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# Interactions between the Northern and Southern Hemispheric Atmospheres and the Essence of Monsoon*

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Based on the theoretical consideration and the statistical analysis of NCEP / NCAR reanalyses data, it is clear that the causes of seasonal variations of the atmospheric general circulation, the cross–equatorial air flows and the interactions between the Northern and Southern Hemispheric atmospheres are primarily due to the seasonal variations of incoming solar radiation. The primary driving forcing of the tropical monsoon, characterized by the cross–equatorial meridional wind component, is the planetary thermal convection, and the semi–permanent planetary waves due to the seasonal variation of the differences between the thermal characters of earth surface (ocean and continent) are the secondary forcing. The calculation results show that the efficiency ratio of the first to second forces, on the average, is 2:1. The two forces are in phase in the eastern hemisphere, resulting in pronounced Asian–Australian monsoon prevails, but out of phase in the western hemisphere, resulting in weak seasonal variations and monsoon over the tropical Atlantic and the tropical eastern Pacific. Besides, the semi–permanent planetary waves in the middle–high latitudinal zones owing to the seasonal variations of thermal contrast of land and ocean and the incoming solar radiation are favourable for the Asian–Australian monsoon to extend to the extratropical regions. At high altitudes, the air flows compensating the low–level monsoons also undergo significant seasonal variations. Thus there is a clear picture of globally three–dimensional general monsoon system.

**Key words**: planetary thermal convection; driving force; cross–equatorial flow; seasonal variation; monsoon.

## 1. INTRODUCTION

In the 1930s, Li's studies (1936a) clearly showed that there exists interaction between the Northern Hemisphere (NH) and the Southern Hemisphere (SH). He found that strong cold wave occurring over East Asia in boreal winter can cross the equator and intrudes into the SH and arrives at 12°28′S of the northern Australia; and that in Australia the cold–outburst in Southern winter may cause the growth and development of hurricane over the western Pacific Ocean in the NH (Li, 1936b). It must be pointed out that at that time weather observational

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stations were very sparse from the western Pacific Ocean through the tropics of the Indian Ocean, but Li's analyses were very strict and his conclusions from some cases were incontestable. However, researchers in that period were still confined to the geographical climatology concept of the " doldrums" , and thus they could not believe the existence of large–scale and strong cross–equatorial flow (CEF). With the increase of weather observational stations, especially the establishment of upper–wind observational stations and the image data weather satellites could provide, Li's findings have been entirely confirmed. Even from climatology, at low–levels, the sources of the South Asian monsoon and part of the East Asian monsoon just come from the CEF from the tropics of the Indian Ocean in the SH, and another source of the East Asian monsoon is simply the CEF from Sumatra to Pulau Sulawesi in Indonesia; at upper–levels, there are the CEFs opposite to the above CEFs in direction. These have been elementary knowledge in meteorology by now (Tao and Chen, 1987; Krishnamurti, 1996; Zeng et al., 1994; Ding, 1994; Lau et al., 2000). However, how large and strong are the scale and strength of the CEFs and interactions between the NH and the SH? What are the relations between them and seasonal variation of the global general circulation? Or, how is the status of monsoon in the globally general atmosphere circulation? Is the primary cause of monsoon the seasonal difference of thermal contrast of continent and ocean? Or, is it mainly caused by the seasonal variation of solar radiation from south to north (which causes the interactions between the NH and the SH)? These questions still need to be investigated and are worth paying attention to due to their importance for the understanding of the essence of monsoon. This paper focuses on these questions, and our theory is analyzed and verified by diagnosing the NCEP / NCAR 1958–1997 reanalysis data (Kalnay et al., 1996).

## 2. SEASONAL VARIATIONS, INTERACTIONS BETWEEN THE NH AND THE SH AND THE ESSENCE OF TROPICAL MONSOON

Now we consider three cases.

Imagining first case: the plane of the celestial equator coincides with the ecliptic along which the sun moves, i.e. the rotation axis of the earth is perpendicular to the ecliptic. Moreover, the earth's orbit is a circle (the sun is the centre of the circle). Although the solar radiation at the top of the atmosphere varies with latitude, it only has daily variation and does not possess annual variations (i.e., month–to–month or season–to–season variations), then besides solar tide, which is not strong and covered by the general atmospheric circulation because from observational results the difference between temperatures of day and night is much smaller than that of the equator and arctic, atmospheric motion should firstly possess the temperature distribution with a warm equator and two cool poles due to the meridional distribution of radiation and the associated zonal circulation (including zonal and meridional circulations). This is just the view of ideal and simple planetary thermal convection: in lower atmosphere, air stream flows to low latitudes from high latitudes; owing to the Corolis force, low–level wind is easterlies and high–level wind is westerlies. However, the single–cell meridional circulation is not real, because on the one hand the efficiency of the single–cell circulation is not high (thereby the motion will be insatiable due to stronger geostrophic wind), and on the other hand the angular momentum of the solid earth must be consumed by the easterlies at low level because of friction (as a result that the system will be adjusted to a state that the earth and the atmosphere respectively share the angular momentum). The Rossby regime is therefore brought: that is, at the same altitude there are both northward flows (most of them in the NH are warmer) and southward flows (most of them in the NH are cooler) crossing latitudinal circle, accordingly the efficiency of heat transport is greatly increased; meanwhile, at low–level there are easterlies as well as westerlies so that the angular momentums of both the earth and the atmosphere are respectively in balance. Consequently, there are three cells in both the NH and the SH, except the planetary thermal convection cells or clock–wise circulations (also called Hadley circulation) in the tropics and polar–high latitudes, at mid–latitude, there is a counter–circulation (i.e., Ferrel circulation) caused by dynamical mechanism (Yeh and Zhu, 1958; Lorenz, 1967). However, in statistic sense this kind of atmospheric circulation does not have annual variations (i.e., without seasons or seasonal variations) because solar radiation at the same latitude has not annual cycle, and climate mean state changes only with latitude and height except for the change in time due to confusion. Additionally, solar radiation is symmetric to the equator, the atmospheric circulation is also symmetric to the equator except that there is large difference between two the hemispheres; as a result, there are not interactions between the NH and the SH and CEF in statistic sense.

Imagining second case: the plane of the celestial equator is perpendicular to the plane of the ecliptic, namely the axis of the earth rotation is on the plane of the revolution orbit; moreover, for the sake of convenience, assuming the earth's orbit is circle (this is not important). As solar rays vertically shine at the north polar point (referred to as the Summer Solstice), the NH is during the day and absorbs solar radiation; the SH is at night without solar radiation. This causes the large difference in temperature between the Arctic and the Antarctic, heat energy will be transported into the SH from the NH, brings strong planetary thermal convection accompanying interactions between the SH and NH atmospheres, lower air flows across the equator to the Arctic from the Antarctic, and the contrary circumstance case occurs at high level. This is just summer of the NH (warm) and winter of the SH (cool). Half a year later, solar rays vertically shine at the south polar point (referred to as the Winter Solstice), then there is an opposite state to the above: the NH is at night and winter (cool), and the SH is during the day and summer (warm), the planetary thermal convection circulation also reverses. The atmospheric circulation has distinctly annual variation no matter there is the Rossby regime or not (Clearly the Rossby regime is required by both the heat transport efficiency and angular momentum balance). As for the position (referred to as the vernal equinox and the autumnal equinox) where the " earth" is located on the line perpendicular to the line of the two points mentioned previously, solar rays vertically shine at the equator, and the received heat is most in the tropics band and decreases with latitude. For this condition, moreover, there are equal day and night, and the total daily mean solar radiation is only one half of that of the Arctic pole at the Summer Solstice, therefore air temperature should be between temperatures of the North and South Poles at the Summer Solstice, and temperature distribution and atmospheric circulation state should almost be equivalent to those of the real earth's atmosphere at the spring and autumn equinoxes. There are three circulation cells in each hemisphere. However, the ascending branch of the planetary thermal convection centers at the equator because the solar radiation is symmetric to the equator. It does not need the interaction between the NH and SH atmospheres except that there is very little CEF due to the effect by which the elevation and degradation of temperature lag behind the increase and decrease of solar radiation.

