Quasi-Decadal Variability in the Atlantic Basin Involving Tropics–Midlatitudes and Ocean–Atmosphere Interactions

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ABSTRACT

Observational data are used to emphasise a 5- to 7-yr lag between the main modes of variability in the midlatitudes and in the Tropics. Considering this finding a mechanism for quasidecadal variability based on Tropics–midlatitudes and ocean–atmosphere interaction is described. It appears that the signal associated with the SST anomalies in the northern region of the tropical Atlantic is transferred in midlatitudes through the atmosphere and it will modify the thermal conditions of the ocean upper layers. In 5–7 years, thermal conditions will affect the SST anomalies in the northern Tropics reversing their sign. The results suggest that the Tropics get a negative feedback from midlatitudes so that the Tropics–midlatitudes system is capable of generating an oscillatory mode.

1. Introduction

The studies about ocean–atmosphere interactions were mainly concentrated either in tropical or in midlatitudinal regions. For the tropical Atlantic, the existence of a decadal dipole mode in the SST field, with a north–south axis, is sustained by the studies of Mehta and Delworth (1995) and Carton et al. (1996), who argue that changes in latent heating control SST and thus the tropical Atlantic is unstable to a wind-SST feedback. However, the existence of the dipole structure was questioned in some studies (Houghton and Tourre 1992). It appears that a positive feedback of wind speed, evaporation, and SST play an important role in the Tropics. Semi-empirical (Chang et al. 1996) and dynamic ocean–atmosphere models (Xie 1998), which include this feedback, reproduced the decadal oscillation of the tropical dipole.

Deser and Blackmon (1993) presented evidence for a quasi-decadal cycle in the North Atlantic. The structure of the SST field is characterized by temperature anomalies with opposite signs in the east of Newfoundland and off the southeast coast of the United States. Their mode is characterized by a dominant period of 12 yr in the post-war period. The relationship between the atmosphere and ocean is similar to the one specific for interannual timescales, with strong (weak) winds over cold (warm) SSTs. A decadal cycle in the North Atlantic that was derived from an integration of a coupled ocean–atmosphere GCM was described by Grotzner et al. (1997). The decadal mode, characterized by a period of 17 yr, is based on unstable air–sea interactions. It involves the subtropical gyre and the North Atlantic Oscillation and its memory is related to oceanic adjustment to the low frequency wind stress curl variations.

An important and controversial point for ocean–atmosphere interactions at midlatitudes on interdecadal timescales is represented by the effects of the extratropical SST on the atmospheric circulation. Palmer and Sun (1985) found a significant barotropic atmospheric response to SST anomalies imposed only in the North Atlantic basin. A response experiment performed by Hense et al. (1990) using a larger area for the SST forcing shows that, at lower levels, local heating and advection are dominant, while at upper levels the extratropical signal is a remote response to modifications of the tropical convection. These results are in agreement with the study of Graham et al. (1994), which, using numerical experiments, suggested that the Tropics play an important role in forcing the extratropical atmospheric circulation.

Recently, Tropics–midlatitude interactions in the Atlantic basin received increased attention. Tourre et al.
ering the period January 1945–December 1989. They derived from individual observations in the Comprehensive Ocean–Atmosphere Data Set (COADS) covering the period January 1945–December 1989. They are analyzed on a $1^\circ \times 1^\circ$ global grid, but for this study the fields were compiled on a $2^\circ$ latitude $\times 2^\circ$ longitude grid. The following quantities from the COADS dataset are used: sea surface temperature, sea level pressure, surface zonal and meridional wind, zonal and meridional wind stress, heat flux, oceanic friction velocity cubed, and precipitation.

For the COADS winds a new scientific Beaufort equivalent scale was used that reduces wind speed bias and artificial wind speed trends in the post–World War II period. The estimates of heat and radiational fluxes, when combined to form the net heat flux at the ocean surface, do not yield a physically plausible implied oceanic heat transport. This problem is circumvented by a simple linear inverse calculation that provides a systematic way to fine tune parameters in the bulk formula. The surface marine observing system is not adequate to truly resolve global anomalies, especially in the decade following World War II. Some regions of the Tropics that were void of data in the early years have experienced an increase in coverage through the years. Objective analysis used to fill in the gaps cannot compensate entirely for poor sampling. This effect is particularly troublesome in the Tropics and southern oceans where observations are clumped along ship tracks with data void areas in between.

Maps based on zonal and meridional wind components, from National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data (Kalnay et al. 1996), at different levels in the atmosphere are also constructed.

