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The North Atlantic Oscillation and the latitude of the Gulf Stream

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ABSTRACT

The physical processes determining the path of the Gulf Stream as it leaves the continental shelf of the USA are complex and involved. Understanding these processes is important to global climate studies because the Gulf Stream plays a major rôle in the distribution of heat in the northern hemisphere. Here we show that during the last 3 decades, the latitude of the Gulf Stream has been clearly correlated with the North Atlantic Oscillation (NAO); high values of the NAO index, which correspond to stronger westerly and trade winds, favouring more northerly paths of the Stream about 2 years later. The time-delay may be associated with the adjustment time of this part of the ocean circulation. If allowance is made for persistence of the Gulf Stream position from one year to the next, more than half the interannual variation in the position can be predicted.

1. Introduction

The intense current on the western boundary of the North Atlantic, the Gulf Stream, dissipates the bulk of the kinetic energy put into the ocean by the wind, results in a large transport of thermal energy to approximately 35°N (10^{15} W) and, downstream of where the Gulf Stream leaves the continental margin at Cape Hatteras, a large transfer of heat from the ocean to the atmosphere (Cornillon, 1992). The current structure, transport and water mass properties of the Gulf Stream vary geographically and temporally. These variations range from interannual and seasonal shifts, through substantial mesoscale (20–60 day) fluctuations, to rapidly translating and growing meanders with periods as short as 4 days downstream of Cape Hatteras (Watts, 1983). As a consequence its path presents difficulties for the most advanced ocean circulation models and the Gulf Stream is frequently predicted to follow the coast too far north before separating and turning east (Haidvogel and Bryan, 1992).

Ocean circulation theories predict that the position of the Gulf Stream/North Atlantic current system and the subpolar-subtropical front is set by the line of zero Ekman pumping at which there is no convergence or divergence of water in the wind-mixed surface layer of the ocean (Parsons, 1969; Veronis, 1973; Pedlosky, 1987; Cornillon and Gangopadhyay, 1991; Gangopadhyay et al., 1992). Warren (1963) and Robinson and Niiler (1967; Niiler and Robinson, 1967) have argued through conservation of vorticity that the detailed path of the current depends on upstream conditions; the position, angle, curvature and bottom velocity at some point along the Stream controlling the downstream path displacement. This idea has been verified statistically by Vazquez and Watts (1985), Tracey and Watts (1986) and Cronin et al. (1992). Thus, when Glenn and Robinson (1995) carried out real time operational forecasts of weekly Gulf Stream evolution between Cape Hatteras and the Grand Banks using the Harvard

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Open Ocean Model the evolution was driven more by internal dynamic processes like advection rather than by surface fluxes.

Monthly charts of the path of the north wall of the Gulf Stream have been available from surface, aircraft and satellite observations since 1966, and these have been used in several studies of the path's variability. Time-series of the latitude of the north wall have been extracted and analysed from these data at 6 longitudes between 65 and 79°W for 1966–77 by Taylor and Stephens (1980) and subsequently up to 1993 (Taylor et al., 1992; Taylor, 1995, 1996). Drinkwater et al. (1994) have examined the latitude of the north wall from the 1970's to 1992 at each degree of longitude from 50 to 75°W. Miller (1994) has analysed the onshore/offshore position of the north wall at 10 cross-isobath transects equally spaced between 75 and 80°W from 1976 to 1988.

The latitude of the north wall has been used as an indicator of climatic fluctuations over the North Atlantic (Taylor et al., 1992; Hays et al., 1993; Taylor, 1995; Willis et al., 1995; George and Taylor, 1995; Frid and Huliselan, 1996). There is therefore a need to know how the north wall's position is related to atmospheric conditions over the ocean basin. In the present paper, interannual changes in the position of the north wall from 1966 to 1996 are compared with variations in the North Atlantic Oscillation. It is shown that statistical predictions of the latitude of the Gulf Stream appear to be possible.

