Ocean-Atmosphere Variability over the Pan-Atlantic Basin

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Abstract

Ocean and atmosphere variability is investigated over the whole Atlantic basin in a 51-year record of sea surface temperature (SST). In the tropics, SSTs variations are separated into two time scales: decadal (8–16 years) and interannual (< 5 years). A strong cross-equatorial gradient mode dominates decadal SST anomalies with centers of action having opposite polarities at 15°N and 15°S, while interannual variations are characterized by SST anomalies of the same polarity throughout the tropics. Sea level pressure (SLP) regressions onto the cross-equatorial gradient index reveal extratropical teleconnections associated with the North Atlantic Oscillation (NAO), and with the South Atlantic. At the same time, a Pan-Atlantic spatial pattern is also found in SST regressions. Lagged regressions of SLP on the cross-equatorial SST gradient index shows the extratropical decadal oscillation that is out of phase between hemispheres. These results suggest that an extratropical forcing could excite the tropical Atlantic variability.

1. Introduction

Ocean and atmosphere climate variations with time scales longer than the typical El Niño–Southern Oscillation (ENSO) cycle, but shorter than the centennial time scale are a major focus of the international Climate Variability and Predictability Program (CLIVAR). Decadal variations of sea surface temperature (SST) in the Pacific are characterized by an ENSO-like spatial structure (Zhang *et al.*, 1997). This linkage between the tropics and extratropics in the Pacific has been extensively studied with a new focus on the decadal variations from observational datasets (Nitta and Yamada, 1989; Trenberth, 1990; Trenberth and Hurrell, 1994; Mitchell and Wallace, 1996; Tanimoto *et al.*, 1997; Kachi and Nitta, 1997) and by numerical simulations (Graham *et al.*, 1994; Lau and Nath, 1994; Yukimoto *et al.*, 1996). At the same time, other

studies (Latif and Barnett, 1994, 1996; Zhang *et al.*, 1997; Robertson, 1996; Nakamura *et al.*, 1997) suggest that the North Pacific exhibits its own self-sustaining mechanisms for the decadal oscillation.

The North Atlantic also displays pronounced extratropical decadal variations (Deser and Blackmon, 1993; Kushnir, 1994; Delworth, 1993; Halliwell and Mayer, 1996; Carton *et al.*, 1996) with large signatures in the subsurface and intermediate layer (Levitus, 1989). In the tropical Atlantic, a dipole mode where SST and sea level pressure (SLP) in the Northern and Southern Hemispheres oscillate like a seesaw (Chang *et al.*, 1997) is believed to have strong direct and remote impacts on the precipitation and other climate variables' pattern over the northeastern part of Brazil (Wagner, 1996; Nobre and Shukla, 1996) and Sahel (Folland *et al.*, 1986).

This paper examines decadal variability over the whole Atlantic basin with a focus on the interaction of the tropics and extratropics. This study could serve as a base for future comparative studies to understand what is responsible for the similarity and differences between the Atlantic and Pacific.

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Earlier empirical orthogonal function (EOF) analyses of the tropical Atlantic SST variability by Servain (1986, 1991) extracted two dominant modes: one with the above-mentioned dipole structure, and the other with a spatially homogeneous anomaly pattern of the same polarity over the tropics. The temporal indices associated with these two modes appear to have comparable variance with the dipole mode showing a preferred decadal time scale. Recent works by Chang *et al.* (1997) and Nobre and Shukla (1996) further indicate that the decadal dipole mode is accompanied by large-scale simultaneous correlation patterns in SLP, surface wind and latent heat flux fields in the tropical Atlantic. The SLP (SST) field has a dipole structure whose centers of action, with the opposite polarities to each other, are located on either side of the equator at 30 (15) degrees.

