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Local Hadley circulation over the Asian monsoon region associated with the Tropospheric Biennial Oscillation

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With 5 Figures

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Summary

The Tropospheric Biennial Oscillation (TBO), a major interannual variation phenomenon in the Indo-Pacific region, is the result of strong ocean-atmosphere coupling over the Asian-Australian monsoon area. Along with other meteorological and oceanographic parameters, the tropical circulation also exhibits interannual oscillations. Even though the TBO is the result of strong air–sea interaction, the circulation cells during TBO years are, as yet, not well understood. In the present study, an attempt has been made to understand the interannual variability of the mean meridional circulation and local monsoon circulation over south Asia in connection with the TBO. The stream function computed from the zonal mean meridional wind component of NCEP/NCAR reanalysis data for the years 1950–2003 is used to represent the mean meridional circulation. Mean meridional mass transport in the topics reverses from a weak monsoon to a strong monsoon in the presence of ENSO, but in normal TBO years mean transport remains weak across the Northern Hemisphere. The meridional temperature gradient, which drives the mean meridional circulation, also shows no reversal during the normal TBO cycle. The local Hadley circulation over the monsoon area follows the TBO cycle with anomalous ascent (descent) in strong (weak) monsoon years. During normal TBO years, the Equatorial region and Indian monsoon areas exhibit opposite local Hadley circulation anomalies.

1. Introduction

On interannual time scales the Asian summer monsoon exhibits a fairly distinct biennial tendency. Years of heavy rainfall tend to be followed by years of reduced rainfall. This biennial component is known as the Tropospheric Biennial Oscillation (TBO) and appears in a wide range of parameters such as precipitation, sea surface temperature (SST), surface pressure and wind. The origin of TBO is subject to debate. Meehl (1997) and Meehl and Arblaster (2001, 2002a, b) proposed an air–sea feedback mechanism involving Indian and Pacific Oceans as the cause of TBO. According to this theory, dynamic coupling between the ocean and atmosphere, in conjunction with the seasonal cycle of convection over the tropical Indian and Pacific Oceans and associated large-scale east–west circulation in the atmosphere, is responsible for the TBO. Factors such as SST in the Pacific Ocean and Indian Ocean and 500 hPa height were proposed as important factors for TBO. Meehl et al. (2003) stressed the importance of SST anomalies in Pacific and Indian Oceans as a mechanism for TBO generation. Chang and Li (2000) and Li et al. (2001) demonstrated that the TBO is an inherent monsoon mode, resulting from multi-region interactions between Asian and Australian monsoons and adjacent tropical Oceans.

Large-scale tropical circulations, such as Hadley, Walker and Monsoon circulations, are the strongest driving forces of the general circulation in the low latitudes. Year-to-year variations of these circulations have a great impact on climate variability. These variations arise from revesals in the temperature gradient between continents and adjacent oceans. Both the Walker and Hadley Cells are the result of thermal contrast and they act as a mechanism to transport moist static energy. Ferrel Cells are indirect cells driven by transient baroclinic eddies which transport heat and momentum poleward (Holton, 1992).

Mean meridional circulation has been explored by Lorenz (1969), Oort and Rasmusson (1970) and Trenberth et al. (2000) etc. Oort and Rasmusson (1970) analysed the annual variation of monthly mean meridional circulation, the results of which have been well supported by other studies such as Newll et al. (1972), Peixoto and Oort (1992), Trenberth et al. (2000) and Dima and Wallace (2003). Lindzen and Hou (1988) and Hou and Lindzen (1992) studied the role of concentrated heating on the intensity of the Hadley circulation and in turn global climate. Oort and Yienger (1996) observed significant seasonal variation in the strength, latitude and height of the maximum stream function for both Hadley Cells. They also noticed significant correlation between the strength of tropical Hadley Cells and ENSO.

Earlier studies focussed on the Hadley circulation as the mean meridional circulation of the tropical atmosphere. However, when focus is on the circulation associated with monsoon and its interannual variability, local meridional circulation is found to be more important than the mean meridional circulation as suggested by Slingo and Annamalai (2000). The definition of Hadley circulation then seems to have extended to any local meridional circulation. For example, Wang (2002) discussed the local Hadley circulation induced by ENSO in the eastern and western Pacific. Goswami et al. (1999) discussed local Hadley circulation as part of the south Asian monsoon circulation. They also proposed a monsoon Hadley circulation index based on the meridional wind shear between 850 hPa and 200 hPa averaged over the south Asian monsoon area to measure the strength of the local Hadley circulation over the monsoon area. Ju and Slingo (1995) and Soman and Slingo (1997) suggested that changes in the local Hadley circulation may have a role in the influence of ENSO on the interannual variability of the Asian summer monsoon.