2. Latitude of the Gulf Stream

Monthly charts of the north wall of the Gulf Stream have been published by the US Naval Oceanographic Office in *Gulf Stream Monthly Summary* from 1966 to 1974, and by the US National Oceanic and Atmospheric Administration in *Gulf Stream* from 1975 until 1980 and *Oceanographic Monthly Summary* from 1981 until 1994. Additional charts for 1995 and 1996 have been provided by the US Navy. The monthly charts were analysed following the same procedure used in Taylor and Stephens (1980), Taylor et al. (1992) and Taylor (1995). The latitude of the north wall was read from each chart at six longitudes (Fig. 1): 79, 75, 72, 70, 67 and 65°W. Fig. 2 shows the latitude series from 1966 to 1996

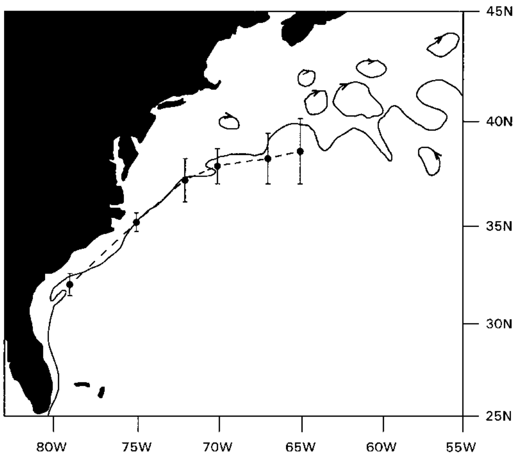

Fig. 1. The region of the north wall of the Gulf Stream studied, indicating the longitudes where the latitude of the north wall was estimated. The solid lines show the position of the north wall and associated eddies during August, 1984. The broken line shows the mean position of the north wall between 1966 and 1996. The error bars show 2 standard deviations either side of this mean position and so illustrate the range of latitudes encompassing 95% of the north wall positions.

at each of these longitudes. The eastern series have greater variability because of meandering of the Stream, but the time-series do not show any systematic variations associated with changes in the source of the charts. Seasonal variations are much smaller than interannual variations in these series and there is little consistent pattern to the mean seasonal cycle (Taylor, 1995 and Fig. 3 below).

Principal components analysis (Kendall and Stuart, 1966) was used to find the pattern of variation common to the 6 longitudes. This is preferable to simple averaging of the 6 latitude measurements which would emphasise the eastern longitudes, where the north-south movements of the Stream are largest, and possibly obscure smaller but coherent north-south shifts further west. Correlation coefficients were calculated between the time-series at the six longitudes and principal components calculated from the resulting correlation matrix. (Miller, 1994, has presented empirical orthogonal function analyses based on the variance-covariance matrix of north wall position data). Each principal component is calculated as a weighted average of the six standardised latitude series using weightings which can be

