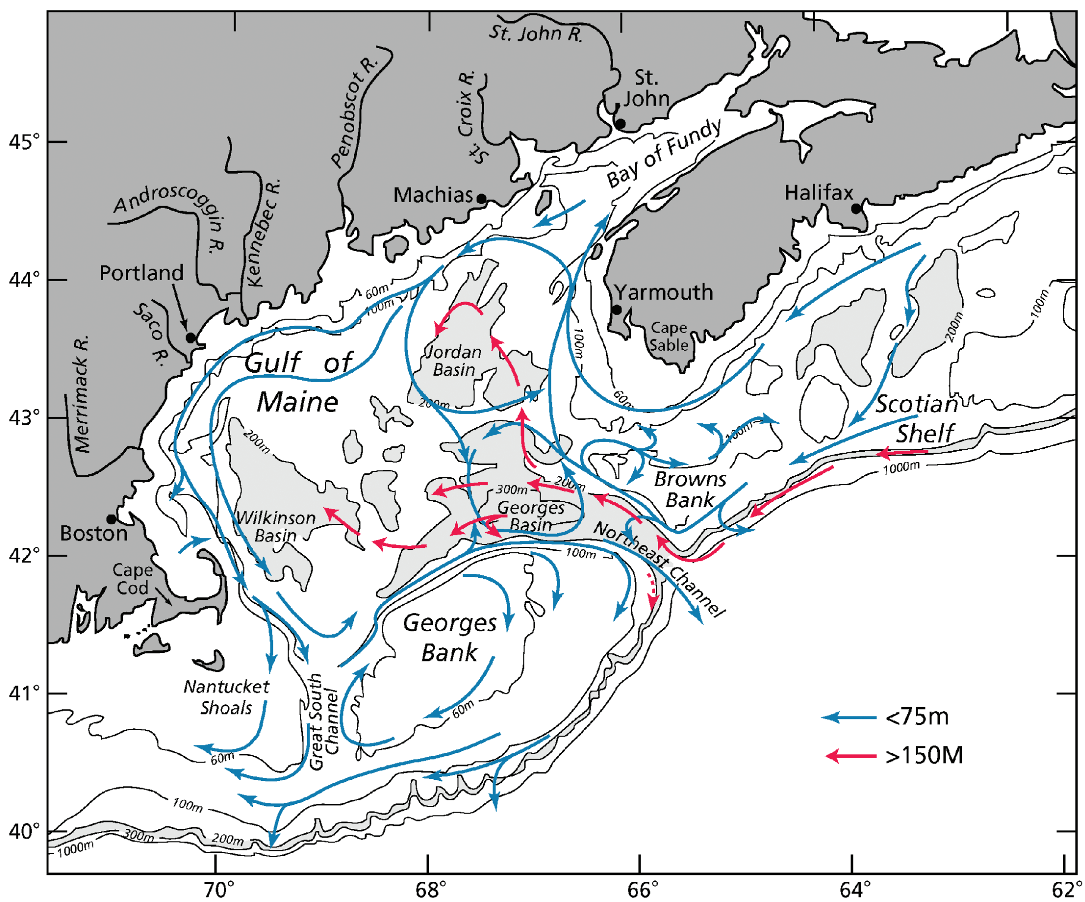


FIGURE 1. Schematic diagram of surface layer (blue arrows) and deep layer (red arrows) circulation in the Gulf of Maine during the stratified season (courtesy of Butman and Beardsley 1992).

Spinrad 1986) of the gulf. Above the slope water on the east, cool, fresh Scotian Shelf water moves into the Gulf of Maine (GoM), while on the western side, the flow is persistently outward, consisting primarily of Maine surface and intermediate water (Brooks 1992). The pattern of axial currents near the sill of the NEC is revealed by the average from a set of vessel-mounted Acoustic Doppler Current Profiler (ADCP) transects collected over a full M2 tidal cycle in June 1994 (Figure 2). During this period, the inflow currents were confined roughly to the eastern half of the NEC, which appears to be the prevailing pattern according to U.S. GLOBEC average currents at selected depths from 1993 to 1995 (Figure 3). Axial currents deeper than 125 m on the western side of the NEC were highly intermittent, with an overall mean of roughly zero. During the 1990s, the U.S. GLOBEC Georges Bank Program sponsored a wide variety of comprehensive biophysical observations in the GoM with a natural focus on Georges Bank. Among these were current meter and hydrographic measurements in the NEC designed to monitor exchanges between "upstream" (Scotian Shelf) and "offshore" (slope and Gulf Stream) waters and those of the GoM (Figure 3). In the period 1993–1996, Smith et al. (2001) noted a distinct change in the interannual variability of the inflow regime from enhanced warm, saline deep (>75 m) inflow in the eastern NEC to a time of predominant cold, fresh inflow episodes in the shallow layers off CS and in the NEC during 1995–1996. Moreover, the transport anomalies at CS and in the NEC were found to be generally out of phase, that is, increased inflow at CS was associated with reduced inflow in the deep NEC and cooler, fresher conditions at both sites and, conversely, increased flow of deep NEC water was associated with reduced inflow at CS and warmer and saltier conditions.

Smith et al. (2001) used a simple box model to estimate the influence of the observed changes in boundary fluxes on the mass and salt balances within the GoM. Comparing the last (April 1995–September 1996) to the first (October 1993–March 1995) half of the measurements, they found that the volumetric flow rate through the GoM had increased by 10^5 m^3/s (roughly 17%) and that enhanced freshwater fluxes in the surface layer had produced a decrease of 0.73 in the salinity of the outflow waters. Furthermore, the estimated CS

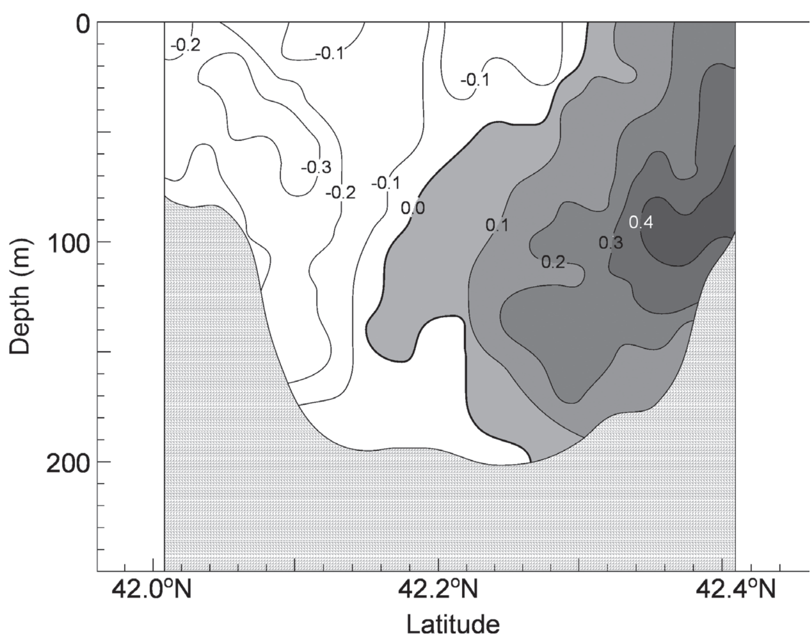


FIGURE 2. Mean axial (305°T) current component derived by averaging data over a series of vessel-mounted Acoustic Doppler Current Profiler (ADCP) transects near the sill of the Northeast Current during June 1994 (inflow: shaded gray, outflow: white).

