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DIAGNOSTIC ANALYSIS OF MEAN MERIDIONAL CIRCULATION ANOMALY IN LOW LATITUDES IN RELATION TO ZONAL MEAN SST ANOMALY

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ABSTRACT: The mass stream function of zonal mean meridional circulation is calculated in terms of NCEP/NCAR monthly meridional wind speed and vertical velocity, and the climatic and anomalous features of zonal mean SST and meridional circulation are investigated. Results show that (1) a joint ascending branch of Northern and Southern Hadley circulation is on the side of the summer hemisphere near the equator ,being well consistent with the extremum of $\left[\overline{SST}\right]$,and a strong descending by the winter-hemispheric side.(2)El Niño-related $[SST]'$ in low latitudes is an important outer-forcing source for anomaly meridional circulation, which is affected by seasonal variation of basic airflow and $\left[\overline{SST}\right]$, and interannual and interdecadal changes of $[SST]'$.

Key words: meridional circulation; sea surface temperature; anomalous relationship

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1 INTRODUCTION

Mean Meridional Circulation is one that is active on meridional planes constituted by v and ω averaged over the entire meridional circle. As early as in the middle phase of the 19th century, Ferrel presented the basis structure of MMC, which consisted of three circles of circulation on the meridional surface[1].

In his theoretic study conducted in the 1950's, Ye et al. pointed out that inhomogeneous heating was one of the factors for the formation and maintenance of the 3-circle circulation on the plane[2]. With the progression of research on air-sea interactions, especially on climatic effects by tropical oceans in the 1960's, significant gains have been obtained in the study of inhomogeneous heating[3]. Green[4] and Bjerknes[5] once made diagnostic analysis of effects of sea surface temperature anomalies for the El Niño episode on the general circulation and found that positive SST anomalies were increasing the Hadley cell over a wide longitude span. In the meantime, Wu[6] simulated the anomalies of general circulation for the 1982 ~ 1983 El Niño episode, with the result showing that persistent positive SST anomalies over the equatorial eastern Pacific could form the Hadley cell in the winter hemisphere and strengthen the Ferrel cell. Wang[7] also made some analysis of MMC in similar experiments to show that during the same episode the sea surface temperature anomalies (SST') was forced to produce a complete anomalous meridional circulation (MMC'); its ascending branch is situated on the austral side of the equator, being consistent with the latitude where positive SST' center lay for tropical central and eastern Pacific; its descending branch appearing over the boreal tropics where the MMC' intensity varied with that of the El Niño event and the season.

From the above result of diagnostic analysis and numerical experiments, we know that it may

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be possible for planetary scale systems such as the Hadley cell to have significant anomalies when they are subjected to serious external forcing anomalies. The conclusion needs justification by direct diagnosis using real data. It was based on such consideration that the current work attempted to use monthly mean data generated from 40-year reanalyzed items of atmospheric data by NCEP/NCAR[8, 9] in calculating the MMC. Diagnostic analysis is employed to study the climatology and anomaly of (1) SST and (2) MMC in the middle and low latitudes. The work is successful in surfacing the causes for anomalous mean meridional circulation in the middle and low latitudes.

2 DATA AND PRE-TREATMENT

2.1 *Data*

(1) Global monthly mean meridional wind speed (v) and vertical velocity ($w = \mathrm{d}p/\mathrm{d}t$), which covers a period of 492 months from January 1958 to December 1998 and distributes at 17 hectopascal layers of 1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10. The interval of the mesh holding them is $\Delta l \times \Delta j = 2.5^{\circ} \times 2.5^{\circ}$. [9] is the data source.

(2) Global sea surface temperature data, which come from the same source as (1).

2.2 *Pre-treatment*

Generally, a set of atmospheric elements field of v and ω can be expressed as

$$\begin{aligned} & f(i, j, k; t_y, t_m) \\ & i = 1 \sim 144,\ j = 0 \sim 72,\ k = 1 \sim 17, \\ & t_y = 1 \sim 41\text{year},\ t_m = 1 \sim 12\text{month} \end{aligned} \tag{1}$$

where i, j and k are subscripts of the longitude l_i, latitude j_j and isobaric layer P_k on which the gridpoint is; t_y and t_m are the sequence of year and month, respectively.