The third is the reality: the ecliptic is inclined by about 23°26′21″ to the plane of the celestial equator. Only discussing the present circumstance: the solar rays vertically shine at the Tropics of Cancer (23°26′21″N) and Tropics of Capricorn (23°26′21″S) during the Summer Solstice and the Winter Solstice, respectively, and vertically at the equator during the spring and autumn equinoxes. Solar radiation has distinct seasonal variation, and the atmosphere circulation may be divided into four seasons: spring, summer, autumn and winter. In boreal summer, there exists heat transport from the NH into the SH; in boreal winter, there is heat transport from the SH into the NH. Therefore, for the planetary circulation there must exist

CEF in both summer and winter. The tilt of the earth's axis is a main cause by which the atmospheric circulation (even geographical climate system) possesses both seasons and interactions between the NH and the SH. Further analyses show that during the Summer Solstice, the center of planetary heat convective cell is located at the Tropics of Cancer and it is needed by the mean meridional circulation: at low–level there are CEFs into the NH from the SH, and on average they can arrive at about 23°26′21″N. Due to the effect of the Corolis force, the easterly component of northward air in the SH accelerates, and the westerly component will accelerate when the air crosses the equator into the NH. At high–level, there are compensative flows, contrary to flows at low–level. During the Winter Solstice, there is an opposite instance to the Summer Solstice. These are just the planetary circulation background and first driving force of tropics winter and summer monsoons. Second, as indicated long ago by meteorologist (and mentioned in the first imagination), there are the Rossby regime, planetary wave and counter–circulation (thereby three circulation cells exist in each hemisphere) in the four seasons of the real atmosphere. Because of the slow rotation of the earth, there are certain relations between the circulation cells through planetary waves (even zonal waves at different latitude circles are different in zonal wave number, amplitude and phase); especially, monsoons in some longitude zones are enhanced by the tropical semi–permanent planetary waves (even their amplitudes are much smaller than those of mid–high waves) superimposing the above–mentioned planetary thermal convection circulation (their meridional velocities have the same signs), and those in rest regions are lessened (their meridional velocities have opposite signs). Additionally, the tropical monsoon could reach some regions of mid–latitudes if the tropical semi–permanent planetary wave also suitably matches with the mid–latitude semi–permanent planetary wave (this is called as association). These are the second driving forces that make the tropics monsoon localization and meridional extension. As a result, the Asian–Australian monsoon is strongest (Figs. 1 and 2). That is simply the essence of tropics monsoon.

Since the regionalized and strengthened planetary heat convective circulation at low level is called the tropics monsoon, it is natural that the other branch of the localized and strengthened planetary heat convective circulation at upper level is also termed as monsoon [in fact, it is called planetary monsoon in Chang's paper (1978), however, it is pointed out only in Zeng and Zhang (1998), Xue and Zeng (1999), Li and Zeng (2000), and Zeng (2000) that the seasonal variation of the atmosphere circulation there is more significant and the concept of monsoon is extended to the stratosphere and higher level]. Similarly, due to association between tropics and mid–high latitude circulations, it is rational that the systems with significant seasonal variations in subtropic, temperate and frigid zones are the monsoons in the corresponding regions, which consequently brings a concept of global monsoon system (Zeng and Zhang, 1998; Xue and Zeng, 1999; Li and Zeng, 2000; Zeng, 2000). In fact, in geographical climatology combined with zoology, the temperate broad–leaf forest monsoon region etc. were defined. Moreover, the East Asian winter monsoon from mid–latitudes to subtropics is stronger than that to the south of the regions.

## 3. MERIDIONAL CIRCULATIONS

Let the meridional velocity component be $v$ (positive northward), and the zonally mean meridional wind be $[v]$, namely,

$$[v]=\frac{1}{2\pi}\int_0^{2\pi} v\,d\lambda. \tag{1}$$

According to the continuity equation and the boundary conditions of $[\omega]=[dp/dt]$ at the

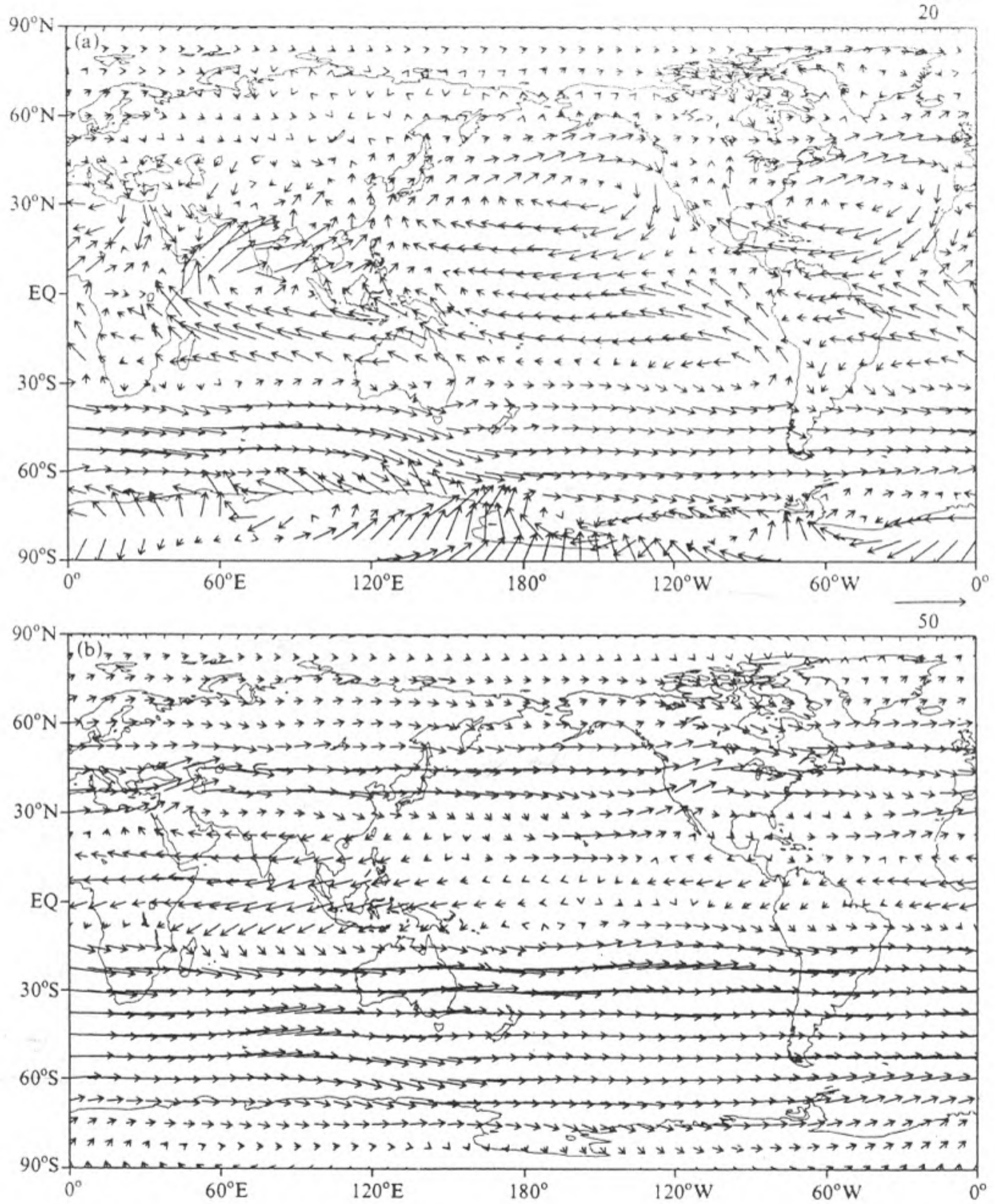


Fig. 1. Global distributions of mean wind field at 925 hPa (a) and 200 hPa (b) for JJA mean for the period of 1958–1997.

upper and lower surfaces ($p = 0$ and $p = p_s \approx 1000$ hPa) of the atmosphere are zero ($[\omega]$ is only approximate to zero at $p = p_s$), from $[v]$ the zonally mean "vertical velocity" (positive downward) at different iso-$p$ surfaces can be obtained as

