Article ID: 1006-8775(2004) 02-0160-11

CHARACTERISTICS OF THE NORTHERN HEMISPHERE SUB-TROPICAL HIGH SEASONAL SPLITTING OVER THE ASIAN MONSOON SECTORS AND ITS POSSIBLE MECHANISM

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ABSTRACT: The splitting of the Northern Hemisphere sub-tropical high (SH) during spring to summer and its possible mechanisms has been analyzed. Results indicate that the splitting of SH occurs over the Bay of Bengal to the Indo-China peninsula. However, remarkable contrast exists in the Hadley cell at the lower and upper levels over these sectors during March to May. The land surface sensitive/latent heating both play an important role, and decay the local Hadley cell over the Indo-China peninsula by enhancing the upwelling. In contrast, the dominant land surface sensitive heating over the Bay of Bengal only damages the low-level Hadley cell. Thus, the splitting of SH should occur over the Indo-China peninsula, rather than the Bay of Bengal at lower levels. In addition, the analysis suggests that the faster seasonal snow melting in the east of Indo-China peninsula can enhance the land surface sensitive heating atmosphere and weaken the local Hadley cell, such seasonal change benefits the splitting of the SH.

Key words: seasonal transition; sub-tropical high splitting; mechanism analysis

CLC number: P424.4 **Document code**: A

1 INTRODUCTION

The Northern Hemisphere subtropical low-middle troposphere is dominated by a high-pressure zone, which is called subtropical high (SH). The SH often exhibits a cell with an enclosed circulation center in summer. According to its center location, the SH can be further divided into the North African high, Iranian high, western North subtropical Pacific high (WNPSH) and North American high during the boreal summer. The WNPSH is dominated by the westerly and easterly winds at mid-latitude to its north and south of tropical regions, respectively, therefore, it plays a very important role in the interactions between the middle and lower latitudes circulations. The weather and climate in East Asia are greatly influenced by the WNPSH; evidence suggests that the onset of South China Sea (SCS) summer monsoon and Mei-yu (monsoon rainfall) in the middle and lower reaches of the Yangtze River are closely related with the activity of the WNPSH[1].

The SH exhibits a remarkable seasonal change, it is weak and southward in winter, and strong and northward in summer. In the meanwhile, it exhibits an obvious east-west and north-south propagating in association with seasonal shifts of the atmospheric heating. Previous studies have documented the mechanism that the SH splits into a number of cells in summer[2, 3].

Received date: 2003-05-03; revised date: 2004-08-20
Foundation item: Project "863" (2002AA135360); Key Project from the National Natural Science Foundation of China (40135020); National Natural Science Foundation of China (40375014); Funding Program for Outstanding Young Teachers from the Ministry of Education; Open Project from LASG of the Institute of Atmospheric Physics of the Chinese Academy of Sciences
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For example, Li and Chou[4] dynamically examine and suggest that the splitting of the SH can be explained by the atmospheric internal dynamics. However, it is noted that the SH starts to break up over the Asian monsoon region in early spring, and the cells are not distinct until summer, therefore, It still unclear what results in the SH first splits during the seasonal change.

He et al.[5] explored the seasonal change of Asian monsoon circulations on the basis of TBB data, they found that the splitting of the SH occurs over the Indochina Peninsula as early as in April. Guo's analysis[6] suggests that the SH splitting is linked with the seasonal reversal of sea surface temperature (SST) over the Bay of Bengal during March and April. The summer onset occurs firstly over the low latitudes of Asia, and the outbreak of convection over the Indochina Peninsula is considered as a precursor of summer season, therefore, the early split of the SH over the Asian monsoon region suggests that there is close relationships between the change of the SH and land-sea thermal contrast. In this study, we are to explore the characteristics of regional circulation, and document the possible mechanisms responsible for the splitting of the SH over the Asian monsoon region during March to May. We focus local Hadley cell, SST, snow cover, land surface, and circulation with respect to the seasonal change of SH to address this issue.

2 DATASETS

The climatological monthly sensible and latent heat on 2.5° × 2.5° in grids were derived from the NCEP/NCAR reanalyzed dataset during 1982–1994. The SST was from the U.K. Meteorological Office, which covers the period 1980–1994 in 1° × 1° on grids. The percentages of snow cover were provided by the satellite observations by the Japan Meteorological Agency (JMA) for the period 1987 – 1996, with a resolution of 1° × 1° for the grids. The climatological pentad mean OLR fields from NOAA's 1979 – 1994 satellite observations with a resolution of 2.5° × 2.5°. The pentad-based TBB climatological mean fields are from 1980–1994 satellite observations by GMS of the JMA with a resolution of 2° × 2°. Therefore, all data except the snow cover give us a picture of climatology during early 1980's to the early 1990's.