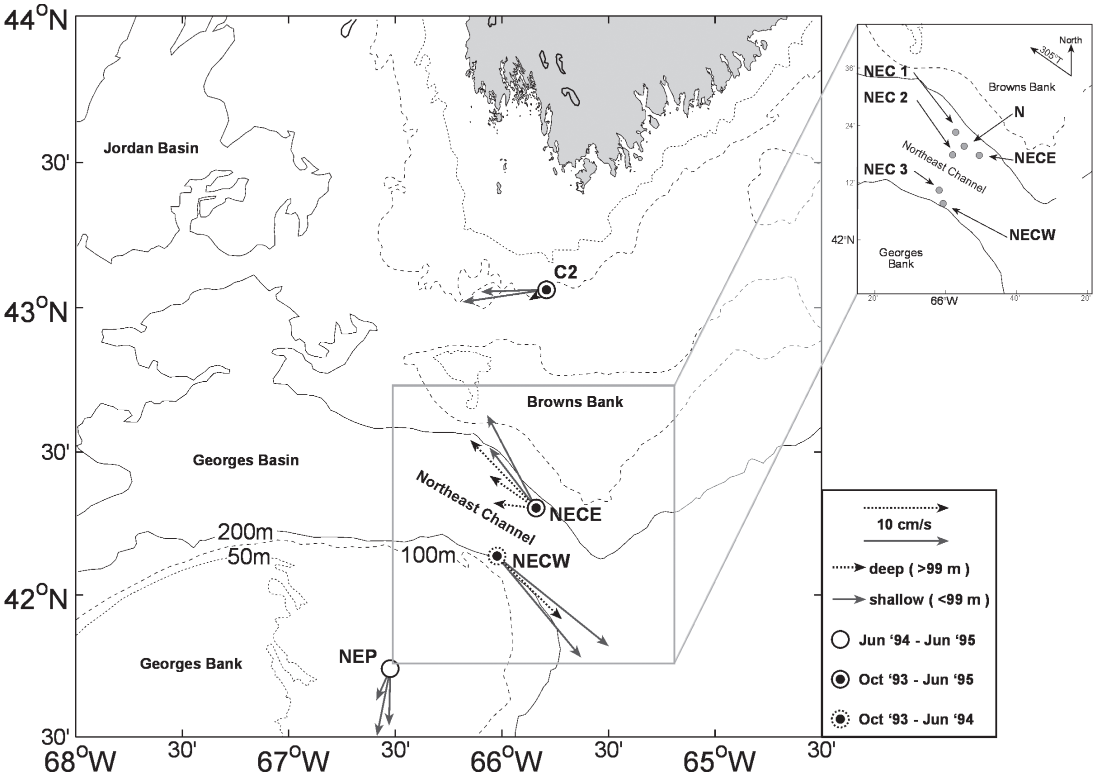


FIGURE 3. Long-term average currents collected during October 1993 to June 1995. Eastern (NECE) and western (NECW) moorings in the Northeast Channel (NEC) lie on the 200-m isobath near the sill. The xa Sable mooring (C2) lies on the 110-m isobath inshore. Inset—Locations of historical moorings in Northeast Channel, including NEC 1–3: 1977–1978 (Ramp et al. 1985), NECE–NECW: 1993–1999, GLOBEC moorings sites (Smith et al. 2001), and Buoy N: 2004–2008 NERACOOS (Northeast Regional Association for Coastal Ocean Observing Systems) mooring site (Pettigrew et al. 2008).

transport (297 × 10^3 m^3/s) was roughly twice that calculated by Smith (1983) for the 1979–1980 period (140 × 10^3 m^3/s), whereas the deep NEC transport (143 × 10^3 m^3/s) was slightly more than half that found by Ramp et al. (1985) for the 1977–1979 period (260 × 10^3 m^3/s). Nevertheless, the estimated average volumetric flow rate through the system over this period (563 × 10^3 m^3/s) is close to the climatological mean value of Loder et al. (1998) (500 × 10^3 m^3/s). For purposes of this paper, that level of interannual variability in boundary mass fluxes will be considered "normal."

More recently, scientists from the University of Maine have maintained (first on behalf of GoMOOS [Gulf of Maine Ocean Observing System]; now for NERACOOS [Northeast Regional Association for Coastal Ocean Observing Systems]) a single mooring on the eastern side of the NEC, in close proximity to both the GLOBEC and Ramp mooring sites (Figure 3 inset). Among other instrumentation, this mooring contains a long-range ADCP for monitoring currents over the water depths from 8 to 202 m and a surface current meter at 2 m. Recent hydrographic and nutrient data from an NEC transect near the sill suggest that the elements of the three-component exchange process are still in place (Figure 4), although aliasing by the strong tidal currents may obscure the true average properties. Here, we report results from this new mooring in comparison with results from the previous studies. We calculate boundary fluxes and annual cycles of flow in the NEC and estimate with a box model changes in mass balance. Finally, we discuss possible causes and ecosystem-level impli-

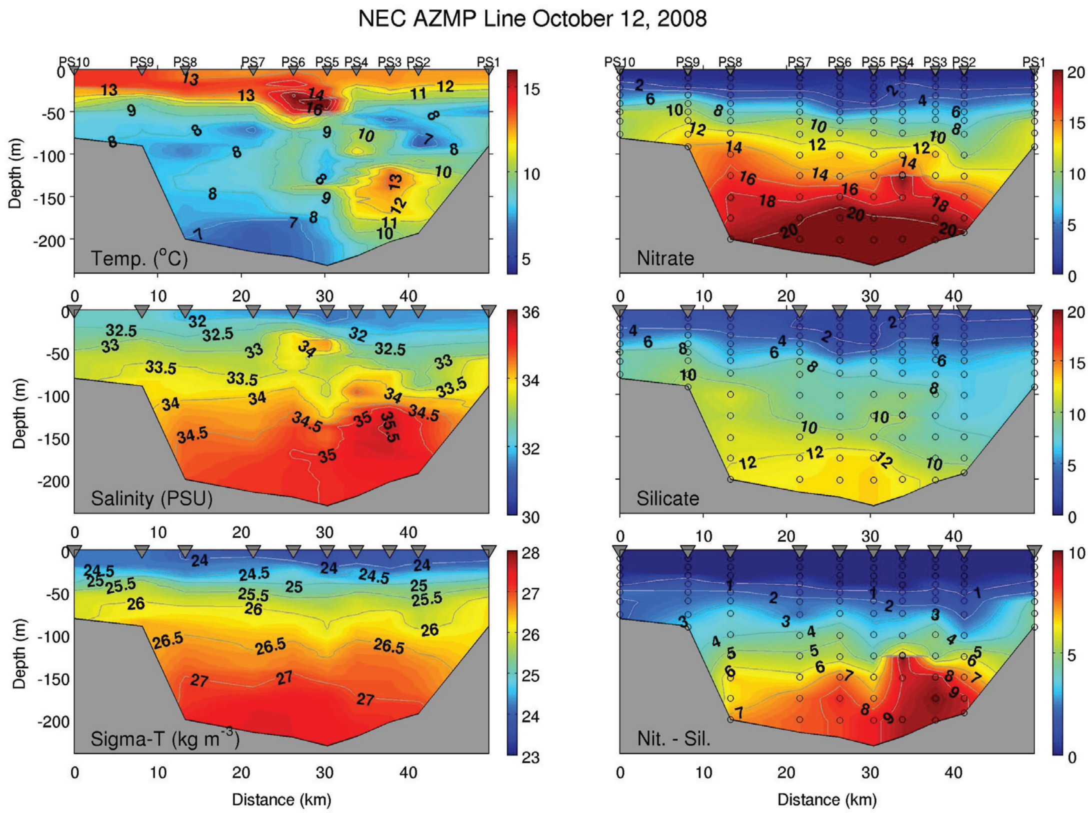


FIGURE 4. Hydrographic properties: temperature, salinity, and sigma-t (left); nutrients: nitrate, silicate, and nitrate residual (right) from a Northeast Channel (NEC) transect near the sill on October 12, 2008. This section runs roughly between the 100-m isobaths on Browns and Georges Banks, passing through the historical eastern and western NEC mooring sites (Figure 3).

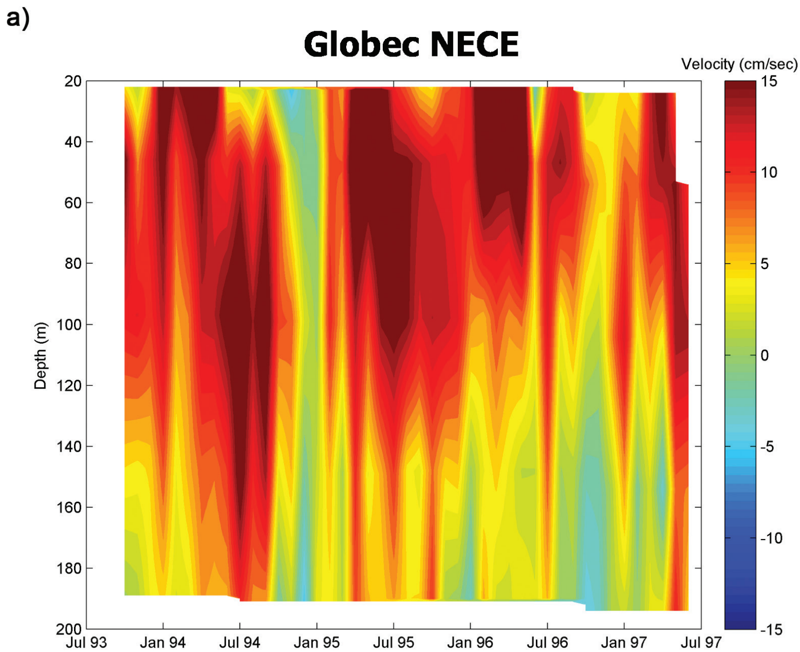
cations of the new mode of behavior in the NEC currents.

