

STUDY ON THE VARIATION IN THE CONFIGURATION OF SUBTROPICAL ANTICYCLONE AND ITS MECHANISM DURING SEASONAL TRANSITION—PART I: CLIMATOLOGICAL FEATURES OF SUBTROPICAL HIGH STRUCTURE*

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ABSTRACT

Climatological characteristics of subtropical anticyclone structure during seasonal transition are investigated based on NCEP/NCAR reanalysis data. The ridge-surface of subtropical anticyclone is defined by the boundary surface between westerly to the north and easterly to the south (WEB in brief). In Afro-Asian monsoon area, the subtropical high in troposphere whose ridgelines are consecutive in wintertime takes on relatively symmetrical and zonal structure, the WEB tilts southward with increasing height. In summer, the subtropical high ridgelines are discontinuous at low levels and continuous at upper levels, the WEB tilts northward from the bottom up. Under the constraint of thermal wind relation, the WEB usually tilts toward warmer zone. May is the period when subtropical high modality most significantly varies. The structure and properties of subtropical high during seasonal transition are different from area to area. A new concept "seasonal transition axis" is proposed based on formation and variation of the vertical ridge axis of subtropical anticyclone. The subtropical high of summer pattern firstly occurs over eastern Bay of Bengal in the beginning of May, then stabilizes over eastern Bay of Bengal, Indo-China, and western South China Sea in the 3rd pentad of May, it exists over the South China Sea in the 4th—5th pentad of May and establishes over central India in the 1st—2nd pentad of June. The three consequential stages when summer modal subtropical high occurs correspond to that of Asian summer monsoon onset, respectively. To a great extent, the summer monsoon onset over the Bay of Bengal depends on the reversal of meridional temperature gradient in vicinity of the WEB in upper troposphere. The meridional temperature gradient at middle-upper levels in troposphere can be used as a good indicator for measuring the seasonal transition and Asian monsoon onset.

Key words: subtropical anticyclone, structure, WEB (westerly-easterly boundary), seasonal transition, Asian monsoon onset

I. INTRODUCTION

The subtropical anticyclone, which belongs to planetary scale system, is the connecting gear that links tropical with middle-latitude circulations. It has significant

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impact on weather and climate. Previous studies (e. g. Huang et al. 1962) have examined its structure, modality, and active laws. Qu and Pan (1963) pointed out that in the lower troposphere the subtropical high ridge over China mainland is connected with that over the Pacific, in the upper troposphere it is linked with Asian high based on analysis of case study. The subtropical anticyclones at upper levels shift northward earlier than at lower levels. With its northward movement the subtropical anticyclone structures in temperature and pressure resemble that of waves propagating over middle-latitudes. These results are only synoptic characteristics of subtropical anticyclones. Liu et al. (2000) investigated the subtropical anticyclone structure from perspective of meridional deviation. Zonal mean subtropical high belts covering Southern and Northern Hemispheres are symmetric with respect to the equator, and the ridgelines are close to the equator with increasing height. Seasonal variations exhibit that the subtropical high ridgelines as a whole within the troposphere simultaneously southward or northward shift. Liu and Wu (2000) pointed out that some traditional concepts in the studies on the subtropical anticyclone are inadequate and need to be re-considered. Some important issues about subtropical anticyclone structure and its variations should be further studied.

The subtropical anticyclones possess considerable variability on a wide range of temporal and spatial scales. Within the annual cycle there are two time variations, from winter to summer the boreal subtropical anticyclones move northward and their strength enhance, and the opposite variations occur from summer to winter. However, during seasonal transition the concrete modalities and properties of subtropical anticyclones are not well understood. In transition season such as spring, winter monsoons will be replaced by summer monsoons. We know that the summer monsoon onset is the most important seasonal and sub-seasonal phenomenon of the monsoon, so the essential variations of the subtropical anticyclone structure take place. In this paper, the subtropical anticyclone belt in the troposphere is regarded as a whole system. Its attributes involving spatial structure, quality, and evolutionary law are explored with a view of climatology. Our studies focus on the Afro-Asian monsoon area, the subtropical anticyclone belt covering northern Africa, Asia and western Pacific is chosen as main research object, the variation in the configuration of subtropical anticyclone during the seasonal transition from winter to summer is investigated.

II. DATA AND METHODOLOGY

1. Data

The major data used in this work are the NCEP/NCAR reanalysis data with global coverage (Kalnay et al. 1996). The wind, geopotential height, temperature, vertical motion, and specific humidity at 17 standard pressure levels have a horizontal resolution of $2.5^{\circ} \times 2.5^{\circ}$ grid. Pentad means used are constructed from daily means for the period 1980–1998, the time domain for monthly mean dataset has been extended to a range of 1958 to 1997. Also employed are the daily mean outgoing longwave radiation (OLR) data on $2.5^{\circ} \times 2.5^{\circ}$ grid from the NOAA satellite observation spanning from 1980 to 1998.