3 RESULTS

3.1 *Seasonal variations of the SH*

Fig.1 shows seasonal variation of the 500-hPa geopotential height (GPH). We chose the counter of 586 to trace the seasonal evolution of the SH, and found that the Iran high, WNPSH and North America high mainly display as splitting, merging and re-splitting during their east-west and north-south shifts, and the earliest splitting of the SH occurs in late spring over the Bay of Bengal, which is mainly characterized by the zonal merging of cells in the early period (February – March) and splitting of cells along 15°N before they are migrating eastwards or westwards. Similar features can also be found by OLR (the figure was not shown). For instance, we chose the threshold of 250 W/m^2 to outline the SH, then found that before April, the SH mainly exhibits merging over the Asian monsoon region, it begins to split in April over the Indochina Peninsula, after that, the two individual cells, namely the WNPSH and Iran high start to propagate towards east and west, such findings are consistent with the previous study based on TBB analyses by He et al.[4]

The seasonal change of SH starts to break up might firstly takes place over the Bay of Bengal to the Indo-China Peninsula. To determine the splitting time and location of the SH in the troposphere However, we chose the 16-year pentad-mean of OLR in order to avoid the limitation of 500-hPa GPH in reflecting the vertical structure, and selected the threshold of 250 W/m^2 to represent the dominated area of the SH[7]. Fig.2 shows time-longitude cross- section of OLR along 15°N between 80°E and 140°E. It is found that the value of OLR starts to decreases below 250 W/m^2 over the northeastern Indochina Peninsula around 105°E, Bay of Bengal, and South China Sea in Pentad 21, 24 and 27, respectively. It means that the splitting of the High, as reflected with OLR, first occurs over the Indo-China Peninsula instead of the Bay of Bengal. Similar results can be obtained with TBB data when the 250°K is used as the characteristic line of the SH (the figure was not shown).

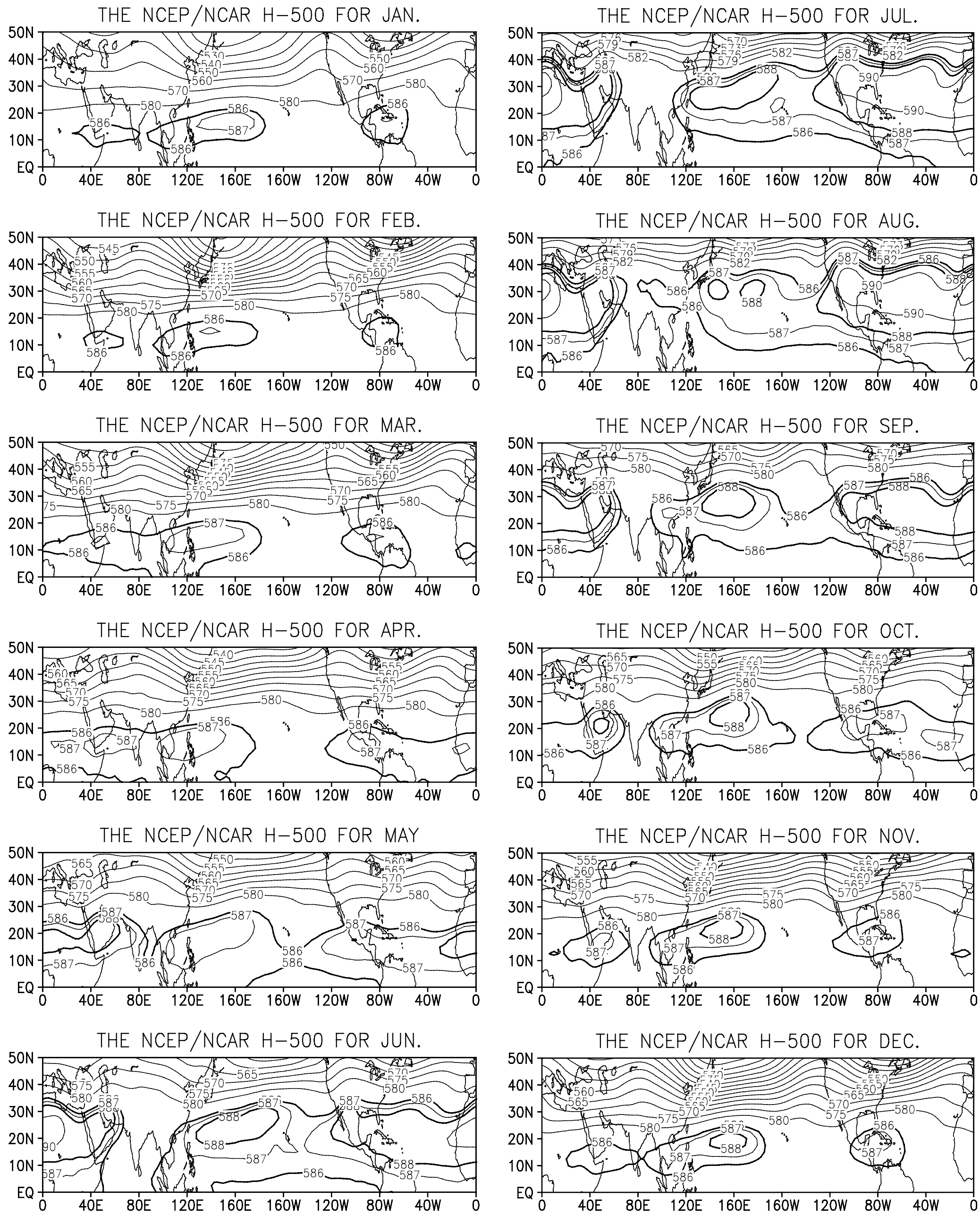

Fig.1 Seasonal change of climatological boreal 500-hPa geopotential height.