(1) The spatial field is decomposed following the circulation decomposition principle of Lorenz[1]:

$$f(i, j, k; t_y, t_m) = [f](j, k; t_y, t_m) + f^*(i, j, k; t_y, t_m) \tag{2}$$

in which

$$[f](j, k; t_y, t_m) = \sum_{i=1}^{144} f(i, j, k; t_y, t_m)/144 \tag{3}$$

$$f^*(i, j, k; t_y, t_m) = f(i, j, k; t_y, t_m) - [f](j, k; t_y, t_m) \tag{4}$$

in which [f] and [f^*] are the mean of f over the entire circle of latitude and deviation of f from [f]. On the basis of it, 3-dimensional element series of v and ω can be decomposed to yield results in a form identical to Eq.(4).

$$\begin{pmatrix} [v] \\ [w] \end{pmatrix}(j, k; t_y, t_m) = \sum_{i=1}^{144} \begin{pmatrix} v \\ w \end{pmatrix}(i, j, k; t_y, t_m)/144 \tag{5}$$

It is obvious that they are the time sequences for element fields on the meridional plane. On the other hand, for any 2-dimensional element fields, such as that for SST, a similar expression can be determined for the decomposition:

$$[\mathrm{SST}](j;t_y,t_m)=\sum_{i=1}^{144}\mathrm{SST}(i,j;t_y,t_m)/144 \tag{6}$$

It is obviously that it is the time series of meridional distribution of meteorological elements.

(2) Decomposition of time domains: Following Lorenz's circulation decomposition principle[1], $[v]$ and $[w]$ as given in Eq.(5) can be decomposed for the time domains shown below.

$$\begin{pmatrix}[v]\\ [w]\end{pmatrix}(j,k;t_y,t_m)=\begin{pmatrix}[\bar{v}]\\ [\bar{w}]\end{pmatrix}(j,k;t_m)+\begin{pmatrix}[v]'\\ [w]'\end{pmatrix}(j,k;t_y,t_m) \tag{7}$$

where

$$\begin{pmatrix}[\bar{v}]\\ [\bar{w}]\end{pmatrix}(j,k;t_m)=\sum_{t_y=1}^{41}\begin{pmatrix}[v]\\ [w]\end{pmatrix}(j,k;t_y,t_m)/41 \tag{8}$$

which is multi-year mean (climatological) fields of $[v]$ and $[w]$ on the meridional plane in the t_m month while

$$\begin{pmatrix}[v]'\\ [w]'\end{pmatrix}(j,k;t_y,t_m)=\begin{pmatrix}[v]\\ [w]\end{pmatrix}(j,k;t_y,t_m)-\begin{pmatrix}[\bar{v}]\\ [\bar{w}]\end{pmatrix}(j,k;t_m) \tag{9}$$

which are respectively anomalous fields of $[v]$ and $[w]$ on the meridional plane in the t_m month of t_y year.

Similarly, time-domain decomposition can be done for the $[\mathrm{SST}]$ in Eq.(6):

$$[\mathrm{SST}](j;t_y,t_m)=[\overline{\mathrm{SST}}](j;t_m)+[\mathrm{SST}]'(j;t_y,t_m) \tag{10}$$

where

$$[\overline{\mathrm{SST}}](j;t_m)=\sum_{t_y=1}^{41}[\mathrm{SST}](j;t_y,t_m)/41 \tag{11}$$

It is the meridional profile of $[\mathrm{SST}]$ in terms of multi-year mean (climatological) distribution in t_m months while

$$[\mathrm{SST}]'(j;t_y,t_m)=[\mathrm{SST}](j;t_y,t_m)-[\overline{\mathrm{SST}}](j;t_m) \tag{12}$$

which is the anomalous profile of $[\mathrm{SST}]$ in the t_m month of t_y year.

We have now prepared basic data in Eq.(8), Eq.(9), Eq.(11) and Eq.(12) for performance of the current study.

3 METHODS

The mass stream function calculation method is used to determine mean meridional circulation.

For illustrative and quantitative presentation of the MMC on the meridional plane (j, p) for the t_m month of t_y year, Palmen et al[10]. and Vuorola et al[11]. in the 1960's suggested a method describing the mass stream function (y) for the MMC, which was also given based on the distribution of [v] in boreal winter and summer.

