3.5 ON THE ORIGIN OF THE TROPICAL ATLANTIC DECADAL OSCILLATION BASED ON THE ICOADS

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1. INTRODUCTION

Many authors examined a decadal oscillation in the sea surface temperature and the atmospheric field variables of the tropical Atlantic Ocean. The oscillation is clearly discernable from the El-Nino events of the Pacific Ocean and also from the decadal oscillations observed in the mid-latitude oceans such as the northern Pacific and the northern Atlantic (e.g. Deser and Blackmon 1985; Zhang and Wallace 1996; Cane et al. 1986; Watanabe and Jin 2002; Horii and Hanawa 2004). The decadal oscillation of the tropical Atlantic Ocean has a unique spatial pattern and operates on a time scale comparable to, or shorter than, that of the mid-latitude decadal oscillations. The tropical Atlantic decadal oscillations have garnered attention due to their connection with the drought of northeast Brazil and the Sahel region of Africa (Hastenrath et al. 1977; Moura and Shukla 1981; Nobre and Shukla 1996; Chang et al. 1997).

A few of people suggested the consideration of solar activity during the assessment of climate variability on decade-to-century time scales about two decades ago (Karl 1985). The suggestion has not attracted much attention because many people thought that the variability of solar flux was too weak to induce any notable climate signals on the earth's surface. On the sensitivity of global surface temperature to solar forcing as well as other forcings, Hartmann (1994) emphasized the importance of relative humidity in climate change. According to his estimation for the tropical oceans, the effects on the evaporation rate by 1 K increase in the surface temperature at a fixed relative humidity approximately equals to 1% decrease in relative humidity at a fixed surface temperature.

In this work, we would like to assess the implication of the variability of relative humidity in connection with the possible effects of the solar cycle on the tropical Atlantic decadal oscillation. For our purpose, we carried out an analysis of the surface observables of the tropical Atlantic Ocean by calculating lag-correlation and lag-covariance values between the time series of diverse variables of a certain point or region.

2. DATA AND METHODOLOGY

2.1 *Data*

The basic data set is the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) downloaded from the National Centre for Environmental Prediction of the United States. The

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ICOADS or its predecessor has been used for climate analysis by many authors (e.g., Deser and Blackmon 1985; Wright 1986; Nobre and Shukla 1996). The final ICOADS summary data were released in 2001 and the downloaded data comprehensively cover the previous fractional data sets for different time periods (Diaz et al. 2002). Because we were interested in variability over large spatial and temporal scales, we used two-by-two degrees grid box value data. This also served to avoid missing values in the time domain. The data comprise monthly values of sea surface temperature (SST), surface meteorological parameters, and many other quantities derived from these observations. All the results in this paper are based on the monthly mean values of various parameters. Monthly mean is one of the statistics documented in the ICOADS.

In addition to the ICOADS, we used the sunspot number data set that was obtained from http://science.nasa.gov/ssl/pad/solar/sunspots.html. Based on previous works by Foukal and Lean (1990) and by Labitzke and van Loon (1995), we supposed the variability of the sun's illumination or the solar constant to be in direct proportional to sunspot numbers.

2.2 ***Methodology***

Somewhat differing from former researchers' processing of the ICOADS, we dealt with individual time series for each data box by selecting data boxes having less than a certain percentage of missing values. Data boxes missing less than 5% of their values were used for an ocean basin wide analysis 1958 to 2001 and data boxes missing less than 10% of their values were used for an extended time series analysis of data collected along the Europe-South America ship track in 1900-2001. At first missing values had been replaced with temporal interpolations for every year. Values still missing were replaced with linear interpolations for individual calendar months. No more than three adjacent missing annual or individual calendar month values were found for the selected time series, except for the World War I and II periods. Spatial averages were taken in rare but necessary cases, but only after temporal interpolations were completed. Missing values were never replaced with values generated using only spatial interpolation.

