Impact of the Anomalous Thawing in the Tibetan Plateau on Summer Precipitation in China and Its Mechanism

GAO Rong*[1,2,4] (高 荣), WEI Zhigang[2] (韦志刚),
DONG Wenjie[1,3] (董文杰), and ZHONG Hailing[2] (钟海玲)

[1] *Key Laboratory of Regional Climate-Environment for East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, START Regional Center for Temperate East Asia, Beijing* 100029

[2] *Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou* 730000

[3] *National Climate Center, China Meteorological Administration, Beijing* 100081

[4] *Graduate School of the Chinese Academy of Sciences, Beijing* 100039

(Received 21 November 2003; revised 29 September 2004)

ABSTRACT

The impact of the anomalous thawing of frozen soil in the late spring on the summer precipitation in China and its possible mechanism are analyzed in the context of the frozen soil thawing date data of the 50 meteorological stations in the Tibetan Plateau, and the NCEP/NCAR monthly average reanalysis data. Results show that the thawing dates of the Tibetan Plateau gradually become earlier from 1980 to 1999, which is consistent with the trend of global warming in the 20th century. Because differences in the thermal capacity and conductivity between frozen and unfrozen soils are larger, changes in the freezing/thawing process of soil may change the physical properties of the underlying surface, thus affecting exchanges of sensible and latent heat between the ground surface and air. The thermal state change of the plateau ground surface must lead to the thermal anomalies of the atmosphere over and around the plateau, and then further to the anomalies of the general atmospheric circulation. A possible mechanism for the impact of the thawing of the plateau on summer (July) precipitation may be as follows. When the frozen soil thaws early (late) in the plateau, the thermal capacity of the ground surface is large (small), and the thermal conductivity is small (large), therefore, the thermal exchanges between the ground surface and the air are weak (strong). The small (large) ground surface sensible and latent heat fluxes lead to a weak (strong) South Asian high, a weak (strong) West Pacific subtropical high and a little to south (north) of its normal position. Correspondingly, the ascending motion is strengthened (weakened) and precipitation increases (decreases) in South China, while in the middle and lower reaches of the Changjiang River, the ascending motion and precipitation show the opposite trend.

Key words: Tibetan Plateau, thawing of frozen soil, summer precipitation

1. Introduction

The Tibetan Plateau is the largest and highest hypsographic plateau in the world. It covers one-fourth of the land area of China with an average height of about 4000 m above sea level. It has significant dynamical and thermal impacts on the atmospheric circulation, weather and climate changes over East Asia.

It is generally held that the ground surface of the Tibetan Plateau is a heat source from spring to winter, but the atmosphere over the plateau is a heat source from April to September and a heat sink from October to the next March; as far as the whole earth-atmosphere system is concerned, the plateau is a heat source in the summer half of the year and a heat sink in the winter half of the year (Zhang and Qian, 2002; Zhao and Chen, 2002; Zhou et al., 2002). Changes in the heat source/sink in the plateau region significantly affect the South Asia high (SAH), West Pacific subtropical high (WPSH), precipitation in eastern China,

*E-mail: gaorong@tea.ac.cn

and the establishments of the South Asian monsoon and East Asian monsoon. Snow cover is an important aspect of the thermal state of the ground surface of the plateau, and its variation reflects to a certain extent the change in the thermal state of the plateau, which further influences the circulation over East Asia (Li et al., 2001; Ren, 1991). Studies (Guo and Wang, 1986; Yang and Yao, 1998; Fan et al., 1997; Zhang and Tao, 2001; Chen et al., 2000; Luo, 1995; Wei et al., 1998; Feng et al., 2001) have indicated that in the positive anomaly years of snow cover over the plateau, the Asian summer monsoon is weak, its onset is late, and its northward progress is slow, the WPSH lies south of its normal position, and precipitation appears in the type II and III patterns in China (see below); in the negative anomaly years, the Asian summer monsoon is strong, its onset is early, and its northward progress is quick, the WPSH lies north of its normal position, and precipitation appears in the type I and II patterns in China.