Following Lorenz's continuity equation averaged over the latitude circle in a spherical-pressure coordinate system

$$\frac{\partial}{a\partial j}\left([v]\cos j\right)+\frac{\partial}{\partial p}\left([w]\cos j\right)=0 \tag{13}$$

the total mass stream function y can be defined as

$$A=-2pa^2[w]\cos j / g=\frac{\partial y}{\partial j}$$

$$B=2pa[v]\cos j / g=\frac{\partial y}{\partial p} \tag{14}$$

in which A is the mass transported upward over a unit radian on the meridional plane and B is the mass transported northward over iso-latitudes for unit pressure difference on the meridional plane. As they meet the Euler condition of

$$\frac{\partial A}{\partial p}-\frac{\partial B}{\partial j}=0 \tag{15}$$

y is the analytical function of j and P, whose total differentiation is

$$\mathrm{d}y=A\mathrm{d}j+B\mathrm{d}p \tag{16}$$

with the integration of y independent with track..

Referring to [12], we give a y algorithm of deriving A and B and then calculating MMC with the aid of [v] and [ω]on the meridional plane. It is made up of the following components.

(1) Monthly mean [v] and [ω] are determined for all gridpoints on the meridional plane using monthly mean v and ω. Then, Eq.(14) is used to obtain the values of A and B at every internal points of the mesh for the meridional plane (Fig.1a). In Fig.1, the horizontal grid intervals are 2.5° and the vertical ones are shown in Tab.1.

(2) y =0 at the boundary j=0, j=72 (corresponding to the points of South and North Poles) and the point k=0, k=18 (corresponding to P_T =0 hPa and a lower boundary of virtual atmosphere P_d =1050 hPa).

(3) Through iteration, the y values are determined for all internal gridpoints:

$$y^{t+1}_{j,k}=0.25\left(y^{t}_{j+1,k+1}+y^{t}_{j-1,k+1}+y^{t}_{j+1,k-1}+y^{t}_{j-1,k-1}\right)+G_{j,k}\left([w],[v],j,p\right) \tag{17}$$

where the forcing term $G_{j,k}$ is determined with Points A and B in Fig.1b:

$$\begin{aligned}G_{j,k}=0.0625\{\Delta j\{[(2A_2+A_5+A_6)-(2A_4+A_7+A_8)]\\ -[\Delta p_l(2B_0+2B_3+B_2+B_4+B_6+B_7)\\ -\Delta p_h(2B_0+2B_1+B_2+B_4+B_5+B_8)]]\}\end{aligned} \tag{18}$$

Tab.1 The thickness of K' layer pressure

K'	$1\frac{1}{2}$	$2\frac{1}{2}$	$3\frac{1}{2}$	$4\frac{1}{2}$	$5\frac{1}{2}$	$6\frac{1}{2}$	$7\frac{1}{2}$	$8\frac{1}{2}$	$9\frac{1}{2}$
$\Delta P_{K'}$ /hPa	10	10	20	20	30	50	50	50	50
K'	$10\frac{1}{2}$	$11\frac{1}{2}$	$12\frac{1}{2}$	$13\frac{1}{2}$	$14\frac{1}{2}$	$15\frac{1}{2}$	$16\frac{1}{2}$	$17\frac{1}{2}$	
$\Delta P_{K'}$ / hPa	100	100	100	100	150	75	75	50	