Regime Shift/Mass Balance Changes

Regime Shift in Circulation

Between its deployment in early June 2004 and recovery in July 2008, NERACOOS Buoy N has achieved 94% data return. A contour plot of the monthly mean axial (305°T) current component at that site for the period July 2004–July 2008 is compared to a similar figure for the GLOBEC mooring eastern NEC during July 1993–July 1997 in Figure 5. The differences are striking. In the GLOBEC data, persistent inflow occurs over the full depth of the water column, with only occasional, weak reversals at depth on a seasonal timescale (note that seasonal reversals appear to be more common in the latter portion of the GLOBEC records). On the other hand, the Buoy N data show frequent, sustained outflows, especially at depth, with occasional sustained outflows at all depths, such as in the winters of 2004–2005 and 2006–2007, as first reported by Pettigrew et al. (2008). The phases of the seasonal cycles appear to be similar in both records, but the recent data are definitely biased toward outflow.

In order to quantify these differences, we intercompared the axial current components within the layers associated with the three-component exchange model, assuming that the average depths of the layers are shallow inflow on the east (0–75 m), deep inflow on the east (75–200 m), and outflow on the west (0–125 m). Dealing first with the depth-averaged currents, Figure 6 shows monthly mean inflows on the eastern side of the NEC (NECE) and on the western side (NECW, for the



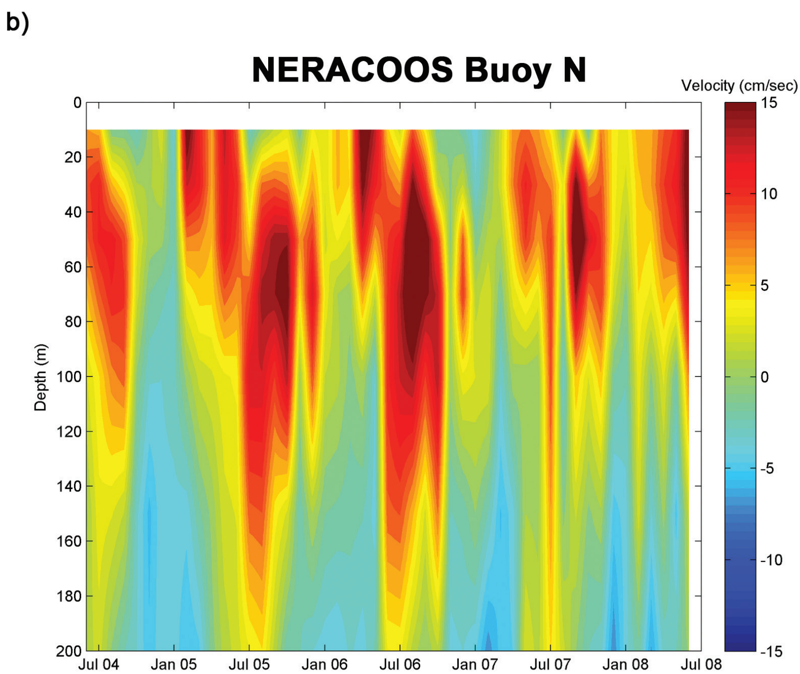


FIGURE 5. Comparison of 4 years of axial (305°T) current component data from (a) GLOBEC NECE (eastern Northeast Channel) mooring (July 1993–June 1997), and (b) NERACOOS (Northeast Regional Association for Coastal Ocean Observing Systems) Buoy N (July 2004–June 2008). GLOBEC estimates are based on currents measured at 20, 50, 100, 150, and 200 m (as indicated by symbols on the left axis), whereas NERACOOS Acoustic Doppler Current Profiler (ADCP) data have a vertical resolution of 20 m.

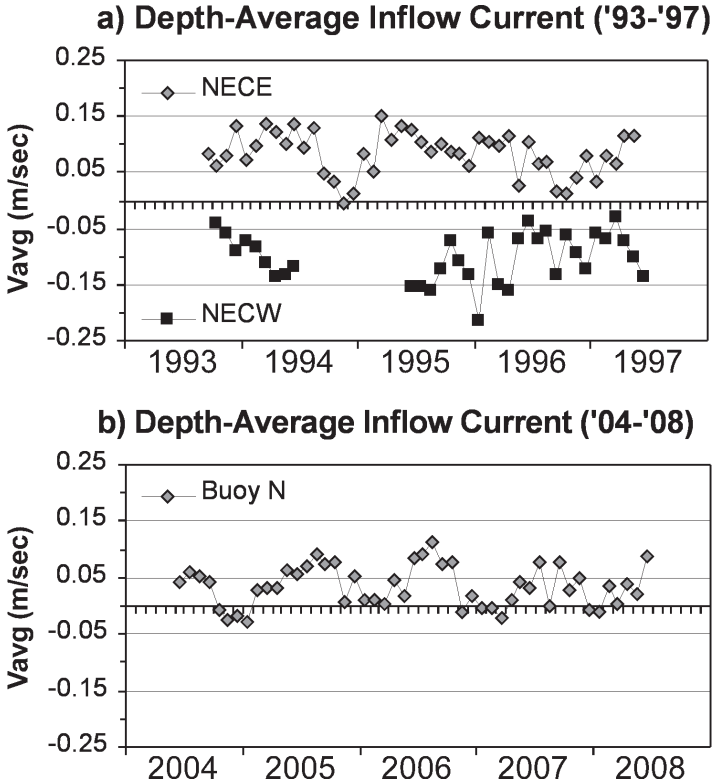


FIGURE 6. Monthly mean inflow currents (305°T) during the 1990s (a) and 2000s (b).

1990s only). Except for a single month in 1994, the depth-averaged inflow current at NECE during the 1990s was positive, with magnitudes of 8–10 cm/s. Outflow current magnitudes at NECW during the same period were of the same order (i.e., –8 to –10 cm/s). On the other hand, the net depth-averaged inflow at Buoy N during 2004–2008 fluctuated, exhibiting summer maxima but overall weaker inflow (~3–4 cm/s) with frequent seasonal reversals to net outflow conditions in winter.

Observed inflow/outflow currents on the east and west for the 1993–1997 (Figure 7a, 7b) and 1998–1999 (not shown) periods are similar. On the east, currents show generally stronger inflow in the surface layer, with some synchronous features in both layers (e.g., quiescent period in November 1994). However, occasional bursts of surface layer inflow create vertical shear of order 10 cm/s between layers. As noted earlier, outflow currents on the western side appear to penetrate to roughly 125 m, below which the flow is variably in and out of the gulf. Furthermore, a vertical shear of order 10–20 cm/s between layers persists on the west side of the NEC. Similar features are found in the current structures from the 1998–1999 period (not shown). Finally, the currents on the eastern NEC at Buoy N during 2004–2008 show pulses of summer inflow, alternating with extended periods of winter outflow in the bottom layer, while the surface layer inflow maintains a weak shear of order 5 cm/s (Figure 7c). More specifically, at this site, the net inflow below a depth of 125 m is effectively zero while the average inflow above that layer is 5.8 cm/s. Clearly, the character of the flow regime in the NEC has changed dramatically between the two periods analyzed here (the 1990s and 2004–2008).

