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Seasonal and interannual variations in geostrophic velocity in the Middle Atlantic Bight

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[1] More than 6 years of measurements from the TOPEX/POSEIDON (T/P) altimeter are used to study the seasonal and interannual variations of the geostrophic velocity anomalies in the Middle Atlantic Bight region. Geostrophic velocities from T/P data are compared with the simultaneous low-pass filtered current meter data. The correlations are all above 95% significance for the three current meter observations at the 1000-m, 2210-m, and 2990-m isobaths. The seasonal mean geostrophic currents from 63°–75°W show coherent variations along isobaths, with seasonal reversals: toward the southwest during the winter and toward the northeast during the summer. The EOF analysis indicates that the seasonal reversals disappeared during 1996. This disruption is part of the intensification of the slope sea gyre and is related to the southward shift of the Gulf Stream, which acts as the boundary between the subpolar and subtropical gyres. The Gulf Stream moved farther south during 1996–1998. The variations in the Gulf Stream position may be caused by the wind stress/wind stress curl change. *INDEX TERMS:* 4512 Oceanography: Physical: Currents; 4528 Oceanography: Physical: Fronts and jets; 4546 Oceanography: Physical: Nearshore processes; 4572 Oceanography: Physical: Upper ocean processes; 4599 Oceanography: Physical: General or miscellaneous; *KEYWORDS:* geostrophic velocity, slope current, Middle Atlantic Bight, TOPEX/Poseidon, sea surface height

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1. Introduction

[2] A closed cyclonic gyre between the Gulf Stream and the continental shelf was first derived by *Sverdrup et al.* [1942], based on the slope of coastal sea level. This narrow band of ocean between the Gulf Stream and continental shelf was named the "Slope Sea" by *Csanady and Hamilton* [1988]. Combining results from the Middle Atlantic Slope and Rise (MASAR) experiment with earlier evidence, *Csanady and Hamilton* [1988] constructed an empirical scheme of slope water circulation. The dominant feature of this scheme is a closed cyclonic gyre in the western Slope Sea and an open cyclonic circulation pattern in the eastern Slope Sea that are separated by the onshore flow near the eastern end of Georges Bank. North of Cape Hatteras slope and shelf water turn and flow eastward along the northern edge of the Gulf Stream.

[3] Many studies have been carried out in the Middle Atlantic Bight (MAB) region. These studies show that the mean flow over the continental shelf and slope within the MAB is toward the southwest along the isobaths [*Beardsley et al.*, 1985; *Aikman et al.*, 1988; *Rossby and Benway*, 2000]. This southwestward flow is stronger during winter and is weak or reverses during summer. Based on oxygen isotope measurements, *Chapman et al.* [1986] and *Chapman and Beardsley* [1989] have suggested that the mean flow is continuous between the Scotian shelf and the MAB and that it is continuous as far north as the southern coast of Greenland. However, *Loder et al.* [1998] found the upstream buoyancy forcing is mainly from the Baffin Island Current.

[4] So far, most studies in the MAB have been focused on the shelf region and have been highly localized. Although a few long-term records of currents have been obtained over the upper slope [*Beardsley et al.*, 1985; *Csanady et al.*, 1988; *Aikman et al.*, 1988], the different conditions during the observational periods made it difficult to reach a consistent conclusion on the seasonal variations. The seasonal reversal of the slope current observed in the Nantucket Shoals Flux Experiment (NSFE79) [*Beardsley et al.*, 1985] was not apparent in the Shelf Edge Exchange Processes (SEEP-I) experiment [*Aikman et al.*, 1988]. Different mean currents were also observed off the Scotian shelf [*Smith and Petrie*, 1982]. The 1-year- or 2-year-long records are too short to study the interannual variations or to compute an accurate annual cycle. Although *Csanady and Hamilton* [1988] observed the slope flow at two transects off New Jersey and Virginia, the alongshore variations of the upper slope current in the MAB have not been studied. Do the slope currents vary coherently alongshore? What are the seasonal and interannual variations in the currents? These are the questions we are trying to answer in this study.

[5] With satellite altimetry measurements, it is possible to study large-scale MAB circulation variations over many years. *Han and Tang* [1999, 2001] studied seasonal and

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interannual variations in the Labrador Sea transport by combining TOPEX/POSEIDON (T/P) altimetry data with hydrographic and wind data. In this study we use altimetric sea surface height (SSH) data to investigate the seasonal and interannual variations in the geostrophic velocity anomalies over the entire MAB slope region (water depth from 500 m to 2000 m). Comparisons of shelf velocities with in situ observations suggest that tidal corrections for the altimeter are not sufficiently accurate to extend the study to the shelf. The ocean tidal corrections in the merged geophysical data records (MGDRs [*Benada*, 1997]) are generally adequate only for the regions where the water depth is deeper than 2000 m. The residual signal from an inaccurate tidal correction is aliased to longer periods by the T/P sampling. Four different tidal corrections are checked (see detail in Appendix A). None of them can reduce the variance in the SSH derivatives from which the geostrophic velocity is deduced. However, on the basis of in situ measurements, the tidal signal should contribute about half of the variance of the total velocity in shallow water.