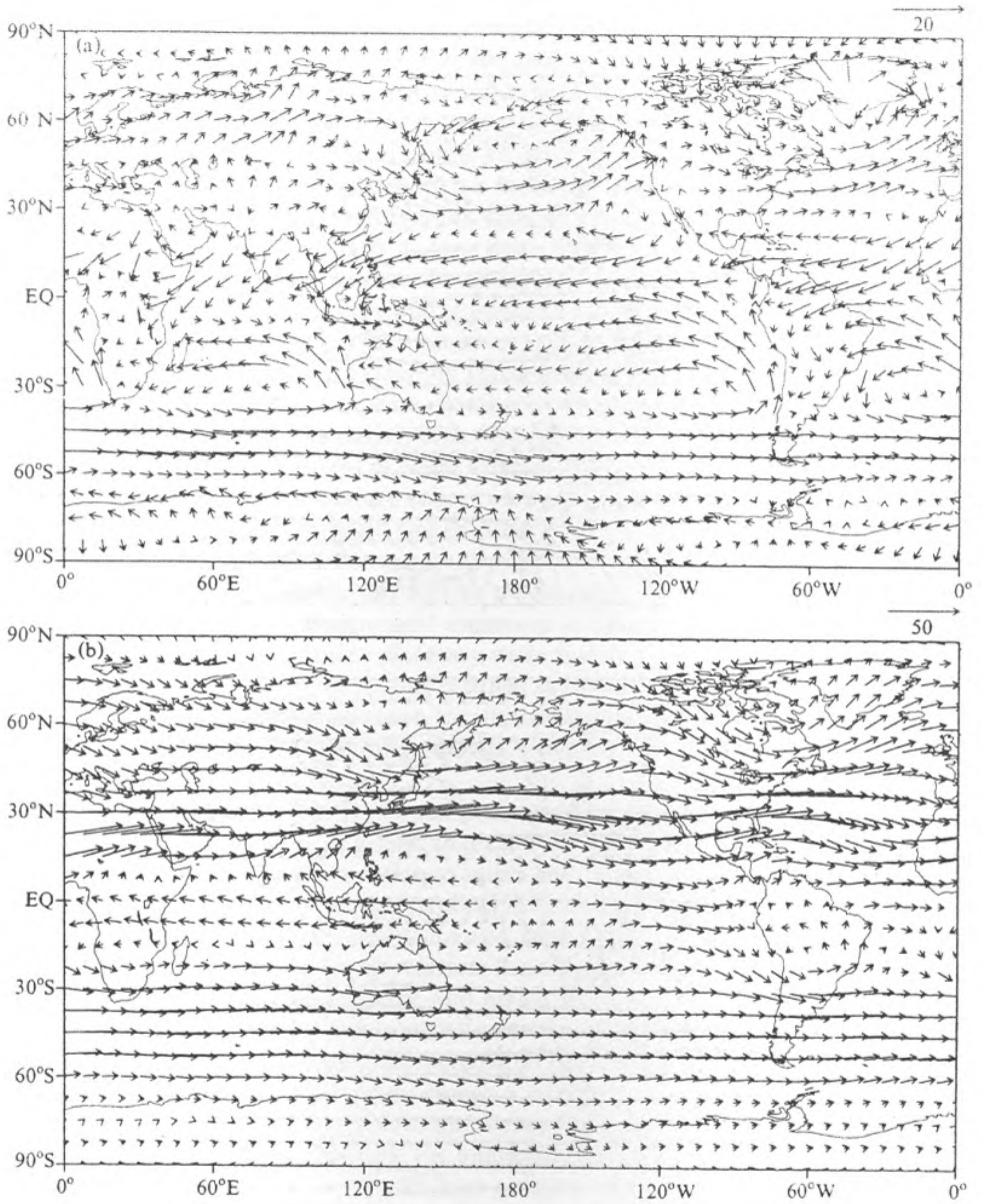


Fig. 2. Same as in Fig. 1, but for DJF mean.

$$-[\omega]=\frac{1}{a\sin\theta}\int_0^p \frac{\partial[v]\sin\theta}{\partial\theta}\mathrm{d}p, \quad (2)$$

where $\varphi$ is latitude, $[v]$ and $-[\omega]$ are two components of meridional circulation.

Based on the NECP / NCAR 1958–1997 reanalysis data, the zonally-mean meridional wind $[\bar{v}]$ (the climatology average of $v$ is $\bar{v}$) for summer, winter and annually mean conditions are shown in Figs. 3 and 4, and the corresponding meridional circulations are shown in Fig. 5 (Note that in Kalnay et al., (1996), wind under highland fabricated by computer is not creditable, and thereby the corresponding $\omega$ is also spurious. However, except for the south of 60°S, the ratio of highland to the whole latitude circle in other latitudes is not large, but the $[\bar{v}]$ and $[\bar{\omega}]$ to the south of 60°S are lack of creditability).

As shown in Fig. 3a, during boreal summer, within the tropics of two hemispheres from about 30°S to 20°N, in the low–level atmosphere under 700 hPa, there are northward jets with a maximum $[v]=3$ m s$^{-1}$ at levels near the earth surface; in higher atmosphere from 500 hPa up to about 100 hPa, there are southward air streams stronger than 0.5 m s$^{-1}$, and its maximum of $|[\bar{v}]|>3$ m s$^{-1}$ is at about 200 hPa; the maximum of $[\bar{v}]$ lies to the south of the equator; all the values of $|[\bar{v}]|$ at other latitudes and heights are obviously smaller. The distribution of meridional wind in boreal winter (Fig. 3b) is basically opposite to that in boreal

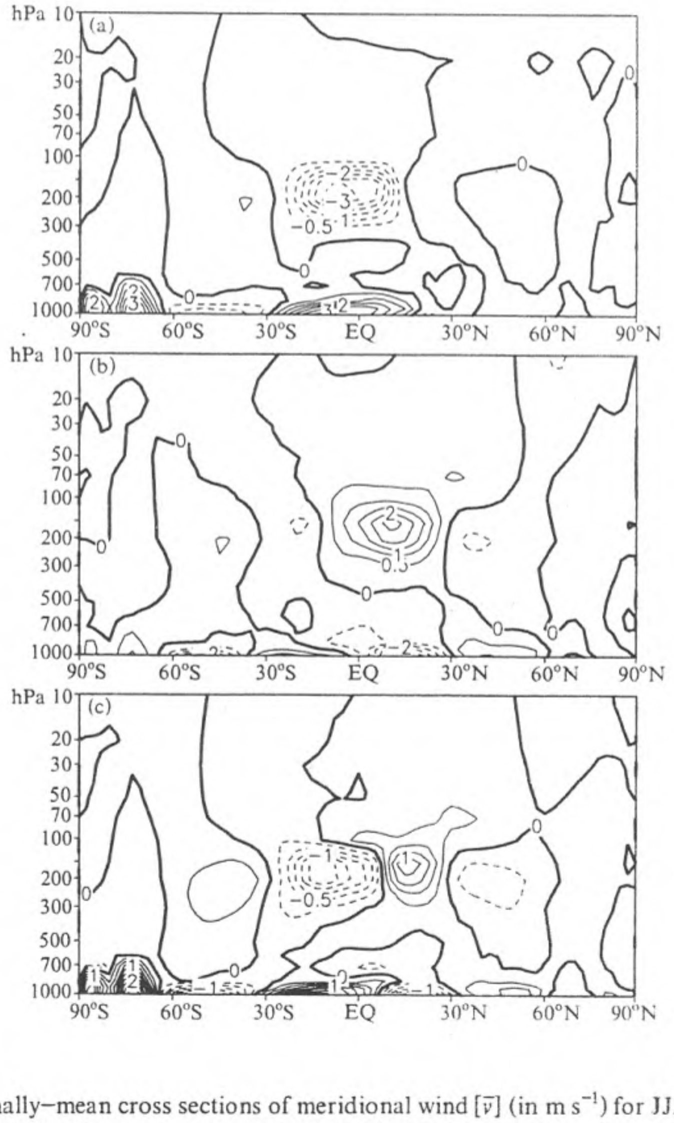


Fig. 3. Zonally–mean cross sections of meridional wind $[\bar{v}]$ (in m s$^{-1}$) for JJA (a), DJF (b) and annually (c) mean conditions in the period of 1958–1997.

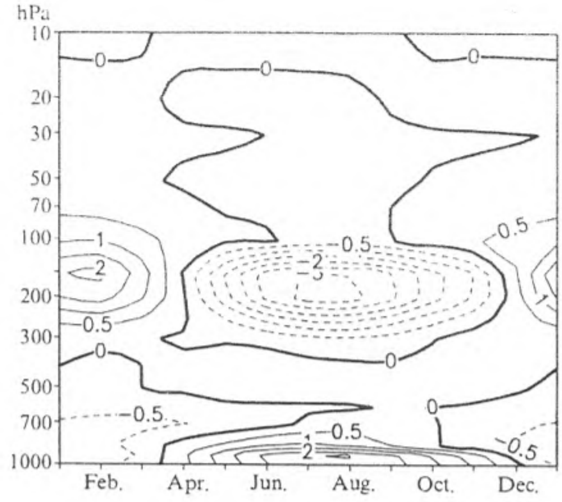


Fig. 4. Month–height cross section of zonally–mean meridional wind $[\bar{v}]$ (in m $s^{-1}$) at the equator for the period of 1958–1997.

summer, however, the strength of meridional wind is weaker than that in boreal summer (the maximum of $|[\bar{v}]|$ is 2 m $s^{-1}$); the maximum of $[\bar{v}]$ is located to the north of the equator, and, compared with the summer $|[\bar{v}]|$ in the whole zonal it has a clearly migration into the NH. Even in the surface layer of south of the equator $[\bar{v}]>0$ as same in summer. For the annually mean $[\bar{v}]$ (Fig. 3c) 5°N is roughly a division, at low–levels there are northward and southward flows to the south and north of the boundary line and the maximum is about 1 m $s^{-1}$; at high altitudes, there are inverse currents to those of low levels and the maximum may be larger than 1 m $s^{-1}$; along the line, air is of convergence at low altitudes and of divergence at high levels, but $[\bar{v}]$ to the south of the line is stronger than that to the north of the line. The division is located to the north of the equator, and the south current is stronger than the north branch. These reflect that summer circulation is stronger than winter circulation. This might be caused by a greater difference between the land areas of the NH and the SH.

