Strengthening of the boreal winter Hadley circulation and its connection with ENSO*

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Accepted on May 18, 2007

Abstract Empirical orthogonal function (EOF) analysis is carried out for the year-to-year variability of the boreal winter (DJF) mass stream function of the mean meridional circulation (MMC) during the period 1948—2005. The results demonstrate that it is dominated by the equatorially asymmetric and symmetric modes. Further analysis shows that the former mode is linked with the boreal winter Hadley cell mainly on the decadal time-scale, and the latter on the interannual time-scale. The asymmetric mode index (AMI) with a clear upward trend contributes to the decadal strengthening of the boreal Hadley circulation, and is closely correlated with the tropical SST warming, especially in the region of Indo-west Pacific warm pool (INWP). Furthermore, the AMI also contributes to the abrupt change of the correlation coefficient between the boreal Hadley circulation and ENSO after 1976. The symmetric mode index (SMI) with robust and stable linkage with ENSO shows a significant interannual variability, suggesting that the variability of the Hadley circulation is mainly associated with ENSO on the interannual time-scale.

Keywords: **the Hadley circulation, interannual time-scale, decadal time-scale.**

In 1735, Hadley postulated a single-cell circulation to explain easterly winds in the tropics. Later studies showed the limitation of Hadley's theory. And some authors[1—6] pointed out that the global circulation model should consist of three cells for each hemisphere, with the dominance of the Hadley cell in the winter hemisphere. These circulations are important to balance the heat, momentum and moisture and have a great impact upon the Earth's climate variability. For example, the ascending and descending branches of the Hadley circulation determine the climate of various tropical regions and influence the middle and high latitudes[7,8].

Recently, many scientists pointed out that the boreal winter Hadley cell has been strengthening over the past several decades[9—12]. Quan[10] suggested that the warming of the tropical oceans and increased El Niño frequency and amplitude after 1976 attributed to this strengthening. However, after removing the ENSO signal from the index of Hadley circulation, the upward trend still exists, and therefore Mitas et al.[12] indicated that this is in contrast to the partial attribution of Quan[10]. These studies show that what role ENSO plays in the intensification of DJF Hadley cell is still an open question. Meanwhile, the annual march of the climatological MMC can be decomposed into two roughly comparable components[13]. However, the principle modes in the year-to-year variability of DJF MMC and their connections with the enhancing of the boreal Hadley circulation are not clear at present. In this study, we employ the empirical orthogonal function (EOF) analysis to determine the principle modes of year-to-year variability of the DJF MMC and explore their possible contribution to the strengthening of the boreal Hadley circulation.

1 Data and methods

In this study, the monthly mean zonal and vertical winds are taken from the NCEP/NCAR reanalysis[14]. These data have a horizontal grid interval of 2.5° latitude by 2.5° longitude, and provided on 17 unevenly spaced pressure levels. The SST data come from NOAA Reynolds dataset on a grid interval of 2.0° latitude by 2.0° longitude[15]. These data all cover the period of 1948—2005. An ENSO index during 1948—2004 comes from the website (http://

* Supported by National Natural Science Foundation of China (Grant Nos. 40325015 and 40528006) and National Key Progam on Basic Research and Development Projects (Grant No. 2006CB403600)

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jisao.washington.edu/data-sets/globalsstenso/).

In this study, the MMC is depicted by the conventional mass stream function computed by using the zonally averaged mass continuity equation in the form of

$$\frac{\partial[\bar{v}]\cos\varphi}{R\cos\varphi\partial\varphi}+\frac{\partial[\bar{\omega}]}{\partial p}=0 \quad (1)$$

where v is the meridional velocity, ω is the vertical velocity in pressure coordinates, R is the mean radius of the earth, and p is the pressure. The operators "—" and "[ ]" represent temporal (i.e. monthly) and zonal averaging, respectively. The form of the zonally averaged continuity (Eq. (1)) allows the definition of a two-dimensional streamfunction ψ, defined by:

$$[\bar{v}]=g\frac{2\psi}{2\pi R\cos\varphi\partial p} \quad (2)$$

$$[\bar{\omega}]=-g\frac{2\psi}{2\pi R^{2}\cos\varphi\partial\varphi} \quad (3)$$

which can then be used to compute the ψ field by integrated Eq. (2). Then we can obtain

$$\psi=\int\frac{2\pi R\cos\varphi}{g}[\bar{v}]\,\mathrm{d}p \quad (4)$$

Some papers[16,17] discussed the detailed computation process of Eq. (4). In this study the departure from climatological mean is used in the EOF analysis, and consequently the modes represent the anomalies from the climate mean. It should be pointed out that the ERA40 data also show similar results to this paper.