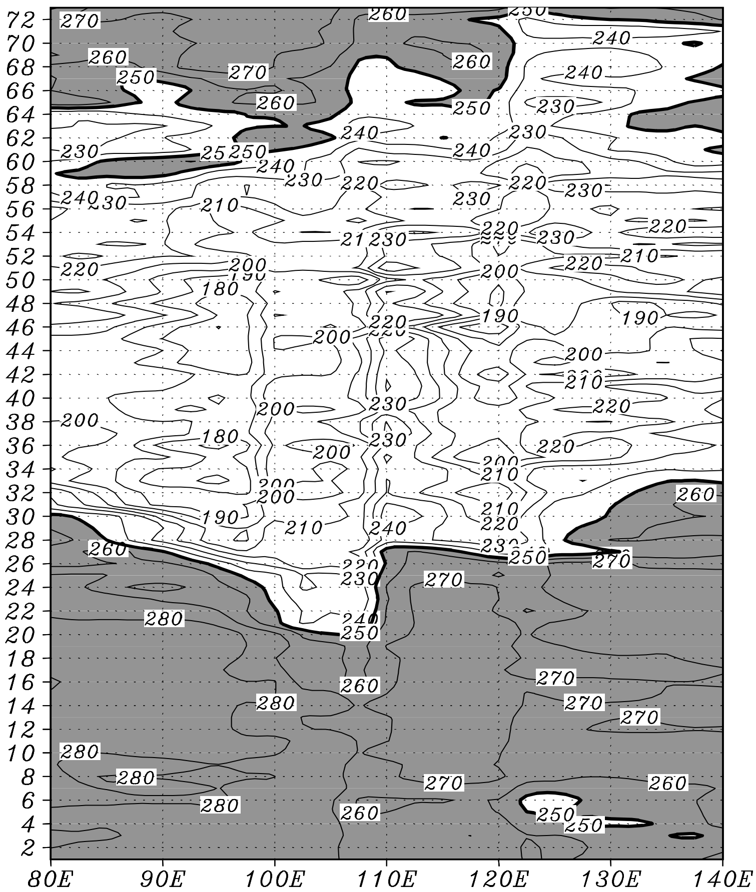

Fig.2 Time-longitude cross section of pentad-based climatologically averaged OLR along 15°N. The ordinate is the time (unit: pentad). The values larger than 250 W/m2 are shaded; the solid and bold lines mark the characteristic contours of 250 W/m2.

3.2 *Seasonal reversal of SST and local Hadley cell*

In the previous study by Guo's approach[6], it was suggested that the Indian Ocean SST first undergoes seasonal hemisphere reversal about the equator that may result in the earliest heating of the atmosphere by the ocean, such SST change might suppress the local Hadley cell over the SST reversal area and give rise to the first splitting of the High occur. To verify this argument, we calculate the Indian Ocean SST in terms of the antisymmetric mode about the equator during February to May (see Fig.3). It is found the first SST reversal occurs in Bay of Bengal of the Indian Ocean within 0° – 10°N in early March. In contrast, the SST reversal takes places in the South China Sea in April, and the Arabian Sea in May. Such results are consistent with Guo[6].

To analyze the seasonal variation of the local Hadley cells corresponding to the seasonal reversal of SST, we applied the meridional wind v and vertical velocity ω and plotted the latitude-altitude longitudinal cross-sections along 90°E and 105°E, respectively (Fig.4). Where the 90°E is directly affected by the SST reversal in contrast to that of 105°E. The local Hadley cell is clearly shown by the circulation around the 90°E with ascending center moving slowly from south to north. In April, however, the shape of the Hadley cell on this longitude is replaced by an anti-Hadley cell at lower-levels (1000–600hPa) over 15°N – 25°N. In May, the low-level anti-Hadley cell strengthens significantly and gives rise to a double Hadley cells structure in vertical. The appearance of the anti-Hadley cell suggests the early SST reversal about the equator and its subsequent effect on local circulation, it suggests that the enhanced local anti-Hadley cells