2. Altimetric and In Situ Data

[6] The altimeter data used are from the joint United States/France T/P mission for the period from December 1992 to December 1998. The satellite repeats its ground track every 9.9 days with an along track resolution of about 7 km. The altimetric measurements from the descending tracks are used to examine the slope water geostrophic velocity anomalies. Gridded SSH maps are used for the large-scale analysis. The corrections supplied in the MGDRs are all applied to the SSH, and the temporal mean SSH (January 1993 to December 1998) at each location is removed to eliminate the geoid.

[7] The geostrophic velocity calculated from T/P SSH (Figure 1) is compared with direct current measurements from the shelfbreak PRIMER experiment [*Pickart et al.*, 1999]. The PRIMER experiment was carried out over the shelf and slope near 70°W. During the PRIMER experiment an array of moorings was deployed for 2 years (December 1995 to December 1997) along a T/P track near 70°W. The near surface currents (90 m, 110 m, 99 m) from three moored VACMs (see Figure 2a), located at roughly the 1000-m, 2210-m, and 2990-m isobaths, are low-pass filtered to remove fluctuations with a period of 48 hours or less. In addition, near surface currents from two ADCP moorings (located on the shelf at the 125-m and 168-m isobaths) are used for comparison (the shallowest bin depths are 25 m and 26 m). The time period for the ADCP moorings is December 1995 to March 1997.

3. Geostrophic Velocity Anomalies

[8] The anomalous geostrophic velocity can be estimated from the SSH anomaly η as $u = -(g/f \partial\eta/\partial y)$, where y is in the satellite along track direction, g is the gravitational acceleration, and f the Coriolis parameter. The once per second T/P SSH measurements are used directly without smoothing along the satellite track or in time. A centered scheme is used to compute the geostrophic velocity anomalies.

[9] To compare the cross track geostrophic currents with the in situ currents, we projected the in situ currents into the cross track direction. Correlations between the two current estimates are high (Figure 1) at the locations deeper than 1000-m isobath: 0.78 (2990 m), 0.83 (2210 m), and 0.82 (1000 m), respectively; all are above the 95% significance level, 0.31, 0.37, and 0.39, respectively. However, correlations with ADCP velocities in shallow water (<200 m) are low, probably reflecting problems with the tidal corrections, or owing to the difference between the velocity at the surface and at 25 m depth. Although we do not have in situ data with which to compare geostrophic velocities between 200 m and 1000 m, in the remainder of this paper, we consider only data from regions offshore of the 500-m isobath, based on high coherence between near-surface geostrophic velocities at the 500-m isobath with near-surface velocities from deeper regions. In addition, the power spectral density of the geostrophic velocities along isobaths between 500 m and 1000 m show peaks at the same frequency band as those located at isobaths deeper than 1000 m. The maximum water depth is chosen at 2000 m to exclude the Gulf Stream.

[10] Cross-track geostrophic velocities are calculated for the six descending tracks between 63°W and 75°W (Figure 2a). Descending tracks are selected because the cross-track velocities are oriented nearly along the isobaths in the direction of the mean currents.

[11] The winter (December–March) mean current anomalies (not shown) are toward the southwest, and the summer (June–September) mean anomalies are toward the northeast, consistent with the results of *Aikman et al.* [1988] and *Rossby and Benway* [2000]. The seasonal anomalies are relatively strong south of the Northeast Channel (42°N, 66°W). To determine whether the currents reverse direction from winter to summer, a mean velocity is estimated from the VACMs for the PRIMER period, December 1995 to December 1997. Combining the VACM mean with the altimetric mean for the same period gives a mean velocity for 1992–1998, $\bar{u}$, as described below.

[12] The total velocity for our study period (1992–1998), $u(t)$, can be divided into a mean $\bar{u}$ and an anomaly $u'(t)$ that is,

$$u(t) = \bar{u} + u'(t),$$

where the anomalous velocity $u'(t)$ is derived from the T/P SSH anomalies for which the average is zero for the 1992–1998 period. However, the average of $u'(t)$ for any period shorter than this period is not zero. Thus, for the PRIMER period,

$$u_{alt}(t) = \bar{u} + u'_{alt}(t) = \bar{u} + \langle u_{alt} \rangle + u''_{alt}(t),$$

where the subscript *alt* represents the T/P altimeter, $\langle u_{alt} \rangle$ is the mean of the anomalous geostrophic velocity from T/P SSH during the PRIMER period and $\langle u''_{alt} \rangle$ is zero over the PRIMER period. Under the assumption that the VACM mean from the PRIMER observation, $\langle u_{cm} \rangle$ is equal to the altimetric mean, $\bar{u} + \langle u_{alt} \rangle$, the mean velocity for 1992–1998 can be estimated as

$$\bar{u} = \langle u_{cm} \rangle - \langle u_{alt} \rangle.$$

[13] Adding $\bar{u}$ to the seasonal velocity anomalies shows that the currents usually reverse direction from winter to

