The dominant influence of the Icelandic Low on the position of the Gulf Stream northwall

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[1] The location where the Gulf Stream separates from the American coast and turns eastward is called its northwall. The interannual fluctuations of the northwall are significantly correlated with the North Atlantic Oscillation with a lag of two years. When the Azores High and the Icelandic Low pressures are taken as independent variables, the latter dominates the relationship with the northwall, and the influence of the Azores High pressure is insignificant. This is consistent with the hypothesis that the major oceanic control of the northwall is in the southward flow of Labrador Sea Water into the Slope Sea. The alternative mechanism that the interaction of westward propagating Rossby waves with the American coast is responsible for northwall fluctuations is considered less likely because its initiation requires perturbations of the eastward winds in the mid-Atlantic region, and they are very likely dependent on the Azores High. The analysis suggests that the time lag between perturbations of the Icelandic Low and the northwall varies between one and three years. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4576 Oceanography: Physical: Western boundary currents; 4504 Oceanography: Physical: Air/sea interactions (0312); 4215 Oceanography: General: Climate and interannual variability (3309). **Citation:** Hameed, S., and S. Piontkovski (2004), The dominant influence of the Icelandic Low on the position of the Gulf Stream northwall, *Geophys. Res. Lett.*, *31*, L09303, doi:10.1029/2004GL019561.

1. Introduction

[2] The Gulf Stream flows north almost parallel to the American coast and turns eastward near North Carolina bringing warm waters to large sections of the North Atlantic. The latitude at which it turns eastwards is often referred to as the northwall of the Gulf Stream. Two mechanisms have been suggested as responsible for inducing fluctuations in the northwall position. One postulates westward traveling baroclinic oceanic Rossby waves as responsible for separating the Gulf stream from the boundary [*Gangopadhyay et al.*, 1992]. The other mechanism suggests that southward flow of the Labrador Seawater (LSW) into the Slope Sea off the North Carolina shelf modulates the northward extent of the Gulf stream [*Rossby*, 1999]. We investigate the relationship between the northwall position and the North Atlantic Oscillation reported by *Taylor and Stephens* [1998]. Our calculations suggest that the atmospheric forcing responsible for this relationship comes primarily from the fluctuations of the Icelandic Low pressure system and the role of Azores High in this process is insignificant. Since the Icelandic Low is the primary source of wind stress over the Labrador region, while both the Icelandic Low and the Azores High contribute to the generation of Rossby waves in the middle Atlantic, this result lends support to the hypothesis that the flow of LSW is the primary mechanism of northwall fluctuations.

2. Mechanisms for Gulf Stream Separation

[3] (a) The first scenario is based on a two-layer model of a wind-driven basin introduced by *Parsons* [1969] and *Veronis* [1973]. Fluctuations in the westerly wind stress in the middle Atlantic generate ocean waves. These waves are reflected from the eastern boundary as slowly propagating Rossby waves. The reflection of these waves from the western Atlantic coast causes the thermocline to vent to the surface and the detachment of the Gulf Stream. The response time of the mechanism is usually equated with the time it would take for the wave to travel from the eastern to the western coast. *Gangopadhyay et al.* [1992] have tested this model with 12 years of data on Gulf Stream separation and found that the best agreement with observations occurred when the response time was taken as 3 years. In recent years Rossby waves have been observed using satellite remote sensing. A review of the methods and results on the wave phase speeds is given by *Cipollini et al.* [2001]. From their Figure 4 we can read the wave speed at 35°N in the Atlantic to be nearly 3.2 cm/sec. Since the width of the Atlantic near the Carolina coast is nearly 5000 km, the travel time across the ocean can be estimated as 5 years. This suggests that the value of 3 years obtained by *Gangopadhyay et al.* [1992] is an underestimate. However, a model presented by *Hong et al.* [2000] suggested that wind disturbances in the mid-ocean regions can directly generate westward propagating Rossby waves. If this model is validated the travel times of 2 to 3 years to the western Atlantic coast would be consistent with this theory.