The time-lag relationship between the variables of the decadal oscillation was checked by computing the lag cross-correlation values of the time series of monthly mean values of diverse variables: SST, surface air temperature, surface air pressure, cloudiness, and the total wind speed. When calculating the lag correlation values, we used as a reference time series the sunspot numbers and the southerly winds that had been digitally filtered by employing a time filter whose response function in the frequency or period domain is shown in Fig. 1.

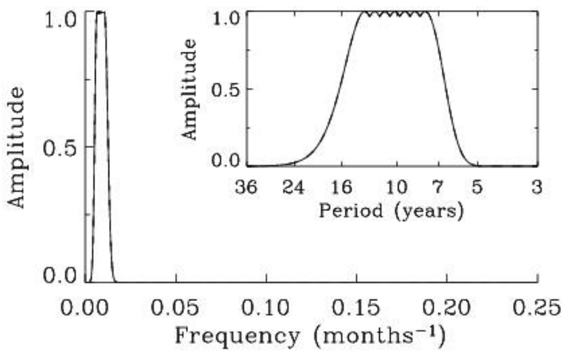

Fig. 1. Response functions of the wavelet filter used for separating the frequency components of the decadal oscillation from the raw time series of various variables such as SST and cloudiness. The detailed of the response is inset.

3. REGIONAL ANALYSIS

When we processed each time series of various variables for each data box along the ship track, the variability with about 11 year period is strongest in the west equatorial Atlantic Ocean. One of them is shown in Fig. 2.

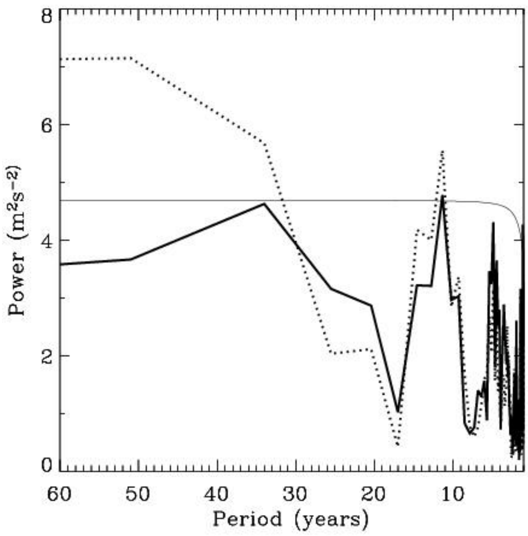

Fig. 2. Power spectra of southerly winds (thick solid) of the data box at 1˚N and 29˚W and 90% confidence level (thin solid) derived by inflating properly the corresponding red noise spectra. The spectrum function in a thick dotted line is for area average values for the region between 2˚N and 6˚S in latitudes.

The data boxes satisfying our requirements upon missing values, the climate winds in synoptic notation and cloudiness in shading in unit of okta, which is a fraction equal to one eighth of the celestial dome, are presented in Fig. 3. The cloudiness pattern is not symmetrical with respect to the Inter-Tropical Convergence Zone (ITCZ) whose position in latitudes can be located with ease from the orientation of the wind vectors.

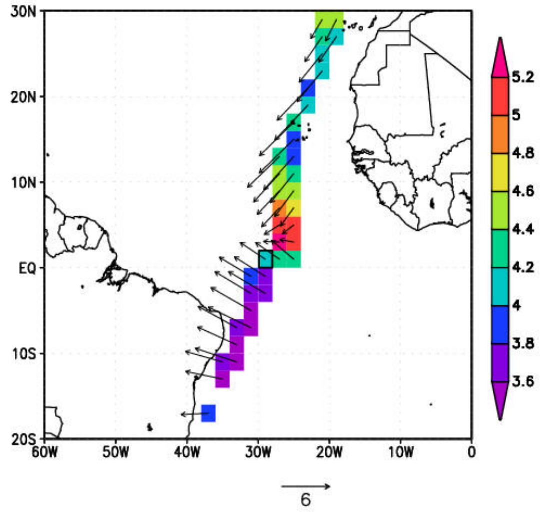

Fig. 3. The climate time mean winds and cloudiness along the Europe-South America ship track. They are based on the ICOADS, 1900-2001. The scales for wind vectors and cloudiness are in the bottom and the right-hand side of the figure, respectively. The southerly winds of a data box centered at 1˚N and 29˚W and marked with a small rectangle highlighted by its thick sides of which time series were used for Fig. 1 and also used as a reference time series for calculating the coefficients of correlation.