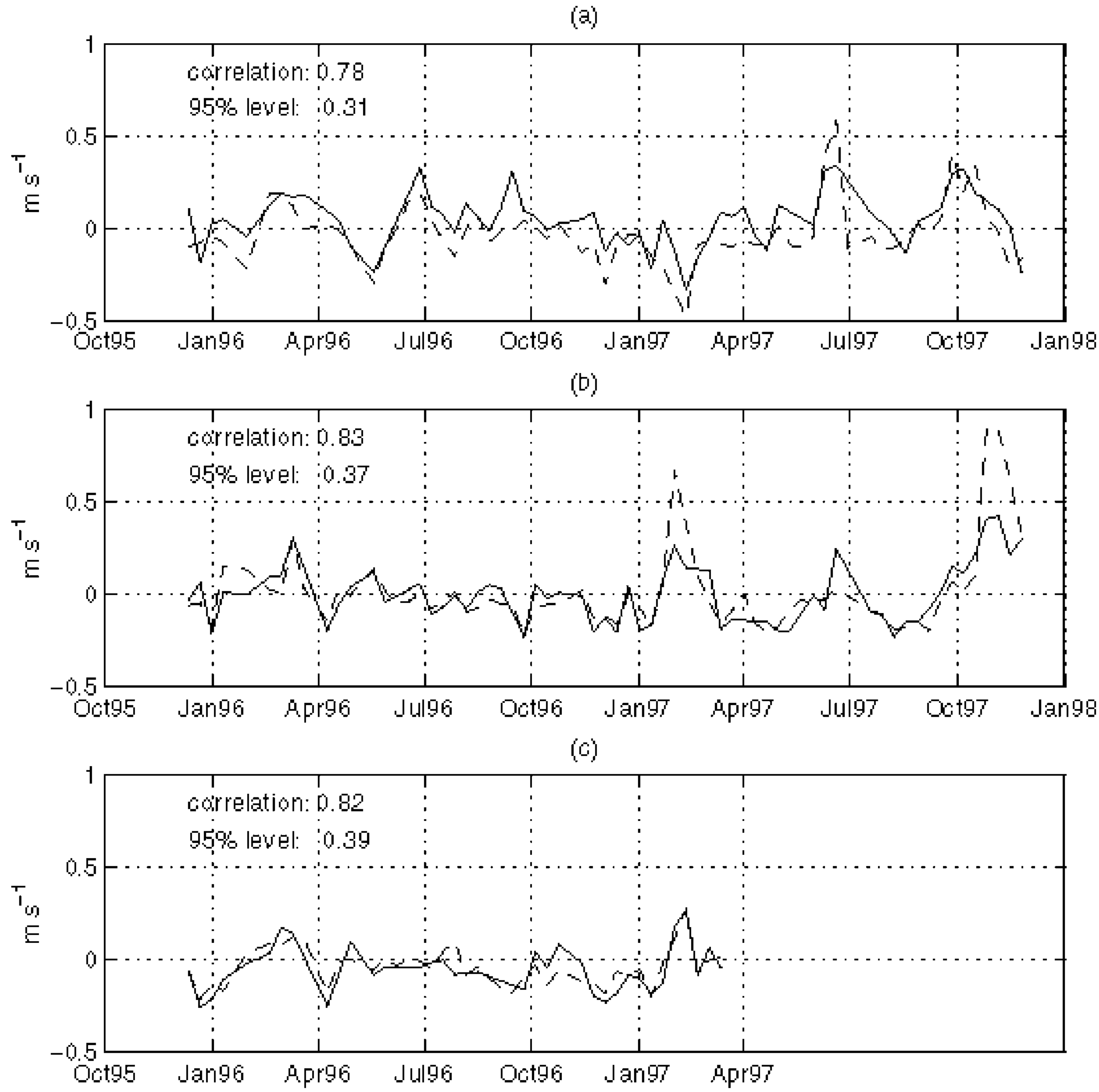


Figure 1. Comparison between the near-surface current meter velocity (dashed line), (projected in the cross-track direction), and the T/P geostrophic velocity (solid line). Current meter depths are (a) 90 m, (b) 110 m, and (c) 99 m; ocean depths are 2990 m, 2210 m, 1000 m, respectively.

summer at the two shallow VACM locations (1000-m and 2200-m isobaths). The seasonal mean velocities during winter are −4.5 and −3.5 cm/s, and during summer are 1.2 and 2.3 cm/s at the 1000-m and 2200-m isobaths, respectively. The in situ measurements at the 3000-m isobath do not show this seasonal reversal. The results here depend on the assumption that the currents above 100 m are comparable to the surface currents.

[14] The large-scale velocity variations are examined using an empirical orthogonal function (EOF) analysis for the six subtracks. For this analysis, no filters are applied to the velocity anomalies. The first EOF mode accounts for 32.1% of the total velocity variance. The second mode (not shown) accounts for 17.3% of the variance and describes localized current variations near the Gulf of Maine. The spatial function of the first mode represents coherent flow along the isobaths over the slope region (Figure 2); the time series is dominated by the seasonal cycle discussed above. However, the time series (Figure 2b) suggests that the usual seasonal reversals disappeared during 1996, leaving the anomalous flow consistently toward the southwest. Compared to the 1993–1995 time period, the southwestward flow is stronger during 1996–1998, which is consistent with the ADCP measurements between New Jersey and Bermuda discussed by *Rossby and Benway* [2000]. We also conducted an EOF analysis after removing the seasonal