Frozen soil is another important aspect of the thermal state of the ground surface of the plateau. The thermal conductivity and capacity of water are 0.57 W m^{-1} K^{-1} and 4.2 M J m^{-3} K^{-1} respectively, while those of ice are 2.2 W m^{-3} K^{-1} and 1.9 M J m^{-3} K^{-1}. The thermal conductivity of frozen soil with high ice content is higher than that of unfrozen soil containing an equal amount of liquid water, and its thermal capacity is also correspondingly reduced. Generally speaking, the freezing of soil results in a reduced thermal capacity, a greatly increased thermal conductivity, a reduced infiltration and an increased run-off in the ground surface layer, and those changes may obviously impact the change in the ground surface heat source. Numerical simulations have shown (Zhang and Lu, 2002; Slater et al., 1998; Wang, 2002) that changes in frozen soil might lead to the subsequent changes in the ground surface sensible and latent heat fluxes, thus inducing changes in the circulation over the plateau. Wang et al. (2003) suggested that if the frozen soil layer in the plateau is deep (shallow), the SAH is strong (weak) and lies east (west) of its normal position, and the WPSH is strong (weak) and lies west (east) of its normal position. In consequence, the anomalies of the summer precipitation are negative (positive) in Northeast China, north China, Southwest China, the middle reaches of the Changjiang River, and the south coast of China, and positive (negative) in the east part of Northwest China, the lower reaches of the Changjiang River and the southeast coast of China.

At present, the feedback mechanism of how the changes of seasonal frozen soil in the plateau impact the climate change is not well understood. The purpose of this paper is to explore the impact of the thawing of frozen soil in the Tibetan Plateau on the summer precipitation in China and its impact mechanism by using the frozen soil thawing date data at the 50 meteorological stations in the plateau, and the National Centers of Environmental Prediction/National Center of Atmospheric Research (NCEP/NCAR) monthly average reanalysis circulation data.

2. Thawing date series of frozen soil in the Tibean Plateau and its interannual variation

It was found from the distribution characteristics of seasonal frozen soil (Gao et al., 2003) that there are inhomogeneity in the spatial distributions of the seasonal frozen soil in the plateau and variance in their interannual changes. The complete thawing of seasonal frozen soil generally occurs in April and May; and the average date is in mid April for early thawing years and at the end of May or the beginning of June for late thawing years. The range is about one and a half months. This difference may impact on the changes in the ground surface heat source of the plateau and thus further influence summer precipitation in China.

Because the lengths of frozen soil data at various stations in the Plateau are different, and since there are also some missing records, in order to use as many stations as possible (i.e., to reflect the real circumstance of the thawing of the seasonal frozen soil in the plateau as accurately as possible) and to use data runs as long as possible, the 1980–1999 complete thawing date data at the 50 stations in the plateau are selected (Fig. 1). They are mainly distributed in the central-east part of the plateau, and stations located in the western part and in no man's land in the northern part are very few. First, the original thawing date series at the 50 stations are established, and then the interannual variation series of the thawing date of the seasonal frozen soil in the plateau (given in Fig. 2) are obtained by normalizing the original series and then

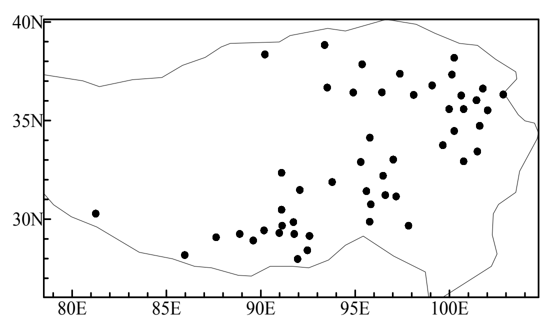

Fig. 1. Distribution of the 50 meteorological observation stations in the Tibetan Plateau.

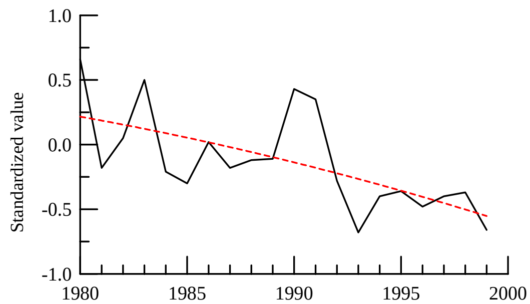

Fig. 2. Interannual variation of the thawing date and trend line from 1980 to 1999 in the Tibetan Plateau.

averaging them over the plateau. It can be observed from the figure that the thawing date becomes earlier from 1980 to 1999, showing a trend consistent with the global warming.

