Gulf Stream Variability and Ocean–Atmosphere Interactions*

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(Manuscript received 15 September 2000, in final form 18 May 2001)

ABSTRACT

Time series of Gulf Stream position derived from the TOPEX/Poseidon altimeter from October 1992 to November 1998 are used to investigate the lead and lag relation between the Gulf Stream path as it leaves the continental shelf and the changes in sea level pressure, surface wind stress, and sea surface temperature (SST), as given by the NCEP reanalysis. The dominant signal is a northward (southward) displacement of Gulf Stream axis 11 to 18 months after the North Atlantic Oscillation (NAO) reaches positive (negative) extrema. A SST warming (cooling) peaking north of the Gulf Stream is also seen to precede the latitudinal shifts, but it is a part of the large-scale SST anomaly tripole that is generated by the NAO fluctuations. There is no evidence that the Gulf Stream shifts have a direct impact onto the large-scale atmospheric circulation. A fast, passive response of the Gulf Stream to NAO forcing is also suggested by a corresponding analysis of the yearly mean Gulf Stream position estimated from XBT data at 200 m during 1954–98, where the NAO primarily leads the latitudinal Gulf Stream shifts by 1 yr. The fast Gulf Stream response seems to reflect buoyancy forcing in the recirculation gyres but, as the covariability remains significant when the NAO leads by up to 9 yr, large-scale wind stress forcing may become important after a longer delay. Because of the high NAO index of the last decades, the TOPEX/Poseidon period is one of unprecedented northward excursion of the Gulf Stream in the 45-yr record, with the Gulf Stream 50–100 km north of its climatological mean position.

1. Introduction

The North Atlantic climate is strongly influenced by the Gulf Stream. A significant part of the meridional heat transfer is due to the gyre circulation, and the Gulf Stream system is associated with an intense heat loss that fuels the atmospheric storm track. The Gulf Stream variability could thus have a strong climatic impact. The observations are too sparse to document the changes in the meridional heat transfer, but the position of the Gulf Stream has been monitored over many decades. It is thus of interest to investigate the cause and effect of its variability.

The variations in the Gulf Stream path exhibit two main modes as it leaves the continental shelf: wavelike fluctuations primarily associated with the Gulf Stream meandering and instability and large-scale lateral shifts reflecting seasonal and interannual changes. It is generally found that the Gulf Stream is displaced to the north in fall and to the south in spring (e.g., Tracey and Watts 1986), while the current reaches its maximum baroclinic transport in early summer (Sato and Rossby 1995). Using 2-day composite AVHRR images to determine the position of the Gulf Stream from 1982 to 1989, Lee and Cornillon (1995) showed that its seasonal shifts were in phase between 70°W and at least 60°W. Kelly et al. (1999) found from 4 yr of altimetric sea surface height data that the largest seasonal signal occurs between 73° and 64°W. Yet, Rossby and Gottlieb (1998) observed only a slight seasonal dependence of the maximum velocity at 52-m depth in 4.5 yr of weekly Doppler current profiles crossing the Gulf Stream near

* Woods Hole Oceanographic Institution Contribution Number 10428.

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70°W, and Taylor and Stephen (1998) found no consistent seasonal cycle in 30 yr of monthly charts of the Gulf Stream north wall derived from surface, aircraft, and satellite observations. Similarly, in the present study the mean seasonal cycle could not be significantly differentiated from the much larger interannual variations in 6 yr of TOPEX/Poseidon altimetric data.

The interannual variability of the lateral shifts in the Gulf Stream position may be due to the atmospheric forcing. In Parsons' (1969) and Veronis' (1973) two-layer steady-state models, the path of the separated western boundary current is defined by the outcropping of the interface, with the latter estimated from a mass balance of the Ekman and geostrophic currents at a given latitude. The latitude of separation thus depends on the integrated zonal wind stress. Although the time-dependent problem has not been solved, the adjustment to a change in the forcing should be determined by baroclinic Rossby wave propagation and take several years in the North Atlantic. Surface cooling (heating) along the outcrop has also been considered (e.g., Nurser and Williams 1990), resulting in a strengthening (weakening) of the jet and a southeastward (northwestward) shift of the separation path. Marshall and Nurser (1988) and Cessi (1990) have argued that the latitude of separation of the Gulf Stream is essentially determined by the dynamics of the recirculation gyres and their nearly constant potential vorticity, which in turn is determined by a balance between forcing and dissipation. Again, the time-dependent problem has not been considered, but we can speculate that the adjustment to buoyancy or wind stress forcing in the recirculation gyres is primarily controlled by the lateral diffusion associated with the eddy field, resulting in a much faster response than via baroclinic Rossby waves. Other mechanisms of variability have been suggested. Thompson and Schmitz (1989) found that an increased southward transport of the deep western boundary current would move the separation point of the Gulf Stream southward, and Spall (1996) showed that such variability could be solely due to the amount of Labrador Sea Water at the crossover point. Alternatively, Jiang et al. (1995) showed that the nonlinearity of the wind-driven circulation could lead for steady forcing to aperiodic fluctuations in the gyre circulation and the western boundary jet.

The observations suggest that the interannual variability of the lateral shifts is correlated with that of the atmosphere, but there are conflicting results on the existence or not of a time lag. Using 2.5 yr of Geosat altimetric height data, Kelly et al. (1996) found that the main path variations were correlated with the wind stress fluctuations over the North Atlantic and sea surface temperature (SST) changes west of 62°W, but not with the surface heat flux. Using frontal analysis from 1977 to 1988 to define the separation latitude of the Gulf Stream where it crosses the 2000-m isobath (near 74.5°W), Gangopadhyay et al. (1992) found that the low-frequency variations were in good agreement with the Parsons–Veronis model when the Gulf Stream was lagging by about 3 yr. Taylor and Stephens (1998) found that the Gulf Stream shifts were correlated during the 1966–96 period with the wintertime North Atlantic Oscillation (NAO), high values of the NAO index (stronger westerlies) favoring a northerly path 2–3 yr later. Using temperature data at 200-m depth to define the yearly position of the Gulf Stream between 1954 and 1990, Joyce et al. (2000) found instead that the correlation with the NAO during winter was maximum at zero lag or Gulf Stream lagging by 1 yr. They argued that the unlagged correlation may reflect a response of the NAO to the Gulf Stream shifts.

Kelly (1991) and Kelly et al. (1996) have suggested that there is a direct relation between the Gulf Stream shifts and the near surface transport. Using the GEOSAT data, they showed that the two variables were closely linked, a larger eastward transport in the recirculation area corresponding to a northerly path. Rossby and Gottlieg (1998) found that the near surface transport remained nearly constant near 70°W, but their results may not be typical of Gulf Stream conditions elsewhere, and Kelly et al.'s (1996) mode of joined Gulf Stream transport/path variability has negligible amplitude near 70°W.

The fluctuations and meandering of the Gulf Stream have been documented from numerous satellite-derived SST images, the northern thermal gradient being traditionally used to locate its position (Lee and Cornillon 1995; Taylor and Stephen 1998). However, Rossby and Gottlieb (1998) noted that the large velocity gradient along the north edge of the Gulf Stream does not necessarily coincide with the SST front but could be displaced anywhere within about 100 km to either side. At low frequency, the meridional shifts of the jet maximum seemed to broadly reflect those of the highest temperature, and the slope water was warmer when the Gulf Stream was closer to the shelf. This led Rossby (1999) to suggest that changes in the influx and admixture of shelf water into the slope water may help to control its latitude.

On the other hand, as reviewed by Frankignoul (1985), large-scale midlatitude SST anomalies on the seasonal scale primarily result from the changes in the atmospheric forcing, primarily via surface heat exchanges and vertical entrainment. Near the Gulf Stream and to the north of it, advection by geostrophic and Ekman currents also plays an important role, leading to SST anomalies with a longer timescales than in the mid ocean (Kelly and Qiu 1995; Halliwell 1998). The relation between Gulf Stream path and SST variability is thus complex and scale-dependent.