Some of the results were tested on a longer period (1856–1991), using annual means SST and SLP grids from Kaplan et al. (1998) datasets on a $5^\circ \times 5^\circ$ and $4^\circ \times 4^\circ$ grid. The datasets of Kaplan are produced by computing leading empirical orthogonal functions (EOFs) from the most recent high quality data: U.K. Meteorological Office Global Ocean Surface Temperature Atlas or GOSTA for SST and the COADS for SLP. EOFs are then used for fitting a first-order linear model of time transition. The optimal estimation is obtained using EOF projection of the analyzed field to obtain a reduced space. From the estimation of the available data covariance patterns, the method fills gaps, corrects sampling errors, and produces spatially and temporally coherent datasets. The analysis was restricted to the tropical and North Atlantic regions, $20^\circ$S–$70^\circ$N and $80^\circ$W–$15^\circ$E.

The results were derived by canonical correlation analysis (CCA) and discrete composite analysis.

### 3. The quasidecadal patterns

The dominant decadal modes, for the Tropics and for the midlatitudes, are separately identified. These patterns are derived as coupled ocean–atmosphere covariability modes from a canonical correlation analysis, between SST and SLP fields. CCA is a multivariate statistical analysis technique exploring the linear relationship between two sets of space-time dependent variables. By this method, the data are decomposed into pairs of spatial patterns in such a way that their time series are optimally correlated. Before the analysis, the data were prepared in the following manner:
monthly anomalies were calculated with respect to climatological values derived for the whole available COADS period (1945–89);

- for each grid point the time series were normalized by their temporal standard deviation (Fig. 1);

- the linear trend was subtracted at each grid point; and

- a 5-yr running mean filter was applied to the data to retained only the low frequencies.

The CCA was performed with the SST and SLP fields covering the whole COADS period, 1945–89. For the Tropics, the analysis was restricted to 20°S–20°N/70°W–15°E and 20°–70°N/80°W–0° for the midlatitudes, respectively. Only the first five EOFs of SST and SLP fields were retained for the CCAs. They explain 92.1% (SST) and 93.7% (SLP) of the variance in the Tropics, respectively, 89.4% (SST) and 88.4% (SLP) for the midlatitudes. In the Tropics, the first canonical mode explains 39.8% of the variance in the SST fields and 21.1% of the variance in the SLP fields. The correlation coefficient between the corresponding time series is 0.99. The time series of the first canonical modes both for the Tropics and midlatitudes are presented in Fig. 2 (upper panel for Tropics, lower panel for midlatitudes). Decadal variability (a period of approximately 12 yr), is observed. The canonical patterns for the tropical Atlantic are presented in Fig. 3. The SST mode has a dipole as structure and it is similar to the patterns obtained by Houghton and Tourre (1992) (unrotated second EOF) and Dommanget and Latif (1998) (unrotated second EOF with reverse sign). It is char-
characterized by a positive center at the northeast coast of South America at about 10°N and by negative values in the southeast and southwest tropical Atlantic. This mode explains more than 80% of the variance in the center positive values and 70% of local variance in the two centers of the tropical area from the Southern Hemisphere. The corresponding SLP pattern also has a dipole-like structure but with positive values more extending northward up to 10°N. It explains a maximum percent of local variance of 70% in the Southern Hemisphere at about 15°S/5°W.

The time series obtained from CCA for the midlatitudes are highly correlated (0.99) and are presented in Fig. 2 (lower panel). Their associated modes explain 17.3% (SST) and 28.3% (SLP) of the total variance. The decadal variability is conspicuous in the time series. Its extreme negative value is observed in 1967±68. Note that this precedes the corresponding extreme negative values for the tropical time series with approximately 7 yr. The leading canonical modes are presented in Fig. 4. The SST mode has a dipole-like structure with maximum positive amplitudes in the western Atlantic between 30° and 45°N and minimum amplitudes in the southeast of Greenland. The north–south symmetry of this mode is not observed in the field of their explained variance. The biggest part of its explained variance, up to 90% is concentrated in the region corresponding to the positive center at 35°–40°N. The SLP mode resembles the NAO pattern. The centers of maximum variance explained by this mode are located southeast of Greenland at approximately 30°N, 45°W. These patterns are similar to that derived by Grotzner et al. (1997). However, the distance between the SLP centers is greater in our analysis.