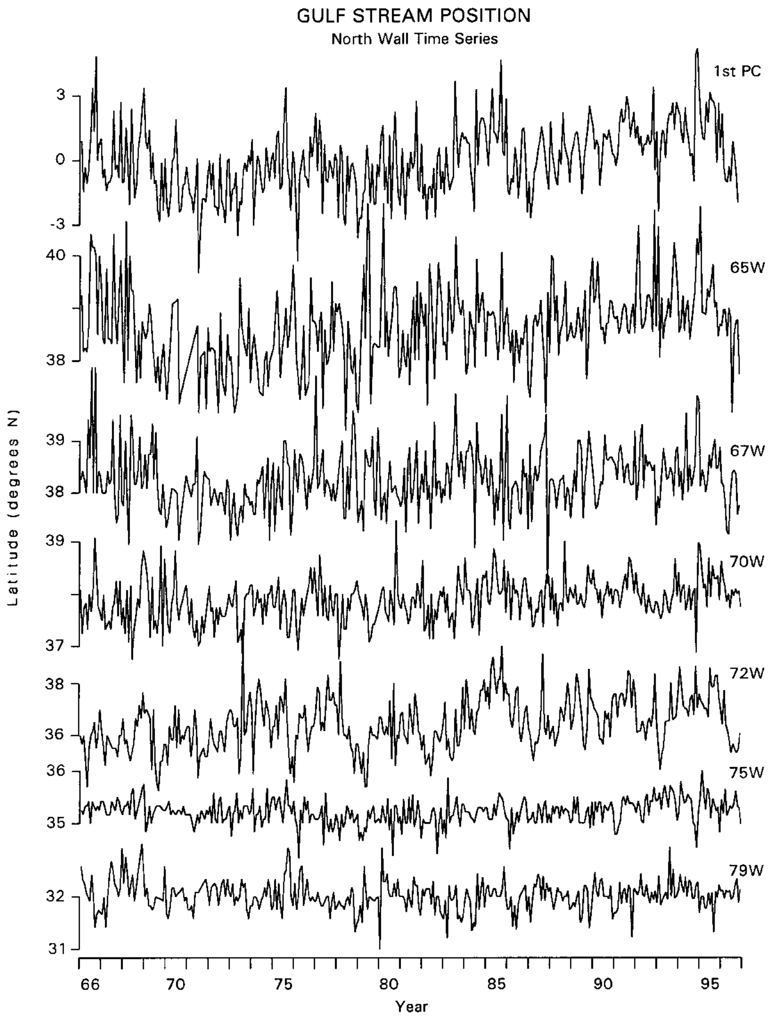

Fig. 2. Monthly series (1966 to 1996) of the latitude of the north wall of the Gulf Stream at 79°W, 75°W, 72°W, 70°W, 67°W and 65°W. The first principal component of these time-series is also shown (in arbitrary units).

expressed as correlation coefficients between the component and the original series.

The standardisation implicit in the correlation matrix complicates the statistical analysis of principal components. Bartlett's test (Kendall and Stuart, 1966) employs a χ^2 test to assess whether the eigenvalues are significant. The χ^2 values and degrees of freedom in Table 1 indicate that only the first two principal components are significant at the 5% level, which is in agreement with a plot of the logarithm of the eigenvalue against the number of the eigenvalue (Craddock, 1973) and with the commonly used criterion of employing only components that have eigenvalues greater than one. In each of these tests the second principal component only just exceeds the significance level.

The first principal component of the position of the north wall (Figs. 2, 3) has positive correlation coefficients of 0.15, 0.54, 0.49, 0.62, 0.57 and 0.48 with the latitude of the north wall at the six longitudes from 79°W to 65°W, respectively, and can therefore be regarded as representing displacements of this whole section of the Gulf Stream. The eigenvalue corresponding to the first principal