Joyce et al. (2000) hypothesized that the SST signal produced by the latitudinal shifts of the Gulf Stream might influence the position of the extratropical winter storm track and thus the NAO. As the latter controls the production of mode water in the subpolar gyre and the Labrador Sea, the resulting changes in the deep western boundary current would in turn affect the Gulf

Stream position, leading to decadal climate changes. Whether the Gulf Stream shifts have an impact on the atmospheric circulation has not been established. Response studies with atmospheric general circulation models have shown that a SST anomaly off Newfoundland could displace the Atlantic storm track during fall and winter (Palmer and Sun 1985; Peng et al. 1995), but the impact of SST anomalies near the Gulf Stream has not been considered. By using an ensemble of simulations forced by the observed global SST and sea ice distribution, Rodwell et al. (1999) found that a significant part of the NAO variability was associated at low frequency with the tripole that dominates the SST variability in the North Atlantic. Using observations, Czaja and Frankignoul (1999) showed that the atmospheric circulation in the North Atlantic sector was related during certain seasons to previous large-scale SST anomalies in the North Atlantic. A SST influence on the NAO was detected during early winter, but the SST anomaly amplitude was small near the Gulf Stream.

Clearly, the relation between Gulf Stream path, SST, and atmospheric variability needs to be investigated further. This is done in the present paper, using time series of the Gulf Stream path derived from the TOPEX/Poseidon (hereafter T/P) altimetric measurements and subsurface temperature observations, together with SST analyzed fields and data from the National Centers for Environmental Protection reanalysis.

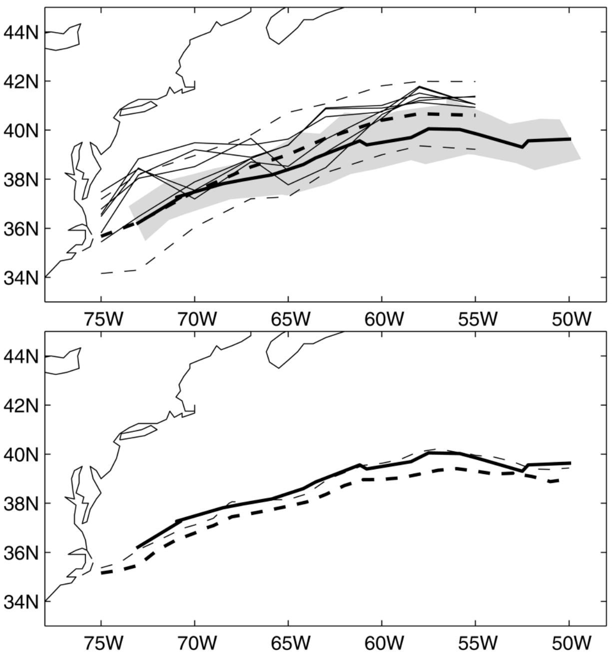

FIG. 1. Top: Long-term mean path of the Gulf Stream as determined from the 1992–98 T/P (continuous line and shaded domain) and the 1954–98 XBT (dashed line) data, where the interval gives ± two standard deviations. The thin lines indicate the Gulf Stream path for each year from 1993 to 1998, from the XBT data. Bottom: mean Gulf Stream path for the 1993–98 period as determined from the T/P data (continuous line) and the 17° isotherm at 200 m (thin dashed line), and mean position of the latter during 1954–1998 (thick dashed line).

2. Data fields

Two complementary datasets have been used to estimate the changes in the Gulf Stream location, one of limited duration but with a good spatial and temporal resolution and the other much coarser but covering 45 years. The first dataset was derived from the T/P sea surface height measurements between October 1992 and November 1998. For each of the 17 ascending and descending subtracks (unequally spaced) crossing the Gulf Stream between 73° and 50°W, the position of the jet maximum was determined by fitting an error function to the altimeter data across the current, using the method of Kelly and Gille (1990). After interpolation at 10-day interval (36 values per averaged year) using a cubic spline, the mean Gulf Stream path was determined and removed to provide time series of path fluctuations (Fig. 1). Attempts at determining a statistically significant mean seasonal cycle failed as the mean monthly departures from the long term mean could not be distinguished from the interannual variability, neither along-track nor for the main patterns of variability as estimated by a decomposition into empirical orthogonal functions (EOFs). To follow standard practice, the annual harmonic was nonetheless removed for each track by least squares fit, although it was verified that it does not significantly affect the results below.

An EOF analysis of the 10-day path fluctuations indicated that the main mode of variability is in phase over the study area, but with negligible amplitude east of 55°W. Since significant changes to the Gulf Stream take place in this region where it approaches the Grand Banks (Rossby 1999), we only consider the 14 tracks that cross the mean Gulf Stream path to the west of 55°W. Figure 2 shows the first EOF (top) and principal component (PC1, bottom) of the path along track fluctuations. As there is little energy at high frequency, monthly averaged data are used hereafter, with virtually no change in the EOF and 31% of the monthly variance explained. The lateral shifts correspond to in-phase displacement with an average amplitude of about 30 km, a minimum near 68°W, and a maximum around 57°W. PC1 varies over a broad range of timescales and has a red spectrum (Fig. 3). It is dominated by an unresolved low-frequency signal, the Gulf Stream path shifting by 60 to 80 km southward. As the shift is in the middle of the record, it imprints a 3 yr timescale that is reflected in the broad negative lobe (not significant at the 5% level) of the autocorrelation in Fig. 3. The higher EOFs (not shown) are noisy and primarily reflect Gulf Stream meandering.

We have also used subsurface temperature data to estimate the Gulf Stream path, following Joyce et al. (2000). In this study, MBT and XBT profiles from the Levitus (1994) atlas were used to estimate the Gulf Stream position between 75° and 55°W from 1954 to

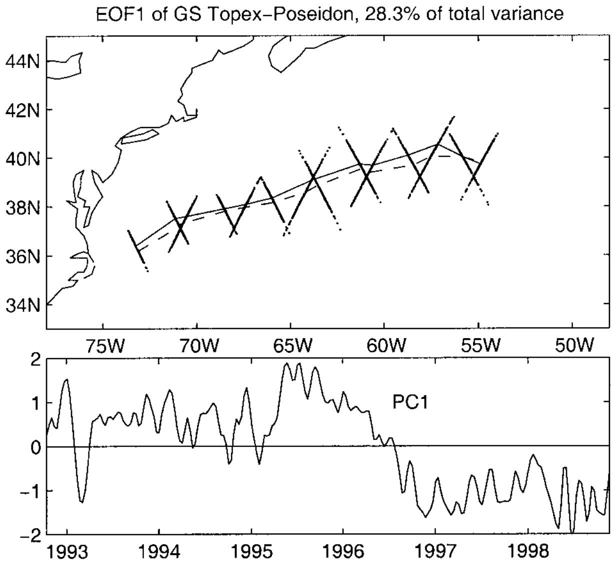

FIG. 2. First EOF (top) and PC (bottom) of the Gulf Stream path fluctuations in the T/P data. The mean Gulf Stream axis is given by the dashed line and the tracks are indicated by the dots, each dot corresponding to an estimated position of the jet maximum. The PC is normalized so that the EOF amplitude indicates typical lateral shifts.

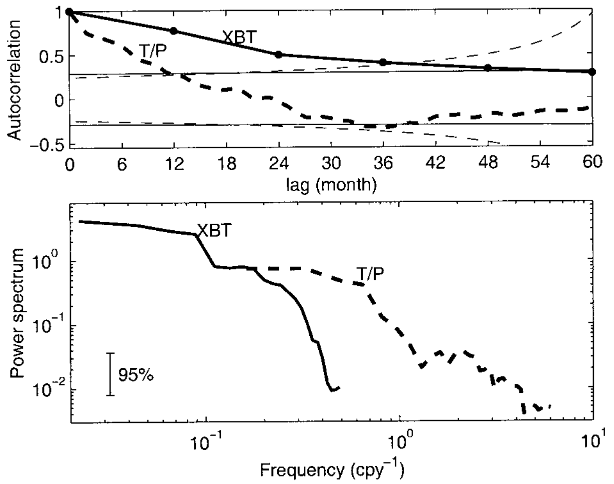

FIG. 3. Autocorrelation function (top) and power spectrum estimated with the multitaper method (bottom) of PC1 of T/P (dashed line) and T_{200} (continuous line). To plot the spectra (in arbitrary units), T/P PC1 was scaled so that its yearly averages have the same mean and amplitude as the XBT data during the overlapping years 1993–98. The thin lines give the 5% level for no-correlation and independent samples.