Boundary Fluxes-Annual Cycles

To shed light on the character of the boundary mass flux in the NEC, methods used to analyze the GLOBEC Phase I observations (October 1993–September 1996) were extended to include GLOBEC data from September 1996–June 1997

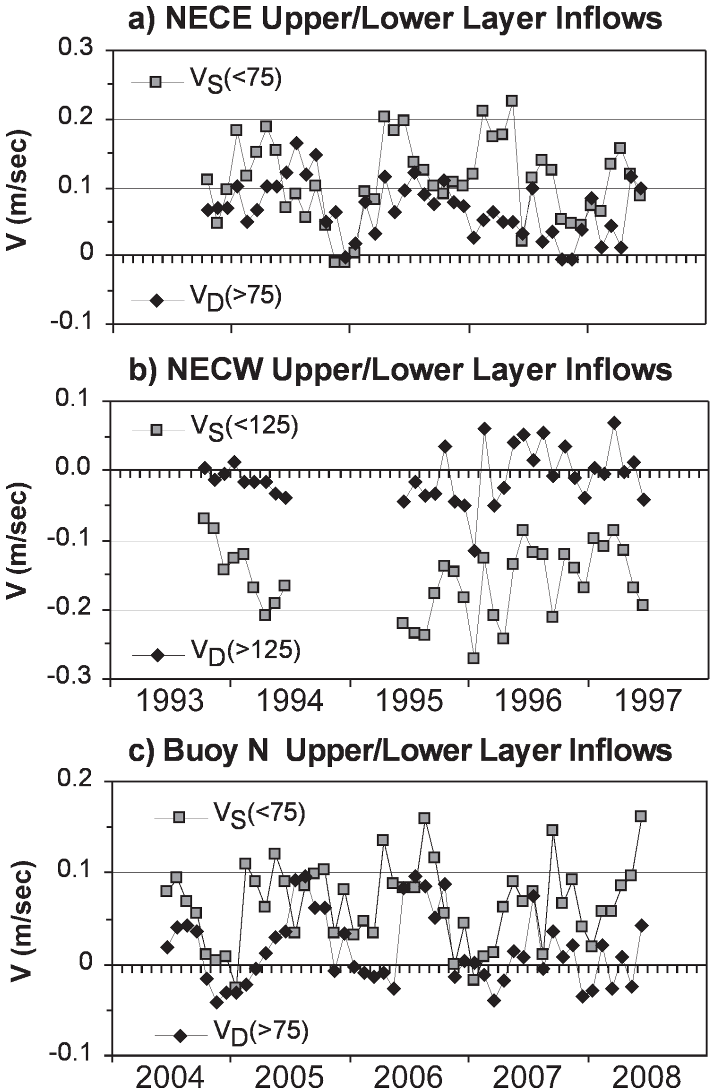


FIGURE 7. Two-layer inflow currents (305°T) during the 1990s on the eastern (a) and western (b) sides of the Northeast Channel (NEC) and (c) during 2004–2008 at Buoy N. The interface between the two-layers is assumed to descend 50 m from east to west on average, based on hydrographic and other data.

and November 1998–September 1999, as well as the NERACOOS data from June 2004–June 2008. Procedures for calculating the mass flux at the NEC mooring sites, detailed in Smith et al. (2001), were applied to calculate monthly mean differential flux indices,

$$q = \int_{z_1}^{z_2} V \mathrm{d}z \cong \sum_{i=1}^{N} V_i \Delta z_i \quad , \qquad (1)$$

where V represents the layer-average axial component (305°T) of the inflow current and Δz_i are discrete intervals within $z_1 \le z \le z_2$ over which the measured inflow/outflow currents are averaged. Consistent with the three-component exchange process, three layer-average differential mass fluxes were computed, corresponding to

$$\begin{aligned}(z_1, z_2) &= (-H, 0)\,\text{depth-average}, H \cong 200\text{ m}\\ &= (-H, -75\text{ m})\,\text{deep layer, and}\\ &= (-75\text{ m}, 0)\,\text{surface layer}\end{aligned}$$

These differential flux quantities, q, are measurable at each of the mooring sites and are considered to be indices of the inflow/outflow volumetric transport in the sense that multiplication by the appropriate along-boundary dimension and suitably offset, they provide an estimate of the total transport in that layer (see next subsection).

Furthermore, the seasonal variations of the inflow currents (Figure 8) and fluxes were quantified using least-squares multiple regression with $n-3$ degrees of freedom, where n is the number of monthly data points (Smith et al. 2001). The estimator was of the form

$$Y_v = B_0 + B_1 \cos\left[\pi\left(t_v - \Phi_1\right)/6\right] + \varepsilon \qquad (2)$$

where t_v is the month number (=0.5 for January, v = 1) and ε is the residual. Table 1 compares the statistically significant annual cycles, and their associated 95% confidence intervals (Δ,δ) (see Smith et al. 2001), for two sets of GLOBEC observations (1993–1996, 1993–1999) and the NERACOOS data (2004–2008). Depth average, surface-layer average, and deep-layer average quantities are denoted by q_T, q_S, and q_D, respectively, and coincident estimates for the annual cycle of the depth-average Scotian Shelf inflow off Cape Sable, Nova Scotia (q_2) are included for comparison.

Several features of the annual cycle regressions serve to quantify both similarities and differences between the GLOBEC and NERACOOS data sets. The major difference, as suggested earlier, lies in the mean fluxes. For instance, the NERACOOS depth-average mean inflow (B_0) is less than 40% of those from the GLOBEC eras, and the annual cycle provides a weak winter reversal (Figure 8b). This reversal is absent from the surface layer (Figure 8d) but pronounced in the deep layer (Figure 8f). The amplitudes of the annual cycles for both periods, though different, are statistically equivalent within the error estimates, for both full-depth- and layer-average fluxes. The phases of the annual cycle of the NERACOOS inflows appear to lag those of the GLOBEC period by the order of 1–2 months, though only one of those differences exceeds the error bounds. Note that the peak of the annual CS inflow cycle (January) is fully out of phase with the deep NEC inflow.

Box Model: Estimates of the Changing Mass Balance

Smith et al. (2001) showed that because of coherent relationships at low frequencies among current measurements in the NEC and across the inner Scotian Shelf off CS, the net volumetric inflow in those two locations could be indexed to the low-frequency (detided monthly mean) differential transports measured at the mooring sites NECE and C2 (see Figure 3). Assuming these relationships hold throughout both the GLOBEC and NERACOOS observation periods, the net inflows at CS and in the NEC shallow and deep layers may be indexed to the differential transports at C2 and NECE as

$$Q_{CS}\left(m^3/s\right) = 1.68 q_2 W_{CS} + 45\times10^3, \quad W_{CS} = 20\text{ km} \qquad (3a)$$

$$Q_S\left(m^3/s\right) = 1.75 q_S W_{NEC} - 112\times10^3, \quad W_{NEC} = 15\text{ km} \qquad (3b)$$

$$Q_D\left(m^3/s\right) = 1.75 q_D W_{NEC} - 112\times10^3, \quad W_{NEC} = 15\text{ km} \qquad (3c)$$

where W_{CS} and W_{NEC} are the effective widths of the inflow current fields, derived from regressions of total transport through a particular segment of the boundary cross section against observations at a particular point on that boundary. Direct evidence for the surface layer inflow relationship is questionable due to the lack of near-surface current data, so the deep NECE regression has been applied following Smith et al. (2001).

The box model conserving mass and salt (Figure 9) formulated by Smith et al. (2001) features the major inflows at CS (given by equation 3a) and in the NEC (equations 3b, 3c), plus small contributions from river runoff into the Gulf (Q_R~3 × 10^3 m^3/s) and the difference between precipitation and evaporation (Q_{P-E} ~ 10^3 m^3/s). The two sinks of mass for the model are the longshore flux, Q_N, on the New England Shelf, and an offshore flux, αQ_N, which are assumed to remain in fixed ratio over the long term.[1] Assuming the river and $P-E$ contributions are negligible, conservation of mass requires:

[1] The basis for this split of the two sinks is represented in Figure 1 as the distinction between the flow that remains inside the shelf break (~200 m isobath) as it exits the region (e.g., through Great South Channel or around the Northeast Peak) and that which crosses the shelf break to the offshore region. This distinction is not critical to our results and conclusions in any way.