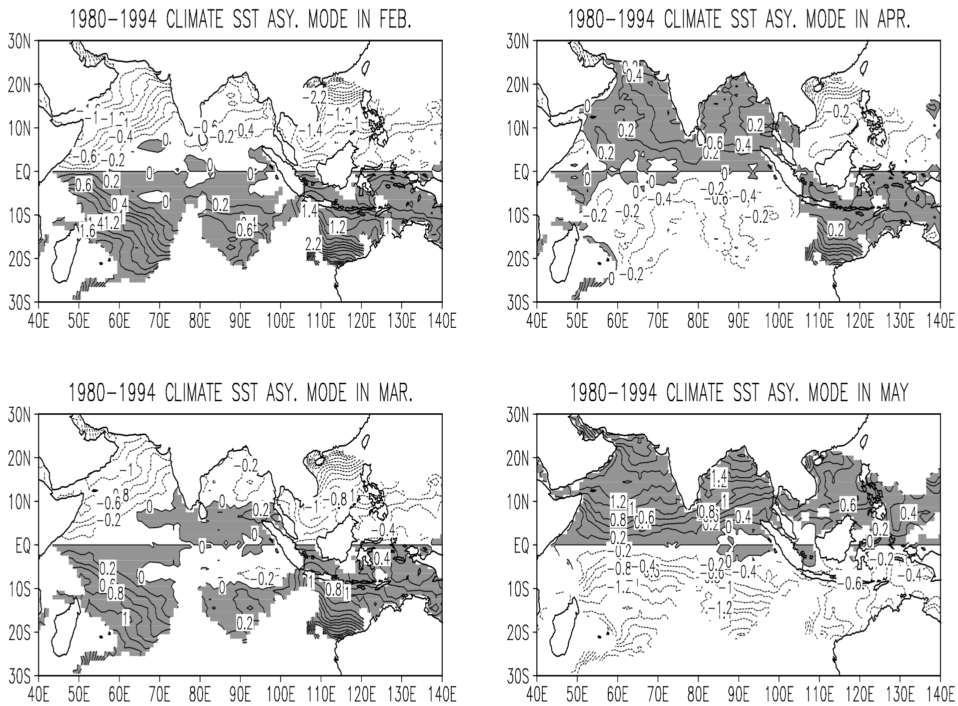

Fig.3 Seasonal evolution of anti-symmetric modes of SST about the equator during February – May. The areas, where the SST is positive are shaded (the SST are from U.K Meteorological Office with 1°×1° in resolution)

over the eastern Indian Ocean is responsible for the splitting of the SH in the lower troposphere, which agrees with the previous observation that the SH splitting first occurs in the region of the Bay of Bengal. However, we did not find any remarkable change on the Hadley cell structure in the upper troposphere. The meridional circulation on the 105°E indicates the local Hadley cell over the Indo-China Peninsula. It is found that its southern ascending branch is mainly over the equator, where the ascending motion is increasing in the near-surface layer at 10°N – 30°N from February to May. In April, the ascending motion has became very strong and developed to the entire column of atmosphere in south of 20°N, In May, no clear structure of Hadley cell can be found on the longitude. Therefore, the Hadley cell is broken up in April as a whole occurs on this longitude.

The Hadley cell over the regions of Bay of Bengal and Indo-China Peninsula show quit difference in the upper-level atmosphere above 600hPa. During the seasonal transition from February to May, circulation over the Bay of Bengal region is dominated by a distinct structure of the Hadley cell, possibly due to the cooling effect of the plateau on the atmosphere in winter. In contrast, circulation over the region of Indo-China Peninsula, where the Hadley cells is gradually disappearing. Such different changes suggests that the early reversal of SST over the Bay of Bengal only decay the structure of the Hadley cell in the lower-level of troposphere.