Even though the TBO cycle involves the atmosphere-ocean interaction, the circulation cells are not well studied in connection with TBO. Our previous work on TBO (Pillai and Mohankumar, 2007) showed pronounced changes in SST, wind etc for TBO years in the presence and absence of ENSO. In the present study an attempt has been made to identify the interannual variability of the global meridional circulation and local Hadley circulation associated with both ENSO–TBO and normal (non-ENSO) TBO years.

2. Data and methodology

The data sets used for the present study are the meridional and vertical components of wind from 1000 hPa to 100 hPa and air temperature at 500 hPa to 200 hPa taken from NCEP/NCAR reanalysis (Kalnay et al., 1996) for a period of 54 years (1950–2003). The Indian summer monsoon rainfall (ISMR) index (Parthasarathy et al., 1994) is used to identify relatively strong and weak TBO years. A year is defined as a strong (weak) TBO year if its ISMR index is more (less) than the previous and following year. TBO years in which the ISMR anomalies are more than half a standard deviation are only used in the composite analysis. ENSO years are identified from area averaged SST anomalies of the nino3 region (5° N–5° S, 150° W–90° W), whose five month running mean should be at least ±0.5 °C for two consecutive seasons after the March–April–May season over the following one year period.

The strength of the mean meridional overturning of mass can be derived from the meridional velocity between 1000 hPa and 100 hPa heights (Oort and Yienger, 1996). The mass transport is computed using observed zonal mean meridional winds.

Zonally averaged mass continuity equation is computed in the form

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

where $[\bar{v}]$ is the temporal and zonal averaged meridional velocity, ω is vertical velocity in pressure co-ordinates, R is the mean radius of the earth and p is pressure.

Introducing a Stokes stream function ψ, given by equation

$$[\bar{v}] = g\frac{\partial\psi}{2\pi R\cos\phi\,\partial p} \tag{2}$$

We can calculate the ψ field, assuming $\psi = 0$ at the top of the atmosphere and integrating the equation downward to the surface.

$$\psi = \frac{2\pi R\cos\phi}{g}\int_{p}^{p_0}[\bar{v}]dp \tag{3}$$

Using this Stokes stream function, we have calculated the mean mass and examined its seasonal evolution for strong minus weak monsoon year composites for ENSO–TBO years and non-ENSO–TBO years. We used a positive sign for ψ in the case of clockwise rotation and a negative sign for anti-clockwise rotation as suggested by Oort and Yienger (1996). According to this sign convention, the strengthening of two tropical Hadley Cells would mean larger positive values of ψ in the Northern Hemisphere (NH) tropics and more negative values of ψ in the Southern Hemisphere (SH) tropics. The difference of mass stream function between two points on a cross section is equal to the amount of mass flowing across a line joining the two points.

The vertical profile of meridional wind (v) and negative vertical velocity (w) averaged over the Indian monsoon area (60° E–95° E) is used to represent the local meridional circulation.

3. Results

To understand the seasonal evolution of the mean meridional circulation of the TBO in ENSO and normal years, composite analysis of stream function for strong minus weak monsoon years are carried out for both ENSO–TBO and normal TBO years separately.

3.1 Interannual variation of mean meridional circulation during ENSO–TBO years

Figure 1 shows the mass stream function for the composite of strong minus weak monsoon years, which include both ENSO and TBO years. The composite analyses were carried out from the previous monsoon to the following monsoon of a strong monsoon in order to understand the seasonal evolution of the circulation when the monsoon changes from weak to strong and then to weak.

During the previous summer (JJA-1) of a strong monsoon, the composite reveals two anomalous Hadley Cells in the tropics. The negative anomalous cell at the Southern Hemisphere (SH) indicates increased mass transport to the south and a positive cell in the Northern Hemisphere (NH) results in increased transport to the north. Thus,