2 Variability of the DJF MMC

Fig. 1 (a) shows the DJF climatology of mass stream function of MMC. The boreal winter Hadley circulation is dominant and its center is located at 15°N, with the maximum value about 18×10^{10} kg/s and a large latitudinal extent ranging between 10°S and 30°N. However, the southern Hadley circulation between roughly 30°S and 10°S centers at 25°S and is weaker even than the austral Ferrel cell. Fig. 1 (a) also indicates that the common ascending branch of the northern and southern Hadley circulations has the same position as the maximum of zonal mean SST[18]. The above results qualitatively agree with those of Wu et al.[19] and Li[20].

2.1 The principle modes of DJF MMC

The first two leading modes of the year-to-year variability of DJF MMC are shown in Fig. 1 (b) and Fig. 1 (c), respectively. The leading EOF mode (EOF1) illustrates that there is a meridional circulation cell across the equator in the low-latitude region, representing a nearly equatorially asymmetric distribution. It accounts for 55% of the total variance. Whereas the second EOF mode (EOF2) with a pair of tropical cells explains 10.3% of the total variance and is basically equatorially symmetric, in which the southern cell is slightly stronger than the northern counterpart.

EOF analysis shows that it is obvious that the year-to-year variability of the boreal winter mass stream function of MMC can be mainly decomposed into two components: the equatorially asymmetric and symmetric modes. These two modes are similar to those in the previous study[13], but they are actually different. The former emphasizes on the year-to-year variability of DJF mass stream function of MMC, whereas the latter on the annual march of the climatological MMC. For convenience, the time series of EOF1 and EOF2 modes of the DJF mass stream function of MMC are defined as the equatorially asymmetric mode index (AMI) and symmetric mode index (SMI), respectively.

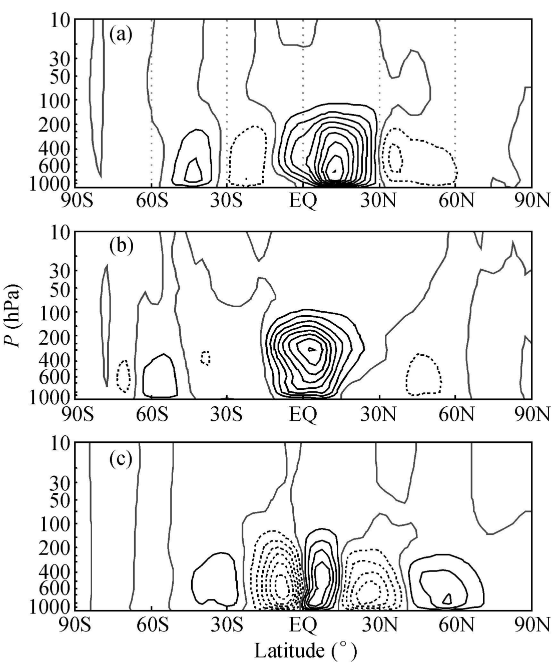

Fig. 1. The DJF climatology of mass stream function of MMC and the first two EOF modes of its year-to-year variability. (a) DJF climatology of the mass stream function of MMC; (b) spatial pattern of the leading EOF mode (EOF1, accounting for 55% of the total variance); (c) the same as (a), but for the second EOF mode (EOF2, accounting for 10.3% of the total variance). The period is 1948—2005, and the contour interval is 2×10^{10} kg·s^{-1}.