3. Correlation between the thawing date and summer precipitation in China

Similar to the effect of snow cover, the frozen soil is not only a product of climate changes but also a factor in affecting climate changes. Different from changing the albedo of the ground surface by which the snow cover affects climate changes, the freezing/thawing process changes the thermal capacity and conductivity of the soil, i.e., it changes the thermal exchanges between the earth and atmosphere, hence impacting climate changes.

Figure 3 shows the correlation coefficients between the interannual variation series of the thawing date of the seasonal frozen soil in the plateau and the summer (July) precipitation at 160 stations in China. It can be seen from the figure that the thawing date is closely correlated with July precipitation in China, with the positive correlation mainly in the Changjiang River and Huaihe River valleys, and the negative correlations in the South China region and the northern part of China. The distribution of the correlation between the thawing date and the July precipitation is close to the precipitation distribution itself, which is rainy in the Changjiang River and Huaihe River valleys and rainless in South China and the northern part of China after the East Asian summer monsoon makes its second jump northward. The positive correlation areas where the correlation significance exceeds the $\alpha = 0.05$ confidence level are mainly located in the middle-lower reaches of the Changjiang River and the lower reaches of the Huaihe River; and the negative correlation areas above the $\alpha = 0.05$ confidence level are concentrated in the South China region, and the eastern part of northwest China.

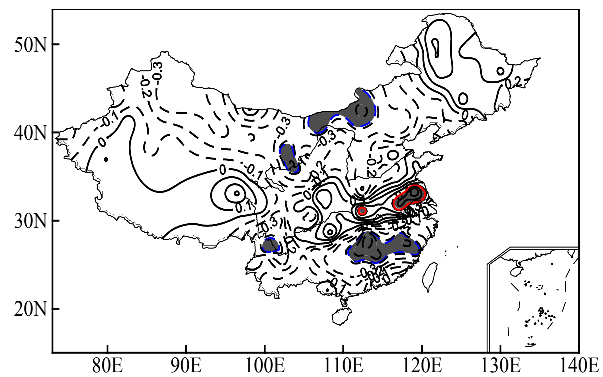

Fig. 3. Correlations between the 1980–1999 thawing date of the seasonal frozen soil in the Tibetan Plateau and the July precipitation in China (solid line denotes positive correlation, dashed line denotes negative, and correlations above $\alpha = 0.05$ confidence level are shaded).

The China Meteorological Administration classifies the summer precipitation in China into type I, II, and III patterns. The above analyses indicate that when the seasonal frozen soil in the plateau thaws earlier, the positive anomaly of summer precipitation will be located mainly in southern China, which corresponds to the type III pattern; and when the seasonal frozen soil thaws later, the positive anomaly will lie in the Changjiang River and the Huaihe River valleys, which corresponds to the type II pattern.

4. Characteristics of the atmospheric circulation over East Asia in anomalous thawing years

Numerical simulations (Wang, 2002; Zhang and Lu, 2002) have indicated that the anomalous changes of frozen soil can induce changes in thermal state of the ground surface. The effect of the heat source of the plateau is an important effect for the changes of East Asian circulation, therefore the abnormity of the thawing date of the seasonal frozen soil in the plateau must result in the abnormity of the East Asian circulation.

4.1 *Characteristics of the Atmospheric Circulation in Anomalous Thawing Years*

In order to reveal the effect of the anomalous thawing of seasonal frozen soil in the plateau on the East Asian circulation, the composite analysis method is used to analyze the difference of East Asian circulations between the early and late thawing years. The anomalies and mean square deviations (σ) of the interannual variation series of the thawing date of seasonal frozen soil in the plateau are calculated, and an early (late) thawing year is determined according to its anomaly being less (greater) than –0.7 (0.7) σ. The years 1993, 1994, 1996, 1997, and 1999 are selected as early thawing years, and 1980, 1983, 1990, 1991 as late thawing years. Here 200 hPa, 500 hPa and 850 hPa denote the upper, middle and lower levels of the troposphere, respectively. For the significance test we use the following t statistics:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sigma}\sqrt{\frac{n_1 n_2}{n_1 + n_2}}\ , \tag{1}$$

$$\sigma^2 = \frac{\sigma_1^2 + \sigma_2^2}{(n_1 + n_2 - 2)}\ , \tag{2}$$

where, $\overline{x_1}, \overline{x_2}, \sigma_1^2, \sigma_2^2, n_1, n_2$ represent the averages, mean square deviation and sample length of thawing early years and thawing late years respectively.