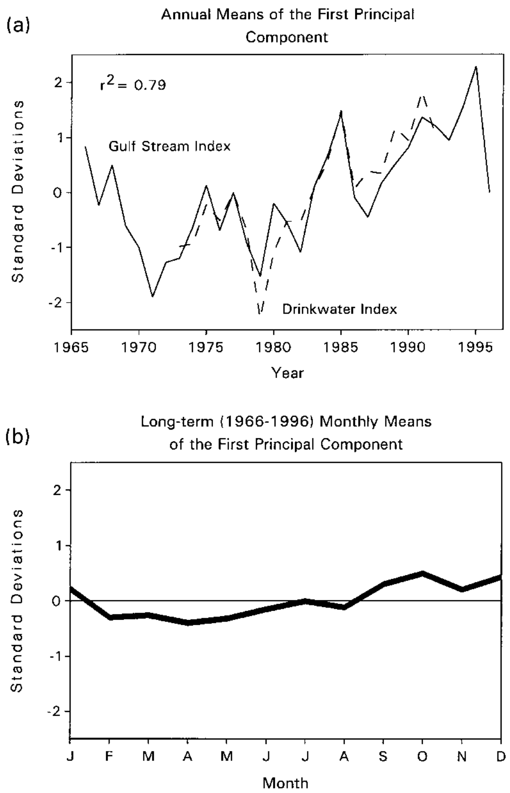

Fig. 3. (a) Annual values of the first principal component calculated from the latitude of the north wall (1966–1996) at 79, 75, 72, 70, 67 and 65°W (solid line) compared with the principal component calculated from the latitudes (1973–1992) at 75, 72, 70, 67 and 65°W from Drinkwater et al. (1994) (broken line). The correlation coefficient (r) between the 2 series is shown. Each component has been normalised to unit standard deviation. (b) Long-term monthly means (1966–1996) of the first principal component.

component has a value of 1.6 so that the component includes 27% (1.6/6) of the total variance of the six variables. This % has undoubtedly been reduced by the short period meandering of the Gulf Stream, for there will be little correlation between meanders that are widely separated in longitude. Long-term monthly mean values of the first principal component (1966–1996) confirm that the seasonal variations are much smaller than the interannual changes (Fig. 3b), and as a result the principal component in Fig. 3a is virtually indistinguishable from that obtained when the annual cycle was removed beforehand. The 2nd principal component has correlation coefficients of 0.83, 0.52, −0.31, −0.20, −0.17 and 0.11 with the latitude of the north wall at the six longitudes and so mainly represents a difference between the eastern and western halves of the front. Monthly and annual values of the first two principal components are available on *http://www.npm.ac.uk/pml/labproj1/web2.htm.*

Drinkwater et al. (1994) have analysed the latitude of the north wall on many more charts than the one per month that have been published, up to one per week or more, but covering a shorter period of years (1973–1992), and without data from 79°W. Further, while the techniques used to prepare the published charts may have varied over the course of the time-series, Drinkwater et al. (1994) have applied a consistent system of analysis to the data. Fig. 3a shows that the trend in the time-series of the first principal component calculated from these data at the 5 longitudes 75, 72, 70, 67 and 65°W, is in agreement with that based on the published charts. The first principal component based on the Drinkwater et al. data, which has an eigenvalue of 2.0 (40% of the variance of the 5 variables), has positive

Table 1. *Summary of principal components analysis*

Eigenvalue	Variance (%)	Cumulative variance (%)	χ^2	Degrees of freedom
1.62	27.0	27.0	105.2	15
1.18	19.7	46.7	39.8	14
0.95	15.9	62.6	15.2	9
0.87	14.1	76.7	6.9	5
0.75	12.5	89.2	2.3	2
0.64	10.8	100.0	0.0	0

correlation coefficients of 0.60, 0.64, 0.61, 0,74 and 0.59 with the latitude of the north wall at the 5 longitudes from 75°W to 65°W, respectively. The larger eigenvalue and correlation coefficients in this case arise because averaging more charts per month removes some of the short period meandering from the data. The agreement shown in Fig. 3a demonstrates that a smaller number of monthly charts are still sufficient to realistically represent the interannual variations, even though there may have been changes in the way they were prepared.

3. North Atlantic Oscillation and the latitude of the Gulf Stream

The Gulf Stream is an intense poleward current on the western boundary of the North Atlantic basin which is part of the asymmetric ocean circulation generated by the prevailing winds (Stommel, 1958). As a consequence, the path of the Stream at the US coast is dependent on the distribution of wind-stress across the whole of the ocean. A major source of interannual variability in the atmospheric circulation over the region is the North Atlantic Oscillation (NAO), which is associated with changes in the surface westerlies across the North Atlantic as far as Europe. Empirical orthogonal function analyses reveal that the NAO is the dominant mode of variability of the surface atmospheric circulation in the Atlantic and accounts for more than 36% of the variance of the mean December to March sea-level pressure field over the region 20–80°N, 90°W-40°E from 1899 to 1994 (Hurrell, 1995). The NAO is present throughout the year in monthly mean data but is most pronounced during the winter (Barnston and Livezey, 1987).