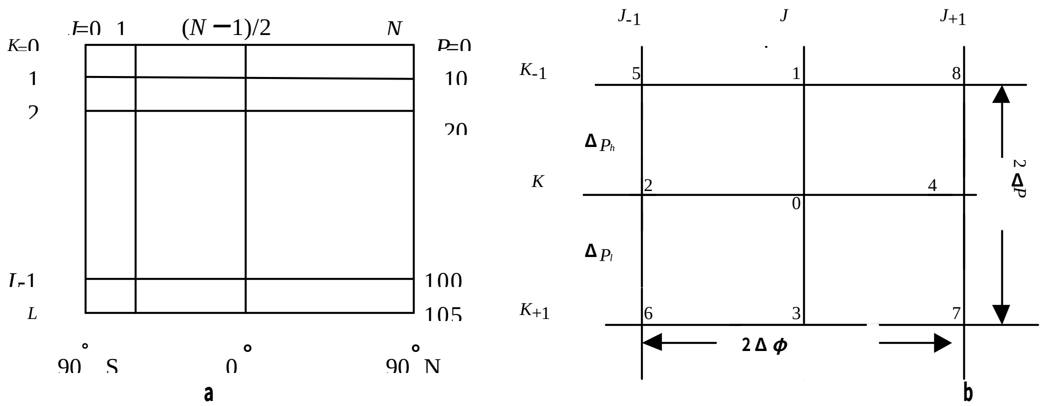

Fig.1 The grid-mesh for calculating mass stream function (ψ) on meridional plane (a) and its details(b) from Ref.[12].

4 RESULTS OF NUMERICAL EXPERIMENTS AND DISCUSSION

The zonal mean sea surface temperature means the [SST] in Eq.(11). It can be decomposed to a climatological state $\left[\overline{SST}\right]$ and anomalous state $[SST]'$. Next are the main characteristics of the two components.

4.1 *Climatological characteristics of zonally mean SST*

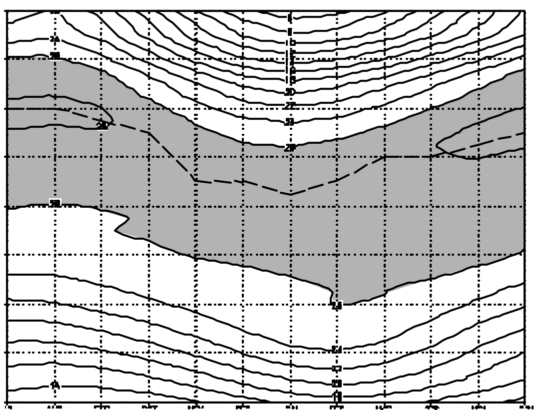

Fig.2 The latitude-time section for $\left[\overline{SST}\right]$, in which the thick dashed line is the maximum of $\left[\overline{SST}\right]$.

Fig.2 is a latitude-time profile of $\left[\overline{SST}\right]$. It is seen that the maximum of $\left[\overline{SST}\right]$, which can be interpreted as the mean position of thermal equator, is on the side of the Northern Hemisphere and changes with season. It is near 20°N in July and August but 5°N from November to February. There is a relatively homogeneous zone of $\left[\overline{SST}\right]$ with a width of 40° in the tropical area, which oscillates north-south with season. There is significant increase of $\left|\partial\left[\overline{SST}\right]/\partial\varphi\right|$ outside it.

4.2 *Climatological characteristics of zonally mean SST*

Fig.3 is a latitude-time profile of $[SST]'$. The most significant point in the figure is the alternative appearance of cold and warm center with time along the equator, which correspond to the El Niño and La Niña episodes as defined in [13]. The El Niño episodes for 1982 ~ 1983, 1986 ~ 1987 and 1998 are among the strongest in terms of duration, latitudes and anomalous values. It is then thought that the El Niño event is the most important cause for SST anomalies.

