NOTES

The relationship between the thermohaline circulation and climate variability

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Abstract The long-term integration with the Global Ocean-Atmosphere-Land System model of the State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics(IAP), Chinese Academy of Sciences has been used in the investigations on the relationship between the thermohaline circulation and climate variability. The results show that the strength of the North Atlantic Thermohaline circulation (THC) is negatively correlated with the North Atlantic Oscillation (NAO). Based on this kind of relationship, and also the instrument-measured climate record such as air pressure and sea surface temperature, the activity of the thermohaline circulation during the 20th century has been evaluated. The inferred variations of the strength of the THC is that, during two multi-decadal periods of 1867—1903 and 1934—1972, the THC is estimated to have been running stronger, whereas during the two periods of 1904—1933 and 1973—1994, it appears to have been weaker.

Keywords: thermohaline circulation, North Atlantic Oscillation climate variability.

The climate system of the Earth can be broken down into a number of components: the ocean, the atmosphere, the lithosphere, the cryosphere, and the biosphere. The ultimate forcing mechanism of oceanic and atmospheric motions is the pole-to-equator gradient of radiative heating of the planet. There exists surplus of heat in the equatorial region and deficit of heat in the polar region. In order to keep the thermal balance of the Earth, the excessive heat collected in the equatorial regions must be transported to the polar regions. The transport is taken up by the meridional circulation branch of the climate system, which is mainly made up of the atmospheric components of the famous Hadley cell, the Ferrel cell, and the polar cell, and also its ocean component of the Atlantic thermohaline circulation.

About 90% of the water in the world ocean are involved in the thermohalien circulation, which is located beneath the wind driven surface currents and at great depths. The power for this slower, deeper circulation comes from the action of gravity on adjacent water masses of different densities. Since density is largely a function of temperature and salinity, the circulation due to density difference is called thermohaline circulation. The contemporary thermohaline circulation is characterized as the Atlantic Great Ocean Conveyor Belt. Intense radiative cooling of the polar ocean surface during the winter causes the formation or extension of sea ice. Cooling and brine rejection (i.e. salt ejection during ice formation) produces an unstable density gradient in the upper ocean allowing the cool and saline dense water to mix down convectively. Just as the tropical ascent is the rising part of the atmospheric direct circulation (i.e. warm air rising), the sinking motion of the ocean is the thermally direct part of the ocean circulation (i.e. cold water sinking). The thermodynamically direct circulation converts potential energy into kinetic energy. These processes lead to the formation of the deep ocean water, which spreads out away from the poles until it slowly ascends toward the equator. At last, the water moves back to the poles from the equator in the form of shallow warm water circulation[1,2].

The Atlantic meridional overturning (hereafter referred to as the thermohaline circulation (THC)) plays an important role in the pole-ward oceanic heat transport. The variability of the THC and also the accompanied change of pole-ward heat transport have strong impacts on the regional or global climate. Thus, the activity of the THC on the decadal to centennial time scales is highlighted both in the recently produced Science Plan of the World Climate Research Program (WCRP)——Climate Variability and Predictability (CLIVAR) Program[3] and in the International Geosphere-Biosphere Program (IGBP)——Past Global Changes (PAGES) Core Project[4]. Recognition on the important role of the THC in the climate system is regarded as one of the important developments in the climate research community in the 1990s.

The incompleteness of the observational record makes it extremely difficult to study the variations of THC and associated processes based solely on the observational data. Thus, as a complementary approach, numerical models are effectively used. The authors once reviewed the international research work on THC systematically, and pointed out that most of the former studies focused mainly on the internally variability of THC in single oceanic general circulation models (OGCM), and could not link closely with the widely cared problems of contemporary climate variability[5]1). The relationship between the THC and contemporary climate is therefore of direct interest to current study. The output from a multi-century integration of a coupled Global Ocean-Atmosphere-Land System model (hereafter referred to as GOALS), developed at IAP's State Key Laboratory of Atmospheric Sciences and Geophysical Fluid Dynamics, forms the basis of the analyses presented here. Based on the physical connections between the THC and regional climate revealed by the model, and also the instrument-measured climate record such as air pressure and sea surface temperature, the activity of the THC during the 20th century has been evaluated.