Rogers (1984) has compared the NAO with the Southern Oscillation from the standpoint of their association with Northern Hemisphere winter distributions of sea-level pressure and 500 mb height. Both were associated with significant pressure differences over much of the hemisphere but the NAO was characterised by a large trend toward lower values up to the 1960's which were not associated with variations in the Southern Oscillation. Rogers concluded that simultaneous occurrences of particular modes of one oscillation with those of the other were due to chance. The long-term changes in the NAO have been accompanied by many changes in the North Atlantic and the Nordic Seas (Dickson et al., 1988; Furnes, 1992), and air-ice-ocean coupling in the Arctic-subarctic region has been proposed as an important feedback mechanism responsible for decadal fluctuations in the Northern Hemisphere atmospheric circulation (Ikeda, 1990).

An index of the NAO has been constructed (Hurrell, 1995) based on the difference of the winter (December-March) pressures between Lisbon, Portugal and Stykkisholmur, Iceland, the pressures having been normalised to unit standard deviation. Figs. 4a, b compare this index with the latitude of the north wall of the Gulf Stream over the 31-year period from 1966 to 1996. While there is little direct similarity between the two series (Fig. 4a), there is a clear correlation ($P<0.01$) between the position of the north wall and the NAO two years previously (Fig. 4b). The probability of such a correlation coefficient occurring due to chance at a lead or a lag of up to 2 years, calculated from the binomial distribution, is less than 0.05. (When calculating significance levels of correlation coefficients the degrees of freedom have been corrected for first order serial correlation by the method of Quenouille, 1952, as in Taylor, 1995). The same lagged relationship can be seen with the annual mean values of the NAO index, the correlation coefficients being 0.02 without a lag and 0.55 ($P<0.01$) with a 2-year lag, and also between the Drinkwater et al. values (1973–1992) and the NAO winter index (correlation coefficients of 0.34 without a lag and 0.65 with a 2-year lag). Therefore, the Gulf Stream was further northward 2 years after high NAO winters, in which westerly and trade wind strengths were stronger, than following low NAO winters with anomalous southerly winds over the eastern United States and anomalous northerly winds across Western Greenland and the Canadian Arctic (Hurrell, 1995).

The principal components in Figs. 2, 3 show that there is a tendency for displacements of the north wall to persist for more than a year. If this persistence is taken into account, more than half of the variance of the Gulf Stream series can be predicted a year in advance. Figs. 4c, d show