Nobre and Shukla (1996) and Chang et al. (1997) showed that the variability of southerlies at the western equatorial Atlantic was a key ingredient of the tropical Atlantic decadal oscillation. Therefore, we were to expect a systematic difference between the coefficients of lag-correlation based on the southerly winds and based on the sunspot numbers. Furthermore, it is quite a natural for us to expect better correlations for the southerlies than for the sunspot numbers. Contrary to our expectation, the sunspot numbers produce more coherent and consistent lag-correlation functions for most of the variables than the southerlies do, which is clear in Fig. 4. In Fig. 4c, the wind speed maximum occurs at the enhanced time period of the other variables correlated. Such a phase relation for the north-east tropical Atlantic does not hold for the same calculation but for the centre of action in the north subtropical Atlantic Ocean. And also the in-phase relationship between the lag-correlation functions of SST and air temperature is unique for the region of north-east tropical Atlantic. Usually, air pressure opposes SST in their temporal variations in most of the oceanic regions of the earth.

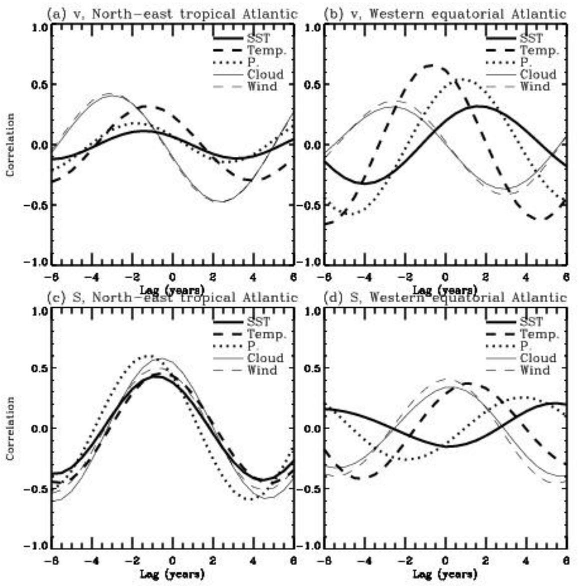

Fig. 4. Lag-correlation functions for the decadal oscillations: figures (a and b) are based on southerly (v) and (c and d) on the sunspot numbers (S), figures (a and c) are for the north-east tropical Atlantic Ocean and (b and d) for the western equatorial Atlantic. The correlated parameters are SST (thick solid), surface air temperature (thick dashed), surface air pressure (thick dotted), cloudiness (thin solid), and the total wind speed (thin dashed). We produced the correlated time series by taking an average of data box values along the Europe-South America ship track in the latitude bands of (a and c) 6˚N to 2˚N and (b and d) 6˚S to 2˚N.

In addition to the locally coherent behavior of the correlation functions, there are some notable common points between the correlation functions based on the different reference time series in Fig. 4. When correlated with the southerlies, the variability of the coefficients of lag-correlation is much larger for the western equatorial Atlantic (Fig. 4a) than for the north-east tropical Atlantic (Fig. 4b). The fact may reflect the geographical dependency of correlation values based on the reference time series of southerlies in the western equatorial Atlantic Ocean.

For the sunspot reference time series, the correlation values are larger for the north-east tropical Atlantic (Figs. 4c) than in the tropical Atlantic (Fig. 4d), which is opposite but somewhat weak compared with those based on southerly winds over the western tropical Atlantic. The stronger correlation values even in the subtropics compared with those of the equatorial Atlantic suggest that the decadal oscillation appeared in our correlation analysis are not confined in the tropics, which is one of the characteristics of the tropical Atlantic decadal oscillations examined before by other authors (e.g., Moura and Shukla 1981; Nobre and Shukla 1996).