1989, the limited data density only providing reliable data at yearly resolution. In the present study, the data were extended to 1998, using online data available from NOAA (GTSPP files provided by NODC). The latitude of the 15°C isotherm at 200 m was taken as an indicator of the position of the Gulf Stream. Because it corresponds to the northern wall of the Gulf Stream, the mean position estimated by this method is to the north of the mean T/P Gulf Stream path by up to 1° latitude in the eastern part of the domain. One can see by Fig. 1 (bottom) that the mean position of the 17°C isotherm at 200 m during the T/P years agrees well with that from the surface jet from the altimeter and it is substantially northward of its 45-yr mean position. Thus the T/P years represent a Gulf Stream that is 50 to 100 km farther north than found during most of the modern record. It will be argued below that it results from the positive phase of the NAO during the 1990s. It is nonetheless conceivable that the observed trend also reflects in part a gradual warming of the gyre over time.

The yearly temperature at 200 m was interpolated along the mean position of the 15°C isotherm and the temperature anomalies with respect to the long-term mean (hereafter T_{200}) used to describe the variability of the Gulf Stream path. As discussed by Joyce et al. (2000), the climatological wintertime mixed layer depth given by the Levitus atlas is much less than 200 m in the region of interest and T_{200} should be little affected by diabatic processes. A warmer temperature along the mean path thus corresponds to a more northerly Gulf Stream and a colder temperature to a more southerly Gulf Stream. Interannual changes are thereafter given in degree Celsius rather than latitude, but the information is similar. As in the T/P data, the main mode of variability has in-phase temperature changes in the entire study area (Fig. 4). In view of the limited data coverage in recent years by XBTs, the correspondence between the two datasets is rather good during the six overlapping years. The power spectrum (Fig. 3) is con-

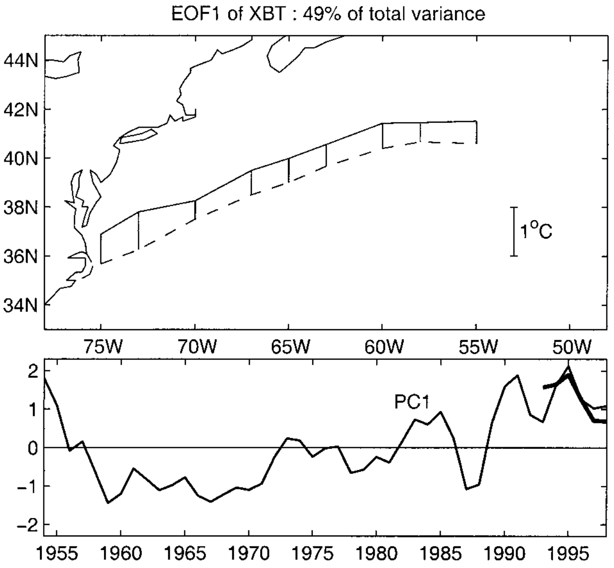

FIG. 4. First EOF (top) and PC (bottom) of T_{200} during 1954–98. The PC is normalized so that the EOF amplitude indicates typical temperature variations. The mean T_{200} position (dashed line) is taken as the zero axis and the temperature given by the vertical lines. For comparison, yearly averages of the T/P PC1 (thick line) were scaled to have the same mean and variance as the XBT data during the overlapping years 1993–98.

sistent with the T/P one and shows that spectral flattening only occurs at very low frequency; the dominant time scale is decadal. The lack of a negative lobe in the autocorrelation at 3 yr confirms that this feature of the T/P series was not significant but due to the limited data length.

In addition, we used monthly (or yearly) fields of sea level pressure and surface wind stress anomalies from the NCAR/NCEP Reanalysis Project (Kalnay et al. 1996) from January 1948 to September 1999. The SST was taken from the $1° \times 1°$ data of Reynolds and Smith (1994) for the T/P period, and from the $2° \times 2°$ Reynolds SST fields for the XBT period. Data provided through the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado (available online at http://www.cdc.noaa.gov/).

3. Statistical analysis

To establish the link among the fluctuations in Gulf Stream path, the atmospheric circulation, and SST we have investigated how the relations between these variables vary as a function of time lag. Lagged correlation is powerful in distinguishing between cause and effect in the extratropical latitudes as on monthly or longer timescale the atmosphere primarily acts as a white noise forcing on the ocean. If the ocean only responds passively, there should be no correlation when the ocean leads by more than the atmospheric persistence time. Because of atmospheric persistence and data averaging, the correlation is large when the two media are in phase but it peaks when the ocean lags if the data are averaged over a duration smaller than the oceanic time scale; otherwise the maximum correlation occurs at zero lag. At larger lag, the correlation decays like the oceanic anomalies. If SST fluctuations influence an atmospheric variable, their cross-correlation does not vanish when the ocean leads; if the atmosphere acts as a negative feedback, there is a sign reversal between lead and lag conditions; if the feedback is positive, the correlation remains of one sign, but still peaks when the ocean follows (Frankignoul 1985). Similar statistical signatures characterize the geostrophic response of the ocean to stochastic atmospheric forcing, although Rossby waves, higher order dynamics, or active ocean-atmosphere coupling add complexity in long lead and lag conditions (Frankignoul et al. 2000).

Several techniques were used to describe lag correlation: projection of one field onto the PC of another, cross-correlation between PCs, and maximum covariance analysis (hereafter MCA) based on a singular value decomposition. The results are similar, but lagged MCA will be mostly used for display as it maximizes the signal-to-noise ratio and does not prescribe the dominant patterns. In the MCA, say an oceanic field $\mathbf{X}(t)$ at time t and an atmospheric one $\mathbf{Y}(t - \tau)$ at time t–τ are expanded into K orthogonal signals

$$\mathbf{X}(t) = \sum_{p=1}^{K} a_p(t)\, \mathbf{p}_p, \qquad \mathbf{Y}(t - \tau) = \sum_{q=1}^{K} b_q(t - \tau)\, \mathbf{q}_q,$$

plus noise, with $\mathbf{p}_k \cdot \mathbf{p}_t = \delta_{kl}$, $\mathbf{q}_i \cdot \mathbf{q}_j = \delta_{ij}$, where the covariance between a_k and b_k is maximum for $k = 1, 2, \cdots$. So-called (Bretherton et al. 1992) homogeneous maps for the ocean and heterogeneous maps for the atmosphere [i.e., the projection of $\mathbf{X}(t)$ and $\mathbf{Y}(t - \tau)$ onto $a_k(t)$] will be shown since they preserve linear relations between the variables. Robustness was assessed by testing the statistical significance of the square covariance and the correlation between a_k and b_k, using a moving-blocks bootstrap approach (von Storch and Zwiers 1999). Each MCA was repeated 100 times, linking the original Gulf Stream dataset with randomly scrambled atmospheric ones (or SST), so that the chronological order between the two variables was destroyed. To reduce the influence of serial correlation, blocks of two successive months were considered when scrambling the monthly atmospheric series and blocks of 6 months (2 yr for yearly data) when scrambling SST. The quoted significance levels indicate the percentage of randomized square covariance and correlation for the corresponding mode that exceed the value being tested. Results are given without detrending, but their stability was assessed by repeating the analysis after removing a first or a second order polynomial by least squares fit. In nearly all cases, only the first MCA mode was significant and stable.

Because the NCEP reanalysis and the SST observations were available over longer periods than the Gulf Stream path, the cross-correlation functions and lagged MCA were also calculated with extended atmospheric and SST datasets. This provided more degrees of freedom at large lags but, as the results are similar, only those based on the common period are displayed.

4. Gulf Stream path and atmospheric variability

To verify whether the latitudinal shifts of the Gulf Stream are related to the NAO, the cross-correlation between PC1 of its path fluctuations and Hurrell's (1995) NAO index was calculated. Note that we use monthly data throughout the year for the NAO index, rather than the usual wintertime averages. The cross-correlation for the T/P period has a broad peak when the NAO leads by 16–18 months and about 12 months, and there is no correlation at the 5% level of significance when the Gulf Stream is in phase or leads (Fig. 5, top). Similar results are obtained when using PC1 of sea level pressure over the North Atlantic sector instead of the NAO index (not shown), and when computing the cross-correlation between the yearly averaged values of the NAO index and T_{200} during the 1954–98 period (Fig. 5, bottom). In the latter case, the correlation is nearly zero when the Gulf Stream leads, becomes significant in phase, peaks when the NAO leads by 1 yr, and slowly decrease at larger lags like the autocorrelation in Fig.