A positive feedback involving wind, evaporation and SST (WES: Xie and Philander, 1994) is believed to be at work in the decadal dipole (Chang *et al.*, 1997). In the WES scenario, enhanced southerly winds blow from higher SLP over the colder SST in the southern subtropics into lower SLP over the warmer SST in the northern subtropics. The Coriolis force turns cross-equatorial southerly wind anomalies into the southwesterly anomalies in the Northern Hemisphere, weakening the climatological northeast trades, suppressing latent heat release from the ocean, and acting to further warm the northern tropical SST anomalies (Huang and Shukla, 1997). Meridional profiles of the zonal-mean latent heat flux forcing on SST anomalies (Wagner, 1996) suggest that flux anomalies are capable of maintaining dipole structure in the presence of the decay process by Ekman pumping. In fact, the numerical study by Carton *et al.* (1996) showed that decadal SST variations in the tropical Atlantic were not well simulated without incorporating the latent heat loss process. Chang *et al.* (1997) proposed that anomalous thermal advection forced by the anomalous southerlies eventually replaced the warm SSTs with cold water. Xie and Tanimoto (1998) suggested that the WES feedback was not strong enough to overcome the thermal damping, nor sustain an internal oscillation. Instead, they proposed that tropical decadal dipole oscillation was excited by the extratropics.

While several EOF analyses document a dipole mode over the tropical Atlantic, other alternative modal decompositions have also been proposed. Houghton and Tourre (1992) performed the rotated EOF analysis for the SST anomalies in the tropical Atlantic, and showed the two dominant modes with one major center of action in one hemisphere but no signal in the other. They suggested that a combination of these two modes looked like a dipole in the tropics, but each of them was temporally in-

dependent. Supporting Houghton and Tourre's result, Enfield and Mayer (1997) obtained a monopole structure of SST anomalies with the same polarity in most of the tropical Atlantic. They further stated that the monopole structure in the tropical Atlantic, and the ENSO in the tropical Pacific, were correlated. Thus there is a paradox concerning the empirical decomposition of the tropical Atlantic SST variations: two hemispheric modes, or one dipole and one monopole mode?

As stated earlier, the dipole seems to be a quite robust structure in the tropical Atlantic so that it could stand out in observational data and ocean general circulation model (GCM) simulation. In fact, a weak dipole appeared in Figs. 3 and 7 in Enfield and Mayer (1997), while Houghton and Tourre (1992) also showed the dipole in the second EOF for the tropical SST fields. The present study attempts to resolve this paradox of modal decomposition by taking advantage of the spectral gap between decadal and interannual SST variability in the tropical Atlantic. An earlier observational study by Servain (1991), and an ocean GCM simulation by Huang and Shukla (1997), indicated that monopole and dipole indices of the tropical Atlantic SST anomalies exhibited interannual and interdecadal time scales, respectively. Large amounts of variance are found on each of these time scales and the spectral gap is present between in both the tropics (Mehta and Delworth, 1995) and the extratropics (Kushnir, 1994; Halliwell and Mayer, 1996). We adopt a time-scale separation method, which has been applied to the North Pacific by Tanimoto *et al.* (1997) and Kachi and Nitta (1997), to separate extratropical SST fluctuations on decadal (7 years and longer) and interannual (3–7 years) time scales.

Furthermore, we will look beyond the tropics and extend our analysis into the whole Atlantic basin. In the extratropics, the North Atlantic Oscillation (NAO; Waker and Bliss, 1932; Wallace and Gutzlar, 1981) is a dominant mode of atmospheric variability, with large variance on the decadal time scale (Hurrell, 1995). Zorita *et al.* (1992) and Peng and Fyfe (1996) obtained NAO-associated SST anomaly patterns with signatures in the northern subtropics. SST anomalies in the extratropical South Atlantic, on the other hand, tend to have an opposite polarity to those in the southern tropics. Xie and Tanimoto (1998) present evidence that SST anomalies in the whole Atlantic are inter-correlated and organized into four centers of action extending from the South Atlantic all the way to Greenland (see also Bojariu, 1997). The present study provides further observational evidence for this Pan-Atlantic decadal variation and examines its temporal evolution in annual-mean SLP, SST, and wind vector fields.