Fig. 4 shows the month–height cross section of zonally–mean meridional wind $[\bar{v}]$ at the equator, clearly reflecting the close links between CEF and seasonal variations. During summer half year, lower air crosses the equator and flows northward, and $[\bar{v}]$ can reach 2 m $s^{-1}$; high–level air is a compensative current (southward), and $|[\bar{v}]|$ arrives at 3 m $s^{-1}$; there is an opposite case in boreal winter, and the intensities of CEFs (0.5 m $s^{-1}$ and 2 m $s^{-1}$, respectively) are also weaker.

From Fig. 5, in the atmosphere under 150 hPa, there are three meridional circulations in both the NH and the SH for annually, summer and winter mean conditions. However, the planetary thermal convection circulations (about between 30°S–30°N) in the tropics and subtropics are primary, and they are one order stronger than others. This can be found from Fig. 3. To more clearly show the three–cell circulation, Fig. 6 suggests the corresponding streamlines to Fig. 5. In boreal summer (Fig. 5a), the center of ascending motion of the planetary thermal convection circulation is in between 5°N and 10°N, the maximum upward current reaches $1\times10^{-3}$ m $s^{-1}$; the center of its descending motion is located at about 25°S, and the maximum descending velocity is $-0.6\times10^{-3}$ m $s^{-1}$. In boreal winter (Fig. 5b), the center of ascending branch is located at 15°S, its maximum ascending velocity is $0.5\times10^{-3}$ m $s^{-1}$;

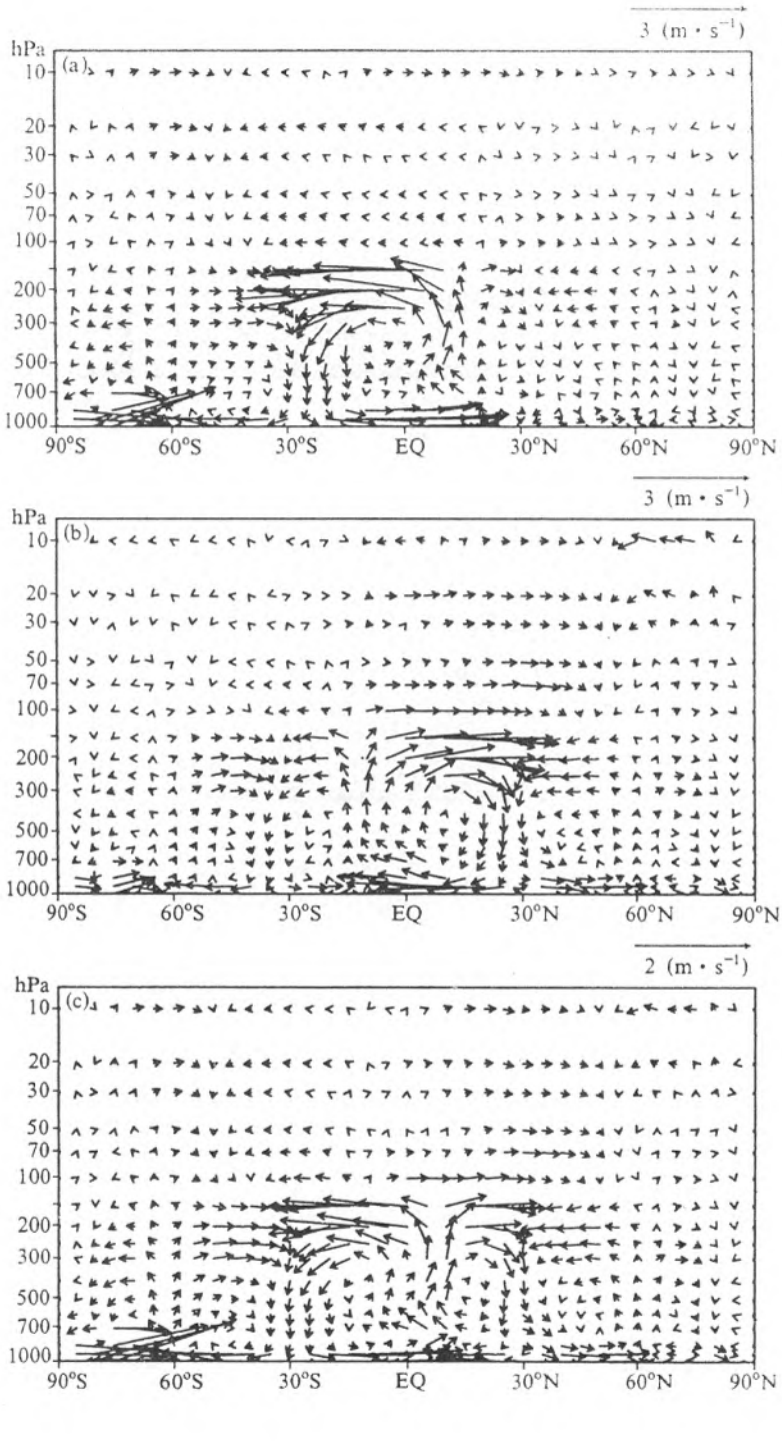


Fig. 5. Zonally–mean cross sections of the average meridional circulation $[\overline{C}_{yz}]$ for JJA (a), DJF (b) and annual (c) mean conditions for the period of 1958–1997.

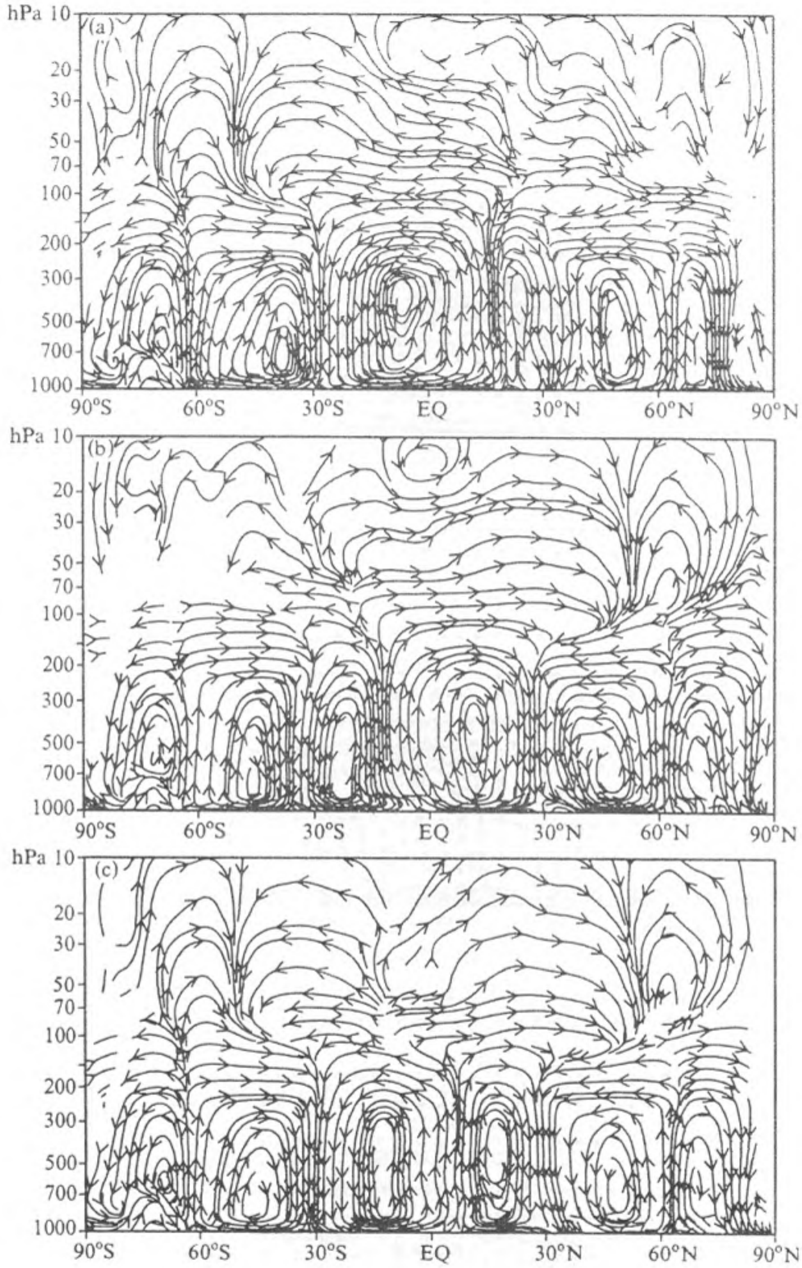


Fig. 6. Streamlines of the zonally–mean average meridional circulation $[\overline{C}_{yz}]$ for JJA (a), DJF (b) and annual (c) mean conditions for the period of 1958–1997.

the center of downward motion is situated at 25°N and its maximum descending velocity is $-0.6\times10^{-3}$ m s$^{-1}$. For the annually mean conditions (Fig. 5c), the rising motion is centered at about 5°N, and the sinking branches are found at 25°N and 30°S, respectively. That the center of the rising motion is located to the north of the equator is caused by stronger summer circulations and asymmetry of seasonal variation [the ascending center stands at the equator in boreal spring, however, it still lies in the NH in autumn (not shown)].