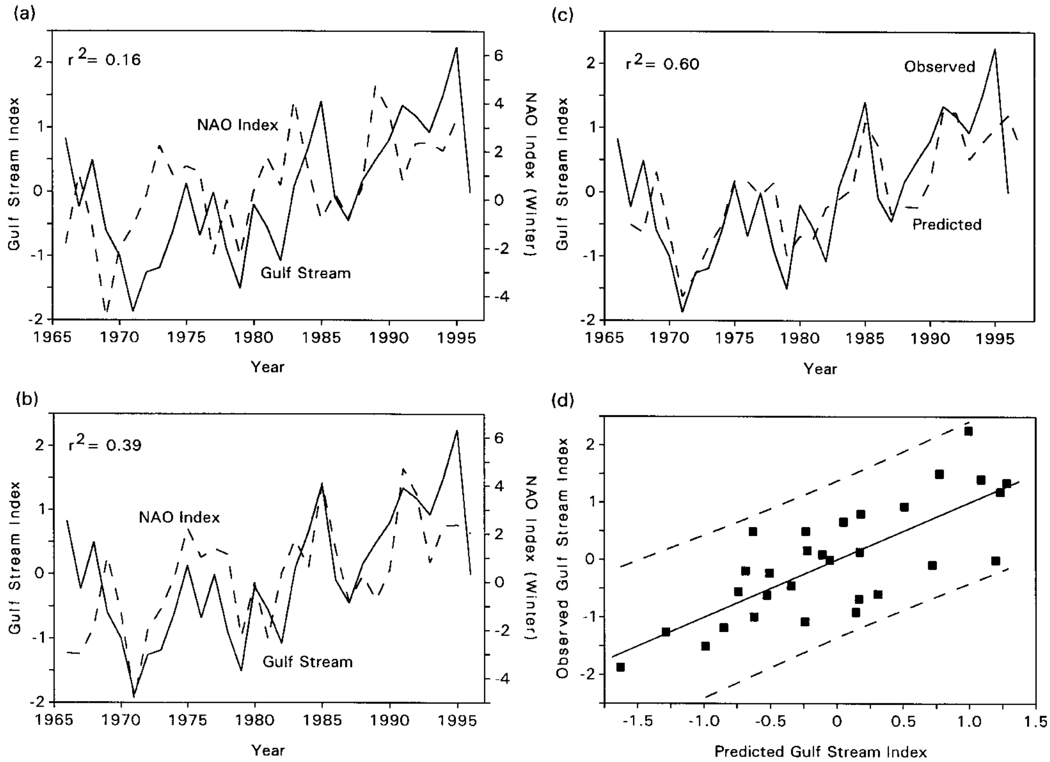

Fig. 4. Winter (December to March) index of the NAO based on the difference of normalised sea-level pressures between Lisbon, Portugal and Stykkisholmur, Iceland (solid line) compared with the latitude of the north wall of the Gulf Stream from 1966 to 1996 (broken line). (a) Unlagged NAO index, (b) NAO index lagged by 2 years. The figure also shows the observed latitude of the Gulf Stream compared with predictions of multiple regression equation (1): (c) as time-series (solid line observed, broken line predicted) and (d) as a scatter plot (the solid line is the 1:1 line and the broken lines 95% confidence limits). The fraction of variance accounted for (r^2) by the correlation is shown in (a), (b), and (c), the correlation coefficients in (b) and (c) being significant at the 1% level after correcting the degrees of freedom for first order serial correlation.

the predictions of the multiple regression equation:

$$\begin{aligned}&\text{predicted Gulf Stream position}\\&= 0.233 \times \text{NAO index 2 years previously}\\&\quad + 0.374 \times \text{previous year's Gulf Stream position}\\&\quad - 0.118. \qquad (1)\end{aligned}$$

This equation accounts for 59.5% of the interannual variation of the north wall ($P<0.01$), of which 49% ($P<0.01$) is due the NAO index and 10.5% ($P<0.05$) is due to the persistence in the Gulf Stream position.

4. Discussion

Variation in the north-south gradient of sea-level atmospheric pressure during winter is the dominant mode of interannual climatic variability in the North Atlantic and is a measure of the strength of the zonal winds over the ocean. The Gulf Stream is an essential part of the ocean circulation which is driven by these winds and so some relationship between its position and the NAO index may be expected. However, it is not clear why the latitude of the Gulf Stream should be related to the index 2 years previously.

A similar delayed response of the Gulf Stream has been observed when attempting to predict