2. The Relationship between the Tilt of WEB and Horizontal Temperature Gradient

The geostrophic wind relation is given as

$$u = -\frac{1}{f} \frac{\partial \Phi}{\partial y}. \quad (1)$$

Consider the Northern Hemisphere subtropical zone, the latitude that the zonal wind zero line locates is φ_0 , according to Eq. (1), we can know

$$u = -\frac{1}{f(\varphi_0)} \frac{\partial \Phi}{\partial y} = 0, \quad \varphi = \varphi_0 \quad (2)$$

$$\frac{\partial u}{\partial y} = -\frac{1}{f(\varphi_0)} \frac{\partial^2 \Phi}{\partial y^2} > 0, \quad \varphi = \varphi_0. \quad (3)$$

Therefore, in this paper the zonal wind zero line is defined as ridgeline of subtropical anticyclone based on the property that Φ gets maximum in y direction.

Apply the thermal wind function

$$\frac{\partial u}{\partial p} = \frac{R}{fP} \left(\frac{\partial T}{\partial y} \right)_p. \quad (4)$$

Consequently, all ridgelines on isobaric surfaces constitute a westerly-easterly boundary surface, called WEB in brief.

Based on Eq. (4), we can get the relationship between the tilt of WEB and horizontal temperature gradient.

In the boreal winter, the atmospheric temperature in the troposphere is degressive from equator to polar region. According to Eq. (4), we obtain $\partial u / \partial p < 0$ due to the meridional temperature gradient in the vicinity of the WEB less than zero ($\partial T / \partial y < 0$). Thus the WEB tilts southward with increasing height.

In the boreal summer, the ridgelines of the subtropical anticyclone in the lower troposphere are broken and the WEB in the middle-upper troposphere gets northward tilting over the Afro-Asian monsoon area because the air temperature over the subtropical continent is higher than that over the Indian Ocean on the same isobaric surface.

When the meridional temperature gradient equals zero, the WEB is perpendicular to the earth's surface.

It is turned out from the above analyses that when the geostrophic relation is valid the WEB always tilts toward warmer region in the vertical. The tilting of WEB is subject to the constraint of the thermal wind relation. Thereby the variation in the configuration of subtropical anticyclone and in thermal structure during seasonal transition can be examined based on the change of WEB tilting, and the mechanism for the variation of Asian monsoon circulation can be further explored.

III. TEMPORAL AND SPATIAL EVOLUTIONS OF THE WEB

Figure 1 shows the seasonal distribution of 500-hPa winds for the winter and summer. The thick solid lines in the figure are the subtropical anticyclone ridgelines represented by $u=0$ lines, but the trough lines indicated by $u=0$ have been removed based on the property that Φ gets maximum in φ direction along zonal wind zero lines. In the boreal winter the subtropical zone is covered by a zonal anticyclone whose ridgeline is

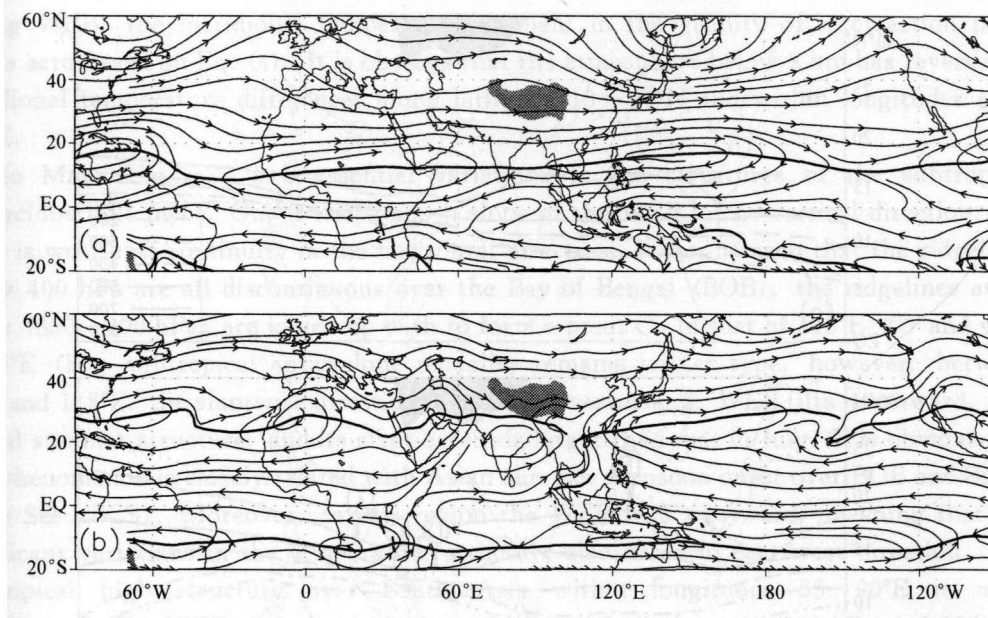


Fig. 1. Climatology of 500 hPa wind for (a) winter and (b) summer based on NCEP/NCAR reanalysis data for the period 1958–1997. Thick solid lines denote the subtropical anticyclone ridgelines. Shadings indicate the terrain above 3000 m.

consecutive and whose strength is not symmetrical. In summer the subtropical anticyclone belt is cut off by Asian monsoon low and the central Pacific trough. Meanwhile, the ridgeline of the subtropical anticyclone is broken over these two areas. This pattern merely manifests the features of the middle tropospheric circulation.