[4] According to this hypothesis atmospheric mechanisms that cause changes in the westerly winds in the mid Atlantic region set off disturbances that influence Gulf Stream separation when the ensuing planetary wave reaches the American coast. Since the NAO index is a measure of the strength of the westerlies, its fluctuations could play a role in determining the variations of the northwall, according to this hypothesis.

[5] (b) The second mechanism, proposed by *Rossby* [1999], (see also *Rossby and Benway* [2000]) holds variations in the southward flux of Labrador Seawater as the primary determinant of changes in the northwall position. As the LSW mixes into the Slope Sea SST and salinity anomalies are created. When the SST anomalies are positive

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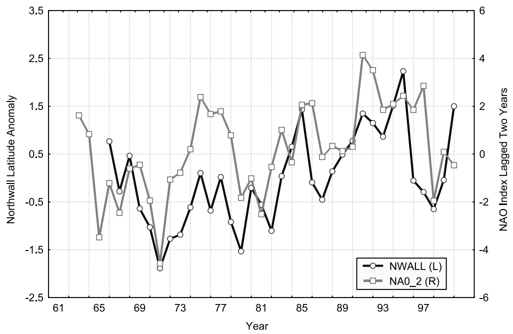

Figure 1. Variations of the Gulfstream northwall (solid line) and the NAO lagged 2 years (dotted line) 1966–2000.

the Gulf Stream is extended northwards, and conversely, it is pushed southwards when the shelf SST anomalies are negative. The flow of the LSW southward to the Slope Sea region was traced by *Talley and McCartney* [1982]. They, however, did not estimate transit times from the source region to points downstream. The great salinity anomaly gave one estimate of flow from the Labrador Shelf to the mid Atlantic bight. It gives a transit time of somewhat greater than one year since the salinity anomaly was observed near St. John's, Newfoundland in June 1983 and reached the Slope Sea by June 1984 [*Petrie et al.*, 1992].

3. Calculations

[6] We used data on the interannual positions of the Northwall compiled by *Taylor and Stephens* [1980, 1998]. They used observations of the latitude of the north-most position of the Gulf Stream at longitudes 79°W, 75°W, 72°W, 70°W, 67°W, removed the seasonal cycle, and presented an index of the wall position using principal component analysis for the period 1966–1993. Following Taylor and Stephens we will call their index GSNW.

[7] *Taylor and Stephens* [1998] have shown that the GSNW is statistically related to the NAO with a lag of two years. They developed a regression equation for the latitude of the GSNW with the NAO index (lagged 2 years) and the GSNW latitude (lagged 1 year) as independent variables. The regression explained 59.5% of the variability of the GSNW index. Using the GSNW position data from 1966 to 1993 we reproduced the regression of Taylor and Stephens in which the independent variables are the NAO index (lagged 2 years) and the GSNW (lagged 1 year):

$$\mathrm{GSNW} = -0.150 + 0.249(\mathrm{NAO})_{-2} + 0.353(\mathrm{GSNW})_{-1} \quad (1)$$

$(\mathrm{NAO})_{-2}$ stands for the NAO index lagged by 2 years with respect to GSNW. This equation accounts for 60.4% of the interannual variation of the GSNW. Taylor and Stephens interpreted the lag of 2 years as representing the travel time of Rossby waves across the ocean. We then repeated this calculation using the updated GSNW data for 1966–2000 posted by Taylor and Stephens on their website, and obtained:

$$\mathrm{GSNW} = -0.079 + 0.226(\mathrm{NAO})_{-2} + 0.374(\mathrm{GSNW})_{-1} \quad (2)$$

This equation accounts for 50.3% of the inter-annual variation of the GSNW.

[8] Note that the percentage of variance explained has dropped from 60% to 50% when the 1994 to 2000 data were included. Figure 1 shows the time series of GSNW together with $(\mathrm{NAO})_{-2}$. We can see that the 2 year lagged NAO index is nearly in phase with the GSNW movements until 1995. There was a major southward shift of the GSNW during 1995–98. The corresponding weakening of the NAO index occurred nearly simultaneously with the GSNW, not two years later, resulting in the worsening of the correlation in equation (2).