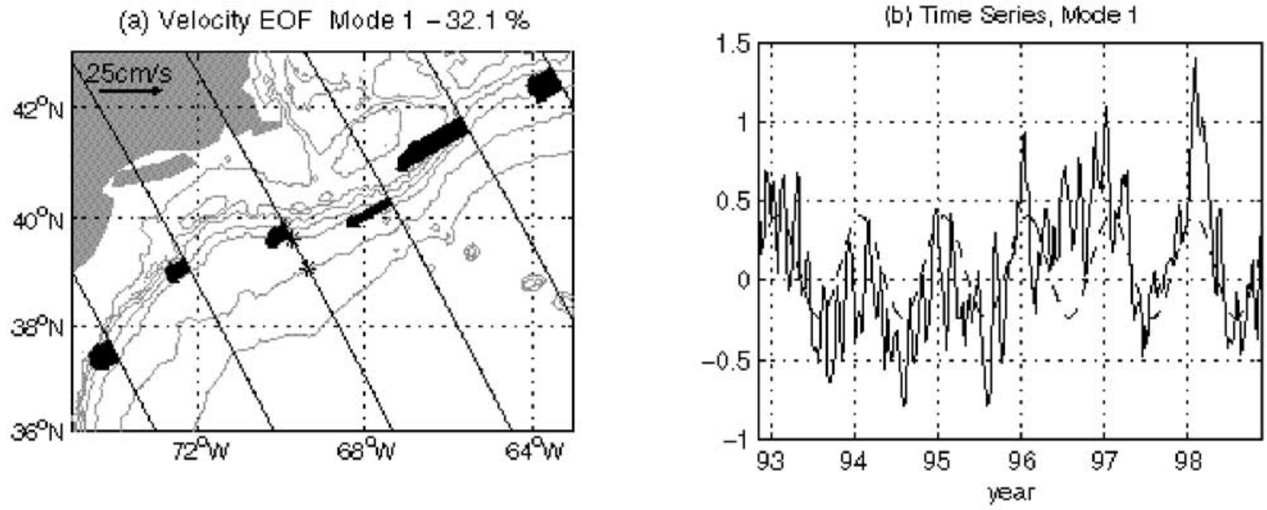


Figure 2. (a) Spatial function and (b) time series of the first EOF of the geosgrophic velocity. A positive value in Figure 2a corresponds to a southwestward velocity anomaly in Figure 2a. The dashed line in Figure 2b is the best fit annual harmonic. Stars are the VACM mooring locations.