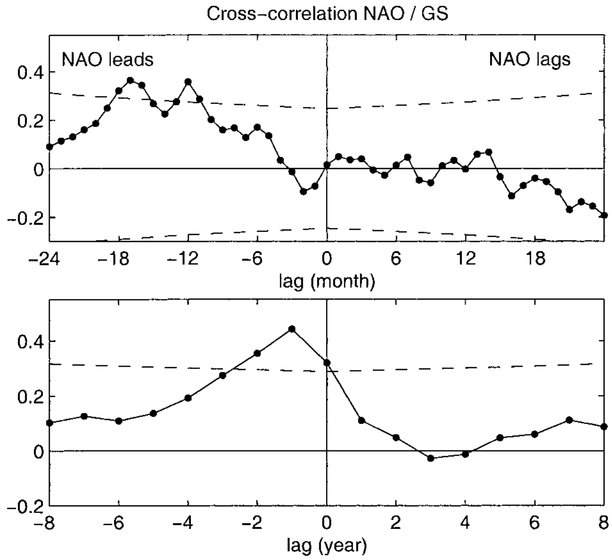

FIG. 5. Lagged correlation between PC1 of T/P (top) and T_{200} (bottom) and Hurrell's (1995) NAO index. The dashed line gives the 5% level for no-correlation and independent samples.

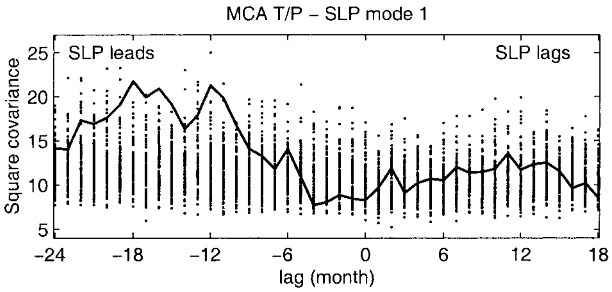

FIG. 6. Square covariance of the first mode of the MCA between T/P Gulf Stream path and sea level pressure as a function of lag (continuous line), and corresponding values in the moving blocks bootstrap (dots).

3. This is consistent with the statistical signature of a passive response to stochastic atmospheric forcing (section 3).

To see whether the NAO is the main atmospheric mode linked to the path fluctuations, a lagged MCA was performed between the T/P Gulf Stream data and the atmospheric variables. As illustrated for sea level pressure in Fig. 6, the square covariance of the first MCA mode is large and highly significant when the atmosphere leads by about 19 to 10 months, with peaks at lag −18 to −16 and lag −12 to −11. There is no significant covariability near zero lag. The results are robust to detrending. The atmospheric pattern is the NAO and the Gulf Stream displacement a latitudinal shift (Fig. 7), a more northerly Gulf Stream path following a positive phase of the NAO as in Fig. 5, with very little pattern dependence on the lag. The Gulf Stream shift resembles EOF1 in Fig. 2 and is also typically of 20 to 40 km (note that the Gulf Stream position is not to scale), suggesting that NAO is indeed the primary cause of the lateral shifts. However, the path is noisier, in part because of the more limited duration of the lagged series. The results are similar with the wind stress and wind stress curl, considered simultaneously with equal weight in Fig. 8 where the MCA shows the characteristic pattern of a positive NAO phase for these variables. Preceding a northward shift of the Gulf Stream, the westerlies are stronger and shifted poleward, and the North Atlantic trade winds intensified, resulting in a negative wind stress curl anomaly between 35° and 55°N, and a positive one farther north. As discussed by Marshall et al. (2001), the north–south migration of the jet stream as the NAO rises and falls leads to an anomalous ''intergyre'' gyre roughly centered on the mean gyre boundary. Note that the signs in Figs. 7 and 8 should be inverted to describe the southward shift of the Gulf Stream that dominates the T/P period. Whether the two dominant lags (−17 and −12 months) reflect distinct phases of the response or correspond to the same broad peak in the lagged covariance, as suggested by the similarity of the patterns in each field, cannot be decided from the limited T/P time series.

A small but significant covariance was also found when the Gulf Stream path leads the atmosphere by 21–22 months, with similar patterns to those in Figs. 7 and 8, but with the opposite sign. However, the time interval between the negative and positive peaks matches the lag of the negative lobe of the PC1 autocorrelation in Fig. 3, and no corresponding covariability was found in the XBT data. Hence, we interpret the 21-month covariability (and a similar phenomenon in the MCA with SST below) as an artifact of the shortness of the T/P data.

The 45-yr XBT dataset provides better information on long lead or lag conditions. A similar analysis was conducted, using yearly averages of the NCEP data. In each MCA, the covariance of the first mode is highest and the statistical significance strongest when the atmosphere precedes T_{200} by 1 yr. The covariance remains significant at zero lag, but not when the Gulf Stream leads. This is very robust and is unaffected by detrending. The peak in square covariance stands out most clearly for wind stress and wind stress curl (Fig. 9), where the square covariance decreases rapidly between lag −1 and −3, then levels off, remaining significant when wind stress and wind stress curl lead T_{200} by up to 9 yr. As illustrated in Fig. 10, the patterns vary little with lag. The atmospheric anomaly patterns are those associated with a positive NAO phase, the small differences with Fig. 8 resulting from the much wider range of conditions encountered in the XBT period. The corresponding Gulf Stream shift is northward and its amplitude comparable to that of the EOF in Fig. 4, which again suggests that the NAO is the dominant cause of the coordinated north–south Gulf Stream shifts. How-

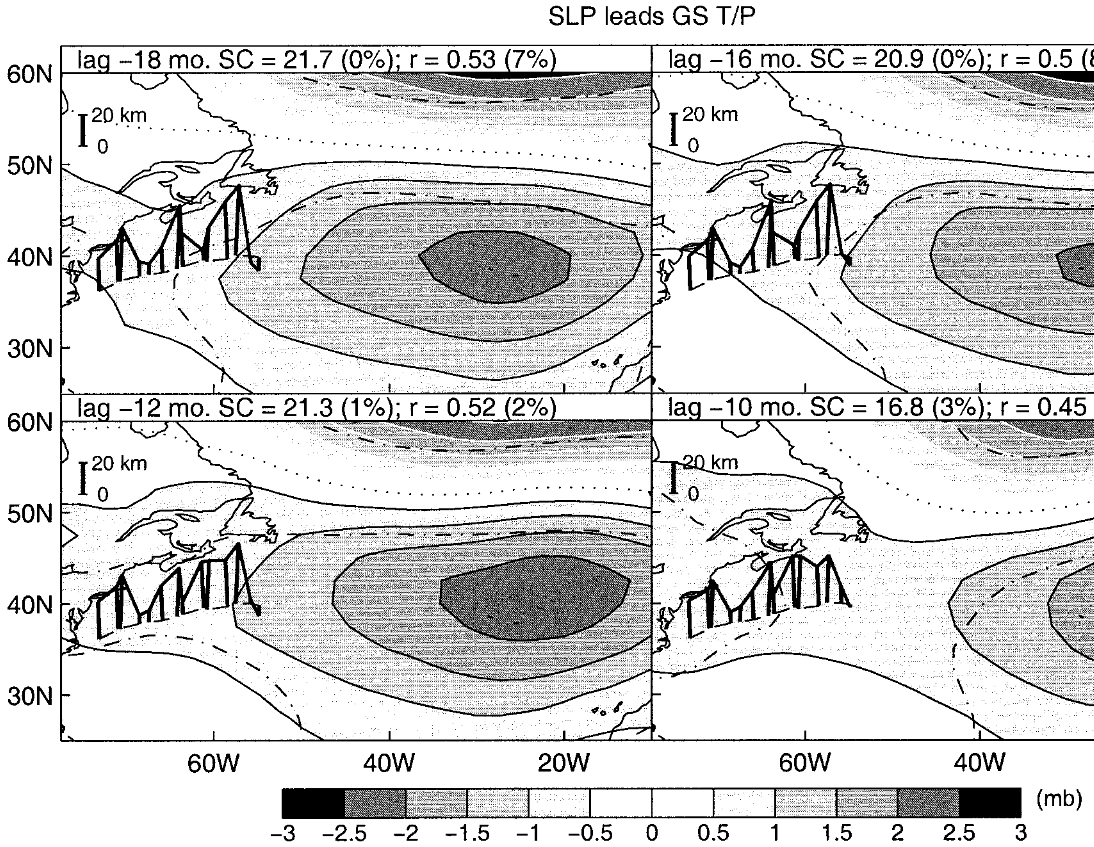

FIG. 7. First MCA mode between T/P and sea level pressure at various negative lags. Homogeneous maps are represented for the Gulf Stream path and heterogeneous ones for sea level pressure. The mean Gulf Stream path (dashed line) is taken as the zero axis, the angled lines give the along track Gulf Stream displacement (to avoid overlap, in the graph the zonal displacement has been divided by 15), and the scale is for meridional displacement. The dashed-dotted line indicates the 5% level for point correlation with the time series of the T/P mode. The latter is normalized so that the maps indicate typical amplitudes. The correlation coefficient *r* and square covariance SC are given with estimated significance level. Positive (negative) contours are in black (white) and dots indicate zero.

ever, significance is lost at lag <-1 yr when detrending or using sea level pressure in the MCA. Hence, the fast adjustment corresponds to that seen in the T/P data and is probably due to buoyancy forcing in the recirculation gyre, as argued below. The sustained significance at large negative lags corresponds better to the propagation time of baroclinic Rossby waves and may thus reflect a slower change in the baroclinic Sverdrup transport.