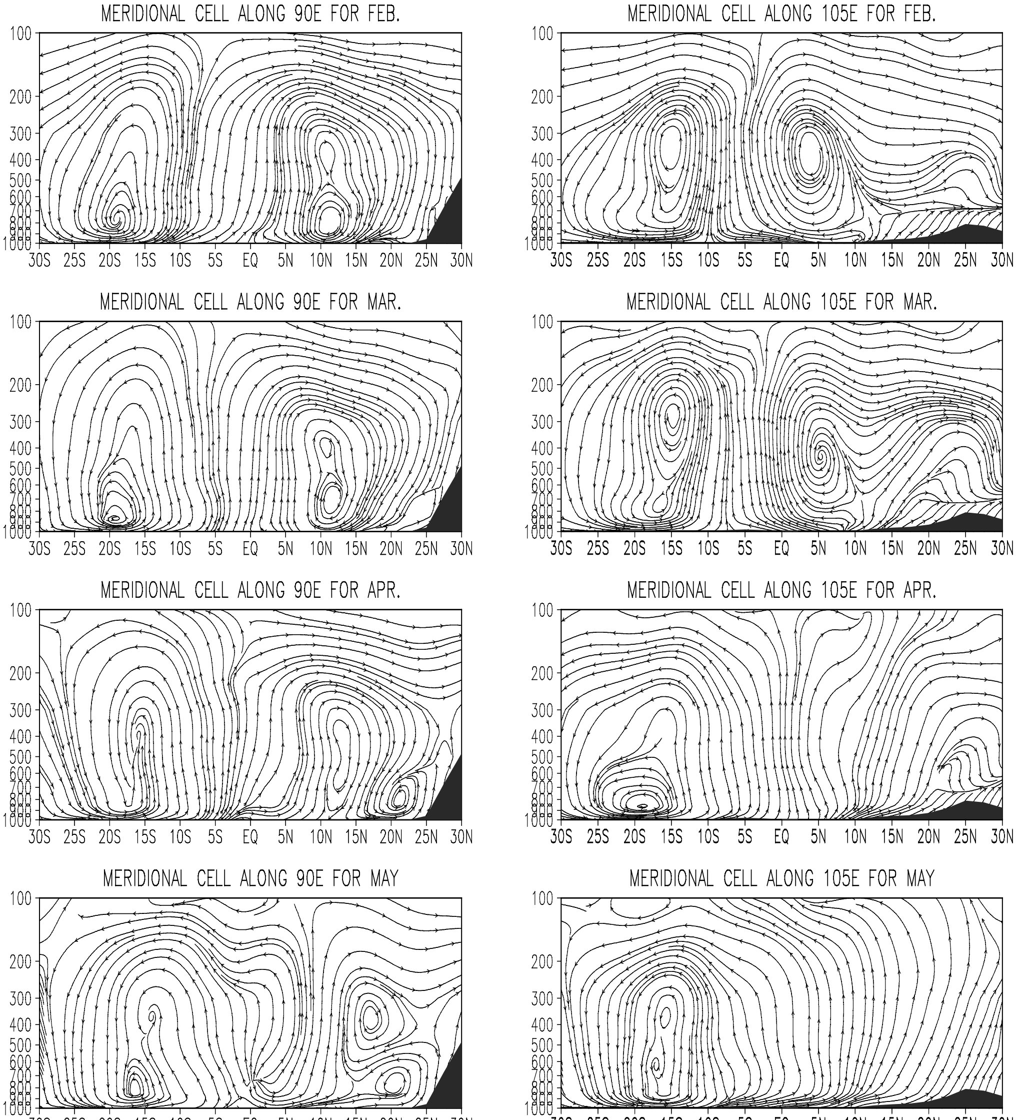

Fig.4 Latitude-altitude cross-section of meridional circulation on the 90°E and 105°E during February to May. The vertical velocity has been multiplied by 100 times and shaded areas are terrain.

Because the changes of Hadley cell structure over the Indo-China Peninsula first take place at low-latitude continent, then, it can be inferred that it may be related with the change of the thermal condition over the lands at the low-middle latitudes, where the SST reversal causes little effect on the circulation.

3.3 *Surface thermal condition and its effects*

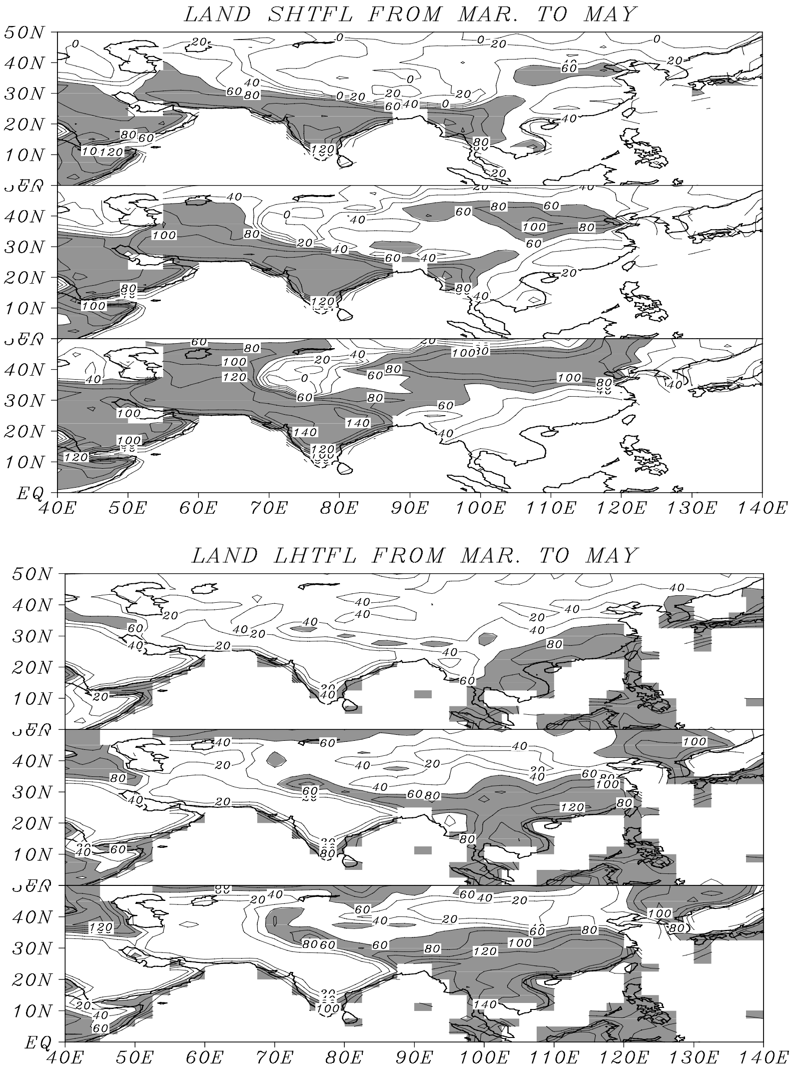

Fig.5 Continental surface fluxes of sensible heat (a) and latent heat (b) during March to May. The contour interval is 20 W/m^2. The panels indicate the changes in March, April and May. The fluxes, greater than 60 W/m^2 are shaded.