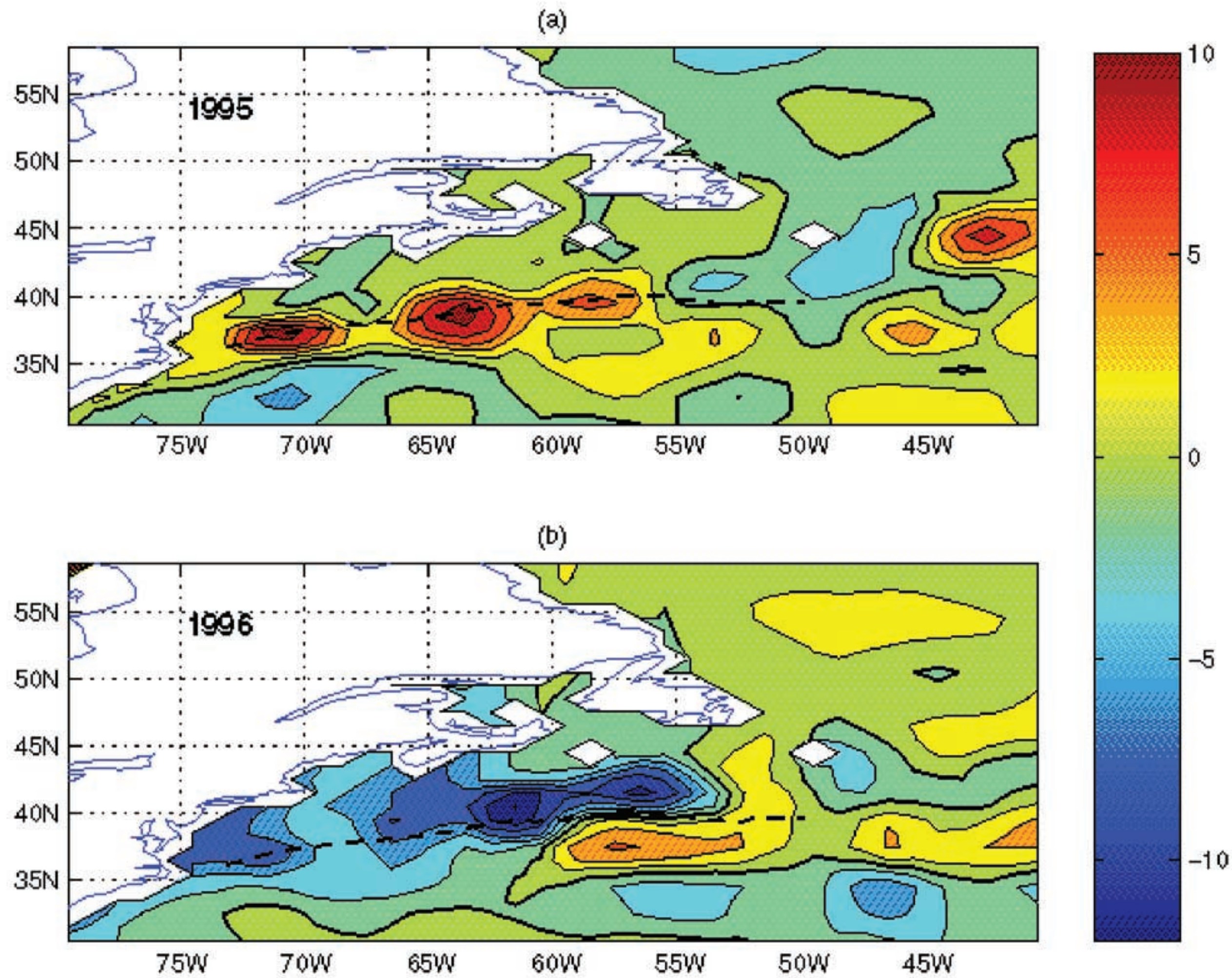


Figure 3. Annual mean SSH anomalies during (a) 1995 and (b) 1996. The contour interval is 2 cm. The thick solid line is zero line, and the thick dashed line is the mean Gulf Stream position.

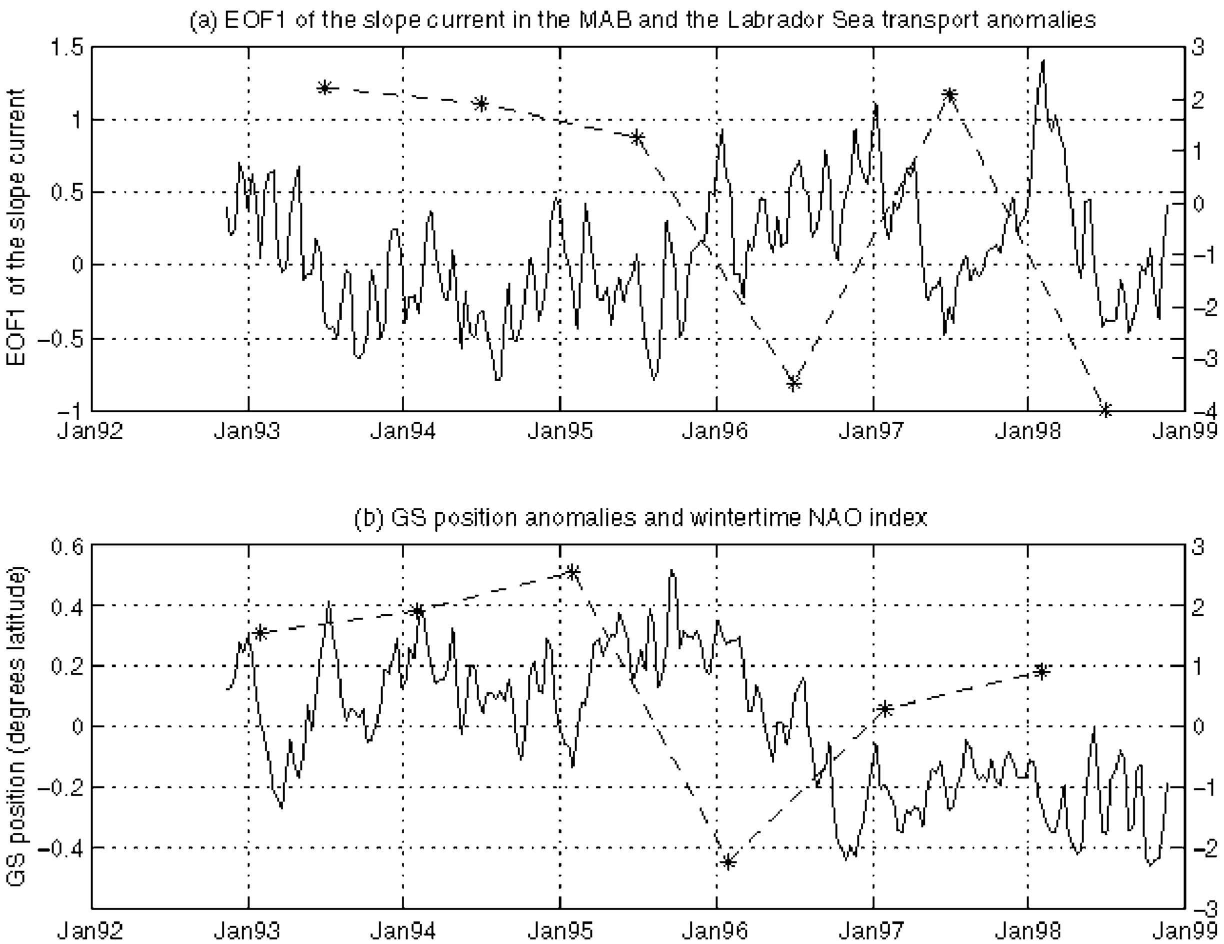


Figure 4. (a) Time series of the EOF mode 1 of the slope current in the MAB (solid line, LHS scale) and the yearly averaged Labrador Sea total transport anomalies (dashed line, RHS scale). A positive value corresponds to a southwestward (southward) anomaly in the MAB (Labrador Sea). (b) Zonally averaged Gulf Stream position anomalies (solid line, LHS scale) and wintertime (December–March) NAO index (dashed line, RHS scale).

cycle from the anomalous geostrophic velocity. This analysis gives the same results for the interannual variations in the slope currents: the disruption of the seasonal reversals during 1996 and the stronger southwestward flow during 1996–1998.