To attempt determining if there is a frequency dependence in the time lag between path and NAO, we calculated the coherence (multitaper method) between the time series of the MCA in Fig. 10 at each significant lag (not shown). The series were highly coherent at periods larger than 5 (short lags) or 8 (large lags) yr, the phase generally indicating a path delay of 1 to 3 yr. This delay tended to decrease with increasing period, suggesting little frequency dependence of the lag, but it is not monotonic at each lag and the error bars are large. Thus it cannot be decided whether the square covariance function in Fig. 10 only reflects the long persistence of the Gulf Stream fluctuations, the contribution of two or more physical mechanisms with different timescales, or a longer phase lag of the response at very low frequencies.

5. Relation with the sea surface temperature

As recalled before, the high resolution AVHRR images are used to track the position of the Gulf Stream axis, but here we focus on relatively large SST scales by using the monthly operational SST products issued by NOAA. Although largely based on the AVHRR imagery, they are constructed by optimum interpolation analysis and thus strongly smooth out features of scale smaller than a few hundred kilometers (Reynolds and Smith 1994).

To illustrate the lagged relations between the North Atlantic SST anomaly field and the north–south shifts of the Gulf Stream, Fig. 11 shows the regression of the $1° \times 1°$ monthly SST anomalies on PC1 of the T/P Gulf Stream path (the signs must again be inverted to describe its southward migration during the T/P period). When

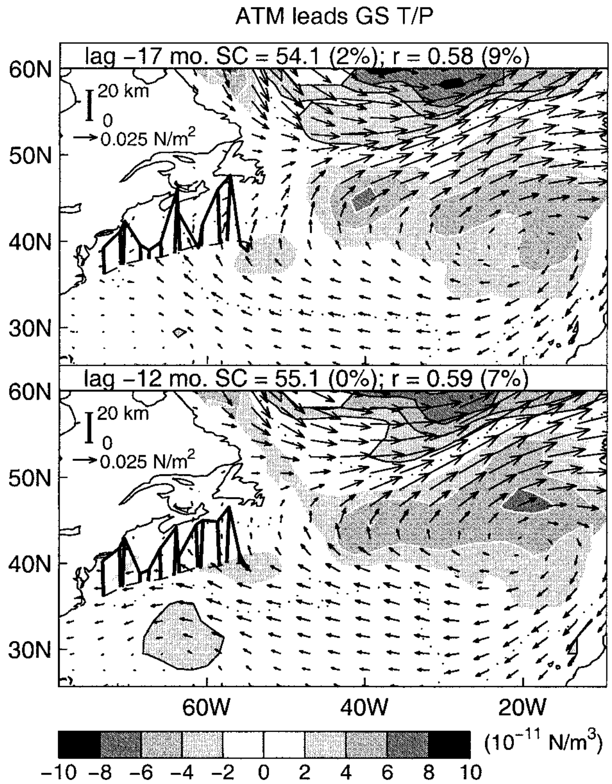

FIG. 8. First mode of the lagged MCA between T/P, wind stress, and wind stress curl at lag −17 and −12. Homogeneous maps are represented for the Gulf Stream path (see Fig. 7 for details) and heterogeneous ones for the atmosphere. The time series are normalized so that the maps indicate typical amplitudes. The correlation coefficient *r* and square covariance SC are given with estimated significance level. Positive (negative) contours are in black (white) and dots indicate zero.

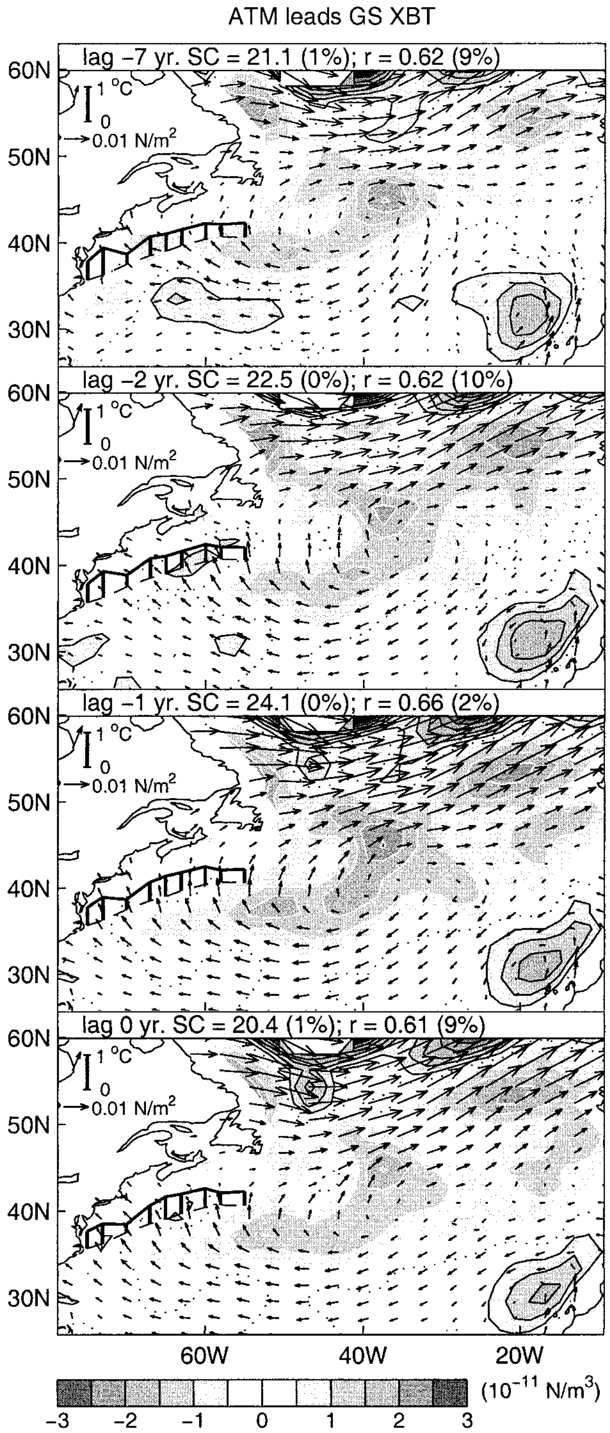

FIG. 10. As in Fig. 8 but for the MCA between T_{200} and wind stress and wind stress curl. The mean T_{200} position (dashed line) is taken as the zero axis and the temperature given by the vertical lines.

SST leads a northward shift of the Gulf Stream by up to 20 months or so, the SST is warmer than normal in much of the subtropical gyre, with a sharp maximum in the slope water area. The SST is also colder than normal north of 45°N, in the eastern Atlantic, and in the North Atlantic trade wind region. The SST anomaly pattern is thus a tripole with maximum amplitude at lag −16 to −12 for the large-scale signal, and −12 to −8 for the slope water. Statistical significance is difficult to establish because both PC1 and the SST anomaly fields are serially correlated, and the influence of serial correlation on significance is poorly known (von Storch and Zwiers 1999). However, as the 5% level for independent estimates generally resembles the 0.1°C con-

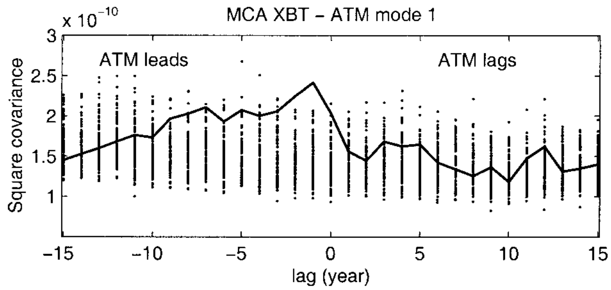

FIG. 9. As in Fig. 6 but for of the first mode of the MCA between T_{200} and wind stress and wind stress curl.