The rest of paper is organized as follows: Section 2 describes the datasets and the analysis procedures,

Fig. 1. Standard deviations of annual mean anomalies in the (a) SST and (b) SLP fields. The deviations of SSTs and SLPs are calculated from the GISST for 1946–1996 and COADS for 1950–90, respectively. Contour interval is 0.1°C for the SST and 0.4 hPa for the SLP.

Section 3 shows the leading two modes that explain the meridional gradients of the inter-tropical SST anomaly field, Section 4 presents the Pan-Atlantic patterns for SST, SLP and wind vector fields and discusses properties of extratropical decadal variations associated with the tropical SST anomalies, Section 5 is a brief summary and discussion.

2. Data and analysis procedures

Two datasets are used: the Comprehensive Ocean-Atmosphere Data Set (COADS; Woodruff *et al.*, 1987), and the Global sea-Ice and SST dataset (GISST; Folland and Parker, 1995). Monthly 5° latitude-longitude resolution SST, SLP, zonal and meridional wind speed fields for the North and South Atlantic (70°N – 50°S) from 1950 through 1990 are computed from individual ship observations contained in the COADS compressed marine reports (Tanimoto *et al.*, 1997; Iwasaka and Hanawa, 1990). The domain contains the Norwegian, North, and Caribbean Seas, southern part of the Labrador Sea, and the Gulf of Mexico but excludes Baffin Bay, and the Mediterranean. In addition, a monthly 2° latitude-longitude SST dataset is constructed from GISST for the same domain with 1946 through 1996. Observations prior to 1946 were not used since unrealistic large differences appeared around World War II (Folland *et al.*, 1986; Deser and Blackmon, 1993). For each of these variables we calculated a monthly climatological mean annual cycle based on the entire period of record, and the annual anomalies were defined as departures averaged over 12 months in a particular calendar year. These annual mean variables are used in statistical analyses in the following

sections. Tropical anomalies are in phase with an annual cycle (Nobre and Shukla, 1996) so that the annual mean values are useful to examine an inter-hemispheric pattern. Figure 1 shows the standard deviations of annual mean SST and SLP anomalies during 1946–1996 and 1950–1990, respectively. In the SST field (Fig. 1a), the deviations do not exceed 0.4°C in most tropical and subtropical domain, except in the coastal regions. SLP standard deviations (Fig. 1b) are typically less than 1 hPa in the tropics and subtropics, and are in excess of 2 hPa poleward of 40° in both hemispheres. The deviations will be referred to when the statistical significance of regressed anomalies are evaluated.

3. Dominant structure in the tropics

3.1 Decadal and interannual time scales in the tropics

First, we examine temporal and spatial characteristics of anomalous SST variability within 20 degrees of the equator. The analysis is performed separately on anomalies of the decadal (8–16 years) and interannual (< 5 years) time scales in recognition of the spectral gap at around 0.12–0.15 (cycle per year) of tropical Atlantic SST anomalies analyzed by Enfield *et al.* (1998). This spectral gap is also indicated by observational and ocean GCM studies (Carton *et al.*, 1996; Mehta and Delworth, 1995; Huang and Shukla, 1997). The temporal filter employed is a four-pole, Butterworth recursive filter, as done in Tanimoto *et al.* (1993). The first two EOFs of decadal (interannual) are shown in Fig. 2 (Fig. 3). For the decadal variability, the strong cross-equatorial gradient appears in both the first (Fig.

Fig. 2. The two leading EOFs for the annual mean decadal SST anomalies (8–16 years) in the tropical (20°N–20°S) Atlantic (upper and middle panels). The percentage of variance explained on this time scale is indicated in the upper right corner at each panel. Contour interval is 0.02. Positive (negative) values are represented by solid (dashed) lines. The bottom panel presents the principal component (PC) of the first (dashed line) and second (solid line) EOFs.

2a; 44.2 % of total variance on decadal time scales) and second mode (Fig. 2b; 31.9 %). The first mode captures both the north-south dipole and substantial zonal variations. A zonally uniform subtropical dipole appears in the second mode. The SST anomalies centered at 10–20° of each hemisphere are always out of phase, although the relatively large variance covers north (south) of equator in the first (second) mode.