4. Discussion

[15] Variations in the slope currents have been attributed to the changes in the upstream region, i.e., the Labrador Sea outflow. However, we argue that the variations are more likely associated with the changes of the Gulf Stream located just south of the Slope Sea. In particular, we examine the disruption of the seasonal cycle of the slope currents in 1996.

[16] The large-scale SSH map (Figure 3) suggests that the SSH anomalies in Slope Sea in 1995–1996 are associated with the SSH changes that occurred in much of the western North Atlantic between 35°N and 45°N. The SSH in 1996 decreased by about 10 cm in the Slope Sea compared to that in 1995. This suggests a stronger cyclonic slope gyre in 1996, which is consistent with the anomalous southwestward flow over the slop. The decrease in SSH along the mean Gulf Stream path (dashed line in Figure 3) suggest a southward shift of the Gulf Stream.

[17] To determine whether the Gulf Stream path change is responsible for the changes in the slope currents, we calculate the Gulf Stream position from the T/P data using the method of *Kelly and Gille* [1990] and *Qiu* [1992]. The zonally averaged Gulf Stream position anomalies (relative to the whole study period) show that the Gulf Stream moved farther south by about 0.8° latitude between 1996 and 1998 (Figure 4b). The correlation between the first EOF mode of Gulf Stream position anomalies and the first mode of the geostrophic slope velocity anomalies is about 0.64 (the 95% significance level is 0.45); this correlation implies that the southwestward current anomaly corresponds to the more southerly Gulf Stream position. In other words, a southward shift of the Gulf Stream corresponds to an intensified cyclonic slope gyre. This correlation is inconsistent with the results of *Bane et al.* [1988], who found that the slope currents were stronger, toward the southwest, when the Gulf

Stream was closer to the shelfbreak. However, their study was based on a shorter time series near the Gulf Stream separation point at about 73°W.

[18] Although there is a significant correlation between the Gulf Stream position and the slope currents, this correlation does not eliminate the possibility that the changes in the slope currents are caused by the Labrador Sea outflow. The hypothesized continuous flow from the Labrador Sea to the MAB [*Chapman and Beardsley*, 1989] implies that a strong southward Labrador Sea transport would cause a strong southwestward flow in the MAB. Figure 4a shows the Labrador Sea transport anomalies (provided by Han Guoqi), where positive anomalies correspond to stronger than average southward transports. On the basis of *Rossby and Benway* [2000], the southwestward slope current in the MAB should have positive anomalies at least from 1994 to 1996 to correspond to the stronger Labrador Sea transport during 1993–1995. However, the slope current is stronger after 1995, which suggests that its seasonal disruption in 1996 is not caused by the Labrador Sea directly. There is another possibility, that the Labrador Sea transport could change the Gulf Stream position, which in turn could cause variations in the slope current. *Rossby and Benway* [2000] suggested that strong Labrador Sea shelf transport causes a southward shift of the Gulf Stream one year later. Changes in the Labrador Sea shelf transport are related to the North Atlantic Oscillation (NAO), with a strong transport corresponding to low NAO with a half-year lag [*Rossby and Benway*, 2000]. However, *Han and Tang* [2001] showed that a high NAO causes an enhanced Labrador Sea transport (Figure 4). In either case, the southward shift of the Gulf Stream cannot be explained by the Labrador Sea transport. The strong Labrador Sea transport in 1993–1995 (Figure 4a) should cause the Gulf Stream to move to the south *before* its actual shift in 1996. This suggests, at least in this case, that the variations in the Gulf Stream position and in the slope currents are not caused by the Labrador Sea outflow.

[19] The above arguments suggest that the disruption of the seasonal cycle in 1996 is related to the Gulf Stream southward shift, but what causes the southward shift of the Gulf Stream? Several studies hypothesize a relationship between the Gulf Stream position and the wind stress/wind stress curl [*Joyce et al.*, 2000; *Taylor and Stephens*, 1998; *Kelly et al.*, 1996]. In addition to a decrease in the strength of the westerlies, the zonally averaged, wintertime wind stress showed a southward shift of the wind pattern during 1996 (Figure 5), typical for a change during negative NAO [*Rogers*, 1997]. The zonally averaged Gulf Stream position and the monthly NAO indices do show significant correlation (0.4, 95% significance level is 0.25) with the Gulf Stream lagging the NAO by about 15 months. The correlation can be as large as 0.8 after removing the signals with periods less than 1 year (95% significance level is 0.58). Therefore the observed changes in SSH and in the Gulf Stream position could be related to the southward shift in the maximum westerlies, as well as to a decrease in the wind speed. However, it should be pointed out that, because the changes in the Gulf Stream position, NAO and the slope current are dominated by the large 1996 event, the relationship between them may not be representative of a longer time series.