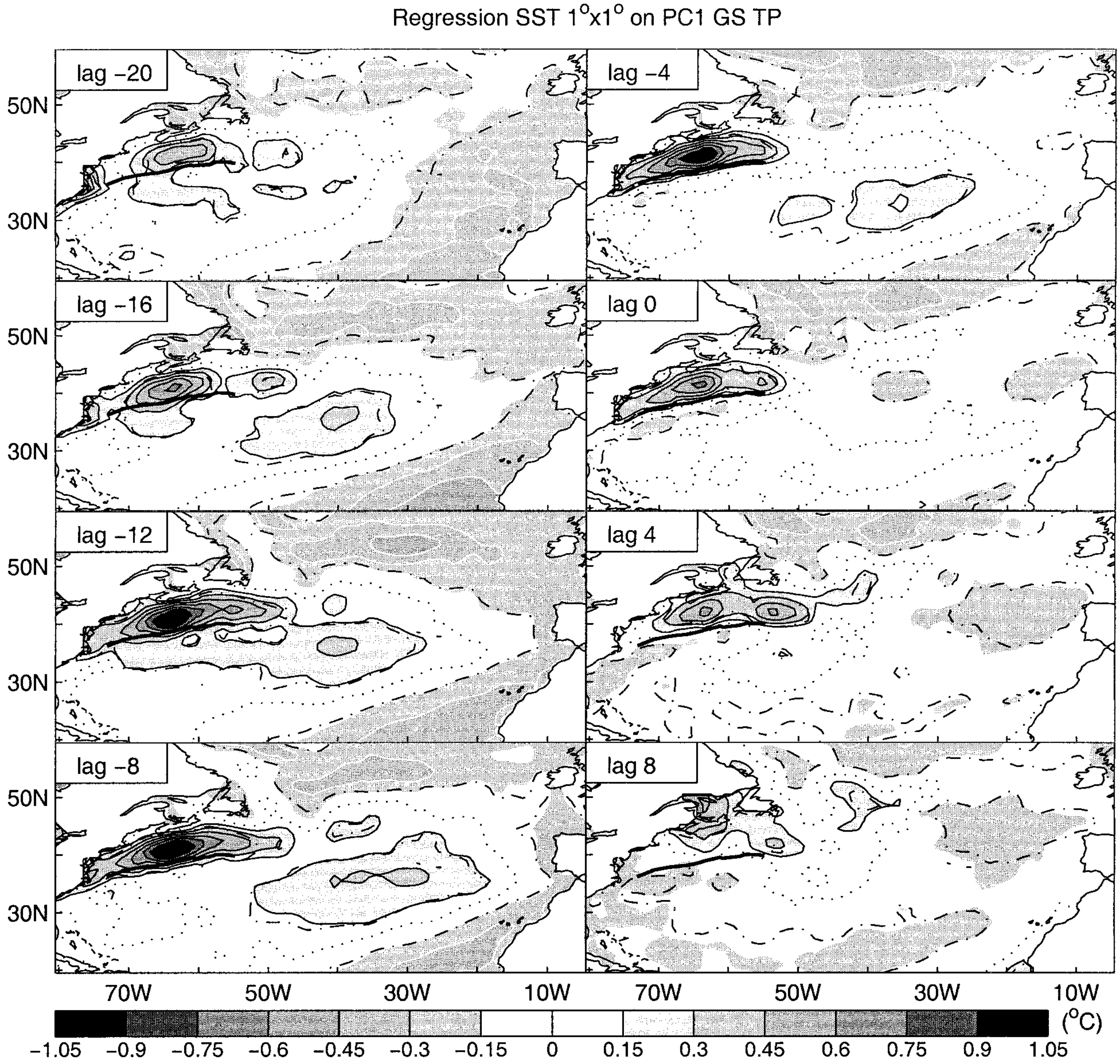

FIG. 11. Lagged regression between SST anomalies and PC1 of the T/P Gulf Stream path. SST leads at negative lags. The dashed–dotted line indicates the 5% level for no correlation. Positive (negative) contours are in black (white) and dots indicate zero.

tour, it can be safely assumed that the largest values in Fig. 11 are significant. Over most of the domain, the correlation weakens as the (negative) lag decreases. Near zero lag, there is a narrow SST dipole along the mean Gulf Stream axis that reflects the northward displacement of the Gulf Stream front. Indeed, the SST at a given time is usually maximum near the center of the jet, decreasing slightly to the south but rapidly to the north. As the SST climatology has similar, but highly smoothed, features, the SST anomaly associated with a northward (southward) displacement of the front should be strong and positive (negative) north of the mean Gulf Stream path and weak and negative (positive) south of it, as seen at lag 0. Figure 11 also suggests that, at small positive lags, the warm SST anomaly is moving eastward, presumably because advection strongly affects the SST in the Gulf Stream region. Significance is lost when the Gulf Stream leads by about 1 yr.

Similar (and robust) results are found in the MCA between the T/P data and SST. The square covariance of the first mode is significant at the 5% level when SST leads by about 20 to 4 months so that the covariance peak nearly coincides with that in Fig. 6, while persisting longer (Fig. 12). As illustrated in Fig. 13, the SST warming (cooling) which precedes a northerly (southerly) migration of the Gulf Stream is indeed part of a large-scale SST tripole extending over the whole North Atlantic. The SST anomaly peaks in the slope

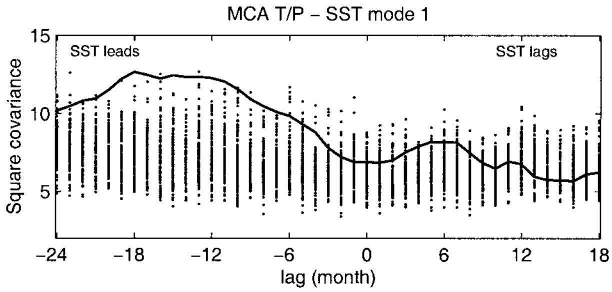

FIG. 12. As in Fig. 6 but for the lagged MCA between the T/P Gulf Stream path and SST.

water near 41°N, 63°W about 3 months after the tripole has been generated. Significance is lost near zero lag (the local SST imprint of the latitudinal shift is too weak to affect the large-scale signal) but there is a small, marginally significant peak near lag 4 (not shown), reflecting the eastward SST advection seen in Fig. 11.

The results can be linked to section 4 by remarking that the SST anomaly pattern at lag −18 in Fig. 13 closely resemble the SST anomaly tripole forced by the NAO. The latter creates SST anomalies primarily via the surface turbulent heat flux (not shown, but see Cayan 1992 or Czaja and Frankignoul 1999), although Ekman and geostrophic advection are important near and north of the Gulf Stream. The SST tripole is the dominant

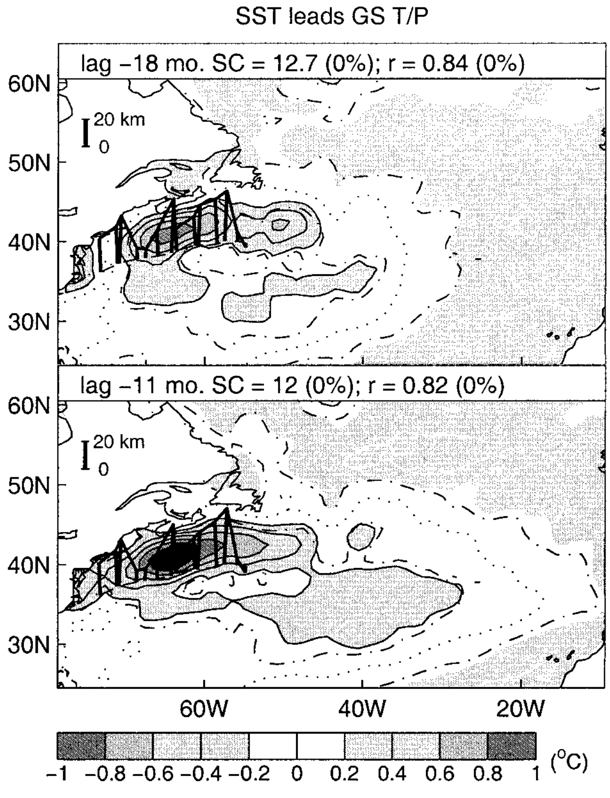

FIG. 13. As in Fig. 7 but for the lagged MCA between the T/P Gulf Stream path and SST.