To reveal the spatial structure of subtropical anticyclone, the WEB's projections are shown in Fig. 2. According to the distributions of subtropical anticyclone ridgelines we can know the three-dimensional structure of the WEB and whole subtropical anticyclone belt. In January (Fig. 2a), it is found that all ridgelines are continuous curves from 850 hPa to 200 hPa, and the ridgelines collocate southward from the lower to upper troposphere. This means that the WEB tilts southward with increasing height. In July (Fig. 2d), the ridgelines in middle and upper troposphere locate at 25–30°N. The WEB keeps southward tilting to the east of 148°E and to the west of 22°E, indicating the basic thermal state that atmosphere near WEB is warmer on south side than on the north side. But the WEB tilts northward or is vertical to the ground over the Afro-Asian monsoon area. The extent of northward tilt is relatively more significant over China coast. It is in this region that the western Pacific subtropical anticyclone in the middle troposphere is tied in the South Asian high in upper troposphere. The ridgelines below 400 hPa are discontinuous.

In April the subtropical anticyclone belt basically keeps winter modality, it remains southward tilting (Fig. 2b). But between 60°E (intersection B) and 110°E (intersection A), 850-hPa ridgeline moves to south of 700-hPa ridgeline. That is to say, the WEB in the lower troposphere first overturns within these longitudes. The ridgeline at 850-hPa even reaches south of that at 500-hPa between 95°E (point D) and 105°E (point C). The intersection points represent the vertical ridge-axis that is perpendicular to the ground

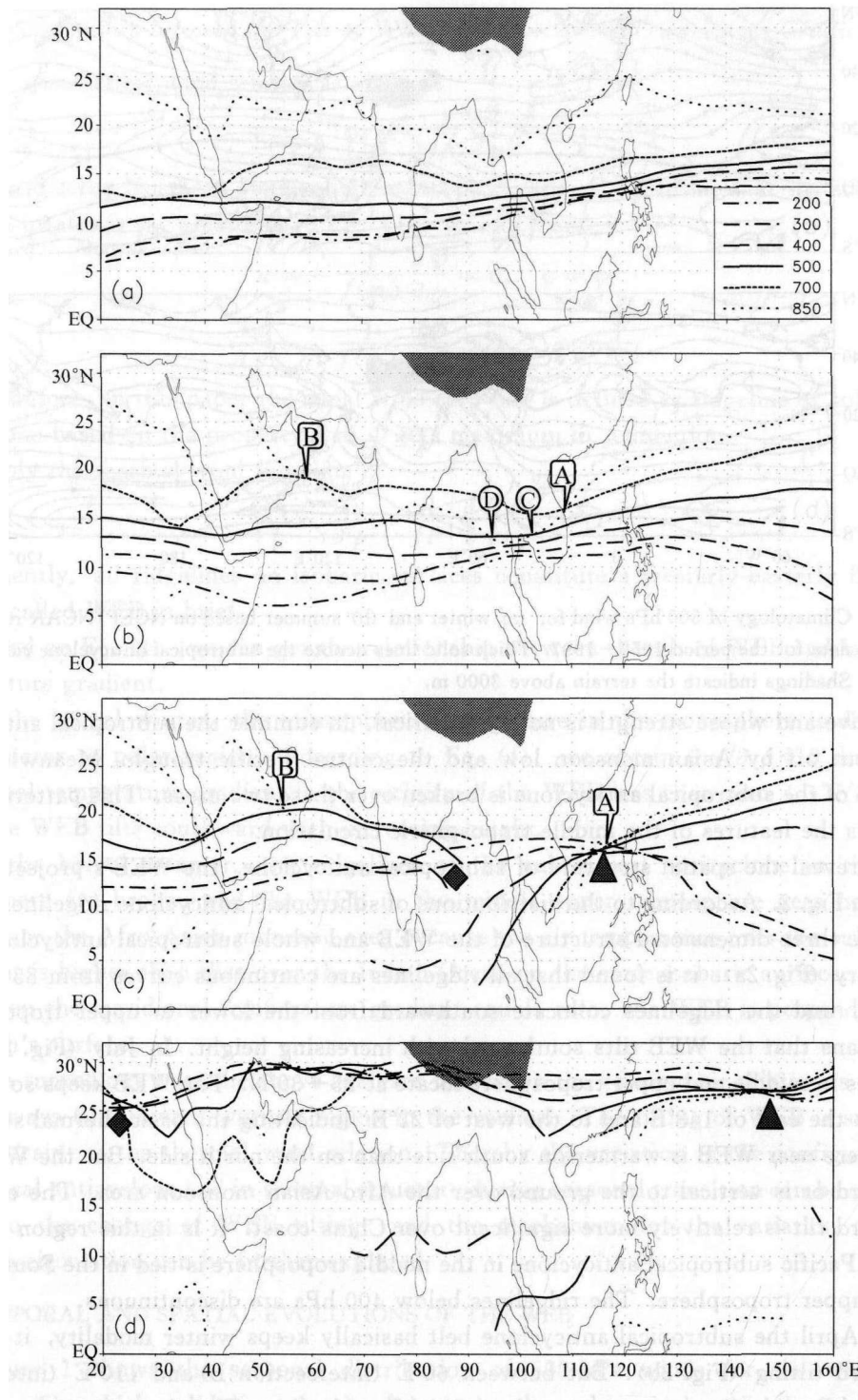


Fig. 2. Distributions of subtropical anticyclone ridgelines for (a) January, (b) April, (c) May, and (d) July. Thick solid lines denote the subtropical anticyclone ridgelines. The numbers in legend denote the isobaric surfaces. Shadings indicate the terrain above 3000 m.

among WEB, the meridional temperature gradient in the vicinity of intersection point equals zero based on Eq. (4). It is obvious that the atmosphere below 3 km has reversed in meridional temperature differences along latitudes 10–20°N and within longitudes 60–110°E.