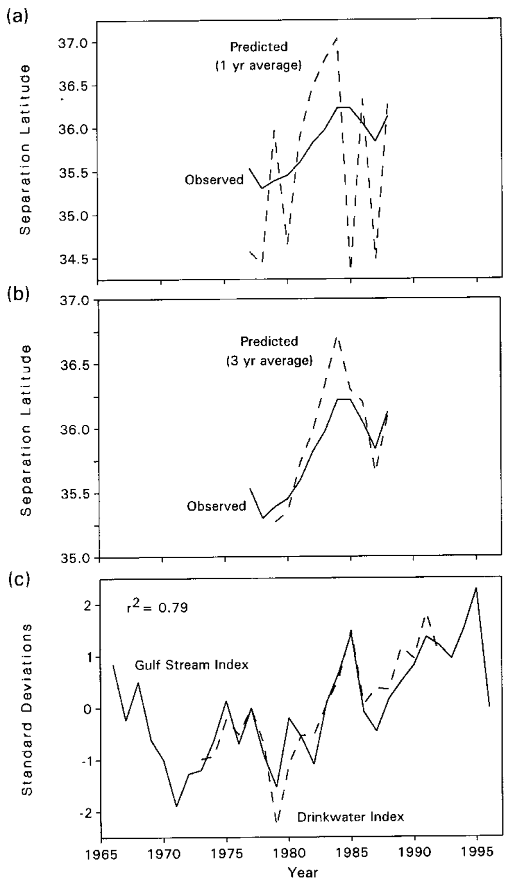

Fig. 5. The latitude of separation of the Gulf Stream, estimated by the intersection with the 2000-m isobath (1977–1988), compared with the predictions of the Parsons-Veronis model (a) when the Ekman drift was integrated over 1 year and (b) when the Ekman drift was integrated over 3 years (these two comparisons redrawn from Gangopadhyay et al., 1992). (c) Annual values of the first principal component calculated from the latitude of the north wall (1966–1994) at 79, 75, 72, 70, 67 and 65°W (solid line) compared with the principal component calculated from the latitudes (1973–1992) at 75, 72, 70, 67 and 65°W from Drinkwater et al. (1994, broken line). Each component has been normalised to unit standard deviation.

changes in the latitude of separation of the current from the US coast. In the 2-layer Parsons-Veronis model of this separation (Parsons, 1969; Veronis, 1973), the position at which the Gulf Stream leaves the coast results from a balance between the Ekman drift and geostrophic flow. When Gangopadhyay et al. (1992) compared the interannual variations predicted by this model with those observed over the 12-year period from 1977 to 1988 they found that the results only agreed if the Ekman drift was integrated over about 3 years (Figs. 5a, b). The latitude of separation which they estimate at a single longitude close to 75°W shows a similar trend over this period to the first principal component of the north wall data (Fig. 5c). Fig. 4 suggests that the delayed response found by Gangopadhyay et al. has been a feature of the last 30 years.

Gangopadhyay et al. (1992) have suggested that the time-lag is related to the time for long baroclinic planetary waves to cross the ocean. Although the Parsons-Veronis model relates the wind forcing across the Atlantic to the separation of the current, it does not indicate how the wind-stress signal is carried to the Gulf Stream. Gangopadhyay et al. suggested this could be a result of the energy carried across the Atlantic by baroclinic Rossby waves, fluctuations in the current field which arise from variations in the wind field and move to the west. They pointed out that the most important of these have length scales of about 1000 km and periods of about 6 months. These waves travel at several kilometres per day so that the time-scale for them to cross the ocean basin is consistent with the two-year delay. However, there is no observational evidence for such Rossby waves travelling at latitudes higher than 35–40°N. On the gyre scale, changes in the NAO (i.e., the westerlies) induce changes in wind-driven currents via the Sverdrup balance between planetary vorticity and wind vorticity. At the centre of the current gyre 33–35°N this balance needs a time-scale of several years for adjustment (c.f. Fig. 1 in Siedler, 1983).

The Gulf Stream is an essential part of the climate system of the North Atlantic. In spite of the complexity of the processes determining its course, Fig. 4 suggests the path of the Gulf Stream possesses a limited degree of predictability for more than a year in advance. Recently, the latitude of its north wall has proved to be a useful proxy variable, indicating climatic effects on biological populations that appear only weakly in direct comparisons with meteorological observations (Willis et al., 1995; George and Taylor, 1995; Taylor, 1996; Frid and Huliselan, 1996). The association with the NAO indicates how the Gulf

Stream time-series is related to variations in the atmospheric circulation of the North Atlantic.

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