The thermal condition over the continent can affect atmosphere by virtue of the sensible and latent heat fluxes. Fig.5 shows changes of the sensible and latent heat fluxes from March to May. Where, we can observe that in March, corresponding to the structure changes of the local Hadley cell on 90° and 105°E, there are four sensible heating centers with large values in southern China, northwestern Indo-China Peninsula, Indian Peninsula and Somalia Peninsula in Africa the Eurasian continent, respectively. In May, the sensible heat is half reduced in the Indo-China Peninsula but gradually increases in the middle latitudes of East Asia; the decrease of sensible heat in the low latitudes is replaced by the increase of surface latent heat (Fig.5b). It is, however, noted that surface sensible heat over the Indian Peninsula and Somalia Peninsula increase sharply in contrast to change of the latent heat. Suppose that the increased surface sensible heat cause the Hadley cell to decay and the High to split, then, the splitting SH should occur in the region of the Indian Peninsula near 80°E. Why doesn't the SH break up on that particular longitude?

To examine the possible effects of sensible heat on the circulation, we cut across the Indo-China and Indian Peninsulas and plotted the cross-sections of meridional cells roughly on 100°E and 77.5°E (see Fig.6). Corresponding to the increase of sensible heat flux in the Indian Peninsula, the structure of the Hadley cell starts to change. In February, we can observe a clear upwelling, merging with the down welling of the Hadley cell over the Northern Hemisphere before it downwards reaches the equatorial region, however, the structure change of the Hadley cell only occurs in the low-level atmosphere in contrast to that of Hadley cell on the 100°E, where the Hadley cell undergoes a major adjustment in March, the upwelling takes place throughout the whole column of atmosphere at low latitudes in April, and it results in the local Hadley cell decay in May.