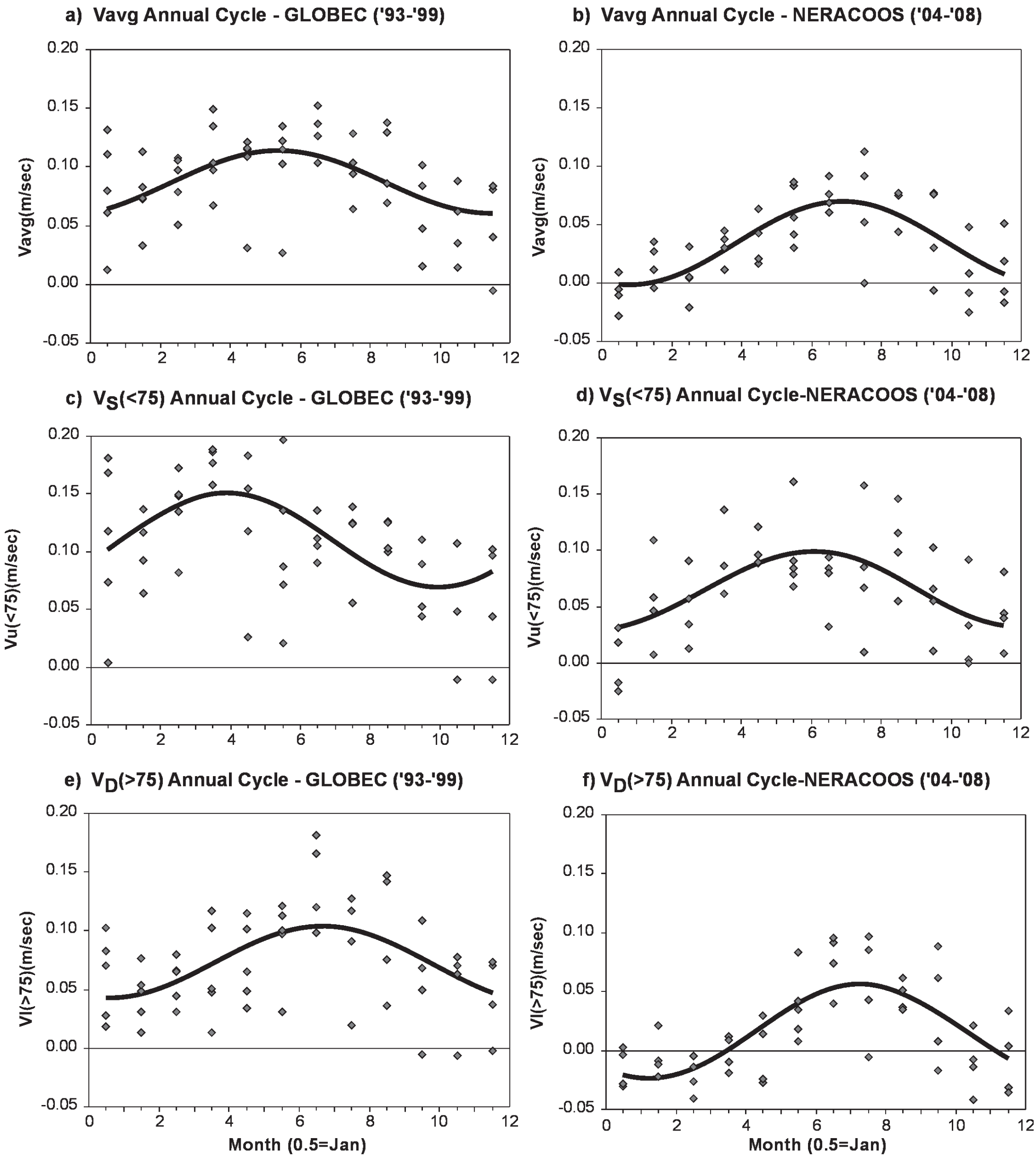


FIGURE 8. Annual cycles for depth (a, b), surface (c, d) and deep-layer-average (e, f) GLOBEC inflow (1993–1999, left column) and inflow currents in the Northeast Channel for NERACOOS (Northeast Regional Association for Coastal Ocean Observing Systems; 2004–2008, right column) data sets.

$$(1+\alpha)Q_N = Q_{CS} + Q_S + Q_D . \qquad (4)$$

To define the differential mass transport at a given location, Smith et al. (2001) chose periods when moored observations were widely available for the inflow as a whole and correlated the relatively well-sampled cross-sectional mass flux estimates to the differential fluxes for the index station (e.g., C2) at low frequencies. The correlation structures in the full data sets indicate that the currents at these locations are the primary determinants of the net mass fluxes into the Gulf of Maine. Also,

Table 1. Layer-average annual cycles for differential transports. q_T, q_S, and q_D are the differential transport indices for depth average, surface-, and deep-layer average inflow in the NEC, respectively. q_2 is the depth-average off Cape Sable, Nova Scotia.

Flux	Quantity	GLOBEC 1993–1996	GLOBEC 1993–1999	NERACOOS 2004–2008
q_T (m²/s)	n	36	54	49
Mean	B_0 (m²/s)	18.5	17.6	7.0
Amplitude	$B_1 \pm \Delta_1$ (m²/s)	5.4±3.2	5.4±2.6	7.2±2.0
Phase	$\Phi_1 \pm \delta_1$ (mon.)	5.2±1.1	5.4±0.9	6.9±0.6
SE	σ_ε (m²/s)	6.7	6.8	5.2
q_S (m²/s)				
Mean	B_0 (m²/s)	8.8	8.4	4.9
Amplitude	$B_1 \pm \Delta_1$ (m²/s)	3.5±1.9	3.1±1.4	2.6±1.1
Phase	$\Phi_1 \pm \delta_1$ (mon.)	4.1±1.1	3.9±0.9	6.0±0.9
SE	σ_ε (m²/s)	3.9	3.7	2.8
q_D (m²/s)				
Mean	B_0 (m²/s)	9.7	9.0	2.0
Amplitude	$B_1 \pm \Delta_1$ (m²/s)	3.2±2.2	3.9±1.9	5.0±1.5
Phase	$\Phi_1 \pm \delta_1$ (mon.)	6.5±1.3	6.6±0.9	7.3±0.6
SE	σ_ε (m²/s)	4.6	4.7	3.6
q_2 (m²/s)				
Mean	B_0 (m²/s)	7.5		
Amplitude	$B_1 \pm \Delta_1$ (m²/s)	3.1±1.8		
Phase	$\Phi_1 \pm \delta_1$ (mon.)	0.4±1.2		
SE	σ_ε (m²/s)	3.8		

during GLOBEC periods when measurements were available from both the NEC and Cape Sable, a robust inverse relationship was noted between the low-frequency (detided monthly mean) deep (>75m) differential transport on the eastern side of the NEC and that of the full-depth inflow off Cape Sable on the 100-m isobath (mooring C2). Hence, to estimate the differential transport at Cape Sable for the late GLOBEC (1998–1999) and NERACOOS (2004–2008) periods, when direct observations were not available, we make use of this inverse relationship between the observed anomalies to estimate the Scotian Shelf inflow at Cape Sable. Specifically, if we define the differential transport anomaly as

$$q'(t) = q(t) - B_0 - B_1 \cos\left[\pi\left(t - \Phi_1\right)/6\right], \quad (5)$$

then the early GLOBEC data reveal a significant inverse correlation of the form (see also Figure 10)

$$q_2'(t) = -0.474 q_D' + 0.070. \quad r^2 = 0.48 \quad (6)$$

Using the estimates of q_2' from the inverse regression (6), along with the observed values of shallow- and deep-layer NEC differential transports for the late GLOBEC and NERACOOS periods, the mass balances for all three periods may be calculated and compared, using the formulae (3a–c) and assuming that river and atmospheric inputs are negligible.

The results of the box model analysis (Table 2) indicate, first of all, that the transports during the latter half of the 1990s are virtually identical to those of the earlier period. Moreover, the estimated total volumetric fluxes off CS and in the NEC are reasonably consistent with earlier estimates of 140 and 260 m³/s, respectively, from direct observations by Smith (1983) and Ramp et al. (1985). However, there has been a drastic

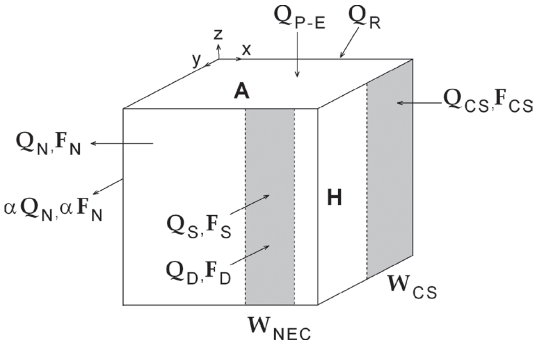


FIGURE 9. Box model for volumetric (Q in m^3/s) and freshwater (F in g kg^{-1} m^3/s) transports in the Gulf of Maine (Smith et al. 2001). Inflow volumetric transport components Q_{CS}, Q_S, and Q_D enter via the Scotian Shelf off Cape Sable (CS) and shallow (S) and deep (D) NEC (Northeast Channel), respectively, via sections of width W_{CS} and W_{NEC}. River discharge (Q_R) and precipitation-evaporation (Q_{P-E}) enter from land and surface boundaries, and Q_N and αQ_N exit via the New England shelf and offshore. A and H are the estimated surface area and mean depth.

change in the mass balance of the gulf between the GLOBEC years of the 1990s and the more recent NERACOOS era, 2004–2008. Specifically, the effective reversal of the net deep inflow transport, due to linkages to outflow on the western side of the NEC, is consistent with the observed pattern of sustained outflow at depth in the NERACOOS data. Moreover, the surface inflow in the NEC, while still positive, is considerably reduced from that in the GLOBEC period. Also, by virtue of the inverse correlation with deep inflow, the Scotian Shelf inflow at CS appears to have increased by 40%. Overall, the results indicate that the mass flux through the gulf is reduced by roughly 30% in recent years. According to Table 2, this reduction is entirely at the expense of the NEC inflow, especially the deep component.