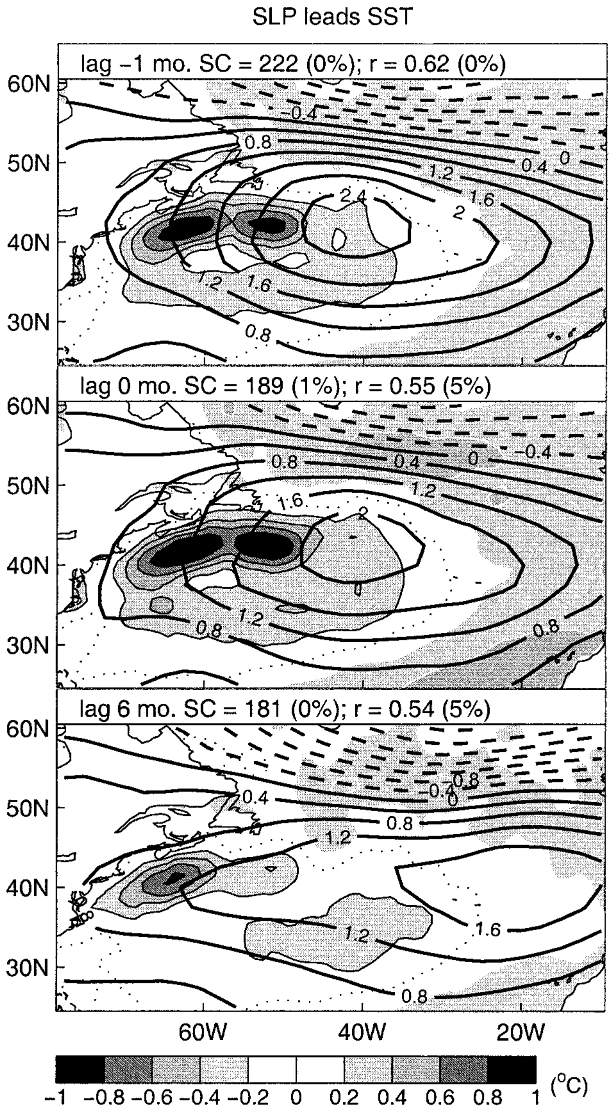

FIG. 14. As in Fig. 7 but for the lagged MCA between monthly SST and sea level pressure at lag −1, 0, and 6. SST leads at positive lags.

SST mode in wintertime conditions, and the large SST amplitude in the slope water is consistent with its shallower mixed layer. The tripole is also the dominant mode in the year-round MCA between sea level pressure and SST (Fig. 14), where the covariability peaks when SST follows the atmosphere by 1 month (or more) but is also strong at zero lag, as explained in section 3. Thus, both the Gulf Stream and the surface mixed layer respond to the NAO changes. As the SST anomaly response time is much shorter than that of the Gulf Stream, the SST changes precede the latitudinal shifts of the jet by about the same time lag as the NAO. The covariability of the Gulf Stream path with SST remains significant at smaller (negative) lags than with the NAO because SST anomalies persists more than the NAO, the SST persistence being probably enhanced by wintertime recurrence and heat transport.

Advection could explain why the SST anomalies take more time to develop in the slope water, that is, why they peak at smaller negative lag with respect to the Gulf Stream in Figs. 11 and 12, a feature that cannot reflect a direct response of the mixed layer to NAO forcing. Dong and Kelly (2000, unpublished manuscript) have shown that the slope current that transports cold water from the northeast was weak during 1993–95, which means less cold water transported to the slope sea, but strong in 1996. This should contribute to the observed cooling of the slope water during the T/P period. As a decrease of the amount of cold, fresh water by the Labrador Current along the shelfbreak may itself be related to a high NAO state (Pickart et al. 1999; Rossby and Benway 2000), the delayed slope water changes may simply reflect the complexity of the oceanic response to the NAO forcing.

A significant covariability between SST and sea level pressure anomalies is also found when SST leads by 5 to 6 months (Fig. 14, bottom panel). This reflects the impact of North Atlantic SST anomalies on the NAO that was detected during early winter by Czaja and Frankignoul (1999). Although the SST influence was seen more clearly (and also at shorter lags) when using seasonal data, it is remarkable that it stands out in only 6 years of data, attesting the strength of the signal. However, statistical significance in the MCA was basically lost at positive lag when limiting the SST to the Gulf Stream vicinity (35°–45°N, 45°–75°W). As discussed before, the MCA between the atmospheric variables and the T/P data showed no evidence of a direct impact of the Gulf Stream shifts on the atmospheric circulation. Thus, the SST anomaly impact on the atmosphere does not appear to be directly related to the Gulf Stream position.

This was confirmed for each season. Since the T/P data are too short, we assessed seasonal impact by considering SST in the small domain above but using the NCEP data between 1954 and 1998. Note that the SST anomalies were on a 2° × 2° grid as the higher resolution data are not available for the whole period. A lagged MCA was done by considering sets of 3 successive months per year for SST and sea level pressure or 500-mb geopotential height anomalies over the North Atlantic, following the procedure of Czaja and Frankignoul (1999). The SST in the Gulf Stream vicinity was found to respond to the atmospheric forcing throughout the year, but no significant covariability could be found when SST was leading.

The relation between Gulf Stream path and SST was also investigated using the yearly XBT data. A significant square covariance between SST and T_{200} was found without time lag. As shown in Fig. 15, the SST anomaly coarsely resembles the SST tripole of the T/P period (Fig. 13), except that the positive SST anomaly in the Gulf Stream vicinity extends farther westward, peaking

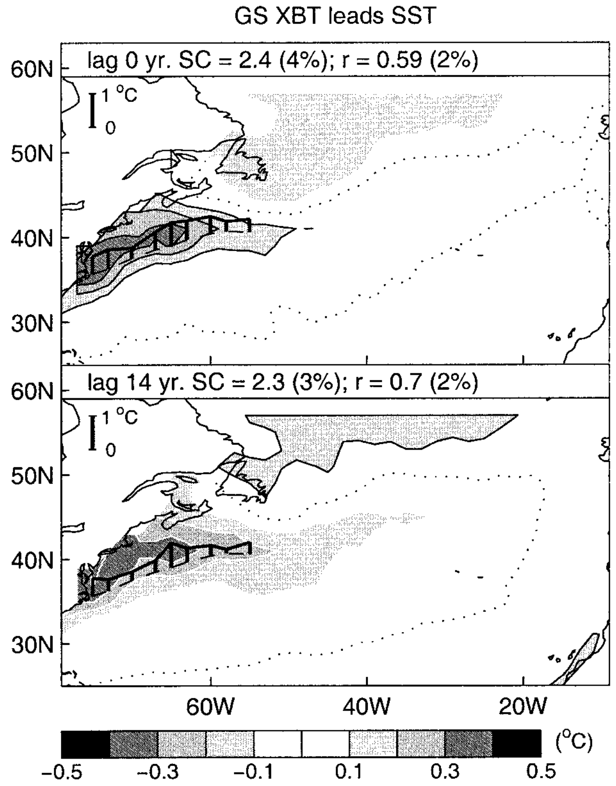

FIG. 15. As in Fig. 7 but for the lagged MCA between T_{200} and SST. The mean T_{200} position (dashed line) is taken as the zero axis and the temperature given by the vertical lines.

near the coast. However, the same feature is found in the MCA between yearly (or monthly) SST and sea level pressure when considering the whole 45-yr period (Fig. 16). This suggests that the differences in pattern between Figs. 13 and 15 primarily reflect long term changes in the atmospheric forcing. Note in Fig. 16 that the SST tripole is also strongly correlated with the NAO 1 yr earlier, presumably as a result of SST anomaly persistence and wintertime recurrence. The strong in-phase relation between the Gulf Stream shifts and SST in Fig. 15 is thus consistent with Fig. 10 and 16.