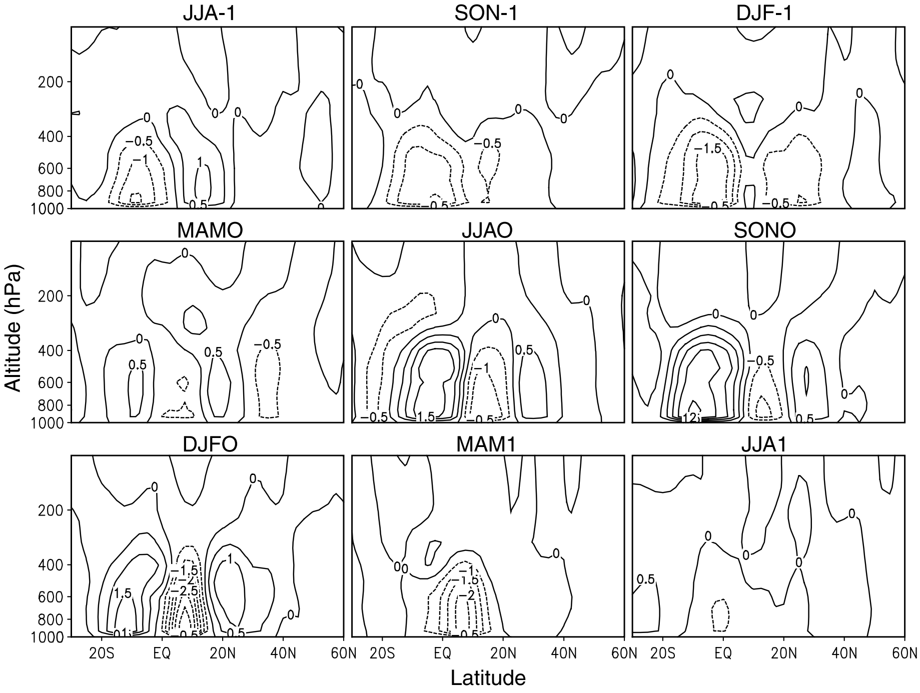

Fig. 1. Latitude-height cross section of the difference in zonal averaged stream function for strong and weak monsoon year composites, which include both TBO and ENSO onset years for seasons from previous summer (JJA-1) to the following summer (JJA1) of a reference monsoon (JJA0). (Contour intervals are $0.5 \times 10^{10}\,\mathrm{kg\,s^{-1}}$)

during JJA-1 both Hadley Cells are intensified. The mid-latitude cells are very weak. The NH Hadley Cell starts to weaken by the autumn (SON-1). The negative cell in the Northern Hemisphere extends across the entire NH tropics by the boreal winter (DJF-1). Throughout this time the SH Hadley Cell has a negative anomaly, indicating the presence of an intensified cell. During the premonsoon season (MAM0), the anomalous SH Hadley Cell is positive, representing the weakening of the cell. A negative cell is seen close to the Equator with a reduced vertical extent. The Ferrel Cell is active in the Northern Hemisphere.

Throughout the strong monsoon season (JJA0), the Hadley Cells are weak in both hemispheres. The anomalous mass transport at the upper levels is directed towards the Equator. The Ferrel Cells are also seen on both hemispheres, but are generally weak. After the strong monsoon season the Northern Hemisphere Hadley Cell anomaly reduces while it strengthens in the Southern Hemisphere. The Ferrel Cell is absent in the Southern Hemisphere. During the boreal winter (DJF0) two Equatorward mass transporting cells are seen in both hemispheres, however, the Southern Hemisphere cell is intense. The Ferrel Cell is seen in the Northern Hemisphere mid-latitudes. Throughout the preceding spring (MAM1), only the Northern Hemisphere anomalous negative cell is present indicating a weakened tropical circulation. During the year following a strong monsoon (JJA1), the negative cell at the Equator also weakens. Thus, during the next season the anomaly is very small indicating a situation not far from normal.

Thus, in the ENSO–TBO composites, both Hadley Cells are strong during the weak monsoon prior to the strong monsoon year and both become slightly weaker by JJA0, however, the stream function anomaly does not reverse in the next strong-to-weak cycle.

3.2 Interannual variation of mean meridional circulation during normal TBO years

Figure 2 represents the seasonal movement of anomalies of meridional circulation in normal TBO years from JJA-1 to JJA1. During the previous summer season (JJA-1), anomalous meridional cells are absent in the Southern Hemisphere tropics and are very weak in the Northern Hemi-