It must be pointed out that the mechanism of thermal transport in mid–latitude band is mainly through Rossby wave, and the effect of meridional circulation on it is very weak. The conclusion was derived long ago (Yeh and Zhu, 1958; Lorenz, 1967; Oort and Peixoto, 1983). As for low–latitudes, besides the planetary thermal convection circulation, it needs to be investigated that how is effect of planetary wave on transporting heat (and energy, e.g., latent heat). We have indicated previously that the semi–permanent planetary wave excited by differential surface specialty is the second driving force that makes monsoon strengthening in local regions. Through studying its transporting energy, we can further clarify the effect of tropical monsoon on the maintenance and evolution of the atmospheric circulation.

It also needs to be indicated that in the stratosphere above 100 hPa, there exist meridional circulations either in the four seasons or in annually mean condition, the meridional circulations in winter hemisphere are stronger than those in summer hemisphere, and they have obviously seasonal variation. They are closely related to the meridional circulations in the troposphere, although they are much weaker than the planetary convection circulations in the troposphere, and their structures are quite different from those of the troposphere: they have no longer hemispheric structure, but only with three cells within 70°S–70°N. The upward branches of planetary thermal convection in the troposphere arrive at the levels above 100 hPa, and the higher, the further declining to north (summer) to south (winter and annual mean). The flows diverge from the center: one crosses the equator (southward in summer and northward in winter), and the other is contrary to that. They arrive at 50° northern and southern latitudes and then become descending current, and there is an anti–circulation cell between 50° and 70° in each hemisphere. All of the three cells extend to 20 or 10 hPa, and the effects of such large–scale and strong circulation is worth investigating further. Undoubtedly, it is closely associated with the heating of ozonosphere and the seasonal variation of the polar night jet. Its ascending branch is the same as that of planetary thermal convection circulation and their seasonal variations are in phase, therefore it is obvious that these circulations are also intimately linked to the seasonal variations of the troposphere and monsoon. This point [see Zeng and Zhang (1998), Xue and Zeng (1999), Li and Zeng (2000)] also merits a further investigation. Additionally, within 30 hPa–10 hPa and 20°S–20°N, there exists a meridional cell symmetrical to the equator in summer and winter. Its ascending branch is in winter hemisphere, and its descending is in summer hemisphere. The cell is clock–wise in summer and anticlockwise in winter. It is also worth a further studying for the reality of this meridional circulation and its effect.

## 4. MASS TRANSPORT

In summer and winter it is necessary that CEF transports a part of heat of one hemisphere to the other. However, is there any cross–equator transport of air mass? In order to discuss this question we carry out some calculations as follows.

Dividing the atmosphere into two layers (let 400 hPa be the division), and calculating the cross–latitude mass transport $I_1$ (upper layer 0–400 hPa), $I_2$ (low layer 400 hPa–$p_s$, where $p_s$ is the surface pressure) and the net transport I of whole layer:

$$I_1 = \frac{1}{g}\int_0^{400\ \mathrm{hPa}} v\mathrm{d}p, \tag{3}$$

$$I_2 = \frac{1}{g}\int_{400\ \mathrm{hPa}}^{p_s} v\mathrm{d}p, \tag{4}$$

$$I = I_1 + I_2. \quad (5)$$

Note that the wind data of NECP / NCAR reanalysis data (Kalnay et al., 1996) are up to 1000 hPa, thus $p_s$ is taken as 1000 hPa. Let $[\bar{I}_1]$, $[\bar{I}_2]$ and $[\bar{I}]$ be the zonal climatological mean of (3), (4) and (5), respectively, we can obtain Fig. 7 (the cases of spring and autumn are not shown) and Fig. 8.

Fig. 7 reveals that whatever it is seasonally or annually mean state, the signs of $[\bar{I}_1]$ and $[\bar{I}_2]$ within 60°S–60°N are opposite at each latitude, i.e., they counteract with each other. However, the mass transport $[\bar{I}]$ of whole layer, although small, exists; even at about 30°N, $[\bar{I}]$ is only a little smaller than $[\bar{I}_2]$ owing to the difference between the phase angles of $[\bar{I}_1]$ and

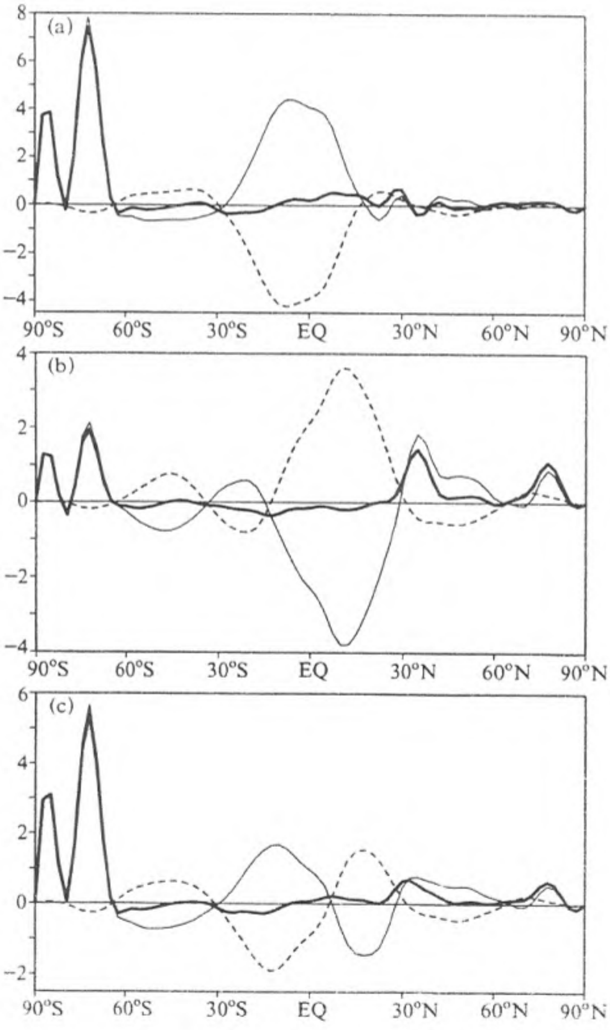


Fig. 7. Meridional profiles of the zonally-mean indices $[\bar{I}]$ (heavy solid line), $[\bar{I}_1]$ (dashed line) and $[\bar{I}_2]$ (light solid line) (in $10^3$ kg $m^{-1}$ $s^{-1}$) for JJA (a), DJF (b) and annual (c) mean conditions for the period of 1958–1997.

$[\bar{I}_2]$, and it reaches the maximum (it is northward transport either in summer, winter or annually mean conditions). Essentially, the annually mean net transport should be zero (ensuring the conservation of the atmosphere mass between every two latitude circles in sense of climatological average), therefore, the calculated annually mean $[\bar{I}]$ should be caused by the errors of the data and numerical method, and the annually mean value $[\bar{I}]$ indicates the range of the errors. It can be seen that $[\bar{I}_1]$ and $[\bar{I}_2]$ of summer and winter are creditable within 60°S–60°N, especially in the tropics. Both $[\bar{I}_1]$ and $[\bar{I}_2]$ are very large in the region of planetary heating convection circulation, and the maximums are about $2\times10^3$–$4\times10^3$ kg m$^{-1}$ s$^{-1}$. There are secondary maximums of $10\times10^3$ kg m$^{-1}$ s$^{-1}$ in the middle latitudes of two hemispheres (it is located at around 30°N in the NH and 45°S in the SH), but the rest values of $[\bar{I}]$ may be unreliable and can be regarded as error except for $[\bar{I}]$ at around 30°N in summer. Hence, it is even needed by seasonal variation that there is cross–equator (or cross–latitude) heat transport, but the low– and high–level flows are mainly compensative and there is almost no net mass transport. Why is there net northward mass transport at around 30°N in winter? It is worth studying.