These results must be considered tentative at this point since they are based on many assumptions. Not the least of these is the inferred inverse correlation between the differential flux anomalies at CS and the deep NEC. This idea is not new however. Brooks (1992) pointed out such a relationship between the deep inflow observations of Ramp et al. (1985) and the freshwater flux into the gulf, both from the Scotian Shelf and from local rivers, the former being the dominant source. According to this hypothesis, in "wet" years, high freshwater input by the Scotian Shelf water, derived in part from the St. Lawrence River, should delay or retard deep NEC inflow by imposing an adverse, barotropic pressure gradient. Conversely, in "dry" years, a weaker barotropic gradient should allow deep injection earlier. It is interesting to note that the increase in the phase lag of the annual cycle of deep inflow during the NERACOOS versus GLOBEC period (Table 1), though not statistically significant, is consistent with this hypothesis. At a more basic level, the 6-month lag between the CS and deep NEC differential transports (Table 1) reflects this inverse relationship between the annual cycles themselves.

Discussion

Possible Causes

As indicated by the box model results, among the possible causes for this drastic change in the magnitude and character of the NEC inflow currents is a substantial increase of the fresher coastal inflows from the Scotian Shelf at CS. In a geostrophic sense, this would require an adverse (positive onshore) barotropic pressure gradient that would, in turn, oppose the deep inflow. In any case, one likely source of enhanced coastal inflow would be an increase in the freshwater input to the Nova Scotian Current by its major sources in the Gulf of St. Lawrence and Labrador Sea. Freshwater input to the Gulf of St. Lawrence is monitored by an index known as RIVSUM, which represents the combined discharges of the St. Lawrence, Ottawa, and Saguenay rivers, the main contributors to the gulf (Sutcliffe et al. 1976). However, records of the RIVSUM index over the past 50 years reveal no major changes in freshwater input to the Gulf of St. Lawrence over the past two decades. In fact, the average discharge in the early 1990s appears to exceed that in the 2000s. On the other hand, according to Loder et al. (1998), RIVSUM accounts for slightly greater than 40% of the freshwater exiting the Cabot Strait and roughly 30% of that carried by the Nova Scotian Current off Halifax. The remainder of the freshwater transport off Halifax is derived from the in-

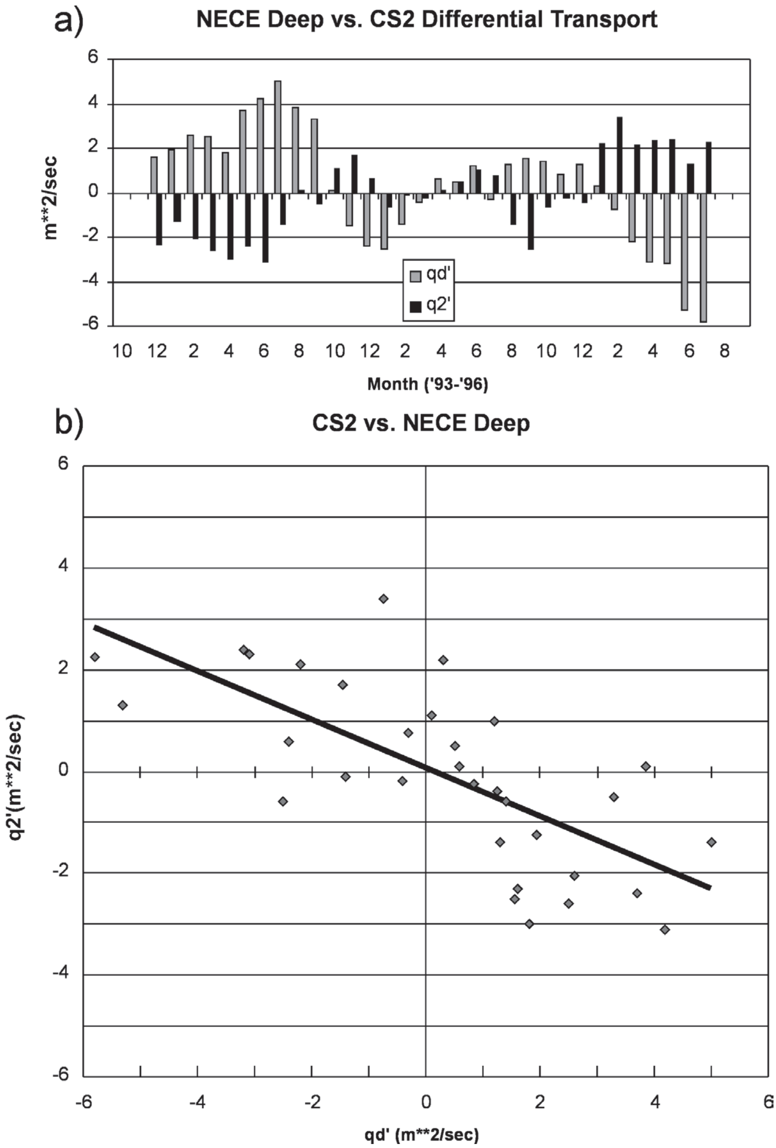


FIGURE 10. Time series (a) and regression plot (b) showing inverse correlation between differential transport anomalies at Cape Sable (C2 on the Scotian Shelf) and in the deep eastern Northeast Channel (NECE; see Figure 3).

TABLE 2. Box model transport estimates.

Mass flux component	GLOBEC I 1993–1996	GLOBEC III 1998–1999	NERACOOS 2004–2008	CHANGE: 2000s vs. 1990s
Q_{CS} (m³/s)	297	301	420	+40%
Q_S (m³/s)	120	121	16	–87%
Q_D (m³/s)	144	140	–60	–141%
$(1 + \alpha)Q_N$ (m³/s)	560	562	380	–32%

shore branches of the Labrador Current that pass through the Strait of Belle Isle and the Avalon Channel. Thus, RIVSUM is, at best, a weak indicator of the freshwater transport on the Scotian Shelf. Similar arguments can be made for the mass balance in the Gulf of St. Lawrence, prominent sources for which lie in the inshore branches of the Labrador Current.

Another approach to this problem might be to look at trends in sea surface height (SSH) anomalies measured by satellite-borne altimeters, which pass over the region regularly. The trend in sea-level height anomaly, derived from multi-mission satellite altimetry for the period 1992–2008, shows a contrast of the sea-level trend between the Scotian Shelf–Gulf of Maine (rise) and the offshore slope water region (fall) over the past 15 years. In fact, according to a global picture (Wunsch et al. 2007), this trend extends eastward to at least the tail of the Grand Banks, geostrophically favoring an accelerated westward flow over that time period. Considering just the contrasting trends between the Yarmouth area and nearby slope water, the order of magnitude of the onshore–offshore height difference developed after just one decade would be the order of 13 cm. In conjunction with the satellite data, consideration should be given to the longer coastal sea level records on the Scotian Shelf from Halifax and Yarmouth, Nova Scotia. Figure 11a, 11b show the