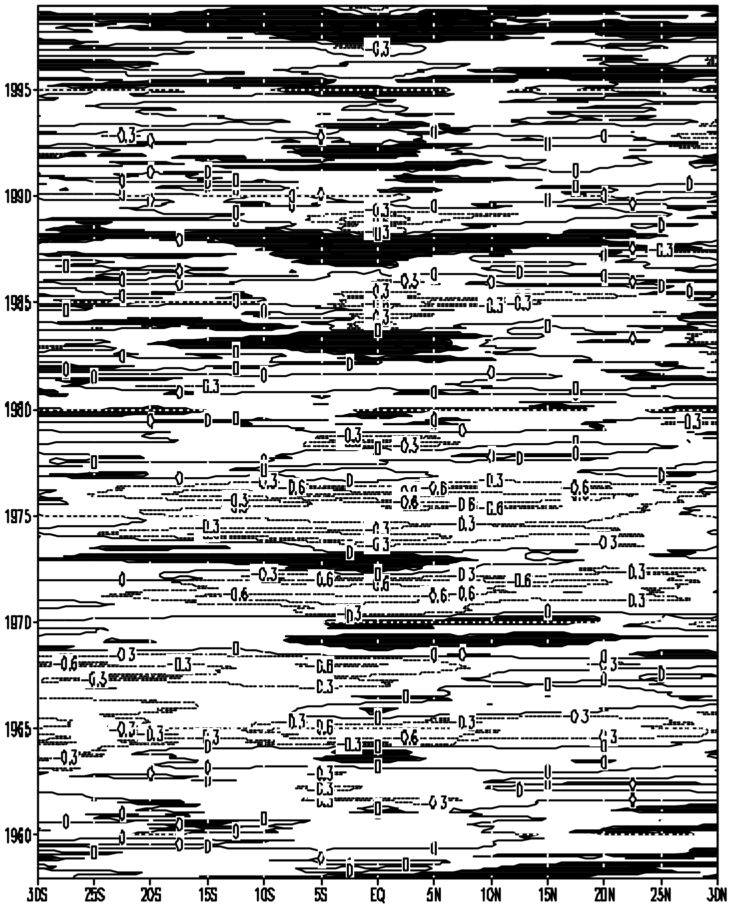

Fig.3 The latitude-time profile for $[SST]'$, in which the shaded area is where it is ≥0.1°C.

Fig.4 gives a latitude-time composite profile of $[SST]'$ for all El Niño events. It is seen that the maximum $[SST]'$ is stable near the equator and changes little with the season. Its intensity is an exception, which changes significantly with the season that is strongest in spring and autumn but weakest in prime summer.

5 CLIMATOLOGICAL ANALYSIS OF ZONALLY MEAN MERIDIONAL CIRCULATION

With the circulation decomposition principle of Lorenz[1], we decomposed MMC expressed by y into climatological state of $\overline{y}(j,k;t_m)$ and anomalous one of $y'(j,k;t_y,t_m)$.

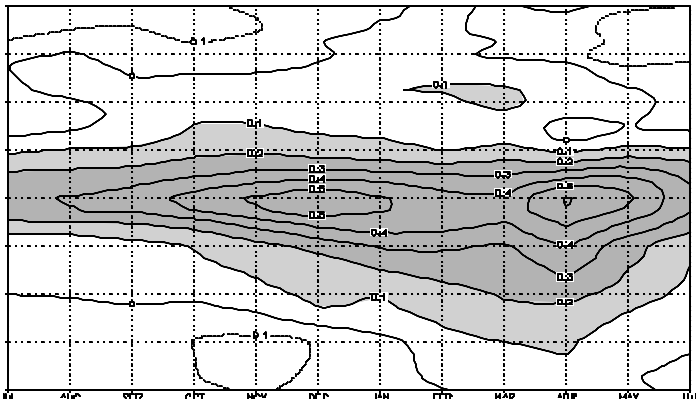

Fig.4 The latitude-time composite profile for [SST]′ in the El Niño events, in which the shaded area is where it is ≥0.1°C.

$$y\left(j,k;t_y,t_m\right)=\overline{y}\left(j,k;t_m\right)+y'\left(j,k;t_y,t_m\right) \tag{19}$$

where the climatological state is

$$\overline{y}\left(j,k;t_m\right)=\sum_{t_y=1}^{41}y\left(j,k;t_y,t_m\right)/41 \tag{20}$$

For the zonally averaged climatological state ($\overline{\text{MMC}}$), the mid- and lower- latitudes are governed by regular Hadley cell and Ferrel cell, known by the mass stream function for monthly climatological mean meridional circulation in individual seasons (Fig.5). They are featured by:

(1) It is known from the distribution of positive (negative) thermal circulation (as expressed by positive (negative) stream function) that a common ascending airflow is on the side of summer hemisphere for the Hadley cell in both Southern and Northern Hemispheres, with location consistent with the thermal equator and oscillating north-south in annual singly periods and intensity oscillating with the season in annual doubly periods; a strong descending branch of the Hadley cell is on the side of winter hemisphere. The Ferrel cells for both the Northern and Southern Hemispheres are located in middle latitudes, which move towards low latitudes in winter but towards high latitudes in summer.

(2) There is some difference in the seasonal change of the Hadley cell for both the hemispheres. It is the strongest in the austral winter (July) with central value of 188 units, which is stronger than that in the boreal winter (January) with corresponding intensity of 175 units; the Hadley cell is an obvious presence in the austral summer while it does not have any enclosed iso-$\overline{y}$ lines in the corresponding season (July).