In May (Fig. 2c), two essential variations in the structures of the subtropical anticyclone take place. One is north-south slope of the WEB in the vertical direction, the other is west-east continuity in the horizontal direction. It can be seen that the ridgelines below 400 hPa are all discontinuous over the Bay of Bengal (BOB), the ridgelines at all levels (850–200 hPa) are joined up with to form a point C. In east of 115°E (C) and west of 55°E (B), subtropical anticyclone modality remains winter type, however, between 90°E and 115°E, the slantwise direction of WEB is overturning. WEB tilts northward, it is typical summer structure, and its slant extent is larger than that in July. It is obvious that this phenomenon is closely related with Asian summer monsoon onset over BOB and South China Sea (SCS). Moreover, in this region the WEB tilts westward, meaning that the significant variations in the temperature structure also occur in east-west direction. The subtropical high structure over South Asia within longitudes 55–90°E is more complicated. The WEB of the main body over central India between 700 hPa and 300 hPa tilts southward, the part of the WEB above 300 hPa tilts northward instead. Therefore, it is inferred that a warmer center exists in the middle troposphere over South India (5–13°N). The "discontinuity" shows that the ridgelines at middle and lower levels break near 90°E. Therefore the primary continuous ridgeline at arbitrary level forms two segments, the position of the eastward extending ridge point staggers several latitudes or several longitudes with that of westward extending ridge point. The distributions of ridgelines at 500 hPa and 400 hPa resemble the situation that the central Pacific trough cuts off subtropical anticyclone belt (Li and Chou 1998). Zonal continuous ridgelines at 200–300 hPa indicate that the South Asian high develops. Thereupon, the structures of subtropical anticyclone belt over Northern Africa, Asia, and western Pacific get more complex and diverse.

In a word, we can find at least several facts as follows: 1) In climatology, the subtropical high whose ridgelines at all levels are consecutive in wintertime takes on relatively symmetrical and zonal structure, the WEB tilts southward with height increasing; the mean position of the WEB is more close to equator; 2) In summer and the Afro-Asian monsoon area, the ridgelines of subtropical anticyclone in the middle and lower troposphere are discontinuous and continuous at upper levels, the WEB tilts northward or is perpendicular to the ground from the bottom up. The mean position of the WEB locates 25–30°N. The slantwise extent of the main body of South Asian high is small, and it belongs to equivalent barotropic structure; 3) The reversal of meridional temperature in the atmosphere below 3 km occurs in April along latitudes 10–20°N and within longitudes 60–110°E; 4) May is the period when the subtropical anticyclone modality most significantly varies. The structure and properties of subtropical high during seasonal transition are different from area to area.

IV. THE BREAKING PROCESS OF THE SUBTROPICAL ANTICYCLONE BELT

It is clearly shown from climatological chart (Fig. 2c) that the breaking of the subtropical anticyclone belt occurs in the middle and lower troposphere in May. To reveal the process of the subtropical anticyclone belt, pentad mean NCEP data are used to explore the temporal and spatial variation during transition season in detail. Figure 3 shows the climatological projections of WEB from the 3rd pentad of April to 2nd pentad of June. In 3rd pentad of April, 850-hPa ridgeline has intersected with 700-hPa ridgeline, the intersection points A and B are situated over western SCS and northwestern Arabian Sea, respectively. Within A and B, the WEB below 700 hPa tilts northward due to secondary land-sea thermal contrast resulting from the distributions of Arabian Sea, Indian Peninsula, Bay of Bengal, Indo-China Peninsula, and South China Sea. From 3rd pentad of April to 5th pentad of April the structure of the subtropical anticyclone in Afro-Asian monsoon area outside A and B pertains to winter pattern. The slanting degree of WEB is smaller over BOB—Indo-China Peninsula than over other areas. This indicates that the temperature difference over here is much smaller than over other longitudes in whole troposphere. In 5th pentad of April, the WEB tends to tilt southward within 700—200 hPa, but the three ridgelines on isobaric surface 400 hPa, 300 hPa, and 200 hPa are joined up with to form a point C near 99°E, it indicates that the vertical ridge axis appears earliest in the upper troposphere over eastern BOB. Subsequently, the ridgelines in the vicinity of intersection C are close and then another intersection point E occurs to west of C in 6th pentad of April.

The intersection point D occurs near 90°E in the 1st pentad of May. The overlap of ridgelines at 300, 400, and 500 hPa levels means that the essential variation takes place in the middle-upper troposphere over longitudes 90—100°E, the meridional temperature gradient turns $\partial T/\partial y < 0$ into $\partial T/\partial y = 0$ or $\partial T/\partial y > 0$. Semi-discontinuous 850-hPa subtropical high is cut off by monsoon low over BOB. In the 2nd pentad of May the intersections C and E move eastward to 106°E and shift westward to 75°E respectively, point D reaches 91°E, meanwhile, 700-hPa and 500-hPa ridgelines also congregate with the intersection C. Till the 3rd pentad of May, the WEB between C and D displays northwestward tilting owing to northward extrusion of upper ridgelines and southeastward extension of lower ridgelines. Thus, the summer modal subtropical high firstly occurs over eastern BOB to Indo-China Peninsula at the beginning of May.