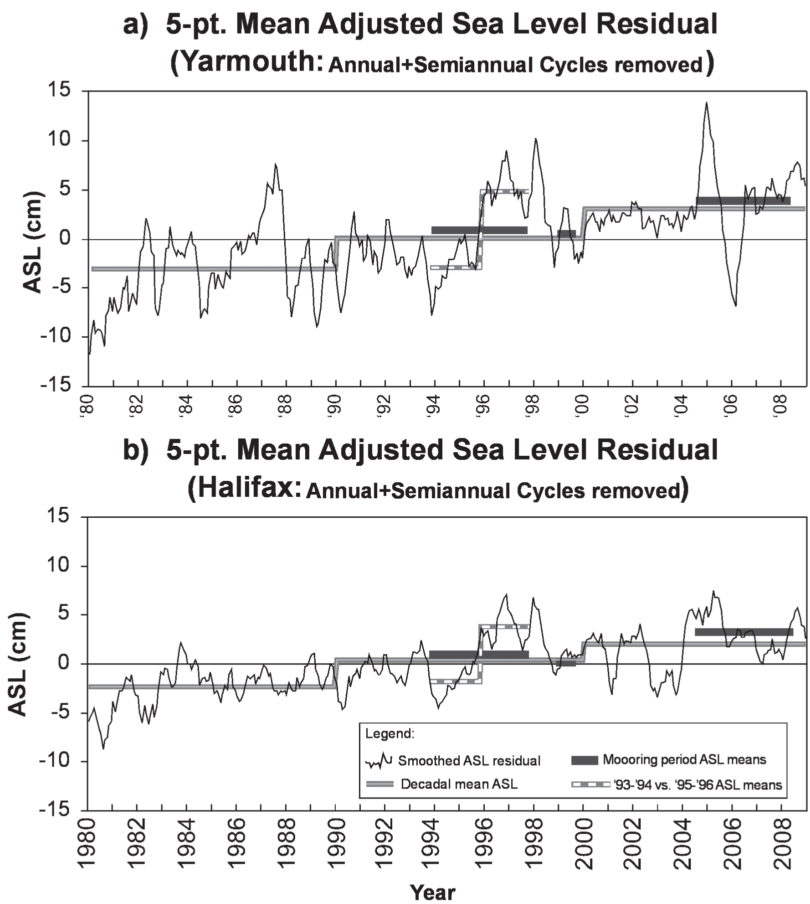


FIGURE 11. Five-point mean adjusted sea level anomaly (1980–2008) records from (a) Yarmouth, Nova Scotia and (b) Halifax, Nova Scotia. Tide gauge records have been adjusted for barometric pressure and annual and semiannual signals have been removed by least-squares regression. Decadal (purple) and mooring period (yellow) means are indicated, as well as 2-year means for the first and last halves of the 1993–1997 GLOBEC period.

nearly 30-year time series (1980–2008) of monthly mean adjusted sea level (ASL) anomalies (corrected for the inverse barometer effect, annual and semiannual cycles are removed by least-squares regression, and 5-point running mean is applied). Ten-year means of these data show a clear positive trend in mean relative sea level of order +2–3 cm per decade, in spite of strong interannual variability. Though a significant fraction of this change may be attributed to postglacial rebound (Peltier 2004), the geocentric altimetry height measurements support the contention that there has been some eustatic sea level rise at both Yarmouth and Halifax over the past two decades. The ASL averages over the various mooring periods are also consistent with the decadal averages, but within a given mooring period, shorter-term averages can produce trends an order of magnitude different (e.g., 1993–1994 versus 1996–1997 averages suggest an ~8 cm increase over 2 years or roughly 40 cm per decade). The shorter-term differences were thought and explained to be related to the Gulf Stream north–south movement (Han 2002, 2007).

Seasonal maps of the SSH derived from multi-mission altimeter data capture some of the synoptic features related to coastal ASL and the NEC current records. In particular, the dominant outflow currents over the full depth of the water column at Buoy N in the fall/winter of 2004/2005 are coincident with a strong, positive SSH anomaly (>10 cm) observed near Yarmouth during the same season (Figure 12d). Continuing in 2005, the Yarmouth anomaly dropped to roughly +6 cm in winter (Figure 12e), then to ~+2 cm in spring (Figure 12f), and became negative by the summer (Figure 12g). These features are all qualitatively consistent with the rise and fall of adjusted sea level in the tide gauge record (Figure 11a).

Thus, it appears that the inverse relationship demonstrated by NEC deep inflow versus Scotian Shelf inflow and the accompanying offshore pressure gradient reflected in Yarmouth SSH is a robust feature of the Gulf of Maine circulation at all timescales from seasonal, to annual, to interannual. A viable hypothesis, therefore, is that a recent rise in sea level off southwest Nova Scotia is associated with both an increased mass flux into the GoM from the Scotian Shelf and an adverse pressure gradient in the NEC, which opposes and reduces the deep inflow of nutrient-rich slope water to the gulf. This increased mass flux may also be exerting its effects on the circulation on the Scotian Shelf and might have its origin further upstream in the Labrador Sea.

Potential Consequences

One of the primary consequences of the regime change in the NEC circulation is alteration in the nutrient supply to the inner GoM and its impact on the ecosystem. The shift in the balance between deep inflows in the NEC and shallower inflows from the inshore Scotian Shelf will decrease the net input of nutrients to the GoM because nutrient concentrations invariably increase with depth and also change the relative inputs of nitrate and silicate because silicate shows less gradient with depth (see Figure 4). Townsend et al. (2010) have shown, based on five decades of nutrient data compiled for the deep waters (>100 m) of the eastern gulf (Rebuck et al. 2009), that nitrate concentrations have been steadily declining since the 1970s, whereas the average silicate concentration has remained roughly constant, leading to a decrease in the traditionally positive residual nitrate (nitrate concentration minus silicate concentration). Less residual nitrate will favor production of diatoms. Similar temporal trends in nutrient concentrations since the 1970s have been observed in Scotian Shelf waters at depths greater than 60 m (Yeats et al. 2011). Since the early 1990s, a decrease in residual nitrate has been noted on the Scotian Shelf (60–100 m, Figure 13a) and in the Gulf of St. Lawrence at virtually all depths (Figure 13b). These conditions in the shelf waters are thought to reflect nitrate losses from sediment denitrification and silicate increases from river input and in situ regeneration (Townsend et al. 2010). However, at the same time, the opposite trend has been observed in the Labrador Sea, where silicate concentrations appear to be decreasing more rapidly than nitrate, leading to an increase in residual nitrate (Figure 13c). This suggests that the changing nutrient ratios in the inshore inputs to the GoM are more closely tied to biogeochemical changes taking place between the Labrador Sea and the Gulf of Maine (e.g., along a shelf-bound route of the coastal currents) than to changes in upstream nutrient sources. Thus, the regime shift in GoM water transport and bio-