Figure 4 displays the differences of July 500 hPa heights between the early and late thawing years, where one can see that there is a large sheet of continuous negative values over the middle-lower reaches of the Changjiang River, South China, and the West Pacific with a center value less than –25 gpm. This demonstrates that the WPSH in the early thawing years is weaker than in the late thawing years. The shading represents significant difference regions. The Changjiang River, South China, and the West Pacific all exceed the $\alpha = 0.05$ significance level. Figure 5a shows the composite position of the July SAH and WPSH, and Fig. 5b shows the ridge line of the WPSH in the early (dashed lines) and late (solid lines) thawing years. The Figure shows that the SAH is weak and lies west of its normal position, and the WPSH is weak and lies south of its normal position, in the early thawing years; the opposite occurs in the late thawing years. The area of SAH within the 12550 gpm contour in the early thawing years is much smaller than in the late thawing years (Fig. 5a), and the July 12550 gpm contour in the late thawing years extends eastwards to about 117°E, about 30° longitude east of that in the early thawing years. The area of the July WPSH within the 5880 gpm contour in the early thawing years is also much smaller than in the late thawing years, and the July 5880 gpm contour lies at 139°E, about 20° longitude east of that in the late thawing years. The ridge line of the July WPSH in the early thawing year is 1–2° latitude south of that in the late thawing years (Fig. 5b), and the latitude difference of the two ridge lines becomes large when approaching the mainland of China.

Figure 6 is the composite anomaly of the horizontal wind at (a) 200 hPa, (b) 500 hPa, and (c) 850 hPa, and (d) the vertical motion at 500 hPa in July in the early thawing years. It can be observed from the figure that a cyclonic anomaly circulation at 200 hPa is centered over the lower reaches of the Changjiang River and extends eastwards to Japan and westwards to the Tibetan Plateau; an anticyclonic anomaly circulation prevails over the Southeast Asia region (Fig. 6a). At 500 hPa, a cyclonic anomaly circulation lies over the South China region and the West Pacific region, and

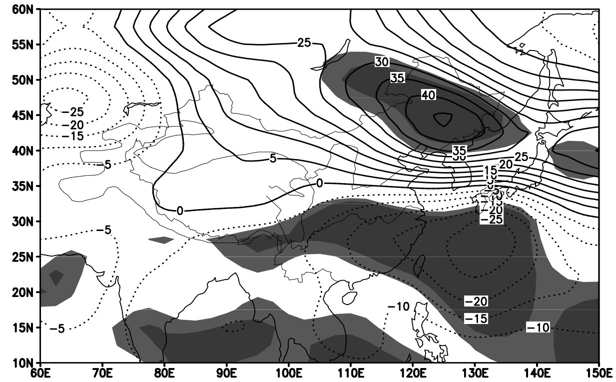

Fig. 4. Geopotential height difference between thawing early years and thawing late years in July at 500 hPa (units: gpm) (solid line is positive, dashed line is negative, shading represents significance above $\alpha = 0.10$)