The configuration of subtropical anticyclone in 4th pentad of May is almost the same as monthly mean pattern (Fig. 2c). After 500-hPa and 400-hPa ridgelines are broken, they deflect toward south. Because point C locates in central and eastern SCS and 850-hPa ridgeline abruptly jumps to north of 20°N, SCS summer monsoon bursts. When vertical ridge axes E and D move westward and arrive at central and western India in 1st—2nd pentad of June, which indicates Indian summer monsoon onset.

Based on the formation and evolution of vertical ridge axes C, D or E, we propose to define the vertical ridge axis as "seasonal transition axis" that denotes alternate winter and summer. The seasonal transition axis C occurs in the first place over 12.5°N, 99°E in 5th pentad of April, transition axes E and D come into being in 6th pentad of April and 1st

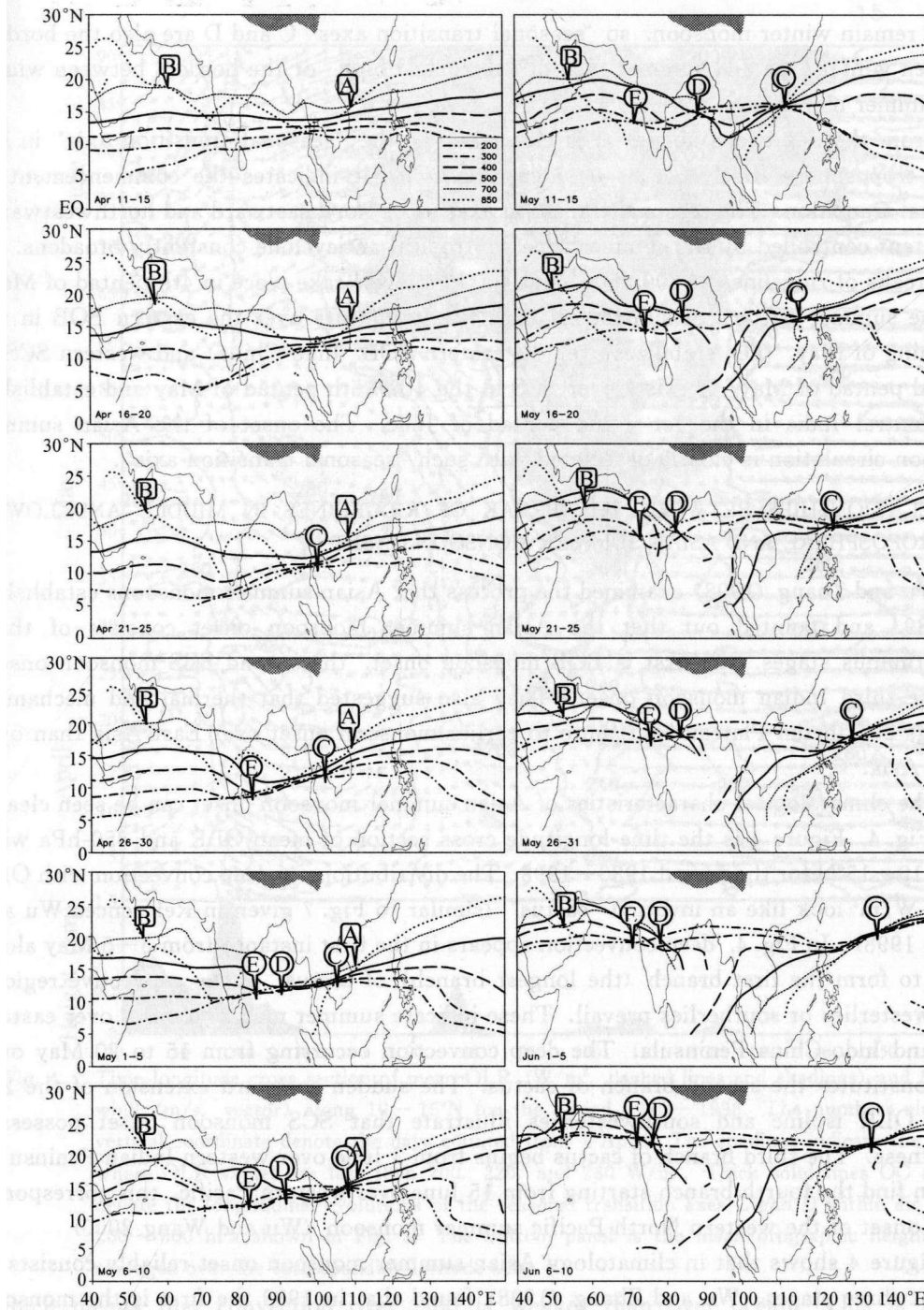


Fig. 3. The projections of the WEB in the troposphere (850–200 hPa) for 3rd pentad of April to 2nd pentad of June. Thick solid lines denote the subtropical anticyclone ridgelines. The numbers in legend denote the isobaric surfaces. Shadings indicate the terrain above 3000 m.

pentad of May respectively. When C, D or E move northeastward and northwestward, the summer type subtropical high broadens its extent. Figure 3 shows that from 2nd pentad of May in the region between C and D prevail southwesterlies, and other regions outside C

and D remain winter monsoon, so "seasonal transition axes" C and D are also the borders between winter type and summer type of subtropical high, or the borders between winter and summer monsoons.