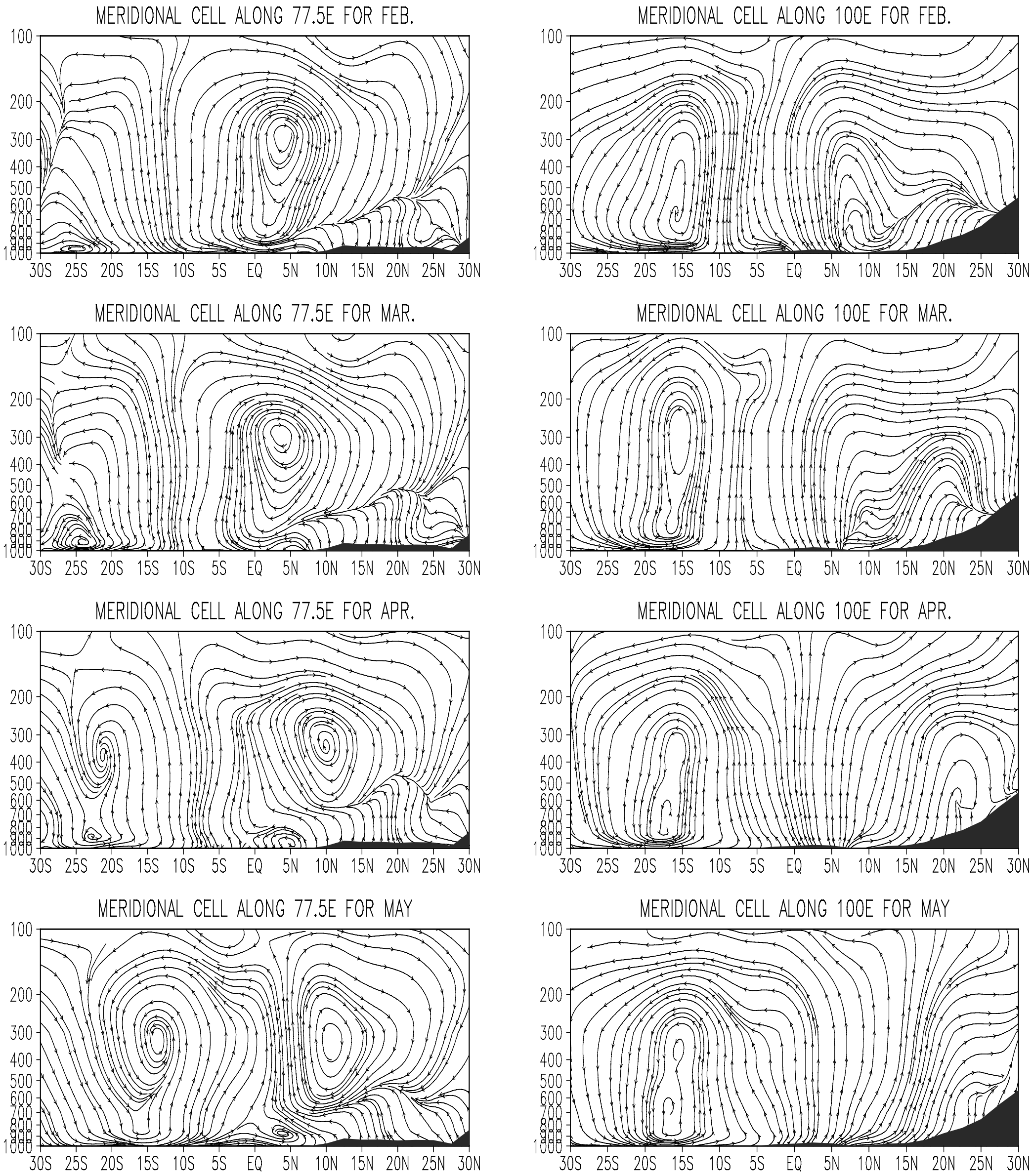

Fig.6 Same as Fig.4, but for the circulations on 77.5°E and 100°E.

It is noted that the magnitude of the sensible heat flux in the Indian region is much larger than that of in the Indo-China Peninsula, but why do the two regional Hadley cells differ so much? It is known that surface sensible heat is only one part of the atmospheric heating. Seasonal changes in the continental latent heat, which increase substantially in April, clearly shows that there are centers of latent heat in the south of China (100°E – 120°E) in March, and the value are larger than other regions. Such suggests that the sensible heat and latent heat, in the northeastern Indo-China Peninsula play an important role in heating the atmosphere, in contrast to the sensible heating in the region of India and Bay of Bengal. According to the time sequence of changes in sensible and latent heat, we can infer that the changes of Hadley cells during April to May, mainly comes from the regional latent heating. Because the weather in middle and lower latitudes in spring they are still dominated by the westerly winds, such westerly winds can produce an advection effect on the heating field, which makes the latent heating center away from the sensible counterpart, and settle latent heating center in the latter’s leeward region. It is then stated that the increase of sensible heat over the continental land surface is one of the reasons responsible for decaying local Hadley cell over the Indo-China Peninsula.

3.4 *Effects of snow cover*

Direct absorption of solar radiation by land surface is one of the immediate causes for sensible heat increasing over the continent. The presence of continental snow cover will also affect the land sensible heating and atmospheric circulations by following two processes. One is by the effect of albedo. Because its high reflectivity, snow cover reflects most of the incoming shortwave radiation, reduces the net input of solar radiation, and then suppress the heating effect by the land surface. The other is by consumption of heating. When snow starts to melt, it will suppress the land surface heating by enhancing the soil moisture[8]. Therefore, the snow cover always cools the atmosphere and delays season march. In contrast, the free snow cover may act the opposite role.

Fig.7 shows that seasonal evolution of snow cover over the Eurasian continent during March to May. It exhibits that all regions, but parts of the continent north of 45°N and mid-latitude Qinghai-Tibetan Plateau, except the basins are covered with snow in March; In April, the snow-covered areas start to decrease, and more significantly decreasing occurs in eastern plateau, however, the pattern remain the similar as it in March; in May, the snow cover undergoes great changes when the Asian snow except that in northeastern Lake Bajkal melt completely. It is observed during the period that the decreasing of snow cover were remarkable in the central area of the plateau, in contrast to that in the Pamirs in western China, but no snow cover is found at the middle and lower latitudes from 105°E to 120°E in East Asia, where the seasonal transition should first occur in these regions due to the regional sensible heating and free snow cover.

To revel the seasonal change of the snow cover and its possible influence on the local Hadley cell, we plotted the seasonal time-longitude cross-section of snow cover along 32.5°N, where it is related to large variability of snow cover and corresponding to the downwelling of Hadley cells (Fig.7b). It is observed that the Qingzang-Tibetan Plateau centered on 90°E and the areas west of 105°E, where the snow cover can sustain until June. In the east of 105°E, however, the snow cover can only stay until February. The areas between 75°E and 80°E is covered by snow cover almost in all seasons. The obvious seasonal changes of snow cover has been found between 85°E and 90°E, in contrast to less variability in west of 75°E. It is noted that the distribution and seasonal changes of the snow cover are close related with the counterparts of land sensible heat flux (see Fig.4), it means that much (less) sensible heat flux is corresponding to larger (smaller) snow covered areas.

The land-sea distribution exhibits mainly in south to north at low-latitude Asia. The variation of SST can change the thermal contrast. Similarly, the variation of continental thermal state will also result in changes of the land-sea thermal distribution. Based on the relationships between snow cover and sensible heating, we can infer that the continental sensible plays an important role in heating the atmosphere from winter to summer at low-middle latitudes of Asia. The atmosphere over the Indochina Peninsula is directly affected by the sensible heating, as a result the Hadley cell shows signs of weakening as early as in March. Because of more land surface sensible heating and the particular geographic location, the Indo-China peninsula is abundant in moisture and convection, which results in that the local Hadley cell is more vulnerable than that in other regions. Such explains why the boreal SH is easier to break up over this area during seasonal transition.