The annual variation of mass transport cross the equator is displayed in Fig. 8. As shown, the absolute values of both $[\bar{I}_1]$ and $[\bar{I}_2]$ are very large in summer and winter, especially in summer; the maximums are $4\times10^3$ kg m$^{-1}$ s$^{-1}$ in summer and $3\times10^3$ kg m$^{-1}$ s$^{-1}$ in winter, and zero in spring and autumn (in spring it becomes zero at around the vernal equinox, but in autumn it reaches zero after the autumnal equinox, at the end of October, showing asymmetry of seasonal variation). It seems that $[\bar{I}_2]$ is larger than $[\bar{I}_1]$, indicating that the net transport is northward in summer and southward in winter. It must be caused by the fact that the total mass of global atmosphere or mean surface pressure $\langle p_s \rangle_S$ of hemisphere has annual variations because there is no zero net mass transport across the equator (there is errors in the net northward transport, see Fig. 8). Here

$$\langle p_s \rangle_S = \frac{1}{S}\iint_S p_s a^2 \sin\theta \mathrm{d}\theta \mathrm{d}\lambda, \tag{6}$$

where the subscript s represents earth surface, the subscript $S$ denotes certain region (e.g., NH or SH), the $S$ in the denominator is the area of the region, $a$ the mean earth radius, $\theta$ the co–latitude. If $S$ takes the global, $\langle p_s \rangle_S$ should not change as a function of time (the conservation of atmosphere mass). In the following, we briefly write $P_s = \langle p_s \rangle_S$.

Fig. 9 shows the annual variations in the average surface pressure $\bar{P}_s$ over the Southern and Northern Hemispheres and the globe from NCEP / NCAR reanalysis data. All the NH, SH and global surface pressures possess seasonal variations. Except for the annual cycle of water vapor, it seems to be difficult to understand why there is an annual range of $\pm 0.2$ hPa for the global surface pressure. It can be only considered as the mean error of data. Removing the error, the surface pressure of each hemisphere has considerable annual variation. The annual range is 1.8 hPa in the SH and only 1.1 hPa in the NH. They do not match. Moreover, during boreal summer, compared with the normal value, the mean surface pressure of the NH is 0.6 hPa lower and that of the SH is 1hPa higher. There is a contrary situation in winter (deviations are smaller). The result is just opposite to the net mass transport across the equator, so there must be errors either in Fig. 8 or Fig. 9.

Besides, there are also significantly interannual and interdecadal variabilities of annually–mean surface pressure averaged over the globe, Northern and Southern Hemispheres from NCEP / NCAR reanalysis data (Fig. 10). The interannual amplitudes of mean surface pressure averaged over the Southern and Northern Hemispheres and globe are 1.3 hPa, 1.1 hPa and 0.7 hPa, respectively. In fact, if there is little influence of water vapor, the

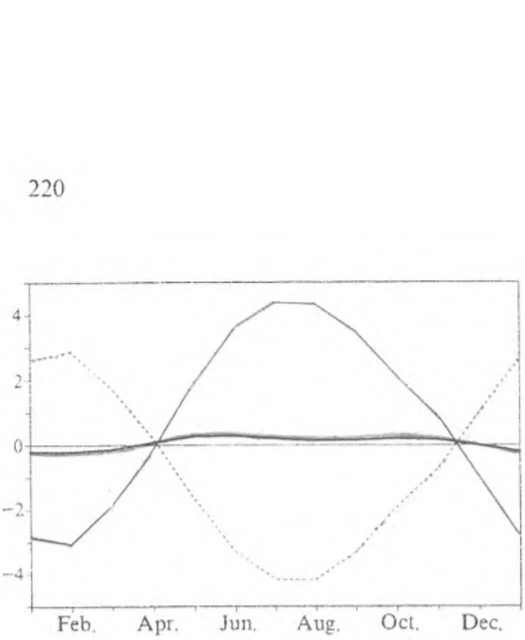


Fig. 8. Annual variation in the zonally−mean indices $[\bar{I}]$ (heavy solid line), $[\bar{I}_1]$ (dashed line) and $[\bar{I}_2]$ (light solid line) (in $10^3$ kg $m^{-1}$ $s^{-1}$) at the equator (EQ) for the period of 1958−1997.

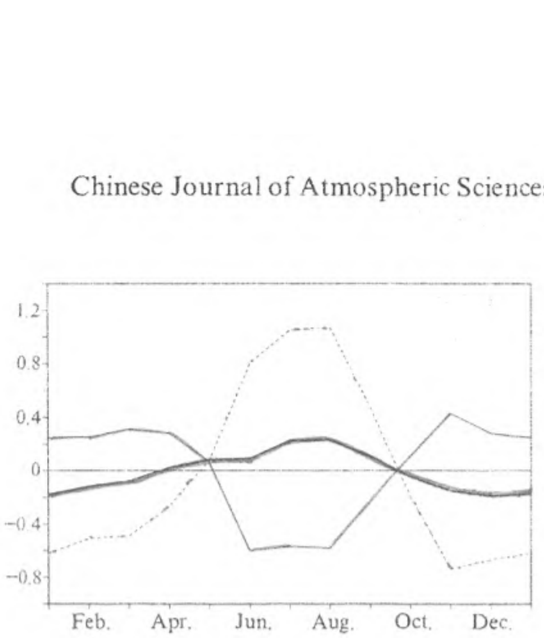


Fig. 9. Annual variation in the average surface pressure $\bar{P}_s$ (in hPa) over the Southern (dashed line) and Northern (light solid line) Hemispheres and the globe (heavy solid line) for the period of 1958−1997. Plotted are departures from the annually−mean values.

global surface pressure should has neither annual nor interannual changes according to the conservation law of mass. However, it has both from the results, and the amplitude of interannual change is three times of annual range. Moreover, it tends to increase before 1977 and to decrease after the year. How to explain it? Is it within the error range of the data? *

## 5. THE ROLE OF MONSOON REGIME

Enlarging slightly the extension of the Asian−Australian monsoon regime, i.e., taking the range 30°E−180°E as the region (E) and making areal mean, comparing them with the zonal mean mentioned above, the role of the Asian−Australian monsoon in planetary meridional circulation and interactions between two hemispheres can be clearly shown.

Let $(v)_E$ be averaged meridional velocity of the region (E), and $(I_1)_E$, $(I_2)_E$, and $(I)_E$ be the values corresponding to $I_1$, $I_2$, and $I$, repectively. The annual cycle of $(\bar{I}_1)_E$ at the equator can be indicated in Fig. 11. Comparing it with Fig. 8, the monthly changes of the corresponding curves are in a basically accord with each other, but the intensity of meridional velocity in the region (E) (Fig. 11) is distinctly stronger than that of the zonal mean (Fig. 8). For instance, the maximums of $(\bar{I}_1)_E$ and $(\bar{I}_2)_E$ in the tropics in summer are $6\times 10^3$ kg $m^{-1}$ $s^{-1}$ and $6.5\times 10^3$ kg $m^{-1}$ $s^{-1}$, respectively, and $4\times 10^3$ kg $m^{-1}$ $s^{-1}$ and $6\times 10^3$ kg $m^{-1}$ $s^{-1}$ in winter. In Comparison of $(\bar{I}_1)_E$ and $(\bar{I}_2)_E$ in the Asian−Australian monsoon regime with the zonally mean condition, therefore, they increase by $2\times 10^3$ kg $m^{-1}$ $s^{-1}$ and $2.5\times 10^3$ kg $m^{-1}$ $s^{-1}$ respectively in summer, and $1\times 10^3$ kg $m^{-1}$ $s^{-1}$ and $3\times 10^3$ kg $m^{-1}$ $s^{-1}$ in winter. For the efficiency of the air mass transport driven across the equator, the ratio of the first

* After submitting this paper, we read a paper by Hines et al. (2000). They pointed out that there is larger errors in the surface pressure of the NCEP data before 1968, especially in the high latitude zones of the SH. However, from the calculations of the paper there seem be error problems more than those indicated by them.

driving force due to the annual variation of solar radiation to the second driving force caused by the difference of the earth's surface characteristics is about 4:2 in summer, 3:1 (high altitude) and 3:3 (low level) in winter. The Asian–Australian monsoon can drive $2 \times 10^3$–$3 \times 10^3$ kg $m^{-1}$ $s^{-1}$ of net mass transport southward in winter and $1 \times 10^3$ kg $m^{-1}$ $s^{-1}$ in summer. Because of the relative lag of high–level circulations after summer, from September the net transport has been shifted to south.