Figures 4a and 4b show the scatter plots of zonal mean values in the 10–20°N and 10–20°S bands, calculated from filtered annual mean SST anomalies, with the last two digits of the calendar year superimposed on each data point. The out-of-phase relationship between SST centers of action can also be documented with a scatter diagram of decadal

variability (Fig. 4a). The 51 annual means scatter on a tilted elliptical track. Approximately $2\frac{1}{2}$ cycles are present on the elliptical track with a period of about 10 years. Several points, at the beginning and ending of the data record, are substantially out of the ellipse track, which might be a consequence of filtering.

In contrast, interannual SST variability is dominated by anomalies of like-sign across the entire basin. A weak SST cross-equatorial gradient and a zonal gradient appear in the leading EOF for the interannual time scale (Fig. 3a), which accounts for nearly one half (49.6 %) of total variance on this time scale. The strong cross equatorial gradient, on the other hand, appears in the second mode (Fig. 3b). This is consistent with the scatter diagram

Fig. 3. Same as in the Fig. 2, but for the SST anomalies on the interannual time scale (< 5 years).

on the interannual time scale (Fig. 4b) in which the longer first (shorter second) axis crosses from the first (second) quadrant toward the third (fourth) one. Most of time data points on the interannual time scale jump between the first and third quadrant, keeping the same polarities in the northern and southern tropics.

These figures indicate the different linear relationships of inter-hemispherical variations on decadal and interannual time scales. Although some noises remain in each panel, the scatters depict that inter-hemispherical variations are in phase (out of phase) on the interannual (decadal) time scales. The same inter-hemispheric relationships are obtained from singular value decomposition analysis (Bretherton *et al.*, 1992) of the filtered SST fields in two sub-domains of the northern and southern tropics (not shown).

3.2 Cross-equatorial gradient index and tropical index

The strength of the cross-equatorial SST gradient in the tropical Atlantic and its impact on adjoining land areas climate have been investigated based on its temporal evolution (*e.g.*, Wagner, 1996; Nobre and Shukla, 1996). To obtain a long time series of the tropical SST gradient, we define a gradient index similar to the dipole index in Servain (1991) by taking the difference between northern (10–20°N) and southern (10–20°S) zonal means of normalized annual-mean SST anomalies from coast to coast. Positive values of the index indicate SST anomalies increasing with latitude. Note that the normalizing process, although it weakens the zonal contrast of anomalies, enables us to compare results of the zonal mean fields to those in the simple ocean-atmosphere coupled model. A second index taken as the sum of normalized annual mean anomalies in 10–20°N and

Fig. 4. Scatter plot of zonal mean SST anomalies in the Northern tropics ($10\text{--}20^\circ\text{N}$: the horizontal axis) and Southern tropics ($10\text{--}20^\circ\text{S}$: vertical axis) on (a) Decadal (left, 8–16 years) and (b) interannual (right, < 5 years) time scales. Open circles mean scatters under the end effect of filtering.

Fig. 5. Upper panel: gradient (solid line) and tropical indices (dashed line) of the normalized annual mean SST anomalies in the tropical Atlantic. The former (latter) are differences (sums) of zonal mean from coast to coast of $10\text{--}20$ degree latitudinal bands. Lower panel: the scatter plot of zonal mean SST anomalies in the Northern and Southern Hemispheres.

$10\text{--}20^\circ\text{S}$ will be referred to as the tropical index. No filtering is applied to the indices.

The gradient and tropical indices series are shown in Fig. 5a. The gradient index is characterized by persistent positive values during the 1950s and 1960s and decadal variability in the second half of the record, with a maximum in 1981 and two minima in 1973 and 1984. In contrast, interannual fluctuations dominate in the tropical index. The variance of the indices are comparable. A simultaneous correlation between the two is less than 0.01. When unfiltered SST anomalies in northern and southern subtropical bands are used (Fig. 5b), a scatter pattern with data points distributed nearly homogeneously among all the quadrants is seen. While such a scatter pattern is indicative of decorrelation of SST anomalies be-

tween two sides of the equator, we have shown that highly correlated scatter patterns emerge on both interannual and decadal time scales (Fig. 4).