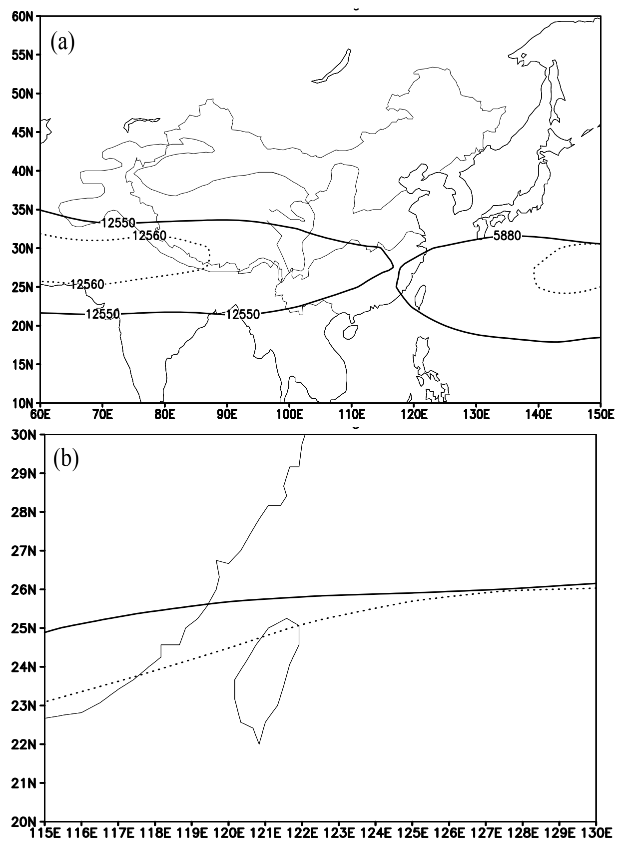

Fig. 5. Composite map of (a) the South Asian High (12550 gpm lines at 200 hPa) and the Subtropical High (5880 gpm lines at 500 hPa) and (b) the Subtropical Ridge over the West Pacific in thawing early years (dashed line) and in thawing late years (solid line).

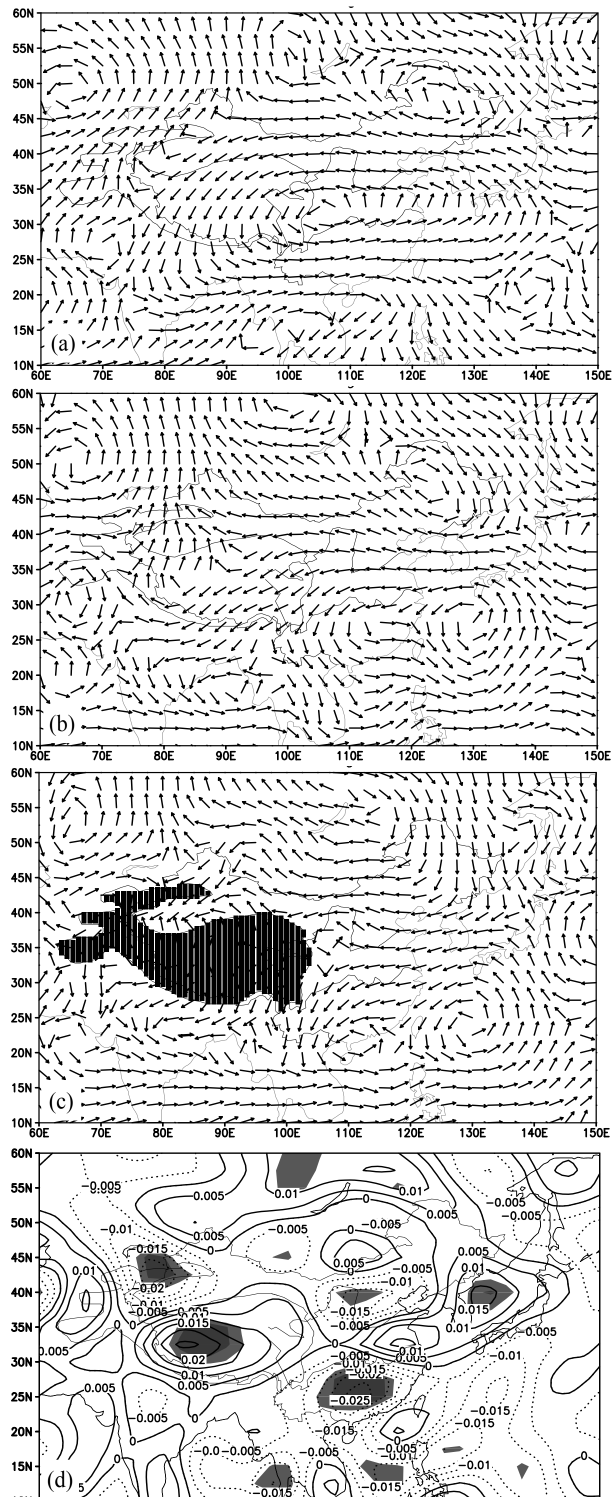

Fig. 6. The difference of the horizontal wind at (a) 200 hPa, (b) 500 hPa, (c) 850 hPa, and (d) the difference of the vertical motion at 500 hPa in July between thawing early years and average years (shading represents significance above $\alpha = 0.10$)