Even though a significant lag −1 yr relation was expected from the T/P results, the square covariance between SST and T_{200} was not significant when SST precedes T_{200} by 1 yr. However, it became significant when a linear or a quadratic trend was removed prior to the MCA. A highly significant covariability was also found when SST follows the Gulf Stream by 12 to 14 yr (Fig. 15). The patterns are strikingly similar to those at lag 0, but with the reversed sign for SST. Checking carefully the large lags in the other MCAs, we found no hint of a corresponding covariability between SST and sea level pressure. Some covariability could be recognized in the MCA between T_{200} and sea level pressure (but not wind stress nor wind stress curl) when T_{200} leads sea level pressure by 14 yr, but the statistical significance was marginal (SC 4%, r 22%) and very sensitive to detrend-

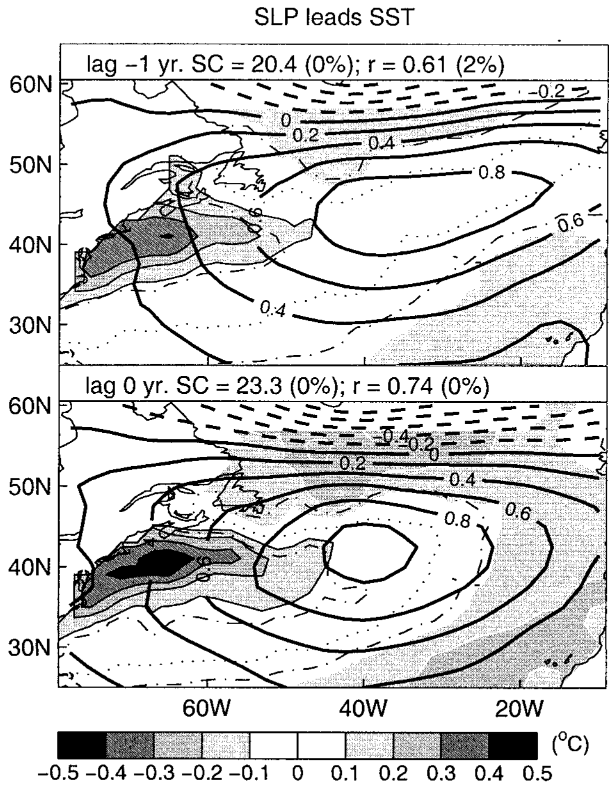

FIG. 16. As in Fig. 7 but for the lagged MCA between yearly SST and sea level pressure at lag −1 and 0.

ing. Thus, only the lag 12 to 14 yr covariability in Fig. 15 appears to be robust.

6. Summary and discussion

Both T/P and XBT data suggest that the main mode of interannual variability of the Gulf Stream path is a latitudinal shift caused by the NAO, a northward (southward) displacement of the jet axis following a positive (negative) phase of the NAO. In the T/P data, the covariability peaks when the Gulf Stream follows the NAO by 11 to 18 months, and no significant covariability with the atmosphere is found at zero lag or when the Gulf Stream precedes. The lack of correlation at zero lag contrasts with Kelly et al. (1996), who found using canonical correlation analysis that the changes in Gulf Stream path in the shorter GEOSAT data were weakly correlated with those of the wind stress curl. However, the canonical correlation did not seem robust as it was dominated by the contribution of high EOFs for both path and curl, and it was only slightly above the estimated 5% significance level.

In the yearly XBT data for the period 1955–98, the covariability with the atmosphere is dominated by a 1-yr delay between the NAO changes and the Gulf Stream latitudinal shifts. The covariability with wind stress and wind stress curl first decreases with increasing Gulf Stream lag but then levels off, remaining significant when the NAO leads by up to 9 yr. The in-phase covariability is also significant, but smaller than when the Gulf Stream follows by 1 yr. Joyce et al. (2000) found that the maximum correlation occurred in phase during the period 1955–89, but they were only considering the NAO during winter so that there is an implicit lag in their calculation. Furthermore, the maximum correlation occurred when the Gulf Stream follows by 1 yr when they extended the XBT data to the 1955–98 period (see their Fig. A2), in agreement with the present analysis. Note that these results explain why the Gulf Stream was northerly during the T/P period, as it was a time of generally high NAO index. In fact, the northerly position of the Gulf Stream in the decade of the 1990s is unprecedented in the 45-yr record.

Our estimate of the dominant lag between the Gulf Stream shifts and the NAO is shorter than in Taylor and Stephen (1998), who suggested a 2–3 yr delay. However, as discussed by Joyce et al. (2000), this delay reduces to 1 yr in the 1975–98 period, so the longer delay may be due to some particularities in the early part of their frontal analysis data. Using data for the 1977–88 period, Gangopadhyay et al. (1992) suggested a 3-yr delay near 74.5°W with the zonally integrated zonal wind stress. For comparison we did the MCA between T_{200} and the atmosphere for the same period. The first MCA mode was not significant. The second one was moderately significant when sea level pressure, wind stress, or wind stress curl leads T_{200} by 2 yr but with different patterns: an anticyclone centered on and to the south east of Newfoundland leading a northward shift of the Gulf Stream west of 65°W (not shown). Thus, a different but much weaker regime seemed to be prevalent during their measurement period, and no trace of it remained when considering the whole dataset.

In the T/P period, a large-scale SST warming (cooling) in the Gulf Stream area also precedes its northward (southward) migration. This mostly reflects the fast response of the mixed layer to the NAO fluctuations, which generate a basin-scale SST anomaly tripole, primarily via surface heat exchanges. Because of SST persistence and, possibly, wintertime recurrence, its covariability with the Gulf Stream path remains significant in the MCA until SST precedes by as little as 4 months. Statistical significance is lost near zero lag, but an imprint of the Gulf Stream front migrations can be recognized in the analyzed SST field. There is also some evidence of SST advection by the large-scale currents. In the Slope Water, the SST anomalies take more time to develop than on the basin scale and peak at smaller negative lag with respect to the Gulf Stream. This appears to be linked to the decrease of the amount of cold, freshwater transported by the Labrador current along the shelfbreak, which may itself be related to a high NAO state (Pickart et al. 1999; Rossby and Benway 2000).

The complex relation between Gulf Stream path and

SST is poorly resolved when using the yearly XBT data, as the SST anomaly tripole primarily varies in phase with the Gulf Stream latitudinal shifts. Contrary to what was expected from the T/P period, the square covariance is not significant when SST precedes T_{200} by 1 yr, unless the data are detrended. There are small differences with the patterns found with the T/P data, which probably reflect long-term changes of the dominant atmospheric patterns. A significant covariability is also found when the Gulf Stream leads SST by 12 to 14 yr, with strikingly similar patterns to those at lag 0 but reversed SST polarity. Whether it reflects an oscillatory behavior with a decadal half-period is not known, but more complex interactions seem be at play on longer time scales.

Even though the influence of the North Atlantic SST on the NAO discussed by Czaja and Frankignoul (1999) was seen in the T/P period, the lateral shifts of the Gulf Stream or SST in its vicinity seem to have no direct impact on the large-scale circulation. This contradicts the hypothesis by Joyce et al. (2000), but the sparcity of in situ data over the ocean and the spatial resolution of the NCEP reanalysis may limit its ability to detect a more local impact.

In summary, the Gulf Stream path seems to respond passively to the variability of the NAO with a delay of a year or so. This is much shorter than expected from linear adjustment to wind stress changes and baroclinic Rossby wave propagation, even when taking into account the proximity of the NAO forcing to the western boundary. On the other hand, the 1-yr delay seems consistent with the assumption that the Gulf Stream separation is controlled by the potential vorticity of the recirculation gyres. The local wind stress forcing is small, and thus buoyancy forcing and the associated SST changes are likely to prevail. They correlate well indeed at the yearly timescale with the potential vorticity in the subtropical mode water (Joyce et al. 2000). Baroclinic adjustment to the large-scale wind stress by Rossby wave propagation is nonetheless likely to contribute to the smaller, but significant, covariability found when wind stress and wind stress curl lead the Gulf Stream by several years.

Acknowledgments. This research was supported in part by a grant from the PNEDC, EC Grant EVK2-CT-1999-00020 (PREDICATE), and NSF Grant OCE98-18465. Thanks are due to J. Dunworth-Baker and F. Besset for their help in the calculations, and to the reviewers for useful comments.

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