From the depictions above, it is clear that 1) the "seasonal transition axis" in the upper troposphere firstly occurs over eastern BOB, it indicates the commencement of seasonal transition. The seasonal transition axes move northeastward and northwestward, the extent controlled by the summer type subtropical anticyclone constantly broadens. 2) The breaks of ridgelines at 700, 500, and 400 hPa levels take place in 4th pentad of May. 3) The summer pattern of subtropical high firstly appears over the eastern BOB in the beginning of May, then stabilizes over the eastern BOB, Indo-China, and western SCS in the 3rd pentad of May. It exists over SCS in the 4th—5th pentad of May and establishes over central India in the 1st—2nd pentad of June. The onset of the Asian summer monsoon circulation is closely associated with such "seasonal transition axis".

V. RELATIONSHIPS BETWEEN THE BREAK OF RIDGELINES IN MIDDLE AND LOWER TROPOSPHERE AND ASIAN SUMMER MONSOON ONSET

Wu and Zhang (1998) examined the process that Asian summer monsoons established in 1989, and pointed out that the Asian summer monsoon onset consists of three discontinuous stages, the first is BOB monsoon onset, the second SCS monsoon onset, and the third Indian monsoon onset. They also suggested that thermal and mechanical forcings of Tibetan Plateau contribute to earlier monsoon onset over East Asia than over South Asia.

The climatological characteristics of Asian summer monsoon onset can be seen clearly from Fig. 4. Figure 4 is the time-longitude cross section of mean OLR and 850-hPa wind along 10—15°N for the period 1980—1998. The distributions of deep convection with OLR < 230 W/m² look like an inverted "cactus" (similar to Fig. 7 given in References Wu and Zhang 1998). In Fig. 4, deep convection appears in the first instance from 3—5 May along 100°E to form the first branch (the longest branch) of cactus, in the convective region, southwesterlies or southerlies prevail. These indicate summer monsoon onset over eastern BOB and Indo-China Peninsula. The deep convection occurring from 15 to 20 May over SCS constitutes the second branch of cactus. The sudden eastward extension of the 230 W/m² OLR isoline and southwesterlies illustrate that SCS monsoon onset possesses abruptness. The third branch of cactus begins from 3 June over western Indian Peninsula. We can find the fourth branch starting from 15 June over western Pacific, this corresponds to the onset of the western North Pacific summer monsoon (Wu and Wang 2000)

Figure 4 shows that in climatology Asian summer monsoon onset reliably consists of at least three stages. Wu and Zhang (1998) found that in 1989 the first is the monsoon onset over eastern coast of the BOB in early May, and is followed by the onset of East Asian monsoon over SCS by 20 May, then the onset of the South Asian monsoon over India by 10 June. It is obvious that the case of 1989 is similar to climatological state, so the results derived from 1989 is representative.

By the way, the regions where the OLR value is greater than 230 W/m² just correspond to the locations with the higher terrain such as 75—85°E and 105—110°E,