The meridional profiles of $(\bar{I}_1)_E$, $(\bar{I}_2)_E$, and $(\bar{I})_E$, are portrayed in Fig. 12. Except for the area to south of 60°S, the data are reliable. Compared with Fig. 7, the distinct differences between them are: the zonally mean meridional transport is strongest in the tropics corresponding to the planetary thermal convection cell, but in the region (E) in winter, there are considerable $|(\bar{I}_1)_E|$ and $|(\bar{I}_2)_E|$ at about 60° and 30° latitudes in both hemispheres except

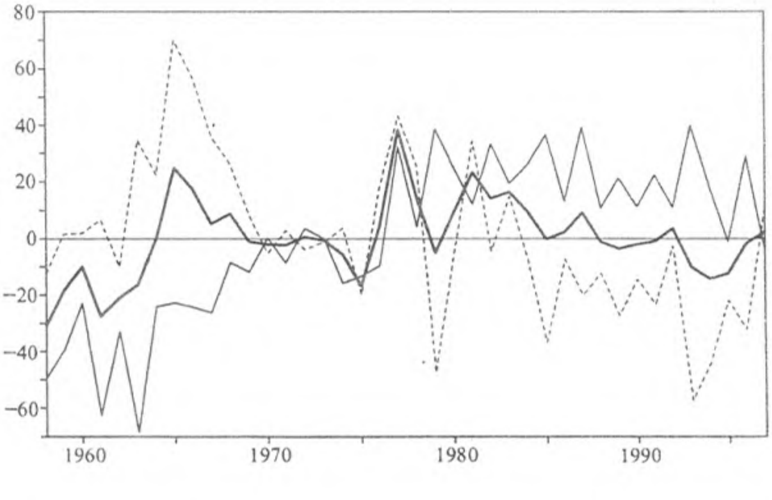


Fig. 10. Time series of the annually–mean surface pressure anomalies $P_{SFC}$ (in Pa) averaged over the globe (heavy solid line), the Northern (light solid line) and the Southern (dashed line) Hemispheres for the period of 1958–1997.

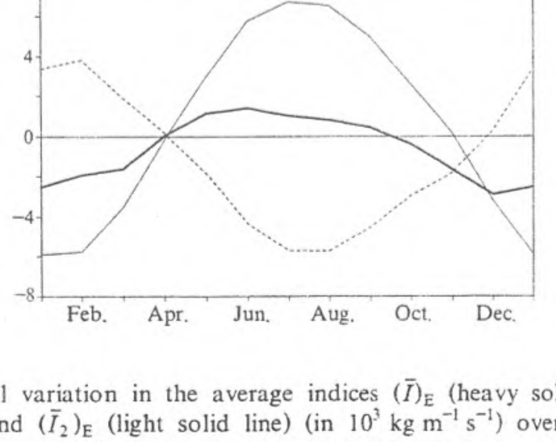


Fig. 11. Annual variation in the average indices $(\bar{I})_E$ (heavy solid line), $(\bar{I}_1)_E$ (dashed line) and $(\bar{I}_2)_E$ (light solid line) (in $10^3$ kg $m^{-1}$ $s^{-1}$) over the sector of 30–180°E at the equator (EQ) for the period of 1958–1997.

the tropics. $(\bar{I}_1)_E$ is positive to the north of 10°S (it is northward transport at high–level) and minimum near zero at around 45°N; $(\bar{I}_2)_E$ at 45°N can reach about $-8\times10^3$ kg m$^{-1}$ s$^{-1}$, stronger than that in the tropics (all of them are southward transport). These features reflect the following fact in the NH: the East Asian monsoon covers the region from mid–high latitudes through low latitudes at low level, the semi–permanent planetary wave of mid–high latitude is in phase with the lower latitude planetary heat convective circulation and semi–permanent planetary wave (There is northward transport with small values at 30°N). In winter, there is net southward mass transport (about $2.5\times10^3$ kg m$^{-1}$ s$^{-1}$) in the tropics of 15°S–15°N and net northward transport ($4.5\times10^3$ kg m$^{-1}$ s$^{-1}$) between 40°S–15°S, consequently, the region near 15°S heaps up mass and becomes a source of divergence outwards from the region (E). In summer, all $(\bar{I}_2)_E$ are positive (northward transport at low altitudes) from 45°S to 40°N, all $(\bar{I}_1)_E$ are negative (southward transport at high altitudes) from 30°S to 40°N, where most of their absolute values are $5\times10^3$ kg m$^{-1}$ s$^{-1}$ or so, and there are two second maximums near 30°–45° latitude in each hemisphere. These also reveal the fact that the Asian–Australian monsoon and the semi–permanent planetary waves of the NH and SH at mid–high latitudes are in phase, the summer monsoon can arrive in the East Asian temperate zone of the NH from the temperate zone of the SH; besides, the net transport in summer is northward within 5°S–15°N, southward within 15°N–25°N, northward within 25°N–45°N and southward to the north of 45°N, indicating that there is banking of mass at about 15°N and 25°N diverging to outside of the region (E). However, the net transport is evidently weaker in summer than in winter, and the question why there is a significantly seasonal difference for the net transport is still worth studying. Moreover, the annually mean net transport is indeed very small due to the offset between winter and summer transports.

It was pointed out long ago that the strong Asian monsoon (i.e., the so–called Asian–Australian monsoon including the East African monsoon and the East Asian monsoon) is associated with the collocation of geographical location of the largest connected continent (the Eurasia and African continent including the Indian subcontinent and Australia) and the largest connected ocean (the Pacific and Indian Oceans) (Kao and Xu, 1962) in the world. This agrees with our results [Note: The Asian monsoon and East Asian monsoon are first systemically investigated in Chu (1934), Tu and Huang (1944)].

Since the planetary thermal convection circulation in the region (E) is strengthened, it must be weakened outside of the region (E) (the region (W) hereafter) by the partly counteraction between it and the semi–permanent planetary wave. Figs. 13 and 14 are for the region (W). The difference between Figs. 13 (for the region (W)) and 7 (for the zonally mean condition) is just opposite to that between Figs. 12 (for the region (E)) and 7, and the difference between Figs. 14 (for the region (W) at the equator) and 8 (for the zonal mean condition at the equator) is also reverse to that between Figs. 11 (for the region (E) at the equator) and 8. In comparison of Fig. 14 with Fig. 11 and Fig. 13 with Fig. 12, the mass transport in the region (W) is much weaker than that in the region (E). Additionally, the profile of the net mass transport of whole layer in the region (W) is simply reverse to that in the region (E). These features are also clearly shown in Fig. 14. The mass transport of the region (W) is weaker than that of the region (E), and the variations of the net mass transport of the whole layer between the regions (W) and (E) are obviously in opposite directions. Especially, the difference between the Figs. 14 and 8 show that at the equator, $|[\bar{I}_1]-(\bar{I}_1)_W|$ and $|[\bar{I}_2]-(\bar{I}_2)_W|$ are respectively about $1\times10^3$ kg m$^{-1}$ s$^{-1}$ and $1.5\times10^3$ kg m$^{-1}$ s$^{-1}$ in summer, and about $1\times10^3$ kg m$^{-1}$ s$^{-1}$ and $2\times10^3$ kg m$^{-1}$ s$^{-1}$ in winter. These features indicate that the efficiency ratio of the first to second driving forces is 4:(1–1.5) in summer and 3:(1–2) in winter (The result basically equals to the estimated value for the region (E)). As a result, the seasonal variation

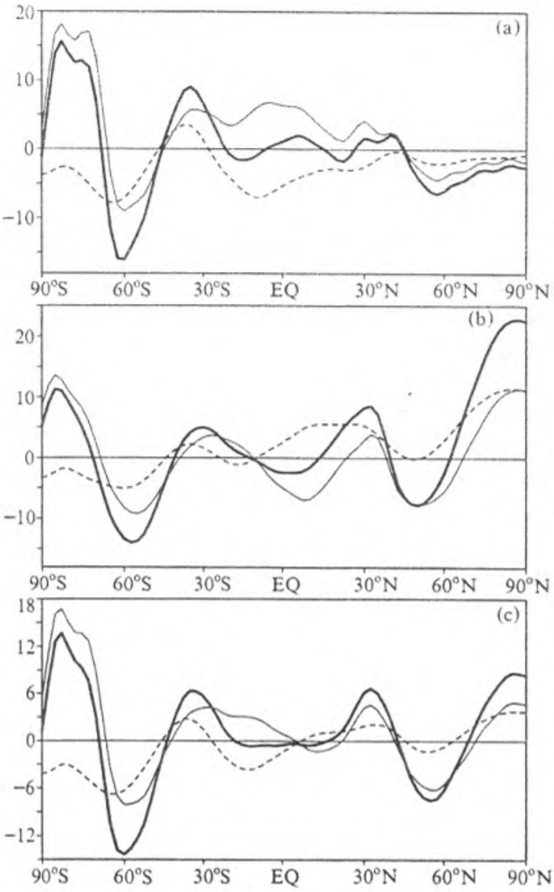


Fig. 12. Meridional profiles of the indices $(\bar{I})_E$ (heavy solid line), $(\bar{I}_1)_E$ (dashed line), and $(\bar{I}_2)_E$ (light solid line) (in $10^3$ kg $m^{-1}$ $s^{-1}$) over the sector of 30–180°E for JJA (a), DJF (b) and annually (c) mean conditions for the period of 1958–1997.