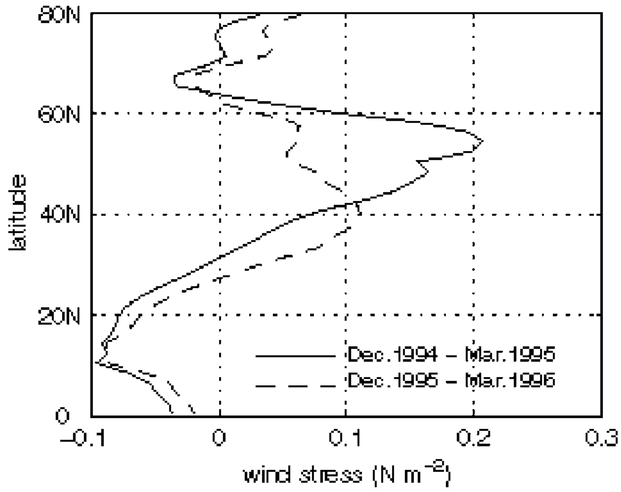


Figure 5. Zonally averaged (0°W–80°W), wintertime (December–March) zonal wind stress. Solid line is for 1994/1995 winter, and dashed line is for 1995/1996 winter.

5. Conclusion

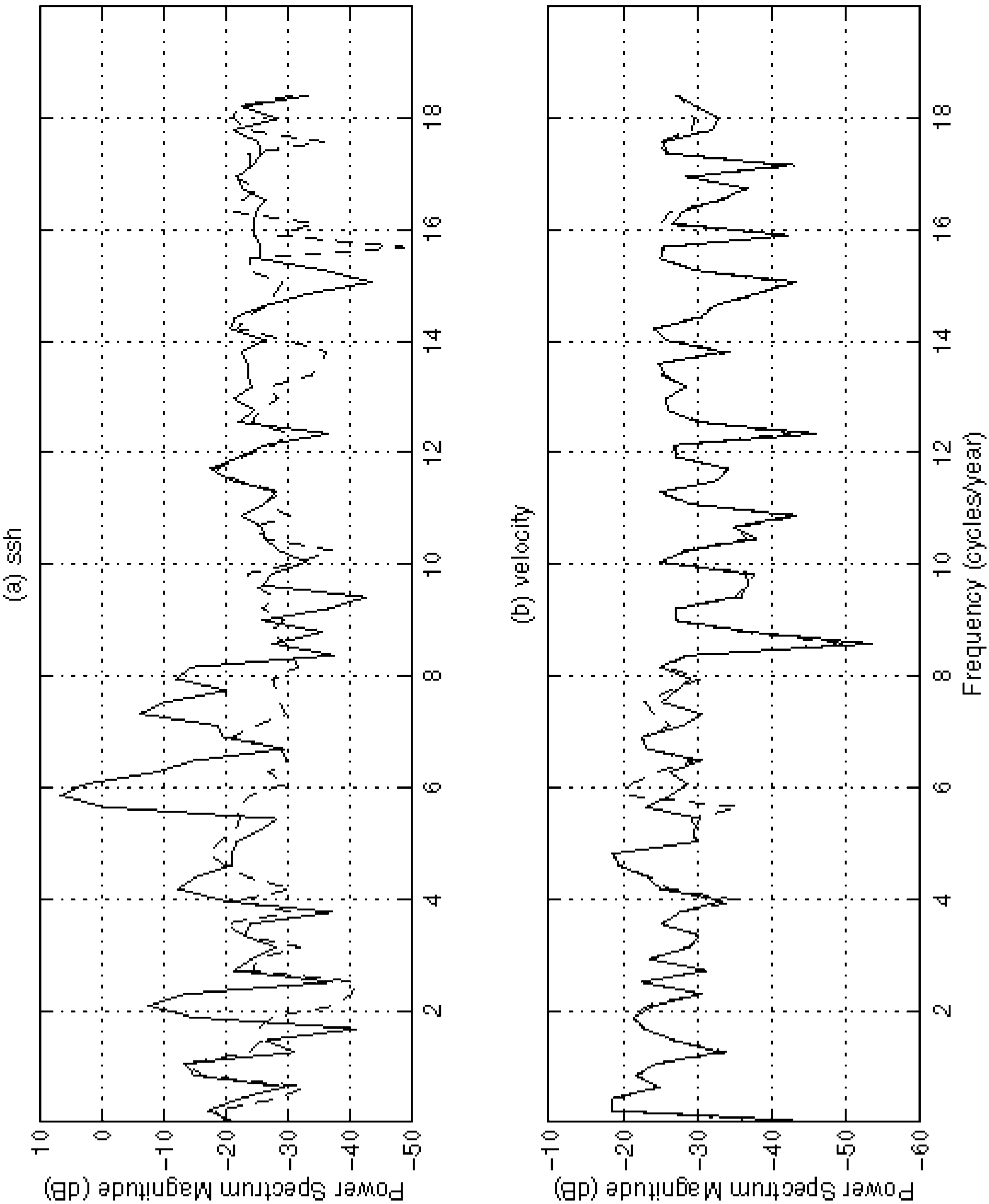
[20] Geostrophic velocities derived from the altimetric SSH data were found to be highly correlated with in situ velocities from recent moored measurements near 70°W. The geostrophic current anomalies from the T/P altimeter show coherent variations from New Jersey to south of the Scotian shelf with seasonal reversals, toward the southwest during the winter and toward the northeast during the summer, consistent with observed currents from previous regional studies. An EOF analysis of geostrophic currents indicates that the seasonal cycle was disrupted during 1996. This disruption is part of the intensification of the slope sea gyre, which is related to the southward shift of the Gulf Stream, the subpolar/subtropical gyre boundary. The southward shift in the westerlies and the decreasing wind speed early in 1996 could be responsible for this southward shift of the Gulf Stream.