Figure 6 shows the two leading EOFs for the unfiltered annual mean SST anomalies in the $20^\circ\text{N}\text{--}20^\circ\text{S}$ of the Atlantic. The first EOF, which accounts for 40.2 % of the total variance, indicates the in-phase signal between north and south of the equator, while the tropical dipole-like structure appears in the second EOF (32.7 %). In fact, the temporal coefficients of the first and second modes coincide well with the tropical and gradient indices (Table 1: simultaneous correlation 0.86 and 0.85), respectively. Since a cross-equatorial SST gradient is pronounced in the second EOF but small in the first EOF, the former (latter) is associated with strong (weak) SST gradi-

Fig. 6. Same as in Fig. 2, but for unfiltered anomalies.

Table 1. Simultaneous correlation between indices

	Tropical Index	Gradient Index
Score of EOF 1 (unfiltered)	0.86	0.46
Score of EOF 2 (unfiltered)	0.40	0.85

ent. These EOFs do not present perfect configurations of the dipole and monopole. Absolute eigenvectors of the first (second) EOF could be relatively large in the north (south) of equator,. Note that a comparable variance of two modes calls for cautions that they may depict an independent propagating signal. However, in the present situation, two modes presented are likely independent because the correlation between two scores is insignificant at any lag time (Maximum coefficient of 0.36 appears on the second mode leading by two years).

4. Pan-Atlantic variations in the ocean and atmosphere

4.1 Spatial patterns

Correlation coefficients of Atlantic basin SST anomalies with the gradient and tropical SST indices are shown in Fig. 7. For the gradient index, a positive center elongates in the 8–20°N zonal band with a maximum of +0.8. In the southern subtropics, a zonal band of negative polarity appears in the 10–25°S, whose amplitude is comparable to that in the northern subtropics with a maximum of

Fig. 7. The simultaneous correlation patterns of the Atlantic SST for the (a) gradient index (upper panel) and (b) tropical index (lower panel). Contour interval is 0.2. Positive (negative) values are represented by the solid (dashed) lines. Dark (light) shaded are the regions in which regressions are more than 0.6 (less than -0.6).

about 0.7. The spatial pattern in tropics is similar to those from previous composite and other statistical analyses (*e.g.*, Wagner, 1996; Nobre and Shukla, 1996; Chang *et al.*, 1997). Positive correlations exceed $+0.6$ in regions south of Greenland. In a narrow coastal region (a few degrees of longitude) off

the east coast of North America, positive correlations extend from Newfoundland through the Gulf of Mexico and Caribbean Sea. In the Southern Hemisphere, negative correlations cover most of the domain. Note that correlation extrema here are above the 95 % statistical significance level (0.42) under the reliable degree of freedom (~ 10). However, the correlation in the small positive center at 10°W , 40°S is less than the significant level. In higher latitudes of the Southern Hemisphere, correlations are somewhat noisy probably due to insufficient observations.

On the other hand, for the tropical index, significant positive correlations cover most of the domain but with little cross-equatorial gradient (Fig. 7b). A maximum ($+0.6$) appears in the $10^{\circ}\text{--}20^{\circ}\text{N}$ zonal band and extends into the southeastern subtropics. Correlations are below the significance level outside the tropics. This mode does not simply represent a monotonic global warming because the interannual fluctuations of the tropical index appears more dominant in the recent five decades (Chang *et al.*, 1997).

Next we will show that these Pan-Atlantic SST patterns are robust feature to different statistical approaches. Figures 8 shows the correlation map with the first EOFs for the unfiltered anomalies and filtered interannual anomalies, respectively. Both panels show a similar pattern to the correlation map for the tropical index. The polarity of correlations is almost identical in most of the domain, with small positive anomalies in the recirculate region of the Gulf Stream. However, the pattern in the southern extratropics is not well-organized on these maps.