In Fig. 4, the lag-correlation functions of most of the variables, except for SST, from the north-east tropical Atlantic leads by about one year those of the corresponding variables from the western equatorial Atlantic in the lag-time domain. Over the north-east tropical Atlantic, cloudiness shows the strongest lag-correlation, being 0.7 at a lag of -8 months, as shown with a thin solid line in Fig. 4c, which reveals that the amount of clouds in the region reaches a maximum before the sunspot or solar luminosity peak time. The lag-correlation values of cloudiness, based on the southerly winds, also show a similar shape as that of the sunspot numbers but with weak strength as in Fig. 4a.

In order to examine steadiness in time of the correlation values evaluated in the previous paragraph, we examined the magnitude change of the coefficients of correlation for the different record length of data beginning from either end of the entire data period. The correlation functions are almost steady irrespective of the data record length used for the calculation of coefficients as long as the data record length is longer than about 24 years.

4. BASIN-WIDE ANALYSIS

Time evolution of various variables at the north and south centers of action may be inferred from the lag-correlation or lag-regression maps. The lag and simultaneous cross-correlation maps of surface air pressure and relative humidity with respect to the normalized southerly winds and sunspot numbers are given in Fig. 5. From the figure, it is evident that the pressure minimum appears at a lag of -2 years in the northern tropical Atlantic while the corresponding maximum appears at the south centre at a lag of 0 year instead of -2 years.

Except for small phase shifts in the lag-time domain, the horizontal structure of air pressure and relative humidity are similar in their shape to the corresponding patterns discovered by other authors. Patterns are similar in that the centers of action were located at the north and south subtropical Atlantic Oceans and large winds anomalies appeared over the western equatorial Atlantic Ocean.

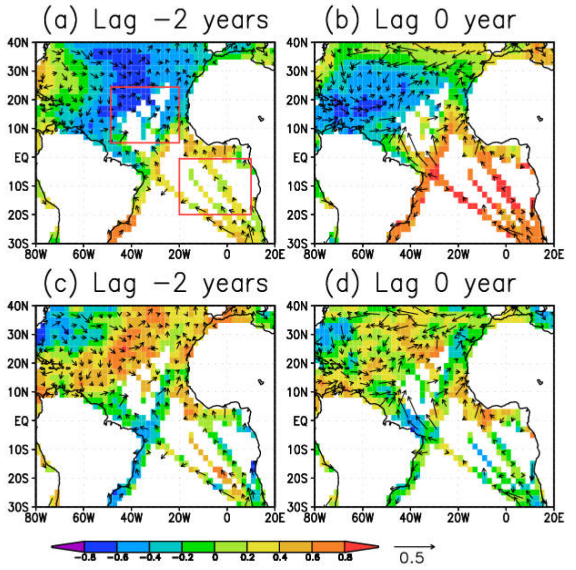

Fig. 5. Lag-correlation maps of the (a and b) surface air pressure and the (c and d) relative humidity in color shading. The employed reference series is the time series of band-pass filtered (8-15 years) sunspot numbers. Lag-time is -2 years for maps (a and c) and simultaneous for maps (b and d). The wind vectors are produced by plotting the covariance values of each wind component regressed with the normalized sunspot numbers. The wind vectors are thinned at every other grid point for clarity. The two centre-regions of action are marked with the red rectangles for further analysis.

Figure 6 is an analogue of Fig. 4 but for basin wide analysis. The figures in the upper portion of the figure are virtually the same as the corresponding ones in the bottom side in many respects. The relative humidity shows a maximum value at a lag of -2 years irrespective of the centers of action and the kinds of reference time series. At the same time, wind anomalies are much larger positively at a lag of -5 years and negatively at a lag of +1 year than at a lag of -2 years in the northern tropical Atlantic (Fig. 6).