the flow over the plateau shows a divergent trend (Fig. 6b). The anomaly circulation situations at 850 hPa and 500 hPa are similar, and this kind upper/lower level configration leads to there being an obvious descending anomaly motion at the 500 hPa level over the plateau and the middle-lower reaches of the Changjiang River and an ascending anomaly motion over South China, North China and the WPSH region (Fig. 6d). This difference exceeds the $\alpha = 0.10$ significant level over the Tibetan Plateau, North China and South China. That is to say, the early thawing of seasonal frozen soil causes the lower heat source of the ground surface, thus suppressing the ascending motion over the plateau, and meanwhile the WPSH lies south of its normal position. Their joint effect results in the enhancing of the ascending motion and precipitation over the South China and North China regions and the weakening in the middle-lower reaches of the Changjiang River.

Figure 7 is the composite map of the horizontal wind anomaly at (a) 200 hPa, (b) 500 hPa, and (c) 850 hPa, and (d) the vertical motion anomaly at 500 hPa in July in the late thawing years. At 200 hPa, an obvious anticyclonic anomaly circulation is centered over the Yunnan-Guizhou Plateau, and a cyclonic anomaly circulation lies over the Southeast Asia region. At 500 hPa, a distinctive anticyclonic anomaly circulation lies over the West Pacific region, while the flow over the plateau displays a convergent trend. The anomaly circulation pattern at 850 hPa is similar to that at 500 hPa, and this kind of upper/lower level configration results in there being a weak and a distinctive ascending anomaly motion at the 500 hPa level over the Tibetan Plateau and the middle-lower reaches of the Changjiang River, and a marked descending anomaly motion in the South China and North China regions and the WPSH region (Fig. 7d). There is no obvious region which exceeds the significance level. The late thawing of seasonal frozen soil in the plateau causes the higher heat source of the ground surface, thus enhancing the ascending motion over the plateau, and meanwhile the WPSH lies north of its normal position. Their joint effect leads to the weakening of the ascending motion and precipitation over the South China and North China regions and their enhancement over the middle-lower reaches of the Changjiang River.

To sum up the above, the early (late) thawing of seasonal frozen soil in the plateau causes a weak (strong) ground surface heat source in July, hence a weak (strong) ascending motion over the plateau, and meanwhile, a weak (strong) WPSH south (north) of its normal position, and a weak (strong) East Asia trough. Their joint effect leads to more (less) precipitation in the South China region, and less (more) precipitation