Figure 9 shows three panels of correlation maps: the second EOF for the unfiltered SST anomalies, the first and second EOF for decadal SST anomalies. The first panel is quite similar to the correlation map for the gradient index except for the complicated structures south of 40°S . The similar linkage of SST anomalies between the tropics and the Southern Hemisphere is well displayed on the first EOF on the decadal time scale (middle panel), and the one between the tropics and the Northern Hemisphere are presented on the second decadal EOF (right panel). In any case, the strong cross-equatorial gradient and the associated Pan-Atlantic SST anomalies are depicted.

Figure 10 presents regression maps of Atlantic SST, SLP and surface wind fields onto simultaneous values of the gradient index. In SLP regressions, a large positive (negative) center of action appears in the southern (northern) subtropics, which overlays the colder (warmer) SST anomalies associated with the strong cross-equatorial gradient of SST anomalies (Fig. 10a). Anomalous equatorial southerlies are consistent with weak winds, diminished latent heat flux, and warmer SSTs in the Northern tropics. In

Fig. 8. The simultaneous correlation patterns of the Atlantic SST anomalies for the temporal coefficient of the leading EOF for the unfiltered tropical SST anomalies (a, upper panel) and of the leading EOF for tropical SST anomalies on the interannual time scale (b, lower panel). Contour interval is 0.2. Positive (negative) values are represented by the solid (dashed) lines. Dark (light) shaded are the regions in which correlations are more than 0.6 (less than -0.6).

the North Atlantic, the positive phase of the NAO appears in the SLP field when the cross-equatorial gradient index is positive, and vice versa. The 5-year running mean of the NAO index (Hurrell, 1995) is correlated at 0.76 with the gradient index (Fig. 10b). The correlation of the gradient index and unfiltered NAO is 0.46. Cyclonic anomalous flows occupy the North Atlantic mid-latitudes between $20^{\circ}\text{--}50^{\circ}\text{N}$, and associated SLP anomaly reaches -1.0 hPa at 35°N . As the northern pole of the NAO, the maximum SLP anomaly south of Greenland exceeds $+2.0$ hPa. In the Southern Hemisphere, there is an anticyclone which is less well-organized in the extratropics, but has an area coverage and amplitude ($+0.9$ hPa) comparable to the North Atlantic cyclonic anomaly. In both hemispheres, SLP regressions exceed one standard deviation around their mid-latitude maxima. The regressions for the anticyclone around Greenland are about one half of the standard deviation.

In most area of the tropics, there are inter-hemispheric southerlies from the cold toward the warm hemisphere with a maximum speed around 1.0 m/s. The eastward anomalous flows in the northern tropics are in geostrophic balance with the low pressure centered around 35°N . These anomalous winds weaken the easterly trades, reduce evaporation from the ocean surface and thus enhance the positive SST anomalies. In the southern subtropics, on the other hand, zonal wind anomalies are neither well-organized nor in geostrophic balance with SLP. The anomalous SLP field, which is less prone to sampling errors than wind velocity, suggests easterly geostrophic wind anomalies between the equator and 20°S , which act to enhance evaporation, and hence negative SST anomalies. Thus this inter-hemispheric relationship between SST and surface wind anomalies confirms that the WES feedback maintains the strong meridional gradient in the tropics. As part of the mid-latitude cyclonic anomalous circulation, northeasterly anomalies are quite substantial in the $40^{\circ}\text{--}60^{\circ}\text{N}$ band. These weakened westerlies suppress local heat release (e.g., Hanawa *et al.*, 1995; Cayan, 1992). A result is that positive SST regression appears south of Greenland.