Appendix A

[21] This appendix describes the tidal corrections checked in this study and the methods used to evaluate the corrections. The four tidal corrections are FES94(13), FES95.1(13), FES95.2, and CSR3.0.

[22] FES94.1 is a pure hydrodynamic solution, based on the finite element model developed by the Grenoble Ocean Modeling Group. This tidal solution includes 13 constituents, (M_2, S_2, N_2, K_2, $2N_2$, K_1, O_1, Q_1, Mu_2, Nu_2, L_2, T_2, and P_1). The geographic coverage of this model is global.

Figure A1. (opposite) Power spectral density for (a) sea surface height (SSH) and (b) cross-track geostrophic velocity on track 126. Solid lines correspond to the raw data, dashed lines to the detided data. Water depth is 200 m. FES95.2 tidal corrections is used.


(a) ssh
Power Spectrum Magnitude (dB)
10
0
−10
−20
−30
−40
−50
2
4
6
8
10
12
14
16
18
(b) velocity
Power Spectrum Magnitude (dB)
−10
−20
−30
−40
−50
−60
Frequency (cycles/year)

The resolution of the numerical model is spatially varying with a finite element grid refined over shelves and along the coasts, down to 10 km.

[23] The FES95.1 and FES95.2 models are improved version of FES94.1 derived by assimilating the earlier empirical T/P CSR2.0 tidal solution. The CSR2.0 solutions were computed by the University of Texas from two years of T/P data and with JGM-3 orbits. In FES95.1, which still includes only 13 constituents, the two major ones (M_2 and S_2) have been adjusted by means of the assimilation. The 11 other constituents are from FES94.1. FES95.2 includes 27 constituents. The eight major constituents, K_1, O_1, Q_1, M_2, S_2, N_2, K_2, and $2N_2$ are from the FES94.1 model. These components are corrected by assimilation, except K_2 and $2N_2$. The other 19 constituents are derived by admittance from the eight major ones.

[24] CSR3.0, developed by Richard Eanes and colleagues at the University of Texas, is basically a long wavelength adjustment to the FES94.1 hydrodynamic model. The CSR3.0 model is based upon 89 cycles (2.4 years) of T/P altimetry.

[25] The FES94(13) and FES95.1(13) used in our analysis are the special runs for the FES94.1 and FES95.1 models from Florent Lyard and Christian Le Provost with finer spatial resolution (0.05°_0.05°) on the East Coast. The value for FES95.2 and CSR3.0 are from the T/P CDROM.

[26] These tidal corrections are evaluated by using two methods: frequency spectra and the ratio between the variance of the data with and without tidal correction. For a good tidal correction, the magnitude of the power spectral density (PSD) at the major aliasing period (60 days for the semidiurnal tides, the dominant tides) should decrease. In addition, the variance of the SSH after tidal corrections should decrease because the tidal correction is removing part of the SSH signal. These arguments also hold for the derivatives of the SSH, which give geostrophic velocity. Similar results are obtained for the four tidal corrections. All the tidal corrections reduce the variance of the SSH by about 90% shoreward of the Gulf Stream region. However, none of them can consistently reduce the PSD and the variance of the SSH derivative in the depth range between 200 m and 2000 m. Since we concentrate on the seasonal variations, the 60-day tidal aliasing signal should not greatly influence the results. This is verified by the similar results from the EOF analysis after removing all the 60-day signal. However, the poor correlations between the geostrophic velocities from the T/P SSH and the ADCP velocities in shallow water (<200 m) prevent us to extend our study farther to the shelf. An example of the PSD for the data on track 126 (moorings was deployed along this track during the PRIMER experiment) at water depth 200 m (Figure A1) shows that the T/P tidal correction removed most of the 60-day signal for the SSH, but not for the SSH derivative, which is increased after applying the correction.

[27] **Acknowledgments.** This study benefited from discussions with LuAnne Thompson, Robert Pickart, Robert Beardsley, and Alberto Scotti. The current meter data were provided by Robert Pickart. The Labrador Sea transport was provided by Han Guoqi. The gridded SSH maps were obtained from D. Chelton and M. Schlax. This study was supported by NASA grants NAG5-6392 and NAG5-8296, contract 960888 (TOPEX/Poseidon Extended Mission) through the Jet Propulsion Laboratory and Office of Naval Research grant N00014-95-1-0575.

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