4. The Tropics–midlatitudes relation

The relation between the Tropics and midlatitudes was investigated by doing cross correlations between the components of the dominant patterns. The cross-correlation function between SST components is presented in Fig. 5. A periodicity of about 12–14 yr is observed in the cross-correlation function. The Tropics and the midlatitudes are negatively correlated in phase at a level of 0.42. A strong correlation of 0.8 is obtained when the midlatitudes leads the Tropics by 7 yr, half the period suggested by the cross-correlation function. If the data are filtered with a 2-yr running mean filter the in-phase correlation is lower than −0.5 and the lagged (7 yr) correlation is greater than 0.6, so that the significance of the peaks in the cross-correlation function is not affected by the filter.

Two CCA analyses, for the Tropics and midlatitudes (the same regions as in the first CCAs) on the SST and SLP fields from Kaplan’s dataset (1856–1991), were separately performed to qualitatively test these results. The cross-correlation function between the components of the analogous patterns (identified to be very similar to the dominant patterns derived from COADS data) is presented in Fig. 5. There is a clear qualitatively similarity between the cross-correlation functions. For the longer period the correlation coefficient is 0.4 when the midlatitudes leads by 5 yr and 0.43 when the Tropics lead by 1 yr (note that this cross-correlation function was constructed based on annual means).

Both cross-correlation functions suggest a causal link between the midlatitudes and the Tropics in which the ocean is likely responsible for transferring the signal from midlatitudes to the Tropics in 5–7 years. A reverse
causal link may be deduced from the cross-correlation functions for lag 0 (COADS) and 1 yr (Kaplan, annual means). In this case the atmosphere is likely connecting the Tropics with the midlatitudes.

5. The physics of the coupled mode

A composite analysis was performed to infer the physics of the coupled mode. In a first step composite maps were calculated based on the SST time series of the first modes derived from the CCA performed for the Tropics. An average map was calculated for the times at which the SST component has values greater than 0.5 of its standard deviation and another average map for values lower than −0.5 of its standard deviation. The difference between corresponding positive and negative maps was calculated. Such composite maps were constructed for several fields: sea surface temperature, sea level pressure, surface wind, zonal and meridional wind component at several levels in the atmosphere, net heat flux, oceanic friction velocity cubed, wind stress curl, and precipitation. The maps cover the region between 20°S and 60°N and 80°W and 15°E (Figs. 6–11), but our study is concentrated on the Northern Hemisphere.

The SST composite map (Fig. 6) is similar to that obtained by Xie and Tanimoto (1998). The northern tropical region (0°–20°N) is dominated by positive SST anomalies (Fig. 6). To study if these SST anomalies are generated by atmospheric forcing, composite maps of heat flux, wind stress curl (which is proportional with Ekman pumping), and oceanic friction velocity cubed anomalies (which is a measure of oceanic mixing), have been drawn. The predominantly negative heat flux anomalies (Fig. 8), which dominates the northern tropical region would lead to a decreasing of SST in this region. Because positive SST anomalies dominate this region, we conclude that this process is not strong enough to influence essentially the SST variations in this region. The oceanic friction velocity cubed (Fig. 8) and wind stress curl (Fig. 8) emphasizes multipolar patterns with different signs over the northern tropical region. Such distributions of oceanic mixing and Ekman pumping anomalies are not able to produce positive SST anomalies over the entire northern tropical region (Fig. 6). Because neither heat flux, nor oceanic mixing and Ekman pumping explain the positive SST anomaly pattern that dominates this region, we may conclude that oceanic processes are determinant in generating this SST pattern. Positive SST anomalies in the northern Tropics (Fig. 6) are accompanied by northward and eastward surface wind anomalies over this region (Fig. 6) and positive precipitation anomalies north of the equator (Fig. 7), indicating an intensification of convection and increase low-level convergence in the ITCZ. Modeling studies (Lindzen and Nigam 1987) suggest that SST anomalies near the equator are capable of producing

![Fig. 4. Canonical modes and their explained variance maps for the North Atlantic.](image-url)
such low-level convergence and influencing the atmospheric circulation (Chang et al. 1999). This generates reduced trade wind, which, in turn, determines less mixing in the ocean near the eastern coast of Africa (Fig. 8). The positive SST anomaly in the tropical Northern Hemisphere is amplified by increased surface advection of warm waters driven by the cross-equatorial wind anomalies east of the South American coast, generated by low-level convergence. Recent numerical experiments confirmed these processes (Chang et al. 1999).