Figure 11 shows the patterns of simultaneous regression of SST, SLP and wind vector fields onto the tropical index. Except to the north of 40°N , wind velocity regressions are small as they are not in geostrophic balance with the SLP regressions. The SLP anomaly pattern, more reliable than wind velocity regressions, indicates westerly wind anomalies prevailing over the tropics. Reduced surface evaporation and equatorial upwelling are the likely cause of the positive SST anomalies in the tropics. In the Northern Hemisphere, a north-south SLP dipole appears between 30°N and 60°N , and westward anomalous flows between $35^{\circ}\text{--}55^{\circ}\text{N}$ are in geostrophic balance. However, mid-latitude SST re-

Fig. 9. Same as in Figure 8, but for the second EOF for unfiltered SST anomalies (a, left panel), the first EOF for the decadal SST anomalies (b, middle panel), and the second EOF for the decadal SST anomalies (c, right panel). Contour interval is 0.2. Positive (negative) values are represented by the solid (dashed) lines. Dark (light) shaded are the regions in which correlations are more than 0.6 (less than -0.6).

gressions show small positive values under the reduced westerlies. Thus, ocean-atmospheric variability in the Pan-Atlantic basin are only weakly associated with the tropical index. In the southern extratropics, SST, SLP and wind patterns are all somewhat noisy, not satisfying the geostrophic relation.

4.2 Space-time evolution

Figure 12 presents the lagged regressions of zonal mean ($10^{\circ}\text{--}40^{\circ}\text{W}$) SST and SLP regressions onto the gradient index. The $10^{\circ}\text{--}40^{\circ}\text{W}$ longitudinal band is chosen to exclude the western boundary and coastal regions. In the SLP field, the quasi-standing oscillations in each hemisphere are dominant on the decadal time scale. In the Northern Hemisphere, the NAO in the SLP field, *i.e.*, higher Azores highs and lower Icelandic lows, are formed at years of lag -8 and -9 . Anomalies at the centers exceed 0.6 hPa.

Both centers of the NAO keep their polarities and positions for a few years, and then begin to change their polarities after the year of lag -3 . The reversed NAO persists for a decade after an intermission by a small positive anomaly after the year of lag $+2$. A negative center appears at 20°S at the year of lag -8 through -6 , and then positive anomalies dominate in the subtropics and are amplified from the years of lag -2 through $+2$. Regressed values in the Southern Hemisphere are comparable to those in the Northern Hemisphere. The anomalies in the Southern Hemisphere change their polarity at the year of lag $+2$ and negative anomalies of the Atlantic expand most during the years of lag 2 through 8.

SST regressions in the same diagram also depict a dipolar oscillation in the tropics with its polarities opposite to the SLP. A standing oscillation appears in the Southern Hemisphere at two centers in the 20°S and 40°S (see Venegas *et al.*, 1996, 1997). This

Fig. 11. Same as in Fig. 10a, but for the regression patterns based on the tropical index.

oscillation seems to have a nearly constant period, at least during these lag years.

5. Concluding remarks and discussion

We have examined the Pan-Atlantic variability of SST, SLP and wind vector fields from a viewpoint of interaction between the tropics and extratropics. In the tropical and subtropical regions, inter-tropical SST variations have two dominant modes with distinct spectral and spatial characteristics: (1) strong cross-equatorial SST gradient varies on decadal time scales and (2) weak gradient of SST anomalies with the same polarity on both sides of the equator that fluctuates on the interannual time scales. A recent eigenvalue analysis of a coupled ocean-atmosphere model also indicates that the dipole and monopole oscillations are the leading modes of decadal and interannual variability, respectively (Noguchi, 1998).

That the cross-equatorial SST gradient associated with a 'dipole mode' tends to vary on decadal time scales does not necessarily mean that a pure dipolar configuration of SST anomalies should be frequently observed. In fact, strong cross-equatorial SST gradient events occur much more frequently than a perfect dipole pattern (Enfield *et al.*, 1998), presumably because of the interference by interannual variability that tends to have the same polarity between the hemispheres. The argument for the independent variations on each side of the equator (Houghton and Tourre, 1992) seems to emphasize the regional signal due to a rotation of the leading EOFs.