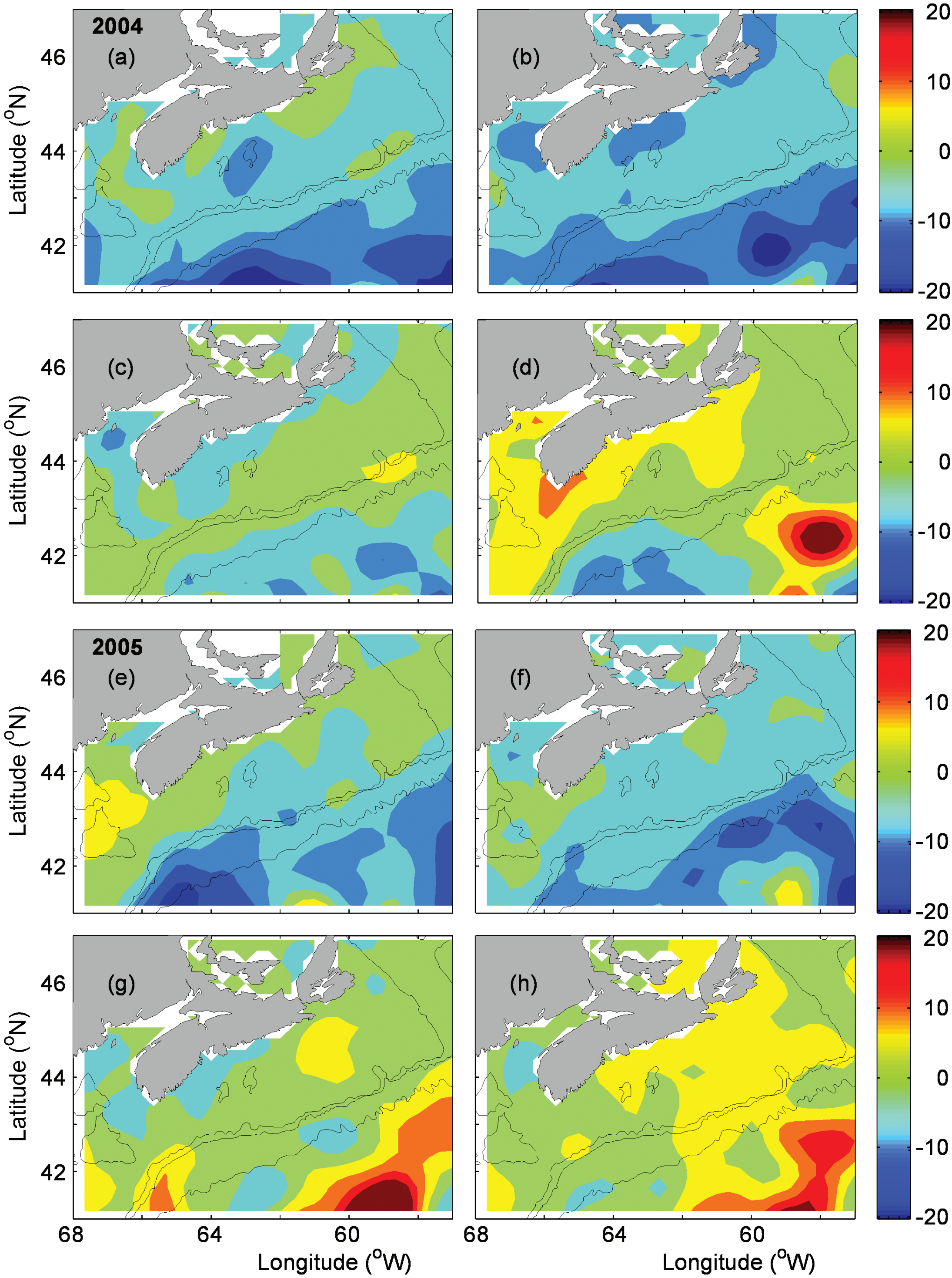


FIGURE 12. Maps of sea surface height anomalies (in cm) for 2004–2005 created from satellite remote-sensing data: (a, e) winter, (b, f) spring, (c, g) summer, (d, h) fall.

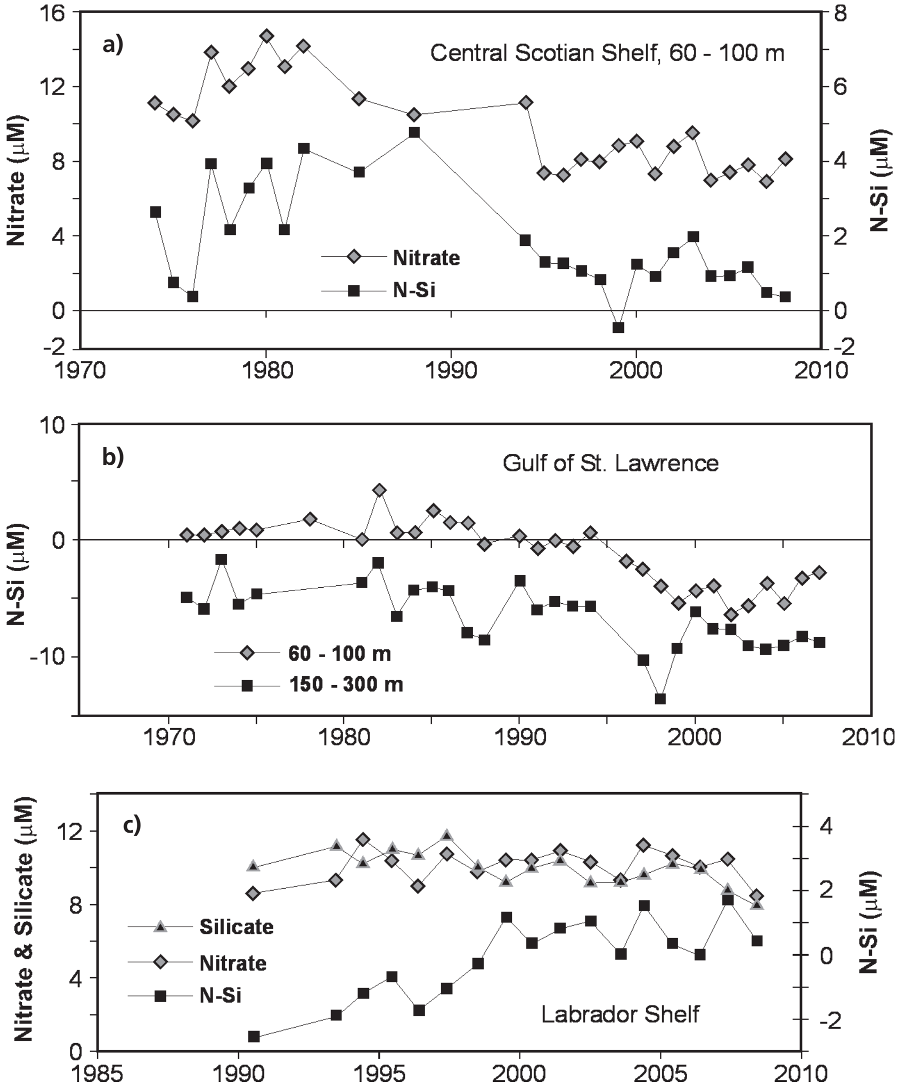


FIGURE 13. Time series for (a) nitrate and residual nitrate based on annual average concentrations for all data for the 60–100 m depth range on the central Scotian Shelf (62–64 W, coastline to edge of continental shelf); (b) residual nitrate for middepth and deep samples in the Gulf of St. Lawrence (Cabot Strait in east to Pointe des Monts in west and Belle Isle Strait in north); and (c) nitrate, silicate, and residual nitrate in the 60–200-m-depth range for the Labrador Shelf stations (53.5 N to 55.0 N) on the annual surveys along the WOCE AR7W section from Labrador to Greenland.

geochemical process in upstream coastal waters combine to generate the observed temporal trends (Townsend et al. 2010) in nutrient concentrations in eastern GoM waters.

With regard to the biological impacts at lower trophic levels of the GoM ecosystem, laboratory and field studies suggest that a competitive interaction exists in the bloom dynamics of diatoms and the toxic dinoflagellate *Alexandrium fundyense* (Sathyendranath et al. 2004; Townsend et al. 2010). The result is an inverse relation in their areal and temporal distributions through some form of reverse alleopathic interference, which appears to have a basis in the nutrient regime (Townsend et al. 2005). Local nutrient concentrations affect phytoplankton growth, with high silicate favoring diatoms and nitrates favoring dinoflagellates. Thus, the changing balance of these two nutrients presently favors the diatoms and may be altering the structure of the planktonic ecosystem with respect to the relative abundances of these two species (Townsend et al. 2010).

Furthermore, the observed oceanographic regime change between the 1990s and late 2000s is reflected by changes in the GoM zooplankton community (Hare and Kane 2012, this volume) deduced from nearly five decades of observations. Their multidecadal analysis, based on earlier studies, reveals distinct changes in the composition of the community between the 1990s, when small-bodied taxa prevailed, and the early 2000s, when the dominance reverted to a group of larger species, including *Calanus finmarchicus*. Linking these changes to environmental variability is problematic, however, because of nonstationarity of the environment–zooplankton linkages.

In contrast to Hare and Kane (2012), observations of the coastal plankton communities in the western GoM (Runge and Jones 2012, this volume) suggest that the period between 2003 and 2005 is marked by a sharp *decline* in *C. finmarchicus* abundance on Jeffrey's Ledge, accompanied by reduced surface salinities. These authors attribute the drop in salinity to either an increase in freshwater transport by the Scotian Shelf inflow (carried to Jeffrey's Ledge by the eastern and western Maine coastal currents) and/or the local input of freshwater by Maine rivers. They also hypothesize that the freshwater is associated with a change in physical forcing of the Jeffrey's Ledge circulation, affecting advection of *C. finmarchicus* onto, or out of, the coastal shelf. If the origin of the freshwater is on the Scotian Shelf, fewer *C. finmarchicus* are thought to be transported by the Maine coastal currents.

Conclusions

Next Steps

Between years 2000 and 2004, a profound change has taken place in the Gulf of Maine circulation and ecosystem. The traditional influx of nutrient-rich slope water has been considerably reduced relative to historical levels, leading to changes in the mass, heat, salt, and nutrient budgets for the gulf system. A simple box model has been used to quantify some of the changes in the mass balance implied by the GLOBEC (1993–1999) and more recent NERACOOS (2004–2008) observations. In accordance with historical observations, the box model predicts that the regime shift would be associated with an increased influx of coastal waters from the Scotian Shelf. Such behavior is consistent with a hypothesis of Brooks (1992) that claims that excess Scotian Shelf water inflow sets up an adverse pressure gradient that limits the deep inflow in the NEC.

An independent test of this hypothesis ought to be available when recent measurements of the CS inflow currents have been processed. If a strong increase of the CS inflow, carrying significant amounts of coastal current waters from the Labrador Sea and Gulf of St. Lawrence, is confirmed, further significant impacts on the Gulf of Maine nutrient regime and ecosystem should be anticipated.

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