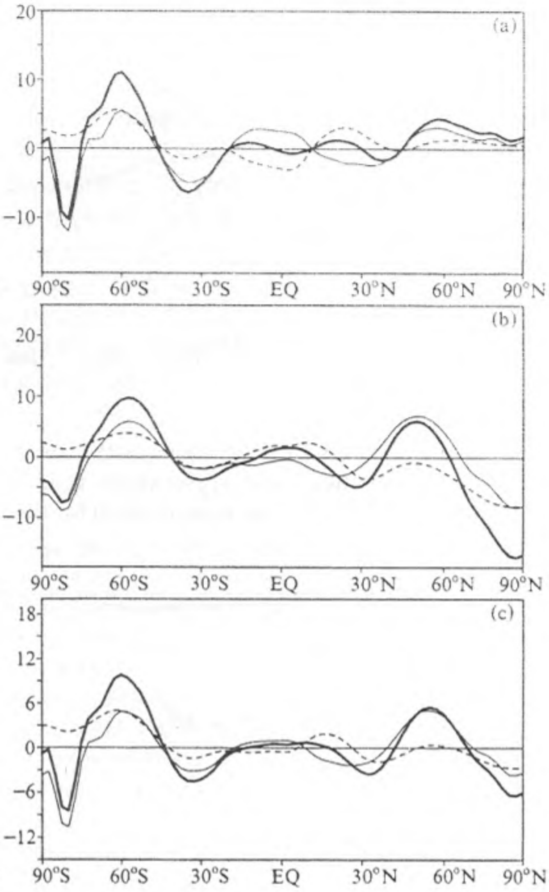


Fig. 13 Meridional profiles of the indices $\bar{I}$ (heavy solid line), $\bar{I}_1$ (dashed line), and $\bar{I}_2$ (light solid line) (in $10^3$ kg $m^{-1}$ $s^{-1}$) over the sector of 177.5–27.5°W for JJA (a), DJF (b) and annually (c) mean for the period of 1958–1997.

in the region (W) is very weak, and the low–level atmosphere in the tropics of the region (the Atlantic and the eastern Pacific Oceans) is almost east trade throughout the entire year.

From the month–height cross section of vertical velocity over the regions of (E) and (W) (Fig. 15), the structures of seasonal variation of the two regions are also basically opposite. At the equator, it is upward current in the (E) region for the whole year, and strongest in winter and summer and weaker in spring and autumn. It is mainly downward current in the (W) region and strongest in summer, but it is upward current at middle and low levels in winter and spring; especially, it is strongest in April and can arrive in the stratosphere. The features of the (W) region mentioned above also clearly suggest that in the region, the semi–permanent planetary wave counteracts the action of planetary thermal convection circulation in the tropic. At the equator, the region (E) occupies 150 degrees, and the outside of the (E) region occupies

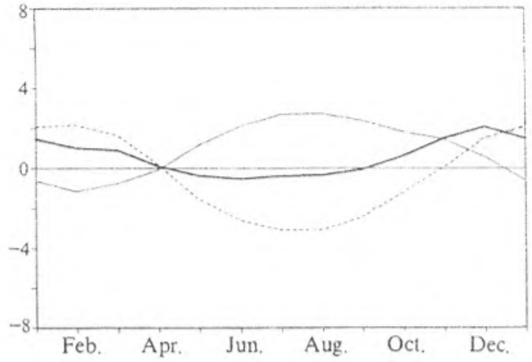


Fig. 14. Annual variation in the average indices $(\bar{I})_W$ (heavy solid line), $(\bar{I}_1)_W$ (dashed line), and $(\bar{I}_2)_W$ (light solid line) (in $10^3$ kg m$^{-1}$ s$^{-1}$) over the sector of 177.5−27.5°E at the equator (EQ) for the period of 1958−1997.

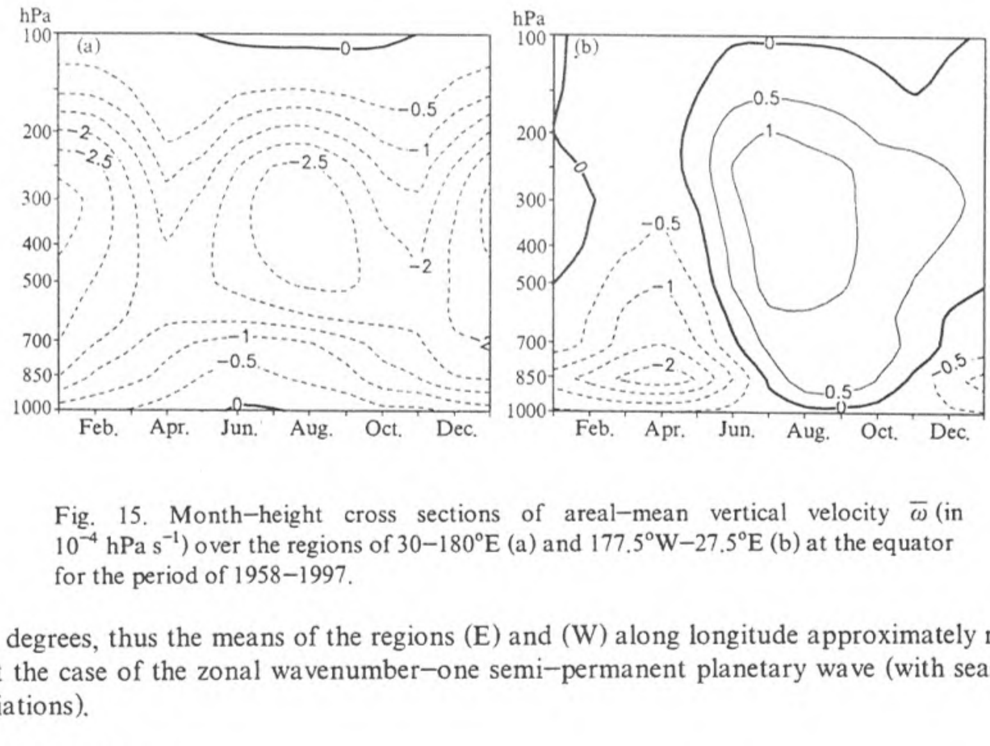


Fig. 15. Month−height cross sections of areal−mean vertical velocity $\bar{\omega}$ (in $10^{-4}$ hPa s$^{-1}$) over the regions of 30−180°E (a) and 177.5°W−27.5°E (b) at the equator for the period of 1958−1997.

210 degrees, thus the means of the regions (E) and (W) along longitude approximately represent the case of the zonal wavenumber−one semi−permanent planetary wave (with seasonal variations).

## 6. SUMMARY

The theoretical consideration and the statistical analysis of NCEP re−analyses data stated above show that the seasonal variations of atmospheric general circulation, the cross−equatorial air flows and the interaction between the Northern and Southern Hemispheric atmospheres are primarily caused by the seasonal variation of incoming solar radiation due to the plane of the celestial equator and the ecliptic. The planetary thermal convection circulation is the first driving force of the tropics monsoon, and the semi−permanent planetary waves owing to the differences between the thermal characters of earth surface (ocean and continent) are the secondary driving forces. The common effects of the two forces bring about the local property of monsoon. From the efficiency of driven cross–equatorial mass transport, the efficiency ratio of the first to second forces is 4:(1–2) in summer and 3:(1–3) in winter, and averagely 2:1. In the eastern Hemisphere, the two forces are in phase, therefore there is prevailing pronounced Asian–Australian monsoon. The regions with stronger seasonal variation from low to high latitudes in the globe are produced by the associations of meridional circulation cells between high and low levels and between north and south directions and the collocations between the cells and semi–permanent planetary waves at mid–high latitudes, as a result, the globally general monsoon system in three–dimensional space is formed. To distinguish the traditional monsoon definition, the system is called the general monsoon system. Additionally, the first and second driving forces are out of phase in the tropical Atlantic and the eastern Pacific Oceans, therefore their prevailing trade and the seasonal variation is weak.

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