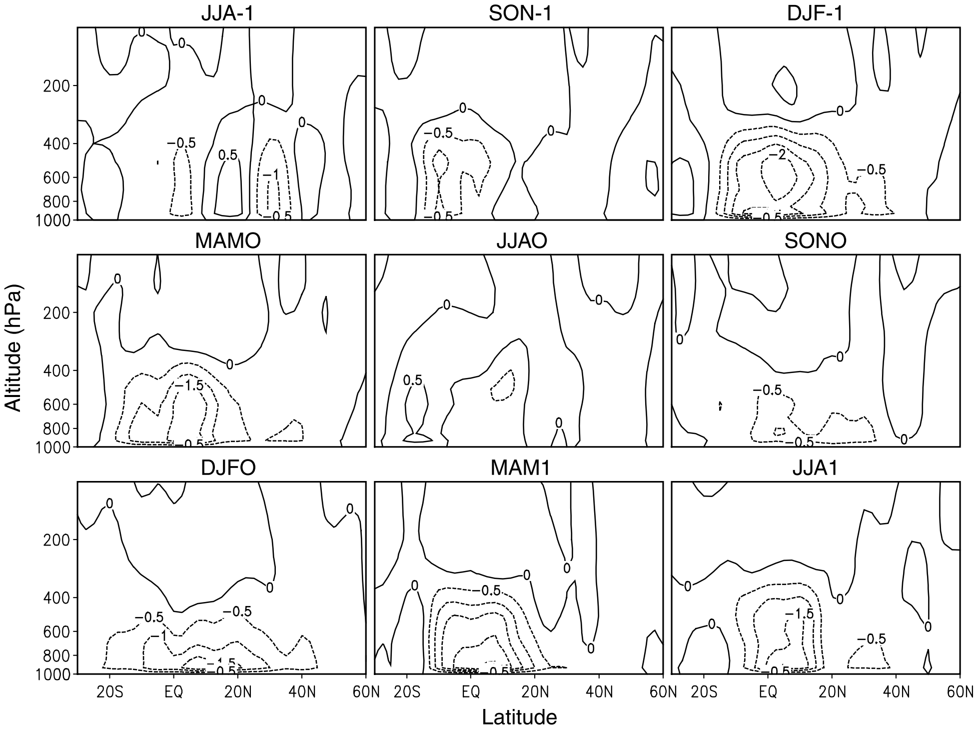

Fig. 2. Latitude-height cross section of the difference in zonal averaged stream function for strong and weak monsoon year composites of normal TBO years for seasons from previous summer (JJA-1) to the following summer (JJA1) of a reference monsoon (JJA0). (Contour intervals are $0.5 \times 10^{10}\,\mathrm{kg\,s^{-1}}$)

sphere. The NH Hadley Cell is weak close to the Equator and is active north of 10° N. The Ferrel Cell is also strong. The negative anomaly cell moves to the Southern Hemisphere by SON-1 and all other cells disappear. Thus, the SH Hadley Cell intensifies in the autumn season. Throughout the winter season (DJF-1), only one anomalous cell is present in the tropics from about 30° N to 20° S. This negative cell in the tropics implies that the Hadley Cell is active in the SH and weak in the NH tropics. This situation persists to the next season (MAM0).

With the onset of a strong Asian summer monsoon, the negative cell becomes very feeble and is confined to just south of the Equator, concentrated at a height of about 500 hPa. So the NH Hadley Cell is slightly weaker than normal. A positive anomalous cell is seen in the SH at about 20° S indicating decreased mass transport. The negative cell stretches from 5° S to 30° N by the autumn (SON0) with the vertical height reduced to less than 500 hPa. This negative cell indicates the weakening of the Hadley Cell across the entire NH tropics. The negative cell is seen from