1 Descriptions of the coupled global ocean-atmosphere-land system model

The atmospheric component of GOALS is a global spectral AGCM, which is rhomboidally truncated at zonal wave number 15 (L9R15). There are nine unevenly spaced levels in the vertical s coordinate. For the purpose of reducing truncation errors, a standard stratification of temperature is introduced into the dynamical framework and the scheme of the reduction of a standard atmosphere is used to improve the model performance. A new k-distribution radiation scheme is implemented into the model. Cloud processes are treated more rationally in this scheme[6]. A diagnosed cloud cover and liquid water path scheme is introduced into the model[7]. To get more insight into the impacts of land surface processes on climate, a simplified biosphere model (SSiB) developed by Sellers and Xue is implemented into the AGCM. There is 1 vegetation layer, 3 soil layers and 11 types of vegetation in SSIB[8]. The oceanic component of GOALS is an OGCM with 20 unevenly spaced layers in the vertical h coordinate. The horizontal resolution is 4° in latitude by 5° in longitude on B-grid. The depth of the maximum flat-bottom is 5 000 m. Domain of the OGCM covers the global scope except the North Pole. The continental outlines are fairly realistic. Both the Drake and Indonesian Passages are opened, and no attempt was made to broaden the Drake Passage gap artificially[9]. A simple thermodynamic sea-ice model formulated based on ref. [10] is incorporated into the ocean model.

The “Prediction-Correction” coupling scheme for monthly mean anomaly has been chosen for the ocean-atmosphere coupling process[11]. The ocean and the atmosphere exchange heat flux and momentum through their interface. The model sea surface salinity was restored to the observational field seasonally. The coupled model (i.e. GOALS) has been integrated for 200 years, preliminary analysis shows that it controls sea surface climate drift successfully and can reproduce the basic characteristics of atmospheric and oceanic circulation reasonably. The output of annual mean physical variables from the 200-year integration forms the basis of the forthcoming analyses.

2 Variability of the thermohaline circulation in GOALS

As shown in fig. 1, the stream-function (200-year mean) is used in describing the meridional thermohaline circulation in the Atlantic Basin. Note the positive values mean anticlockwise direction, and negative values mean clockwise direction. It is apparent that the model can successfully reproduce two major members of the global scale water masses, i.e. the North Atlantic Deep Water (NADW) and the Antarctic Bottom Water (AABW). The southward outflow of NADW is notable, which can cross the equator and reach 30°S.

In this study, the intensity of the THC in the North Atlantic is defined each year as the maximum value of the sinking branch around 60°N of the stream- function representing the annual mean meridional thermohaline circulation. The time series of the index, which represents the fluctuations in the intensity of the annual mean THC, is shown in fig. 2(a). Visual inspection of the figure reveals

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robust variability on inter-annual time scale. The THC oscillated around the annual mean state of $11.6\times10\ \mathrm{m^3/s}$ or so in all 200 years of the integration, the difference between the highest and lowest values is about $2.4\times10\ \mathrm{m^3/s}$. Superposed on the inter-annual variability, there also exists prominent fluctuations on decadal scale. As shown in fig. 2(b), spectral analysis of the time series from the total 200 years demonstrates the dominant period of 24 years.

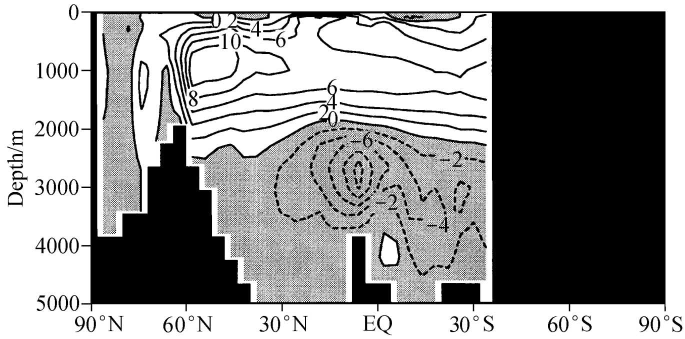

Fig. 1. Modeled annual mean stream-function of the meridional overturning in the Atlantic Basin (unit: $10^6\mathrm{m^3/s}$).