2.2 Variability of the principle modes

Fig. 2 (b) shows that the AMI exhibits a significant upward trend on the decadal time scale (significant at a 99.9% confidence level), suggesting that the variability of the asymmetric mode is helpful to enhancing the boreal Hadley circulation. Moreover, it also undergoes a decadal transform from the negative value to the positive value during the late 1970s, that is to say, the phase of the asymmetric mode has changed, implying that the composite intensity of the Hadley cell in the ENSO warm epoch before 1976 is weaker than that after 1976[10]. Fig. 2 (c) demonstrates that there is no significant trend in the SMI but obvious interannual variability exists, suggesting that the variability of equatorially symmetric mode might not significantly contribute to the strengthening of the Hadley circulation.

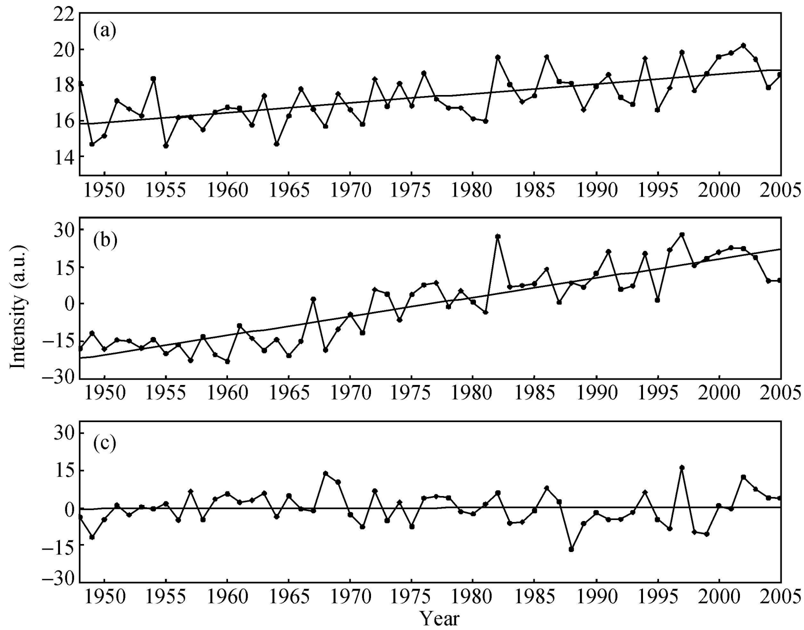

Fig. 2. The time series of the index of the boreal winter Hadley cell intensity (HCI) and the equatorially asymmetric and symmetric modes index. (a) The time series of HCI (trend= 0.05, α= 99.9%); (b) the same as (a), but for the AMI of the DJF MMC (trend= 0.77, α= 99.9%); (c) the same as (b), but for the SMI (trend= −0.15 α= 25.6%). The linear trend over the whole period and its confidence level are also shown.

2.3 Relationship between the boreal winter Hadley circulation and the principle modes

From the above discussion, we can see that the asymmetric mode has a significant decadal upward trend, whereas the equatorially symmetric mode varies mainly on interannual time-scale. Do these two modes indicate the decadal and interannual time-scale variability of the boreal winter Hadley cell[21]? Table 1 shows the correlation coefficients among AMI, SMI and the index of the Hadley circulation intensity (HCI), and its 7yr high-pass and low-pass filtered time series. HCI (Fig. 2(a)) is defined as the maximum value in the latitudinal zone of 0—30°N[6]. As indicated in Table 1, the AMI and SMI are all significantly correlated with HCI, but the symmetric mode can explain minority of the year-to-year variability of the Hadley cell. Further analysis shows that the correlation between the AMI (SMI) and HCI is mainly on the decadal (interannual) time scale. These results imply that the equatorially asymmetric (symmetric) mode of MMC is linked with the boreal Hadley circulation mainly on the decadal (interannual) time-scale.

Table 1. Correlation coefficients among the equatorially asymmetric mode index (AMI) and symmetric mode index (SMI) of DJF MMC and the index of boreal winter Hadley cell intensity (HCI), the 7yr high-pass and low-pass filtered HCI[1)].

	AMI	SMI
HCI	**0.74** (99.9%)	**0.31** (98%)
HCI(h)	0.23	**0.47** (99.9%)
HCI(l)	**0.87** (99.9%)	0.01

1) The HCI(h) and HCI(l) represent the 7yr high-pass and low-pass filtered HCI, respectively. They were generated by the Gaussian type of filter. Values in parentheses indicate the confidence level.