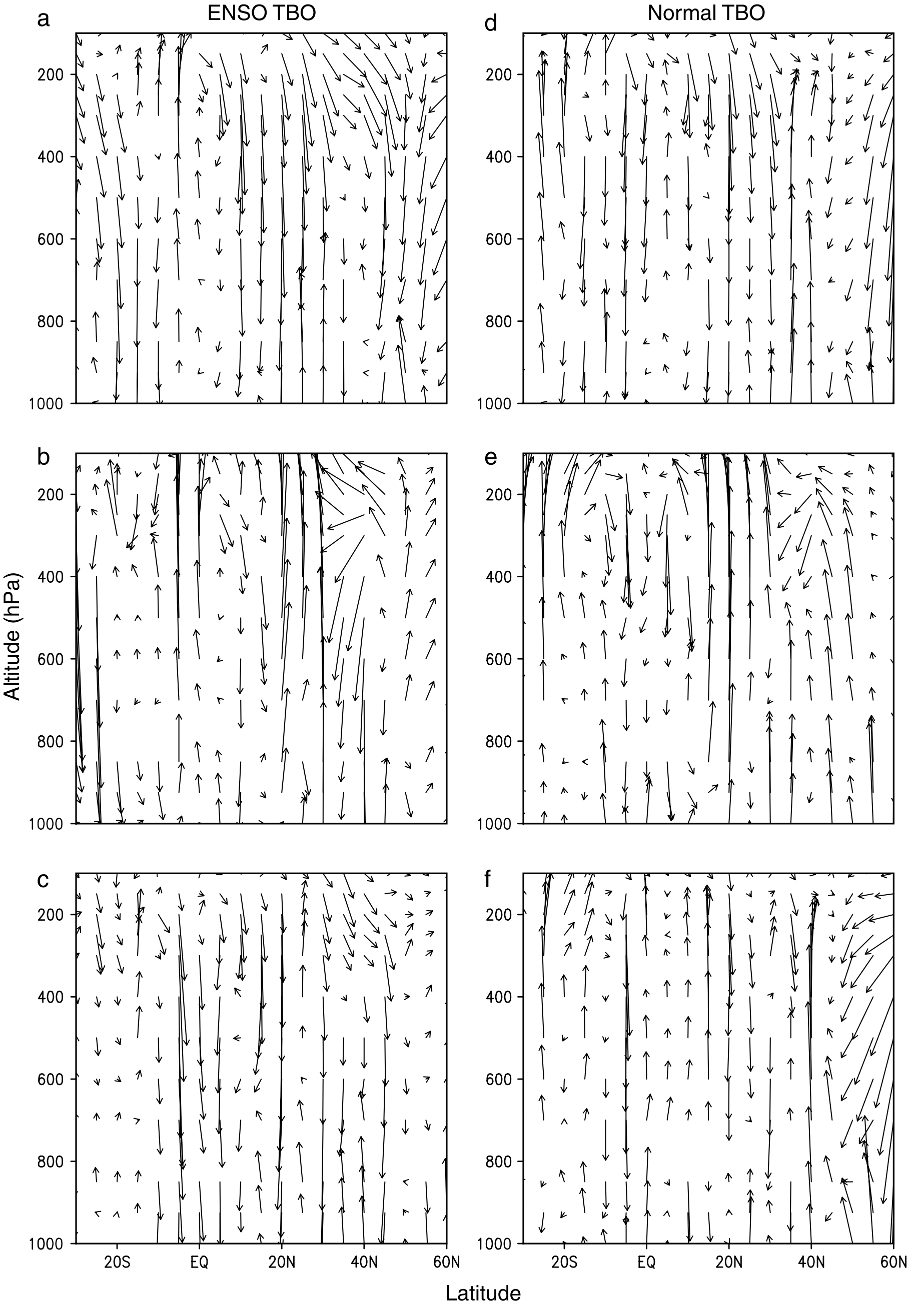

Fig. 3. Meridional cross section of (v, −w) averaged over 60° E–95° E for JJA-1, JJA0 and JJA1. Figures **a**, **b**, **c** for ENSO–TBO composites and **d**, **e** and **f** for normal TBO composites

20° S to 40° N by winter (DJF0) indicating a less active Hadley Cell in the NH and more active cell in the SH tropics up to 20° S. The negative cell is confined between 20° S and 20° N by MAM1, but extends vertically to over 400 hPa. Two negative stream function cells are seen in the NH during the following summer (JJA1) with one cell extending from the Equator to 20° N and another from 30° N to 40° N. Thus, the Hadley Cell in the NH is weakened, whereas the Ferrel Cell is intensified.

In the normal TBO years, the NH Hadley Cell close to the Equator is weaker during the weak-to-strong phase of the TBO cycle. Thus, anomalous cells are not reversing in this cycle of TBO. In the next cycle, from strong to weaker monsoon, the negative anomaly increases and extends more to the north. The reversal of anomalies is not evident in these cases.

3.3 Local Hadley circulation during the TBO cycle

The mean meridional circulation during the TBO years does not exhibit a clear reversal of anomalies from JJA-1 to JJA0 and then to JJA1. So, we concentrate on the TBO cycle of the local Hadley circulation over the 60° E–95° E area from JJA-1 to JJA1 for ENSO only and normal TBO years. Figure 3 shows the height-latitude cross-section of (v, −w) averaged over 60° E to 95° E representing local Hadley circulation. Figure 3(a–c) show the local Hadley circulation for JJA-1, JJA0 and JJA1 seasons for ENSO–TBO composites and Fig. 3(d–f) show the same, but for normal TBO years. The rest of the seasons are not shown but the results are presented below.

3.3.1 ENSO only years

During the JJA-1 season, the local meridional circulation has a narrow band of anomalous ascending motion just south of the Equator, and descending motion in the Northern Hemisphere tropics indicating weak circulation over this region (Fig. 3a). By the following autumn (SON-1), the entire tropics from 30° S to 20° N exhibit anomalous upward motion which continues into the boreal winter. By spring (MAM0), the upward branch of the anomalous local Hadley circulation is confined to 10° S–20° N. During the strong monsoon (JJA0), the upward motion anomaly is seen from 20° S–30° N, except in the region 10° N–15° N (Fig. 3b). Hence, ascending motion is seen over the monsoon region.

After the monsoon, the upward anomaly is confined to the area between 10° N–30° N and the downward anomaly south of this to 15° S. Throughout the following winter (DJF0), the entire Northern Hemisphere tropics have downward motion, and south of the Equator to 20° S upward motion is characteristic. By the following spring (MAM1) the entire tropics has downward motion. By the following monsoon, anomalous downward motion is seen over the 10° S–30° N area (Fig. 3c).

In brief, the local meridional circulation during the Indian summer monsoon exhibits a clear biennial cycle in the presence of ENSO with anomalous ascending motion in strong years and anomalous descending motion in the preceding and the subsequent years.

3.3.2 Normal (Non-ENSO) TBO years

The non-ENSO–TBO composites reveal downward motion in the entire tropics from 10° S to 30° N throughout the previous monsoon (JJA-1) with a small ascending motion at 5° N. The local meridional circulation therefore becomes weak favouring a below normal monsoon (see Fig. 3d). During the autumn season following the weak monsoon (SON-1), the local Hadley Cell has an upward branch located over the Northern Hemisphere and downward motion from the Equator to 15° S. By the boreal winter (DJF-1) the upward motion branch of the anomalous Hadley Cell is located between 10° N and 30° N and the downward anomaly is seen in the remaining part of the tropics. During the spring season (MAM0) before the strong monsoon, the anomalous local Hadley Circulation Cell has an upward branch in the entire Northern Hemisphere and a descending limit in the south between the Equator and 20° S. With the onset of the strong monsoon during JJA0, the local Hadley circulation exhibits downward motion in the Equatorial region from 5° S–10° N and upward motion on either side of this region and across the entire tropics (Fig. 3e). The local Hadley circulation is intensified over the Indian monsoon area by JJA0.