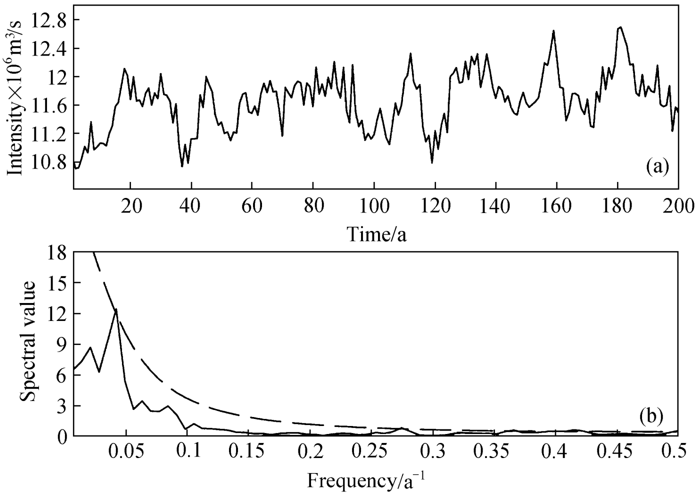

Fig. 2. (a) Time series of the annual mean intensity of the index of the meridional overturning in the North Atlantic. (b) Solid line denotes spectrum of the 200-year THC index time series shown in fig. 1. Dashed line denotes 95% confidence level for accepting the red noise null hypothesis.

In order to reveal the variation of sea surface temperature (SST) associated with the fluctuations of the THC, correlation coefficients between the THC index shown in fig. 2(a) and annual-mean SST over the North Atlantic region are calculated and the result is shown in fig. 3(a). The pattern of the correlation field is characterized by an anti-symmetric dipole mode, with a negative core over the sea southeast to the Newfoundland and a positive core off western coast of the Northern African continent. This implies that when THC is stronger than normal, the western part of North Atlantic is cooler than normal, and the eastern part is warmer than normal.

The spatial pattern of the anomalies of model SST associated with fluctuations in the intensity of the THC is shown in fig. 3(b). These differences are computed by subtracting the mean of two decades

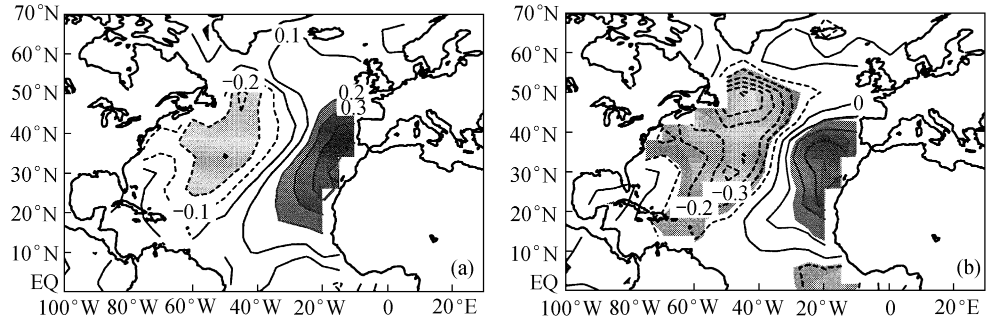

Fig. 3. (a) The pattern of correlation field between the annual mean model sea surface temperature and THC index. (b) Differences in annual mean model sea surface temperature between two decades with anomalous large THC index values and two decades with anomalous small THC index values (unit:℃).

with anomalous small values of the THC index from the mean of two decades with anomalous large values of the THC, and thus can reveal the variation of SST associated with the decadal-scale fluctuations of the THC intuitively. Areas with confidence limits of 95% using *t*-test are shaded. Note that the pattern of SST change bears encouraging resemblance to the pattern of correlation coefficients shown in fig. 3(a), with anomalies of negative polarity southeast to the Newfoundland and anomalies of positive polarity off the western coast of the Northern African continent. The maximum value of positive anomaly is 0.4℃ and the minimum value of negative anomaly is -0.6℃.

3 Connections between the thermohaline circulation and regional climate

The spatial pattern of the correlation coefficients between the THC index series and annual mean model sea level pressure is shown in fig. 4(a), revealing the linkage between the THC and regional climate. Note that only part region over the North Atlantic exceeds the test of 95% confidence limits and appears as a pattern similar to the North Atlantic Oscillation (NAO). This implies that the intensity of THC is negatively correlated with the NAO. By calculating the correlation between the annual mean model THC index series and the annual mean model NAO index series directly, we get a result of -0.26, which exceeds the test of 95% confidence limits. This confirms that the intensity of the THC is indeed negatively correlated with the NAO in GOALS.