4. The Azores High and the Icelandic Low

[9] As noted above we consider the variations of the Azores High and the Icelandic Low separately. The pressures as well as the locations of these centers of action change continuously. In order to quantify these changes we have developed "objective" indices for the pressure, latitude and longitude locations for the centers which can be calculated using gridded SLP data [*Hameed et al.*, 1995]. By examining the monthly SLP maps of the past one hundred years the latitude-longitude domains over which each of the pressure centers wanders were identified. The pressure index is then defined as an area-weighted pressure departure from a threshold value over the domain (I, J):

$$I_p = \frac{\sum_{ij=1}^{IJ} \left(P_{ij} - P_t\right) \cos\phi_{ij} (-1)^M \delta_{ij}}{\sum_{ij=1}^{IJ} \cos\phi_{ij} \delta_{ij}}, \quad (3)$$

where P_{ij} is the SLP value at grid point (i, j), P_t is the threshold SLP value (P_t = 1014 mb for Azores High and Icelandic Low). ϕ_{ij} is the latitude of grid point (i, j). M = 0 for the Azores High and 1 for the Icelandic Low. $\delta = 1$ if $(-1)^M(P_{ij} - P_t) > 0$ and $\delta = 0$ if $(-1)^M(P_{ij} - P_t) < 0$. The intensity index is thus a measure of the anomaly of atmospheric mass over the study sector (I, J).

[10] The latitudinal index is defined as:

$$I_\phi = \frac{\sum_{ij=1}^{IJ} \left(P_{ij} - P_t\right) \phi_{ij} \cos\phi_{ij} (-1)^M \delta_{ij}}{\sum_{ij=1}^{IJ} \left(P_{ij} - P_t\right) \cos\phi_{ij} (-1)^M \delta_{ij}}, \quad (4)$$

and the longitudinal index I_λ is defined in an analogous manner. The location indices thus give pressure-weighted mean latitudinal and longitudinal positions of the centers.

[11] The area domains covered by the indices are: the Icelandic Low (40°N–75°N, 90°W–20°E) and the Azores High (20°N–50°N, 70°W–10°E). Monthly sea level pressure data from NCAR were used in calculating the COA indices. Note that the domains of the two COA overlap because the two centers migrate back and forth over the North Atlantic; however, there is no overlap in calculating their indices because for a given month only those grid points where the SLP exceeds the threshold value P_t are counted for the Azores High, and those for which the SLP is less than P_t are counted for the Icelandic Low. We have

Table 1. Correlations of the Gulf Stream Northwall Latitude Using DJF Averages of Azores High and Icelandic Low Variables With Lags of 1–5 Years During 1966–2000

Variable	1	2	3	4	5
Northwall	**0.58**	**0.34**	0.22	0.16	0.23
IL Pressure	**−0.61**	**−0.63**	**−0.37**	−0.25	−0.29
IL Latitude	**0.48**	**0.49**	0.22	0.18	0.10
IL Longitude	0.08	−0.02	**−0.45**	**−0.51**	−0.27
AH Pressure	**0.48**	**0.52**	**0.35**	0.24	0.27
AH Latitude	0.27	0.23	0.08	0.04	−0.10
AH Longitude	0.21	**0.49**	0.15	−0.01	0.08

Bold print indicates statistical significance at 95% level or higher.

calculated the indices for the years 1899–2002. Recently we have used the indices of the Icelandic Low and the Azores High to explain the variations of zooplankton in the Gulf of Maine [*Piontkovski and Hameed*, 2002].

[12] Building on the result that GSNW is significantly correlated with the NAO, we investigate the relative contributions of the Azores High and the Icelandic Low to the GSNW. We have correlated the pressure, the latitude and the longitude indices of the AH and the IL with the GSNW at different lags for the 1966–2000 period (Table 1). Correlations significant at 95 percent level or more are shown in bold.