Throughout the following autumn season (SON0), the downward branch of the local Hadley circulation extends from 10° S to 15° N and the remaining area has upward motion. By the next winter (DJF0), the entire tropics have upward motion except a very small region in the Southern Hemisphere between 10° S and 5° S which persists until the following spring (MAM1). During the following monsoon (JJA1), the anomalous descending branch of the Hadley circulation is located over the Indian monsoon area. The Equatorial area between 10° S–15° N has an upward motion as seen from Fig. 3f.

It is thus evident that the local Hadley circulation over the summer monsoon area exhibits a biennial cycle with ascending motion during a strong monsoon and descending flow throughout the weak monsoon. In the normal TBO years, the Equatorial region and monsoon area have anomalies of opposite sign.

3.4 Temporal variation of local Hadley circulation

In the previous section it was noted that the local Hadley circulation represented by the vertical profiles of (v, −w) has a clear TBO tendency. In order to find whether this reversal of anomalies is preset in all strong and weak monsoons, time series of local Hadley circulation and monsoon rainfall have been analysed. Local Hadley circulation is represented by an index called the monsoon Hadley (MH) index as suggested by Goswami et al. (1999). The MH index is a circulation index defined as the meridional wind-shear anomaly (between 850 hPa and 200 hPa) averaged over the region 70° E–110° E, 10° N–30° N. The monsoon season standardised anomaly of the MH index is plotted along with the ISMR for the period 1950–2002 and is shown in Fig. 4. From Fig. 4 it is evident that both the MH index and ISMR show a biennial oscillation. The MH index and ISMR have a correlation of 0.663. The index remains positive (negative) during the strong (weak) TBO years indicating a close association between local meridional circulation and the TBO.

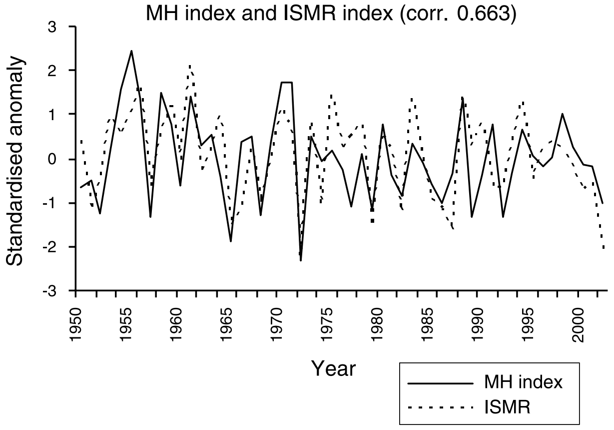

Fig. 4. Time series of standardised anomalies of MH index (continuous line) and ISMR (dotted line) from 1950–2002

4. Discussion

The present study reveals that in the case of ENSO–TBO composites, the Hadley circulation in both hemispheres becomes intense during the previous monsoon (JJA-1) of a strong monsoon year. The JJA-1 pattern of the ENSO–TBO year is similar to the pattern observed by Oort and Yienger (1996) for El Niño onset years in the Pacific Ocean. During the year of strong monsoon, both Hadley Cells are weak. The local meridional circulation follows a biennial cycle from JJA-1 to JJA0. However, in the following summer monsoon period (JJA1) of a strong monsoon year, the Hadley circulation does not become intense, as in the case of JJA-1, and it remains weak from JJA0 to JJA1.

According to Slingo and Annamalai (2000) the heating contrast between the Asian continent and the Indian Ocean basically drives the Hadley circulation. The development of the heating gradient that drives the monsoon circulation can be described by the seasonal cycle of mean meridional temperature, averaged between 500 hPa and 200 hPa over monsoon longitudes. Figure 5a shows the latitude-time profile of mean meridional circulation averaged over 60° E–95° E for ENSO–TBO composites. During the previous year, the positive gradient is located over the Equatorial region and a negative gradient is found over the land area. So, ascending motion is found along the Equator and the mean meridional circulation, as mentioned above, is obtained. The condition reverses in the following year, but after the strong monsoon the gradient does not reverse. Thus, the mean meridional circulation also does not reverse.