In order to confirm the above results, Fig. 3

shows the composite difference pattern of the zonal mean meridional circulation between the high and low years of AMI, SMI, and the high-pass and low-pass filtered HCI. The high (low) year is defined by the criterion that these four time series exceed (±1 standard deviations from the average (not shown). The selected high years of low-pass filtered HCI covers the period of 1997—2004; and its low years are the period of 1949—1951, 1955—1959 and 1962—1964. Similarly, the high years of high-pass HCI are 1948, 1954, 1963, 1966, 1972, 1976, 1982, 1986, 1994 and 1997; whereas its low years are 1949, 1950, 1955, 1964, 1968, 1971, 1981, 1989, 1995 and 1998. As shown in Fig. 3 (a) and Fig. 3 (c), it is clear that there is an equatorially asymmetric distribution of the anomalous meridional circulation during the high years of the low-pass HCI or the AMI, whereas during their low years it is equatorially symmetric with a pair of positive amomalies (Fig. 3 (b) and Fig. 3 (d)). These results reveal that both modes are part of the boreal Hadley circulation, and so the variability of the Hadley cell is not only on decadal but also on inter-annual time scale.

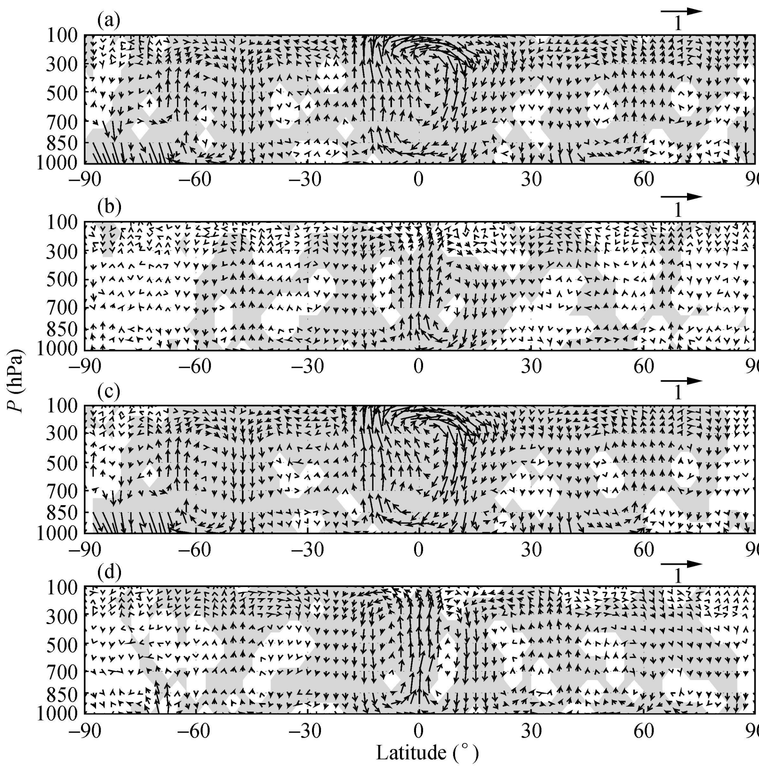

Fig. 3. The composite pattern of the zonal-mean meridional circulation (vector). (a) Between the high and low years of the AMI; (b) the same as (a), but for SMI; (c) the same as (a), but for the low-pass filtered HCI; (d) the same as (a), but for high-pass filtered HCI. The high and low years are defined by the four time series exceeding ±1 standard deviations from the average. The shaded regions exceed 95% confidence level.

3 Further analysis

Many researchers thought that the cross-equator meridional circulation is an indication of monsoon[13, 22, 23], and monsoon is ocean-dominated during boreal winter[10]. Then, does PC1 have a closed relationship with the tropical SST?

3.1 Relationship between the asymmetric mode and SST

Fig. 4 (a) shows the correlation map between the AMI and DJF SST. The predominant correlations between them are mostly distributed in the low-latitude regions including a large area from the tropical India Ocean to the western Pacific warm pool (INWP), the Southeast Pacific and the tropical Atlantic Ocean. And this correlation map is only on the decadal time scale (compared with Fig. 4 (b)), which is very similar to the spatial pattern of the linear trend of DJF SST anomalies (Fig. 4 (d)), suggesting that the tropical ocean SST trend in the regions mentioned above is associated with the intensification of the equatorially asymmetric mode of MMC on the decadal time scale. Note that the SST warming in INWP region with the strongest trend may play a dominant role in decadal strengthening of the Hadley circulation.