(3) There is also some difference in the seasonal change of the Ferrel cell for both the hemispheres. It stays around 40 units throughout the year in the Southern Hemisphere while being strong in winter but weak in summer in the Northern Hemisphere.

It is then clear that there is significant hemispheric difference of $\overline{\text{MMC}}$ in seasonal variation of the Hadley and Ferrel cells and the seasonal difference is smaller for the two cells in the Southern Hemisphere than in the Northern Hemisphere.

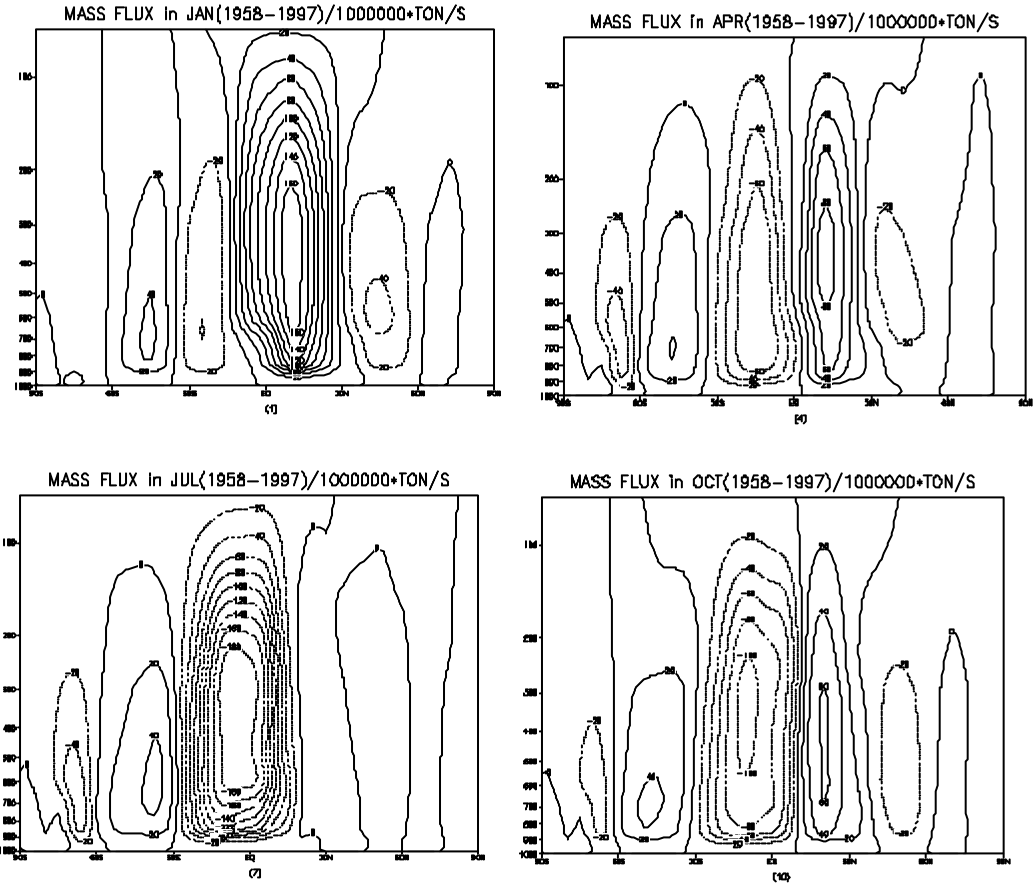

Fig. 5 Monthly mean mass stream function in January (top left), April (top right), July (bottom left) and October(bottom right).

6 ANALYSIS OF INTERANNUAL ANOMALIES OF ZONAL MEAN MERIDIONAL (MMC')

Following Section 3, $[SST]'$ is mainly connected with the El Niño event. During the course, an additional positive thermal forcing (with stable location, low intensity in summer but high intensity in autumn) is superimposed to $[\overline{SST}]$ so that the climatological state in which low-latitude thermal forcing is active will be changed to cause anomalies in MMC. Based on the understanding, focus is placed mainly on the relationship between the El Niño event and MMC'.

From the monthly MMC' composite chart for individual months during the El Niño episode (Fig.6), we know that anomalous meridional circulation is of the following characteristics:

(1) There is an anomalous ascending airflow, strongest in intensity, centering near the equator. As shown in comparison, it corresponds to the strongest heating area in Fig.4 and changes with the season.