In the non-ENSO–TBO composites, the Equatorial region of the NH Hadley Cell is weaker than normal during JJA-1. The Southern Hemisphere counterpart becomes stronger after the monsoon. With the onset of a strong monsoon both the cells are weak, but the anomaly is very

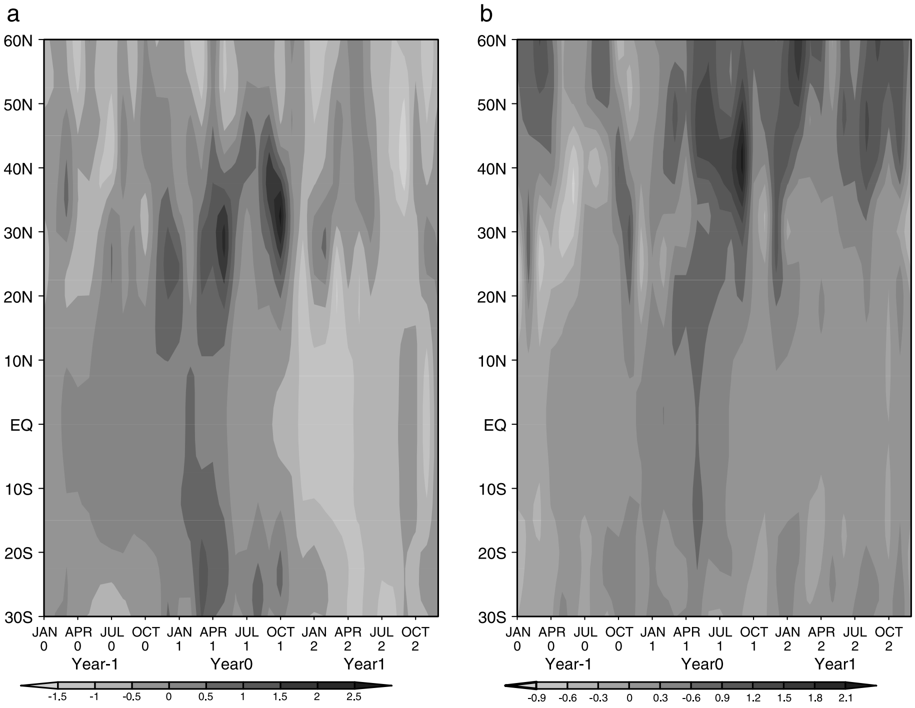

Fig. 5. Midtropospheric (averaged between 500 hPa and 200 hPa) temperature averaged over 60° E–95° E area from previous year to next year of reference monsoon for (**a**) ENSO–TBO years (**b**) non-ENSO–TBO years. 0 along with months denotes year-1, 1 for year 0 and 2 for year 1

weak. Thus, the NH Hadley Cell remains weak from JJA-1 to JJA0. The negative anomaly in the NH covers the entire NH tropics after the monsoon and persists to the next monsoon while no anomalous cell is seen in SH. Thus, from the strong monsoon to next monsoon, the NH Hadley Cell becomes weaker and weaker.

Figure 5b shows the latitude-time cross section of mid-tropospheric temperature for non ENSO–TBO composites. During the previous monsoon season, positive anomalies prevail over the tropics and negative anomalies are seen over 40° N. As the gradient becomes weaker, the cells in the Northern Hemisphere are also weak. During the strong monsoon (JJA0), a positive temperature centre is located around 40° N and positive anomalies also prevail over the ocean. So, the meridional cell becomes weak. This positive pattern continues to prevail to the next year monsoon. Thus, the meridional circulation does not reverse. Li and Zhang (2002) showed that, the role of meridional temperature gradient is very much limited in terms of monsoon variability at the TBO scale. The present study also shows that in the absence of ENSO, the meridional temperature gradient and the meridional circulation driven by this temperature gradient also has no biennial cycle.

The local Hadley circulation shows the TBO cycle over the monsoon area in both composites. The regions of negative and positive anomalies of vertical velocity at 500 hPa (not shown in figures) coincide well with the upward and downward anomalies of local Hadley circulations, respectively. During the previous weak monsoon (JJA-1) year, a downward anomaly is seen over the summer monsoon latitudes. In the ENSO–TBO years the downward anomaly extends to the Equator and an upward anomaly exists between the Equator and 10° N. During the strong monsoon season, the Equator to 10° N area has a downward motion in the normal TBO composite while the 10° N–15° N area has downward motion in the ENSO–TBO case. In both cases upward motion is seen over the monsoon region during the strong monsoon. During JJA1 the entire Northern Hemisphere has downward motion for ENSO–TBO cases, while the 0° N–15° N region has upward motion in the normal TBO case.

This local Hadley circulation pattern agrees closely with the convection and SST patterns of ENSO–TBO and normal TBO composites (Pillai and Mohankumar, 2007). Both these results are in agreement with Slingo and Annamalai (2000), who state that the changes in the local Hadley circulation may be driven by the changes in convection over the maritime continent and over the Equatorial Indian Ocean, which itself is the modulator of the Walker circulation. Thus, in the context of TBO, SST and convection induced circulation has a prominent role.