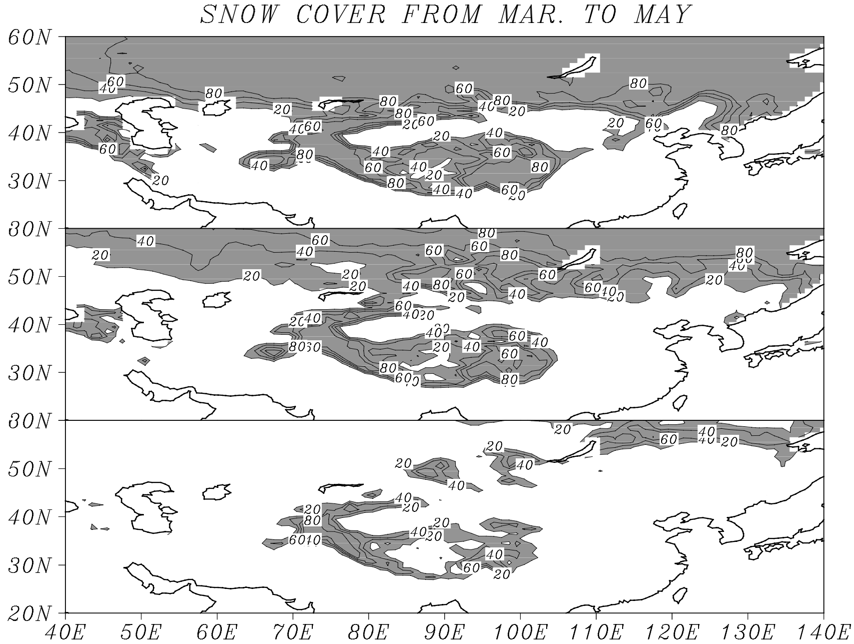

Fig.7a The seasonal evolution of snow cover percentage over the Eurasian continent from March to May. The resolution is 1°×1° and the panels indicate the changes in March, April and May.

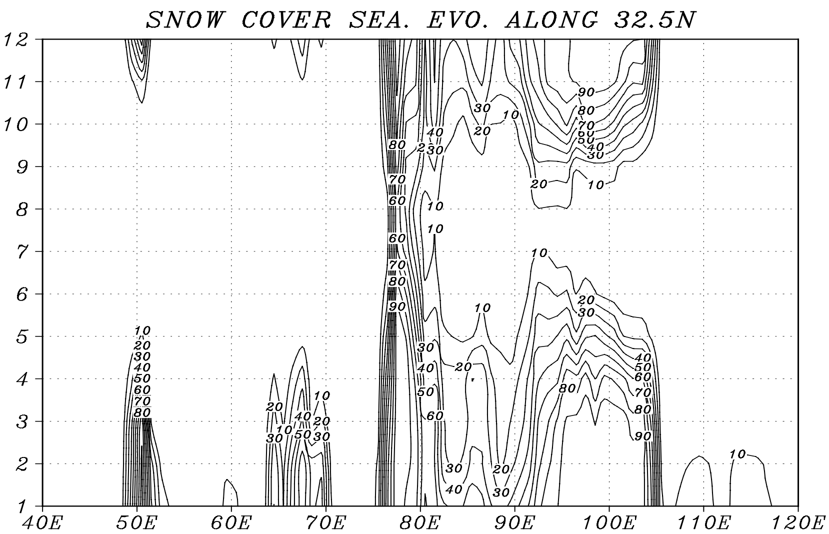

Fig.7b The time-longitude cross section of seasonal snow cover on 32.5°N from January to December.

4 CONCLUDING REMARKS

During the seasonal transition from spring to summer, the Northern Hemisphere SH in whole column of troposphere first split near 105°E over the Indo-China Peninsula in middle of April. After the split, two breakaway cells move toward the west and east, and dominant the Bay of Bengal and South China Sea, respectively.

The Hadley cells over the longitude of the Bay of Bengal and Indochina Peninsula show quite different change, especially at the upper-level atmosphere. The local Hadley cell changes first take place at lower troposphere over the Bay of Bengal, exhibited by a vertical double Hadley cells during March to May with respect to the land sensible heating; the Hadley cell over the Indo-China peninsula is dominated by upwelling throughout the whole column of the troposphere due to the combined land sensible and latent heating.

The hemispheric seasonal reversal of the Bay of Bengal SST can do nothing but decaying the Hadley cell at low-level troposphere over the Bay of Bengal. The adjustment of the Hadley cell in March over the Indochina peninsula is associated with sensible heating at low-middle latitudes in East Asia. The changes of local Hadley cell in April and May over the continent of South China, can be explained by the latent heating of the atmosphere. The decreasing snow cover over the Asian continent at the mid-latitudes shows lower speed in the west of the Tibetan plateau in contrast to that in the east, such changes give rise to the sensible heating increasing first occur at low-middle latitudes of East Asia in east of 105°E. The surface sensible heating is favorable for the decaying the Hadley cell, therefore, such large-scale seasonal climate background change benefits the splitting of the SH.

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