[13] Since we wish to focus on the interactions of the atmospheric pressures centers with the GSNW, we recalculated the regression between the NAO and the GSNW (equation (2)) without the autocorrelation variable $(\mathrm{GSNW})_{-1}$. The result is

$$\mathrm{GSNW} = -0.086 + 0.310(\mathrm{NAO})_{-2} \tag{5}$$

This equation explains 37 percent of the GSNW variance.

[14] Since the NAO index is the difference in the winter pressure anomaly of the AH and the IL, when the NAO is entered as an independent variable in equations (1), (2) and (5), we are fixing the relative weights of AH and IL pressure anomalies at 1 and −1 respectively. By considering the two pressure centers independently we remove this constraint and let the regression choose their coefficients. The result obtained when $(\mathrm{AH_p})_{-2}$ and $(\mathrm{IL_p})_{-2}$ are the independent variables is:

$$\mathrm{GSNW} = 234 + 0.061\left(\mathrm{AH_p}\right)_{-2} - 0.031\left(\mathrm{IL_p}\right)_{-2} \tag{6}$$

r^2 for this regression is 0.40, a slight gain over equation (5). More importantly, we obtain information on the relative contributions of the two pressure centers as shown in the first panel in Table 2. Beta is the standardized regression coefficient for each independent variable. If the dependent and independent variables are standardized to have zero mean and unit variance, the regression coefficients would be Beta. Thus the Beta coefficients compare the relative contribution of each independent variable in explaining northwall variability. We see that the relationship is dominated by the IL by a factor of 7. This conclusion is supported by the partial correlation coefficients, which represent the correlation of each independent variable and GSNW adjusted by the other independent variable. In the last column we notice that the regression coefficient of the AH is not statistically significant as measured by the t- test.

Table 2. The First Column Lists the Independent Variables

Variables	Beta	Partial Corr.	Reg. Coeff.	T 32	P level
AHp(−2)	0.08	0.07	0.06	0.37	0.71
ILp(−2)	−0.57	−0.41	−0.30	−2.6	0.014
ILp(−2)	−0.66	−0.74	−0.34	−6.2	0.000
ILlon(−3)	−0.50	−0.64	−0.08	−4.7	0.000

Beta is the regression coefficient when all the variables are normalized to zero mean and unit variance. The third column gives the Partial Correlation Coefficient. The last three columns give the regression coefficient, its t-value and the corresponding significance level for each independent variable.

[15] Equation (6) indicates that of the constituents of the NAO, the IL appears as the determining partner in the relationship and the AH plays an insignificant role. This inference is confirmed if we omit $(\mathrm{AH_p})_{-2}$ from consideration and calculate the regression with only one independent variable $(\mathrm{IL_p})_{-2}$.

$$\mathrm{GSNW} = 329.7 - 0.320\left(\mathrm{IL_p}\right)_{-2} \tag{7}$$

The r^2 for this regression is 0.39, close to the r^2 for equation (6) above.

[16] The results in equations (6) and (7) suggest that the atmospheric forcing that influences the northwall is mostly in the cyclonic winds of the IL. Recalling the geographic domains of the Icelandic Low and the Azores High, it appears likely that the latter would play a significant role in the generation of westerly wind stress in the mid-Atlantic invoked by the Parsons-Veronis mechanism. The results therefore cast doubt on the Parsons-Veronis hypothesis and support *Rossby*'s [1999] suggestion that the position of the northwall is influenced by the outflow of waters from the Labrador region.

[17] We see in equations (6)–(7) that the IL pressure is negatively correlated with the GSNW, that is, lower pressure in the IL and stronger cyclonic winds in the North Atlantic contribute to a northward anomaly of the northwall about two years later.