Such a progress in the lag-time domain suggests that the change of relative humidity carries a phase difference of about 90 degrees or 3 years in phase angle or time space, in order, with the change of wind speed over the northern tropical Atlantic. The quadrature relationship of wind speed over the north centre region is clearly in contrast with the in-phase relationship of the wind speed with all the other variables over the north-east tropical Atlantic as shown in Fig. 4c.

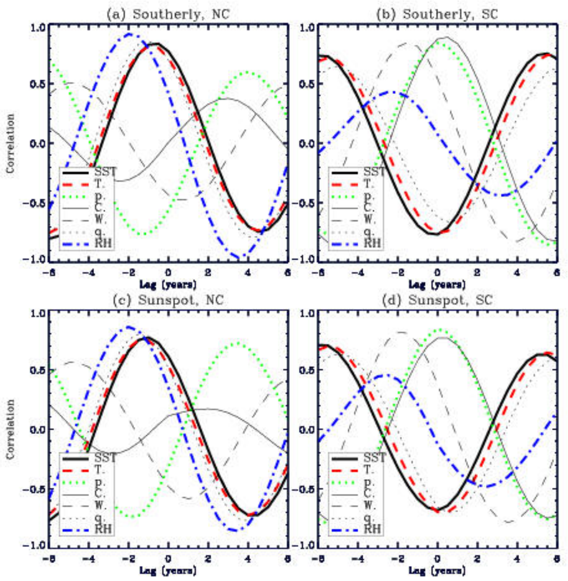

Fig. 6. Lag-correlation functions: figures (a and b) are based on the southerlies and (c and d) on the sunspot numbers, and figures (a and c) are for the north centre of action and (b and d) for the south centre. The correlated variables are SST (thick solid), surface air temperature (red dashed), surface air pressure (green dotted), cloudiness (thin solid), the total wind speed (thin dashed), specific humidity (thin dotted), and relative humidity (blue dash-dotted). The correlated time series are produced by taking average values for the north or south centre-region of action marked with a red rectangle in Fig. 5a.

The relative humidity at a lag of about -2 years shows much larger absolute amplitude at the north centre of action than at the south centre. This suggests that the north centre of action did not have an antipodal relationship with the south centre in the variability of SST, specific humidity, and the total wind speed. Exactly opposite behavior or an antipodal phase relationship between at the poles of a dipole-like pattern are generally presumed in most empirical orthogonal function (EOF) analyses of an oscillatory motion having dipole-like structure. For an unusual case like the tropical Atlantic decadal oscillation, the EOF analysis may not be suitable for determining phase relationship between the variables of the oscillation even though its principal components could represent exactly the oscillation's periods or frequencies.

We confirmed the above statement by repeating EOF analysis to many data sets having an idealized dipole-like horizontal structure added with random noises with a variable proportion. The analysis was conducted while fully reflecting various phase shifts between the temporal variations of the two antipodal centers, from -90 degrees to 90 degrees at a five degrees interval. From the calculations, we found that near but no antipodal phase relationship could be revealed as an eigen mode having disparate amplitudes in magnitude at the two centers of action. Our finding may be helpful in understanding an analogous disparity revealed in Nobre and Shukla's (1996) EOF analysis of SST and surface wind stress over the tropical Atlantic.

When considering strong similarity between the corresponding lag-correlation functions based on the two different reference series in Fig. 6, it is nearly impossible for us to determine the superiority of a reference series from the relative strength of their correlation values. The lag-correlations of the both reference time series are as following. The southerlies lead by three months the sunspot numbers with a maximum lag-correlation 0.92. This value is large but not drastically different from the extreme values of lag-correlation between the reference time series and the variables such as cloudiness and the surface air pressure. Such relationships lead us to say that the decadal oscillations and the associated variability of the southerlies were not completely independent from that of sunspot number for the data period. Although not as significant as the sun's definite effects on the annual cycle of atmospheric motions, the solar cycle might have significant effects, at least as a regulator or perhaps as a direct but weak controller of the oscillation.