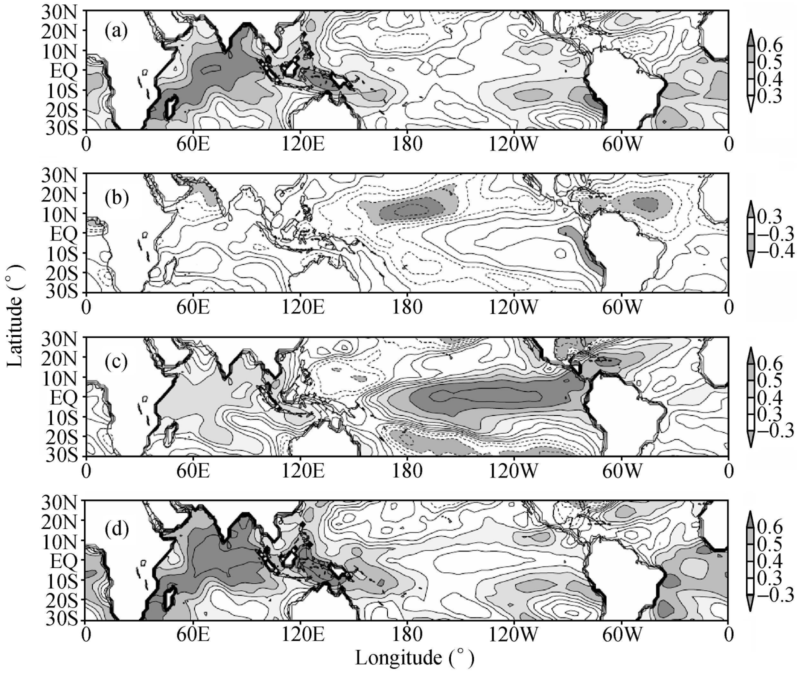

Fig. 4. The horizonal distribution of the correlation between the two modes index and DJF SST. (a) The correlation map between the AMI of the DJF MMC and DJF SST; (b) the same as (a), but after detrending them; (c) the same as (a), but for the SMI and DJF SST; (d) spatial distribution of the linear trend of DJF SST. The shaded regions exceed 95% confidence level. The contour interval is 0.1.

3.2 Relationship between the symmetric mode and SST

The distribution of correlation coefficients between the SMI and DJF SST is shown in Fig. 4 (c). The spatial pattern of the significant correlations robustly shows an ENSO pattern in the Pacific. And the robust correlation coefficient between SMI and ENSO is 0.71 (Fig. 5 (b)), while that between AMI and ENSO is nearly zero (Fig. 5 (a)), suggesting that the Hadley cell might be associated with ENSO mainly on interannual time scale[6, 25]. Additionally, a board region of significant correlations between the SMI and DJF SST could also be found in INWP region (Fig. 4 (c)). This implies that the SST in INWP plays an important role not only in decadal time-scale variability of the boreal Hadley cell, but also in its interannual variability.

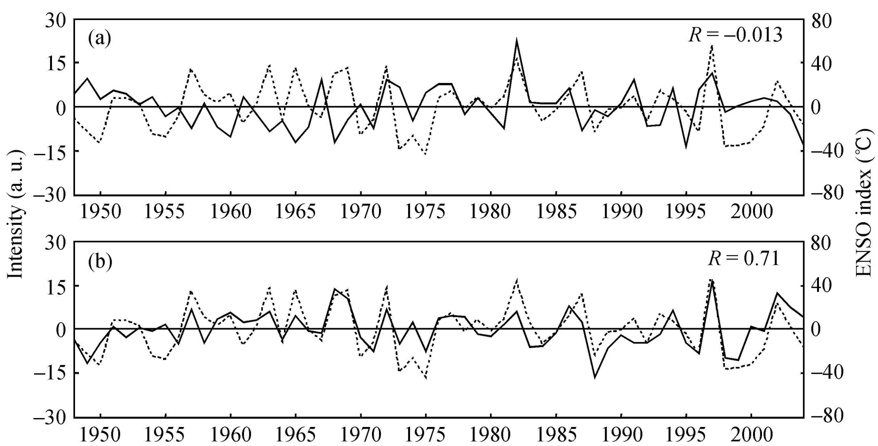

Fig. 5. Time series of the two modes index and ENSO. (a) The time series of AMI (real line) and ENSO (dotted line); (b) the same as (a), but for SMI (real line) and ENSO (dotted line). The trend of all curves is removed.