[18] We note in Table 1 that the IL pressure with a lag of 1 year is also significantly correlated with GSNW. Hence we can try it as the independent variable instead of $(\mathrm{IL_p})_{-2}$

$$\mathrm{GSNW} = 297.1 - 0.300\left(\mathrm{IL_p}\right)_{-1} \tag{8}$$

The r^2 for this regression is 0.32, which is less than the value of 0.39 for $(\mathrm{IL_p})_{-2}$ obtained in equation (7). Let us

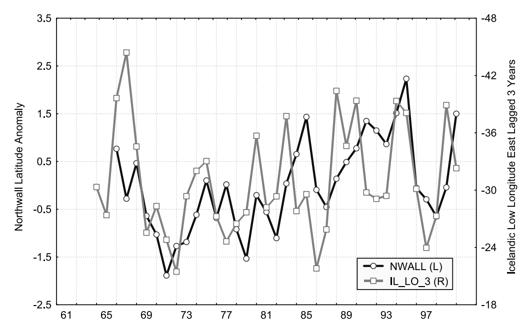

Figure 2. Variations of the Gulfstream northwall (solid line) and the Icelandic Low Longitude lagged by 3 years (dotted line) 1966–2000.

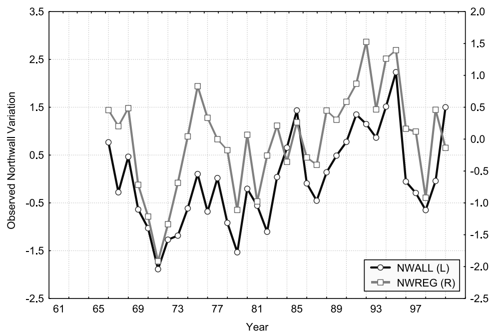

Figure 3. Gulfstream northwall variation (solid line) and the results of the regression equation (9) (dotted line). The regression explains 64% of the northwall variance.

recall from equation (5) that r^2 for NAO is 0.37. The amounts of variance explained by $(IL_p)_{-1}$ and $(IL_p)_{-2}$ are comparable, and it is reasonable to infer that processes associated with changes in the IL pressure that influence the northwall have time scales of one to two years.

[19] We can now consider the possibility of adding another independent variable among the center of action variables that are significantly correlated with GSNW listed in Table 1. The best result in terms of the explained variance and the significance of regression coefficients is obtained when $(IL_{lon})_{-3}$, the Icelandic Low longitude with a lag of 3 years is added as an independent variable:

$$GSNW = 342.8 - 0.343\left(IL_p\right)_{-2} - 0.083\left(IL_{lon}\right)_{-3} \qquad (9)$$

The r^2 for this regression is 0.64. The Beta coefficients and the partial correlations (Table 2) show that the contributions of $(IL_p)_{-2}$ and $(IL_{lon})_{-3}$ are comparable, the former being slightly more important.

[20] Equation (9) suggests that the east-west fluctuations of the IL significantly influence the flow that contributes to the variability of northwall position. The time lag associated with this process is about 3 years, longer than that with the fluctuations of the IL pressure.

[21] Figure 2 shows the GSNW and the IL longitude position (lagged 3 years). The figure suggests that eastward shifts of the IL are associated with southward anomalies in the Gulf Stream northwall and vice versa. The amplitude of the longitude variation is about 15 degrees. It is possible that east-west shifts of this magnitude in the cyclonic winds of the IL can produce significant changes in the wind stress in the Labrador sea region. However, the way in which the longitudinal shifts would influence the southward flow of water and the physical reason behind a three year lag process are not known.

[22] Figure 3 shows the GSNW index in comparison with the regression given by equation (9). The fitted line qualitatively reproduces the southward shift of the GSNW during 1995–1998. It can be inferred from Figure 2 that this shift was influenced by nearly 15° eastward shift in the position of the Icelandic Low during 1992–1994.

5. Conclusions

[23] The results presented in this paper suggest that the interannual variations of the Gulf Stream northwall are influenced by the fluctuations of the Icelandic Low pressure system, while the role of the Azores High is unimportant in comparison. This statistical result is consistent with the hypothesis that the flow of water from the Labrador region to the Slope Sea is the primary influence on the northwall. The alternate mechanism which invokes the westerly wind stress in mid-Atlantic causing westward propagating Rossby waves in the ocean is less plausible because the mid-Atlantic wind stress is likely to be sensitive to the fluctuations of the Azores High.

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