In Table 1, the observed amplitude of the time series of relative humidity is about 0.14% at the north centre of action and slightly smaller at the south centre. A simple estimation using a climate sensitivity analysis method by Hartmann (1994) shows that such rise of relative humidity would suppress evaporation of water from the sea surface, followed by the evaporative cooling and consequently could warm the sea surface because of decrease of evaporation due to higher relative humidity of air and also the role of water vapor as a green house gas. Neglecting the other processes, it might have increased the surface temperature by about 0.14 C, which is greater than the observed amplitude of 0.10 C (Table 1). The smaller amplitude may be due to the marine clouds' blocking of insolation.

Table 1. The climate time means and the decadal oscillation amplitudes at the north center (NC) and at the south center (SC) of action. The amplitude was estimated from the coefficient of lag-regression between the time-filtered (8-15 years) monthly mean values of a variable and the time-filtered (8-15 years) and normalized monthly mean sunspot numbers. The means and the amplitudes are based on data records for 44 years 1958 to 2001.

Area	Par.	T(C)	q(g/kg)	RH(%)	p(hPa)
NC	Mean	24.73	15.07	77.64	1016.57
	Val.	0.10	0.10	0.14	-0.07
SC	Mean	22.13	12.64	75.90	1016.94
	Val.	-0.08	-0.08	0.10	0.13

In order to supplement our previous correlation analyses, we compared a fractional change in relative humidity with that of specific humidity, air temperature, and surface pressure. By taking logarithmic differentiation of an equation which expresses relative humidity in terms of specific humidity, air temperature, and air pressure, the following equation may be written by neglecting small contributions for the average conditions in the lower atmosphere near the surface:

$$\frac{\delta RH}{\overline{RH}} = \frac{\delta q}{\overline{q}} - \left(\frac{L_c}{R_v \overline{T}}\right)\frac{\delta T}{\overline{T}} - \frac{\delta P}{\overline{P}}$$
$$= \frac{\delta q}{\overline{q}} - 20\frac{\delta T}{\overline{T}} - \frac{\delta P}{\overline{P}}.$$

In the above equation the coefficient 20 actually varies from 20.8 to 18.9 when evaluated based on the values of Lc=2.5 x10^6 J kg^{-1}, R_v=466.5 J kg^{-1} K^{-1}, and for $\overline{T}$ =260 K-285 K which represents the average condition of the lower atmosphere. The overbar denotes the climate time mean value and the symbol

δ denotes the oscillatory component of each variable. The above expression is virtually the same as that of Peixoto and Oort (1996) except for the last term related to a fractional change in surface air pressure.

All the terms in the above equation were evaluated for a lag of -2 years and their values are listed in Table 2. The observed amplitude of relative humidity at a lag of -2 years can be explained primarily by a fractional change in specific humidity in the north centre region of action and by the air temperature change in the south centre region. The sign of the observed fractional change in relative humidity with respect to that of the summation of specific humidity, temperature, and pressure is consistent for the both centers of action. The magnitude of each term seems to be more balanced for the south centre of action than for the north centre. Such an unbalance in the north center region of action may be due to sampling problem and/or other unknown physical processes in the area.

Table 2. Percent values (%) of the fractional change of variables: RH, q, T, and air pressure (P). They are evaluated for a lag time of -2 years with respect to the time of maximum sunspot number, at which the fractional change of RH is maximized.