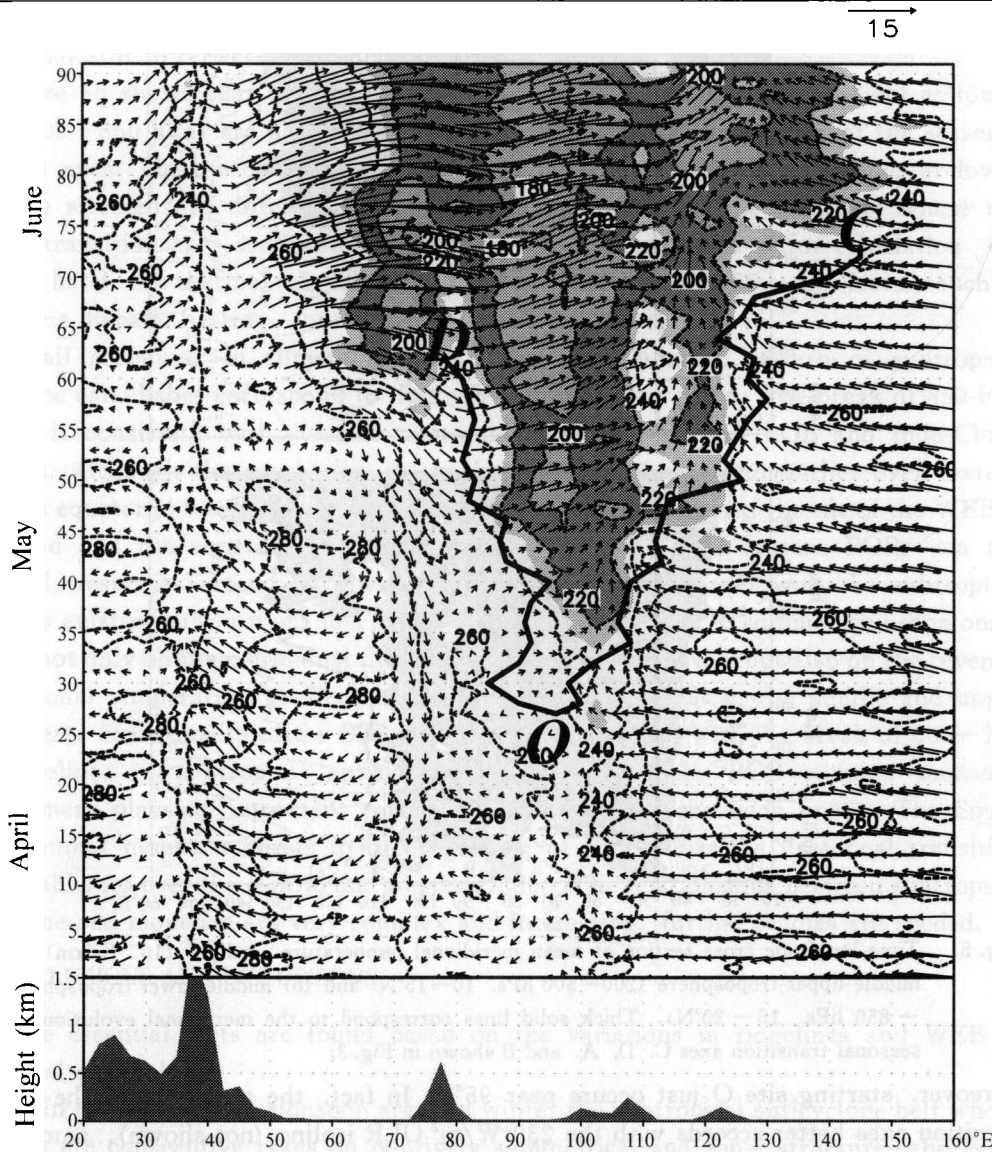


Fig. 4. Time-longitude cross section of mean OLR (W/m^2 , dashed lines and shadings) and 850 hPa wind (m/s, vector) along $10 - 15^\circ N$ for the period 1980 - 1998. The numbers along the vertical coordinate denote the days counted from 1 April. The shadings indicate the regions where OLR values are less than 200, 220, and 230 W/m^2 . Thick solid lines OC and OD denote the longitudinal evolutions of the seasonal transition axes C and D within air column 200 - 500 hPa shown in Fig. 3. The bottom panel is the mean orographic height (km) averaged over the corresponding latitude zone.

which means that convection over land is weaker than over ocean. This is in good agreement with Nakazawa's result (1992).

The thick solid lines OC and OD denote the meridional evolutions of the seasonal transition axes C and D, respectively (Fig. 4). We can find that OC and OD almost overlap with the $240 W/m^2$ OLR isolines. If the $230 W/m^2$ is defined as deep convection threshold, the strong ascending motions happen between OC and OD. This substantiates again that "seasonal transition axis" is the border of summer monsoon activities.

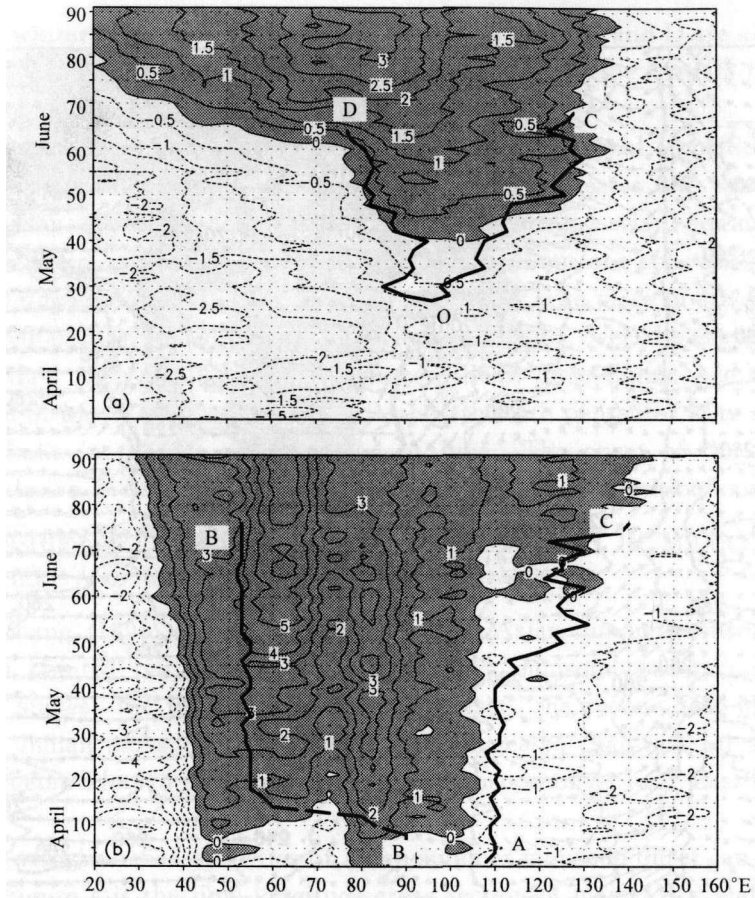


Fig. 5. Time-longitude cross section of mean meridional temperature gradient (10^{-3}K/km) for (a) middle-upper troposphere (200–500 hPa, 10–15°N) and (b) middle-lower troposphere (700–850 hPa, 15–20°N). Thick solid lines correspond to the meridional evolutions of the seasonal transition axes C, D, A, and B shown in Fig. 3.