(2) Anomalous meridional circulation occurs near the equator, with the most significant change in its morphology. The circulation has only one cell in April (Fig.6b) and two weak cells in January, July and October (Fig.6a, c, d).

It is then clear that anomalous meridional circulation is mainly resulted from the forcing of equatorial $[SST]'$ on the equator, with specific morphology subject to seasonal changes in basic airflow (Fig.5) and in $[\overline{SST}]$ and $[SST]'$ for the El Niño episode (Figs.2 & 4), leading to large difference from season to season.

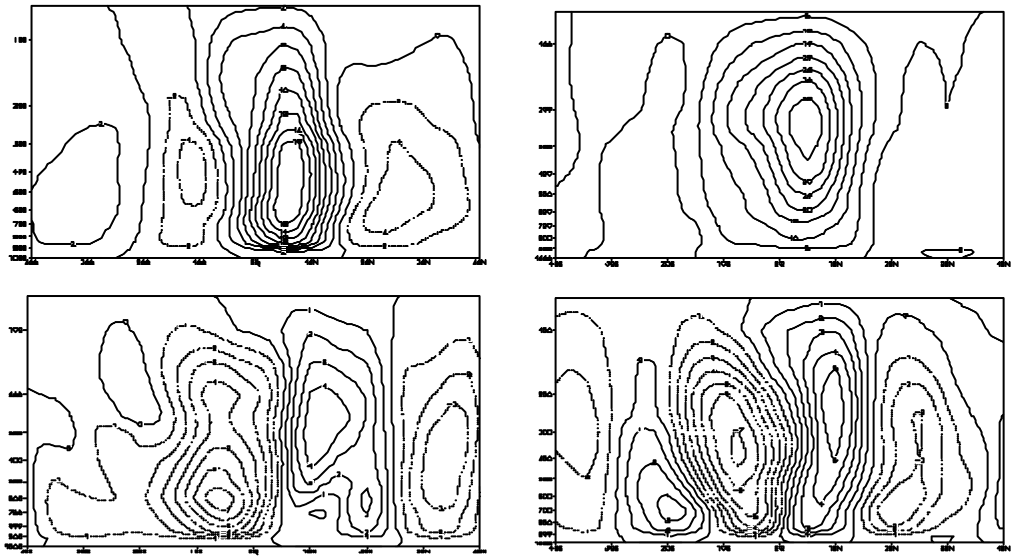

Fig.6 The composite diagram of MMC′ in El Nino events in January (top left), April (top right), July(bottom left) and October(bottom right). Unit: 10^6 ton/s, intervals: 2,5,1,1 unit respectively.

For confirmation, we apply statistical study to the Hadley cell in the monthly figures of y' over 11 El Niño episodes in the 41 years of interest. The results show significant seasonal and inter-annual variations of the Hadley cell intensity, which is also subject to the ENSO intensity. It is a finding consistent with the simulation and experimental results in [7].

7 CONCLUDING REMARKS

a. The center of maximum $[\overline{SST}]$ belt is situated on the side of Northern Hemisphere all the year round. It is then known that the hemisphere is a warm center from the point of thermal forcing of lower boundary.

b. For the El Niño event, the maximum of $[SST]'$ is stable around the equator. With large seasonal changes in intensity (being strongest in spring but weakest in prime summer), it changes little in location with the season. It is possible to view it as an anomalous external forcing source that is marked with stationary location.

c. The common branch of ascending airflow for both Northern and Southern Hemispheres is on the side of the summer hemisphere near the equator, corresponding to where the maximum $[\overline{SST}]$ is; a strong branch of descending airflow is on the side of the winter hemisphere.

d. For the seasonal change of the Hadley and Ferrel circulation cells, the Southern Hemisphere is weaker than the Northern Hemisphere, resulting in smaller seasonal change in the low and middle latitudes of the former than those of the latter.

e. The low and middle latitude $[SST]'$ during the El Niño episode is an important external forcing source generated by anomalous meridional circulation, with its influence much subjected to basic airflow and seasonal changes in $\left[\overline{SST}\right]$ and in-episode $\left[SST\right]'$ and associated inter-annual difference.

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