Action Center	RH	q	T	P
NC	+0.18	+0.67	-0.59	+0.01
SC	+0.13	-0.01	+0.17	-0.01

5. CONCLUSIONS

According to our analysis of ICOADS, the fundamental physical mechanism for a possible connection between the decadal oscillation and the variations in the sun's luminosity may arise from the existence of water-based substance in various phases over the northern tropical Atlantic Ocean. The long wave radiation balance seemed to be influenced obviously by water vapor and liquid water in the atmosphere and the short wave radiation balance also by clouds but in a less extent. In the northern tropical Atlantic Ocean, the 11-year oscillations in the sea surface temperatures can be explained by exploring changes in relative humidity using a simple expression employed for the study of sensitivity of the earth climate to various forcing. And we can point out a small but unmistakable signature of leading of relative humidity maximization prior to air pressure minimization or the sea surface temperature maximization in the north subtropical Atlantic. And the anomaly of wind speed is nearly zero at the time of extreme values of relative humidity (Fig. 7). Consequently, the thermodynamic effects of wind-induced increase or decrease of evaporation may be regarded as reinforcing mechanism of the oscillation rather than a principal forcing agent.

As the ICOADS comprises only surface observations, it is obviously impossible for us to capture the three-dimensional structure of the oscillation. Nonetheless, the following physical mechanism could be envisaged from our analysis. Two years prior to a peak in the number of sunspots or solar flux, sea surface temperature was rising in the northern tropical Atlantic Ocean due to the sun's increasing radiation passing its minimum sunspot number or minimum luminosity period. As suggested by the lag-correlation functions of various variables in

Fig. 6 and lag-covariance values presented in Table 1, the effects of the solar radiation increase associated with the solar cycle seemed to be enhanced due to cloud dissipation but only to trivial extent. Though small, the increase in solar radiation led to an increase in relative humidity by evaporating seawater into air. The increase in relative humidity was sufficient enough to amplify evaporation and net radiation warming of the ocean surface because of the role of water vapor as a green house gas.

The foregoing explanation counts the temporal sequence of evolution in relative humidity, specific humidity, surface air temperature, and SST as discernable in lag-correlations (Figs. 6a and 6c). As stated in the previous section, 0.14% increase in relative humidity could raise SST by 0.14 C approximately. The warm sea surface could easily decrease surface air pressure by supplying sensible and latent heat to the lower atmosphere. Further heating, however, would destabilize the atmosphere, resulting in cloud production. The clouds might stop the continual increase in relative humidity by suppressing evaporation from the sea surface due to their obstruction of insolation. Rainfall also could reduce relative humidity in the region.

By comparing Figs. 6c and 6d, we can say that the total wind speeds increase in the south almost simultaneously with pressure falling or SST rising in the north. As the meridional pressure gradient increases in the equatorial Atlantic following the surface pressure buildup in the south centre, southerlies reach a maximum around three months before the sunspot peak time, which coincides roughly with the minimum of SST, surface air temperature, specific humidity in the south. And SST could also fall by the marine clouds' blocking of sunlight. Over the south centre region, the enhanced winds could lower the SST by evaporation. The less cloudy western portion of the southern tropical Atlantic could not attain the degree of cooling than its more cloud-heavy eastern portion could. The importance of evaporation cooling can be deducible from the sequential evolution of SST, air temperature, specific humidity in order. In the north, the order is reversed. Despite weak but positive solar heating, the south-centre of action eventually cools due to wind-driven evaporation of water from the underlying ocean surface. Consequently, high pressure could develop over the south centre region, which is opposite in phase but with a time lag of about 2 years after decrease in surface air pressure in the north for the assumed phase. In the subsequent phase of the oscillation, the decrease of solar flux may induce a series of temporal evolution of which phase is exactly opposite to the above description.

After subtracting the annual cycle from the unfiltered raw time series of variables investigated, we still have large variances associated with the low frequency components with periods longer than about fifteen years. As we used a digital time filter in order to isolate the tropical Atlantic decadal oscillation, we paid much attention to the adverse effects of time filtering. Our time filtering does not change the character of the sunspot numbers as a reference time series. Lag-correlation functions based on the unfiltered sunspot numbers (not shown) are at first glance indistinguishable from the respective ones based on the time filtered sunspot numbers shown in Figs. 4c and 4d, and 6c and 6d. In spite of the limited record length of the ICOADS, statistical significance appeared high in our correlation and covariance analysis of most of the variables.

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