The simultaneous regressions of ocean-atmospheric variables onto a cross-equatorial SST gradient index reveal a pattern spanning from the southern Greenland coast to the Southern Ocean. The NAO in the SLP field is associated with extratropi-

Fig. 12. The latitude-yearly lag diagram on the zonal mean (10–40°W) of regressed (a) SLP and (b) SST anomalies for the gradient index. Contour interval is 0.2 hPa and dark (light) shaded areas indicate values of more than 0.2 (less than –0.2) in SLP fields. Contour interval is 0.1°C and dark (light) shaded areas indicate values of more than 0.1 (less than –0.1) in the SST fields.

cal SST anomalies (Deser and Blackmon, 1993; Peng and Fyfe, 1996; Kushnir, 1994), and with the cross-equatorial gradient index on decadal time scales. Lagged regression analysis further reveals that the Pan-Atlantic SST and SLP signals vary on decadal time scales from high-latitudes into the subtropics before and after a strong cross-equatorial gradient emerges in the SST field. In contrast, there is no extratropical signal associated with the monopole structure in the lagged regression fields. As Enfield and Mayer (1997) pointed out, there might be a linkage between the weak SST gradient mode in the tropical Atlantic and the ENSO in the eastern Pacific.

Although the tropics-to-extratropics atmospheric bridge like the PNA (Pacific/North American) in the Pacific could also participate in the Atlantic (Wallace *et al.*, 1990), it does not seem to be the only process at work in the Pan-Atlantic variability on the decadal time scale. Xie (1999) and Xie and Tanimoto (1998) showed with a simple ocean-atmosphere model that the tropical Atlantic decadal oscillation might not be self-sustainable by tropical air-sea interaction processes, but may require some external forcing. A recent study by Bojariu (1997) also identified a linkage between the NAO and the tropical dipole, but it did not imply any causality between the two. By examining the temporal evolution of decadal anomalies, the present study suggests a possible extratropical trigger of the tropical Atlantic variability. Equatorward propagation of SLP anomalies was shown by Halliwell (1997),

although he did not trace the anomalies into the tropics. A possible mechanism for such an equatorward propagation is via air-sea interaction (Xie, 1999). In the northern extratropics, a positive SST anomaly induces a westerly (easterly) geostrophic wind anomaly to the south (north). The resultant wind-induced evaporation anomalies shift the original SST anomaly equatorward via the WES feedback, and vice versa in the Southern Hemisphere. Together with Xie and Tanimoto's (1998) modeling work, the results of the present study suggest a possibility of the extratropics-to-tropics teleconnection in the Atlantic basin. Extratropical ocean-atmosphere interaction still remains controversial. The atmospheric GCM response to extratropical SST anomalies is highly model-dependent. This is a major obstacle to testing the hypothesis that extratropical ocean-atmosphere interactions may support self-sustaining oscillations.

Ocean advection is another possible mechanism for meridional propagation of SST anomalies. Sutton and Allen (1997) and Hansen and Bezdek (1996) examined the effect of Gulf Stream advection on the ocean thermal structure in the western North Atlantic. Their time-current path diagram of the SST field indicated a continuous propagation of SST anomalies along the North Atlantic current from the North American coast to the European coast. Along with Halliwell (1997), we have suggested that decadal SLP anomalies might propagate in an equatorward direction over the Atlantic basin. Clearly, mechanisms for tropical-to-extratropical in-

teraction need further investigations.

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環大西洋における大気海洋変動

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グリーンランドから南大洋にかけての環大西洋域における大気海洋変動場を観測されたデータセットを用いて解析した。熱帯における海面水温場は 10 年スケール (8–16 年) と経年変動 (5 年以下) のスケールに分離される。10 年スケール変動では、強い海面水温の南北傾度が北緯 15 度と南緯 15 度付近の間に現れる。一方、経年変動では熱帯全域で同符号の変動を示し南北傾度はほとんど示されない。熱帯の強い南北傾度に対する海面気圧場・海面水温場の回帰係数は中高緯度へのテレコネクションを示す。特に北半球の気圧場では North Atlantic Oscillation (NAO) と関連している。ラグ回帰の結果は、熱帯の強い海面水温の南北傾度が出現する前後に海面気圧アノマリが中高緯度において 10 年スケール変動していることを示す。これらの結果は熱帯大西洋の 10 年スケール変動に対する中高緯度との関連を示唆している。