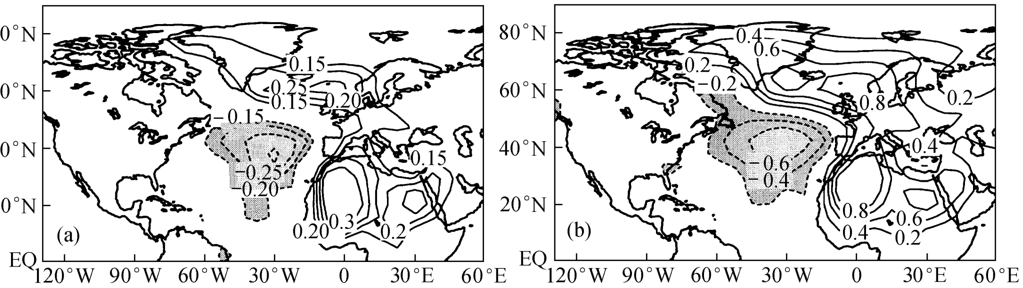

Fig. 4. (a) The pattern of correlation field between the annual mean model THC series and annual-mean model sea level pressure, only the values that exceed the 95% confidence level are shown. (b) Annual mean THC composite field of sea level pressure (high THC index minus low index, threshold being one standard deviation) (unit: hPa).

Another approach to exhibit the connections between the THC and the associated atmospheric variability is composite analysis. We consider composite differences between THC extreme phases. Ensemble members of positive and negative composites are keyed to index values (taken from fig. 2(a)) greater and smaller than one standard deviation, respectively. The resulting large-scale anomaly is shown in fig. 4(b) and is locally significant at the 95% confidence level according to a *t*-test. It can be found in fig. 4(b) that the anomalous pressure pattern encountered during a positive THC phase is associated with a negative NAO phase. In fact, fig. 4(b) reconfirms the negative correlation between the intensity of THC and the NAO.

4 Elementary evaluations on activity of the North Atlantic thermohaline circulation during the 20th century

The scarcity of observational oceanic data makes it impossible to offer a time series for the intensity of the North Atlantic thermohaline circulation during the 20th century. Contrary to the paucity of observational oceanic data, the observational sea level pressure record is relatively abundant. According to the relationship of negative correlation between the THC and the NAO exposed by the GOALS model as discussed in section 3, we can make an elementary evaluation on the actual variability of the THC in the past 100 years or so. *Climate Change* 1995 reported the observational NAO index from 1867 to 1995[12], according to this time series, the activity of the NAO has experienced four phases of weak-robust-weak-robust since the year 1867, and the transition years are 1904, 1934 and 1972, respectively. Therefore, we can infer the variations of the strength of the THC as, during two multi-decadal periods of 1867—1903 and 1934—1972, the THC is estimated to have been running stronger, whereas during the two periods of 1904—1933 and 1973—1994, it appears to have been weaker.

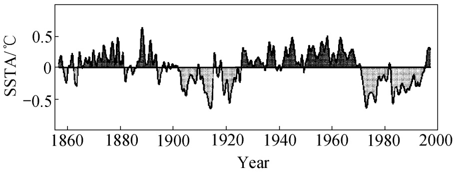

Fig. 5. Time series of the observational area-averaged SST anomalies over the subpolar North Atlantic (45－65° N, 20－60° W) (given by Enfield and Mestas-Nunez,1998, quoted from Gray, 1998).

As mentioned above, accompanied by the strengthening of the THC, the associated changes of SST in the North Atlantic domain are the cooling trend southeast to the Newfoundland and the warming in the other regions. The temporal realization of the Atlantic multi-decadal mode computed from temporal amplitude time series and the area-averaged spatial loading over the rectangular area in the North Atlantic (45－65°N, 20－60°W) first provided by Enfield and Mestas-Nunez (1998) is shown in fig. 5[13]. Positive values indicate warm SST anomalies and imply a stronger THC, consequently, negative values mean warm SST anomalies and suggest a weaker THC. SST in the subpolar North Atlantic are warmed during multi-decadal periods when the THC is stronger, and cooled when the THC is weaker. Generally speaking, the inferred trend of the THC from 1860 to 1995 is similar to that evaluated from the actual activity of the North Atlantic Oscillation.

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