3.3 11yr moving correlation between the two modes index and ENSO

In order to further study the linkage between the AMI, SMI of DJF MMC and ENSO, Fig. 6 shows the 11yr moving correlation coefficients between DJF AMI and ENSO, and DJF SMI and ENSO. As shown in Fig. 6 (a), an abrupt change of the moving correlation coefficients between AMI and ENSO occurs during the 1970s, and the correlation values are positive (negative) after (before) the mid 1970s. Moreover, either before or after the 1970s, the moving correlation coefficients between them are unstable. However, the moving correlation coefficients between SMI and ENSO are stably significant over the whole period (Fig. 6 (b)). These results show a clue to explain the phenomenon that the boreal winter Hadley circulation has a more significant correlation with ENSO after 1976[21], and that the boreal Hadley circulation has been strengthening with increased El Niño frequency and amplitude after 1976[10], because the two correlation coefficients are all positive and may cause more closed correlation between the Hadley circulation and ENSO after 1976. The results also suggest that removing ENSO signal from HCI the upward trend of the Hadley circulation intensity still exists[12] due to strengthening of the left asymmetric mode.

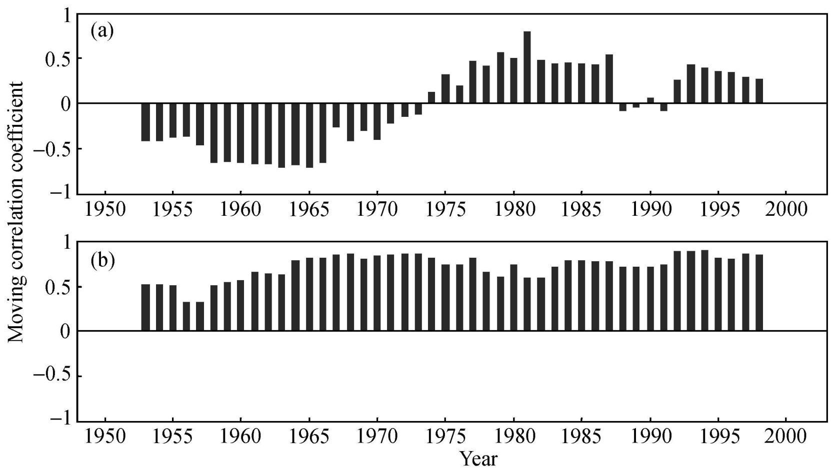

Fig. 6. The moving correlation coefficient between the two modes index and ENSO. (a) 11yr moving correlation coefficient between the DJF AMI and ENSO; (b) same as (a), but for the DJF SMI and ENSO.

4 Summary and discussion

(1) The year-to-year variability of the DJF mass stream function of MMC is dominated by the equatorially asymmetric and the symmetric modes which well represent the decadal and interannual variability of the boreal winter Hadley circulation, respectively.

(2) The asymmetric mode with clear upward trend is linked with the SST warming mainly in the INWP region and contributes to the enhancing of the boreal Hadley circulation. It may also explain the abrupt change of the correlations between the Hadley cell and ENSO after the mid 1970s.

(3) The symmetric mode without significant trend is stably and robustly linked with ENSO over the whole period, suggesting that the closed correlation between the boreal winter Hadley circulation and ENSO mainly results from the linkage between the Hadley symmetric component and ENSO.

However, there are still some open questions left for further exploration, such as the way how the strengthening of Hadley circulation responds to the warming SST. Otherwise, the Ferrel cell is also influenced by the tropical ocean[26] and the annular mode[27]. Thus, whether the clear upward trend of both Hemispheres annular modes would lead to the strengthening of the Ferrel cell is still unknown.

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