Modeling studies (Robertson et al. 1999) suggest that changes in the tropical Atlantic heating (deep convection in the ITCZ) may affect the Northern Hemisphere atmospheric circulation in much the same way tropical Pacific heat anomalies do. Consistent with this picture, the conditions at the ocean surface are associated with a stronger Walker circulation (Fig. 7), which is coupled with a weaker Hadley circulation (Fig. 7). The strong and inverse correlation between the strength of the Walker and Hadley cells was also emphasized by Oort and Yienger (1996). They also suggest that the intensity of the Hadley cell is directly related to the strength of the subtropical jet stream (through the conservation of absolute angular momentum). This implies that a weak Hadley cell is associated with a decreased intensity of the jet stream, this gen-
erating a weaker anticyclonic circulation in the subtropical high. Tourre et al. (1999) associated the quasidecadal variability in the Atlantic basin with fluctuations of the Hadley cell and Wang and Weisberg (1998) emphasized the atmospheric Walker and Hadley out-of-phase circulations as links between the Tropics and extratropics. The weaker anticyclonic circulation is observed at the surface, where the SLP field (Fig. 6) resembles the western Atlantic pattern with minimum in the Gulf Stream region and maximum south of Greenland. This configuration at the surface favors the influx of cold air from the northwest (North American continent) over the Gulf Stream region (Fig. 6). These wind anomalies generate negative SST anomalies in this region by enhanced heat fluxes, ocean mixing, and Ekman pumping (Fig. 8). As cross-correlation function shows (Fig. 5), these SST anomalies are transferred in the northern Tropics in 5–7 yr. In this respect, a new set of composite maps is constructed based on the time series of the first SST mode obtained from the CCA for midlatitudes SST and SLP fields. In this case, only the maps recorded 7 yr later after a local maximum or minimum of the SST time series were used in calculations. In this manner we assume that the resulting maps represent the effects produced by midlatitudes
condition corresponding to negative SST anomalies in the Gulf Stream region in the tropical Atlantic, 7 yr later. The composite maps are presented in Figs. 9–11.

The negative SST anomalies in the northern tropical Atlantic are accompanied by enhanced trade winds (Fig. 9) and reduce convection in the ITCZ (Fig. 10). Anomalous mixing (Fig. 11) and Ekman pumping (Fig. 11) also favor the negative temperature anomalies in this region. The decreased convection in the ITCZ is accompanied by a weaker Walker circulation (Fig. 10) and a stronger Hadley circulation (Fig. 10). In the SLP field (Fig. 9) positive anomalies over the North Atlantic, between 20° and 45°N, are also emphasized. The stronger anticyclonic circulation brings more warm air from south in the Gulf Stream region while the westerlies from the North American continent are weaker (Fig. 9). These mild westerlies increase the heat fluxes into ocean (Fig. 11), reduce mixing (Fig. 11), and the Ekman pumping (Fig. 11) generates positive SST anomalies in the Gulf Stream region. The resulting positive SST anomalies are transferred in the Tropics in 5–7 yr closing a complete cycle.

6. Conclusions

This paper proposes a mechanism for the quasi-decadal variability in the Atlantic basin. The quasi-decadal
in this way the signal is transferred to the midlatitudes through atmosphere, practically instantaneous at this timescale. These atmospheric conditions force SST anomalies in the Gulf Stream region, with opposite sign than those in the Tropics; these anomalies are "transferred" (probably by the ocean) in 5–7 yr in the northern tropical Atlantic region, turning the cycle in the opposite phase; in this way the Tropics get a negative feedback from midlatitudes (after 5–7 yr).

The memory of the cycle likely resides in the ocean and may be determined by the ability of upper-ocean thermal anomalies to persist as was emphasized by the study of Tourre et al. (1999). Also, the mechanism corresponds well with the findings of Bjerkness (1964), who suggested that decadal or longer fluctuations are related to changes in the subtropical gyre, in response to the long-term changes associated with the strength and location of the subtropical high. An important point in this cycle is represented by the atmospheric response to tropical SST anomalies. The potential of SST anomalies in the Tropics to modify the atmospheric circulation in midlatitudes was documented by Graham et al. (1994). Recent studies (Robertson 1999) also suggest that tropical SST anomalies may produce significant changes in the atmospheric circulation, in the Tropics and in midlatitudes.

It appears that the Tropics–midlatitudes and ocean–atmosphere system (based on a negative feedback) can produce oscillatory phenomena. Further work is needed to study how the signal is transferred from midlatitudes to the Tropics. Noting that the SST anomalies over the North Atlantic basin tend to persist at quasi-decadal timescale (Sutton and Allen 1997) we speculate that the subtropical gyre may advect the SST anomalies from the Gulf Stream region to the Tropics.

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