Moreover, starting site O just occurs near 95°E. In fact, the trajectory of the seasonal transition axes better accords with the 230 W/m^2 OLR isoline (not shown), namely, the seasonal transition axes between 300 and 500 hPa represent the boundary more accurately than that within 200–500 hPa. But for comparison with other studies, 200–500 hPa is chosen to delegate the middle-upper troposphere all the same in this paper. Above analyses show how intimate the relationships are between the seasonal transition establishment and Asian summer monsoon onset.

Since the tilting direction of the WEB and the break of ridgelines in the lower troposphere have relevance to monsoon onset, and the slope of the WEB depends on the meridional temperature gradient, the meridional temperature gradient is inevitably capable of reflecting the seasonal transition or monsoon onset. Figure 5 shows time-longitude sections of mean meridional temperature gradient for middle-upper and middle-lower troposphere. The zero isolines of meridional temperature gradient at middle-upper levels are surely coherent with OC and OD that are the trajectories of the seasonal transition axes C and D (Fig. 5a). Therefore, both OLR and the meridional temperature gradient can be

used as indicator to reflect Asian monsoon onset.

Figure 5b shows that the zero isolines of meridional temperature gradient at lower levels (700–850 hPa) are not well consistent with the track BB and AC of the seasonal transition axes. On the one hand, because the latitudes where the ridgelines at lower levels are situated are different from longitude to longitude, the positions where the seasonal transition axes are located exceed the selected latitude zone for calculation. On the other hand, the thermal relation is not valid at lower levels due to other factors such as asymmetric diabatic heating.

On all accounts, in climatology the stages that summer pattern of subtropical anticyclone establishes correspond to that of Asian monsoon onset. The break of 850-hPa ridgeline is consistent with summer monsoon onset over eastern BOB and Indo-China Peninsula, although the southerlies in the lower troposphere occur earlier over eastern BOB, the equatorial westerlies do not extend northward. Only when the tilt of the WEB is overturned and the sign of zonal wind shear is inverted over eastern BOB, can the equatorial westerlies extend northward in great scale and connect with the subtropical westerlies existing to south of the Tibetan Plateau. Thus the BOB summer monsoon onset depends not only on the meridional thermal contrast at lower levels but also on the reversal of meridional temperature gradient in the vicinity of the WEB in the middle and upper troposphere. Simultaneity of the SCS summer monsoon onset with the break of 400–700 hPa ridgelines of subtropical anticyclone indicates that the BOB summer monsoon establishment plays an important role in the SCS summer monsoon onset. The South Asian summer monsoon bursts in the beginning of June when the “seasonal transition axis” establishes over the central and western India. The relationships between subtropical anticyclone and monsoon are very complex and interesting, further studies are needed.

VI. CONCLUSIONS AND DISCUSSIONS

Some essential facts are found based on the variations in ridgelines and WEB of subtropical anticyclone.

(1) In the Afro-Asian monsoon area, in winter the subtropical anticyclone belt whose ridgelines are consecutive takes on relatively symmetrical and zonal structure, the WEB tilts southward with increasing height. In summer, the subtropical anticyclone belt is discontinuous in the lower troposphere and continuous at upper levels, the WEB tilts northward or is perpendicular to the ground from the bottom up. Under the constraint of thermal wind relation, the WEB is always tilted toward warmer region in the vertical. May is the period when the subtropical anticyclone modality most significantly varies.

(2) A new concept “seasonal transition axis” of subtropical anticyclone is proposed. The “seasonal transition axis” indicates either the start of alternate winter and summer or the borders between winter and summer monsoons. The subtropical high of summer pattern firstly appears over the eastern BOB in the beginning of May, then stabilizes over the eastern BOB, Indo-China, and western SCS in the 3rd pentad of May. It exists over SCS in the 4th–5th pentad of May and establishes over central India in the 1st–2nd pentad of June. The onset of the Asian summer monsoon is closely associated with such “seasonal transition axis”.

(3) In climatology the stages of summer modal subtropical anticyclone establishment well correspond to that of Asian monsoon onset. The BOB summer monsoon onset depends not only on the meridional thermal contrast at lower levels but also on the reversal of meridional temperature gradient in the vicinity of the WEB in the middle and upper troposphere. Simultaneity of the SCS summer monsoon onset with the break of 400–700 hPa ridgelines of subtropical anticyclone indicates that the BOB summer monsoon establishment plays an important role in the SCS summer monsoon onset. The meridional temperature gradient in the middle-upper troposphere can be used as a uniform indicator for measuring the Asian seasonal transition and monsoon onset.

In boreal spring, temperature differences between polar region and equator gradually decrease with solar radiation increase. The differential heating of various space-scale exists in Asian monsoon region. There are thermal contrasts with not only the planetary scale but synoptic scale as well. This secondary land-sea differential heating helps to the earlier overturning of the WEB at lower levels. Our results show that the BOB summer monsoon onset depends to a great extent on the reversal of meridional temperature gradient in the vicinity of the WEB in the middle and upper troposphere. However, it seems that this explanation should not satisfy us. We ought to explore its intrinsic mechanism — what factors or processes cause the reversal of the meridional temperature gradient.

It is pointed out based on the above analyses that the formation and variations of atmospheric temperature field radically result from the interactions between thermal and dynamical factors. Which factors induce the first reversal of the meridional temperature gradient and the break of ridgelines at lower levels over eastern BOB? These questions will be discussed in the subsequent part of this research.

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