5. Conclusion

The TBO cycle of mean meridional circulation and local Hadley circulation has been studied using zonally averaged stream function and vertical profiles of v and −w averaged over 60° E to 95° E. The mean meridional circulation exhibits the TBO cycle in the weak-to-strong phase of the monsoon for ENSO–TBO years, but is absent in the next strong-to-weak cycle. In the normal TBO years the NH Hadley Cell always remains weak. The mid-latitude temperature pattern which is the cause of the reversal in mean meridional circulation occurs in conjunction with anomalous stream function patterns. The local Hadley circulation exhibits a clear biennial cycle over the Indian summer monsoon area in the presence and absence of ENSO. In ENSO–TBO years, upward (downward) motion exists in the entire NH tropics during a strong (weak) monsoon. In the case of normal TBO years, this upward (downward) anomaly during a strong (weak) monsoon is seen over the Indian monsoon area only and the opposite anomaly is seen over the Equatorial region. This local Hadley circulation pattern is in agreement with the convection pattern over the maritime continent and Equatorial Indian Ocean and SST in the Equatorial Indian Ocean. From this study it can be concluded that the local Hadley circulation has a significant role in the TBO cycle along with SST, convection and zonal circulation, whereas the mean meridional circulation is insignificant in this cyclic event.

References

Chang CP, Li T (2000) A theory for the tropical tropospheric biennial oscillation. J Atmos Sci 57: 2209–2224

Dima IM, Wallace JM (2003) On the seasonality of the Hadley cell. J Atmos Sci 60: 1522–1527

Goswami BN, Krishnamurthi V, Annamalai H (1999) A broad scale circulation index for the interannual variability of Indian summer monsoon. Quart J Roy Meteor Soc 125: 611–633

Holton JR (1992) An introduction to dynamic meteorology, 3rd edn. USA: Academic Press, 511 pp

Hou AY, Lindzen RS (1992) The influence of the concentrated heating on the Hadley circulation. J Atmos Sci 49: 1233–1241

Ju J, Slingo J (1995) The Asian summer monsoon and the ENSO. Quart J Roy Meteor Soc 121: 1133–1168

Kalnay E, et al (1996) The NCEP/NCAR reanalysis project. Bull Amer Meteor Soc 77: 437–471

Li T, Tham CW, Chang CP (2001) A coupled air–sea-monsoon oscillator for the tropospheric biennial oscillation. J Climate 14: 752–764

Lindzen RS, Hou AY (1988) Hadley circulation for zonally averaged heating centered off the equator. J Atmos Sci 45: 2417–2427

Lorenz E (1967) The nature and theory of the general circulation of the atmosphere. Geneva: WMO publ., No. 218, FP. 115, 161 pp

Meehl GA (1997) The south Asian monsoon and the tropospheric biennial oscillation. J Climate 10: 1921–1943

Meehl GA, Arblaster JM (2001) The tropospheric biennial oscillation and Indian monsoon rainfall. Geophys Res Lett 28: 1731–1734

Meehl GA, Arblaster JM (2002a) The tropospheric biennial oscillation and Asian-Australian monsoon rainfall. J Climate 15: 722–744

Meehl GA, Arblaster JM (2002b) Indian monsoon GCM experiments testing tropospheric biennial oscillation transition conditions. J Climate 15: 923–944

Meehl GA, Arblaster JM, Loschingg J (2003) Coupled-ocean-atmosphere dynamical processes in tropical Indian and Pacific oceans and the TBO. J Climate 16: 2138–2158

Newll RE, Kidson JW, Vincent DG, Boer GJ (1972) The general circulation of the tropical atmosphere, vol. 1. Cambridge: MIT Press, 258 pp

Oort AH, Rasmusson EM (1970) On the annual variation of monthly mean meridional circulation. J Climate 13: 3969–3993

Oort AH, Yienger JJ (1996) Observed interannual variability in Hadley circulation and its connection to ENSO. J Climate 9: 2751–2767

Parthasarathy B, Munot AA, Kothwalae DR (1994) All India monthly and seasonal rainfall series – 1871–1993. Theor Appl Climatol 49: 217–224

Piexoto JP, Oort AH (1992) Physics of climate. New York: American Institute of Physics, 520 pp

Pillai PA, Mohankumar K (2007) Tropospheric biennial oscillation of Indian summer monsoon with and without El Niño-Southern oscillation. Int J Climatol (in press)

Slingo JM, Annamalai H (2000) 1997: The El Niño of the century and the response of the Indian summer monsoon. Mon Wea Rev 128: 1778–1797

Soman MK, Slingo JM (1997) Sensitivity of the Asian summer monsoon to aspects of the sea surface temperature anomalies in the tropical Pacific Ocean. Quart J Roy Meteor Soc 123: 309–336

Trenberth KE, Stepaniak DP, Caron JM (2000) The global monsoon as seen through the divergent atmospheric circulation. J Climate 13: 3969–3993

Wang C (2002) Atmospheric circulation cells associated with the El Niño-Southern oscillation. J Climate 15: 399–415

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