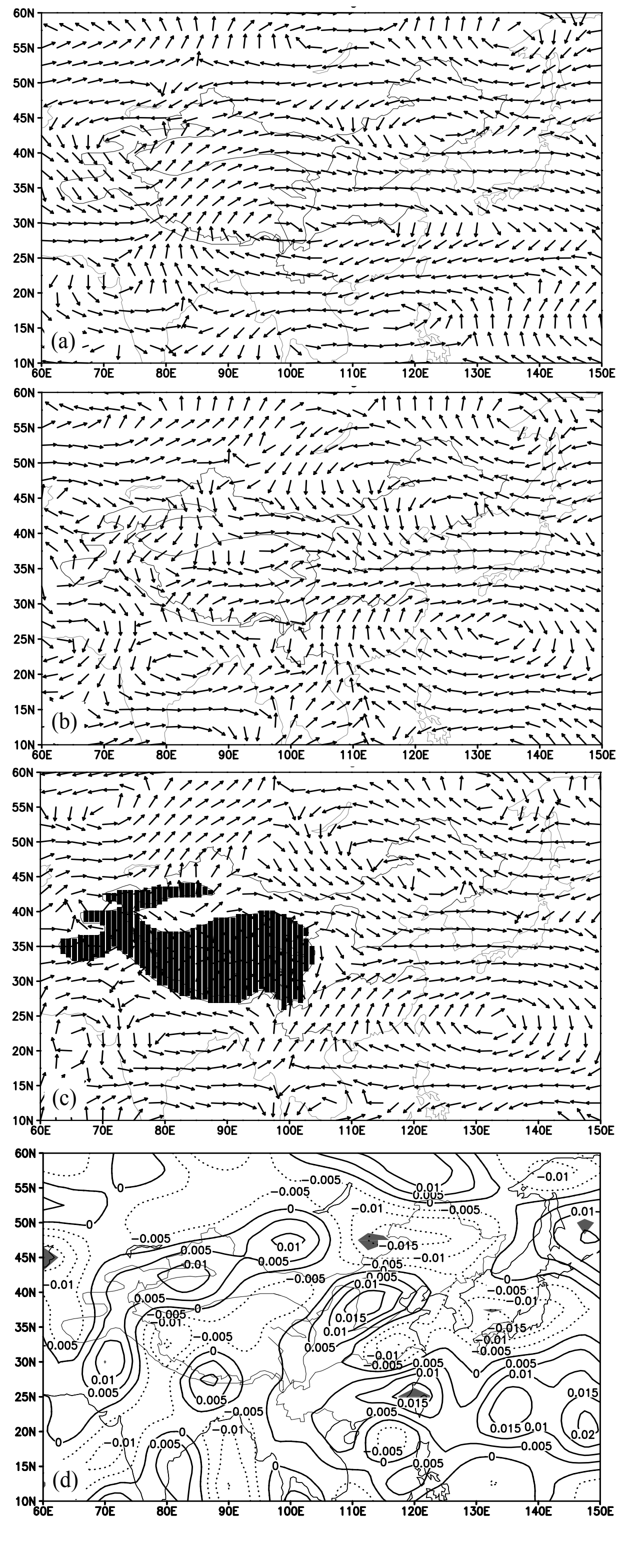

Fig. 7. The difference of the horizontal wind at (a) 200 hPa, (b) 500 hPa, (c) 850 hPa, and (d) the difference of the vertical motion at 500 hPa in July between thawing late years and average years (shading represents significance above $\alpha = 0.10$).

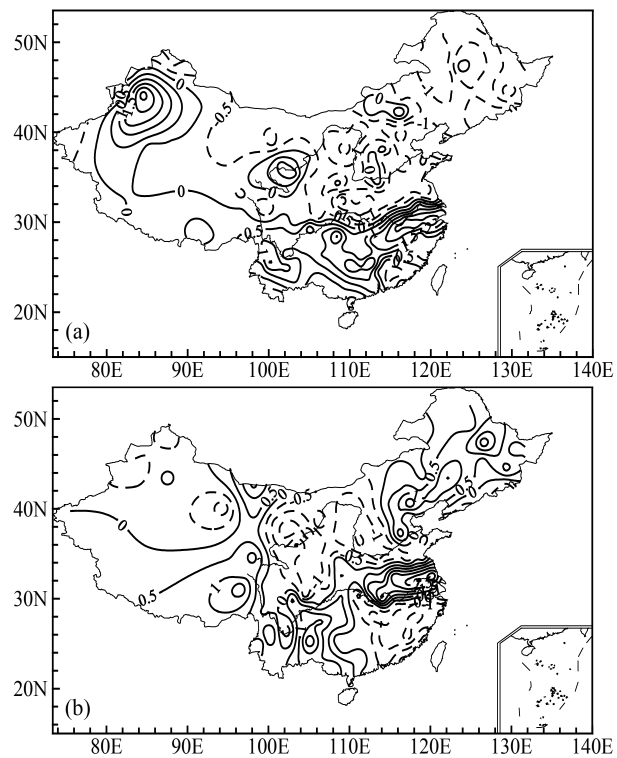

Fig. 8. Standardized July precipitation of the 160 meteorological stations in China in (a) 1999 and (b) 1991.

in the middle-lower reaches of the Changjiang River and the lower reaches of the Huaihe River.

4.2 *Typical case analyses of the anomalous thawing of seasonal frozen soil*

It is found from the above analyses that the anomalous variation of the seasonal frozen soil in the plateau can significantly affect the summer precipitation in China and the circulation over East Asia. Wei et al. (2002) determined 1982, 1983, 1989, 1990, 1993, 1995 and 1998 as high snow years of the plateau, and 1984, 1985, 1991, and 1999 as low snow years. Comparing those years with the anomalous thawing years in this paper, it can be found that there are high and low snow years, and also many normal snow years, in the anomalous thawing years. However, changes in the snow cover over the plateau may similarly cause the abnormity of the summer precipitation in China and the circulation over East Asia. Therefore, in order to remove the effect of changes in the snow cover, the two low snow years of 1999 (early thawing) and 1991 (late thawing) are selected as typical cases to analyze the persistent effect of anomalous thawing.

The analyses of the July precipitation patterns in

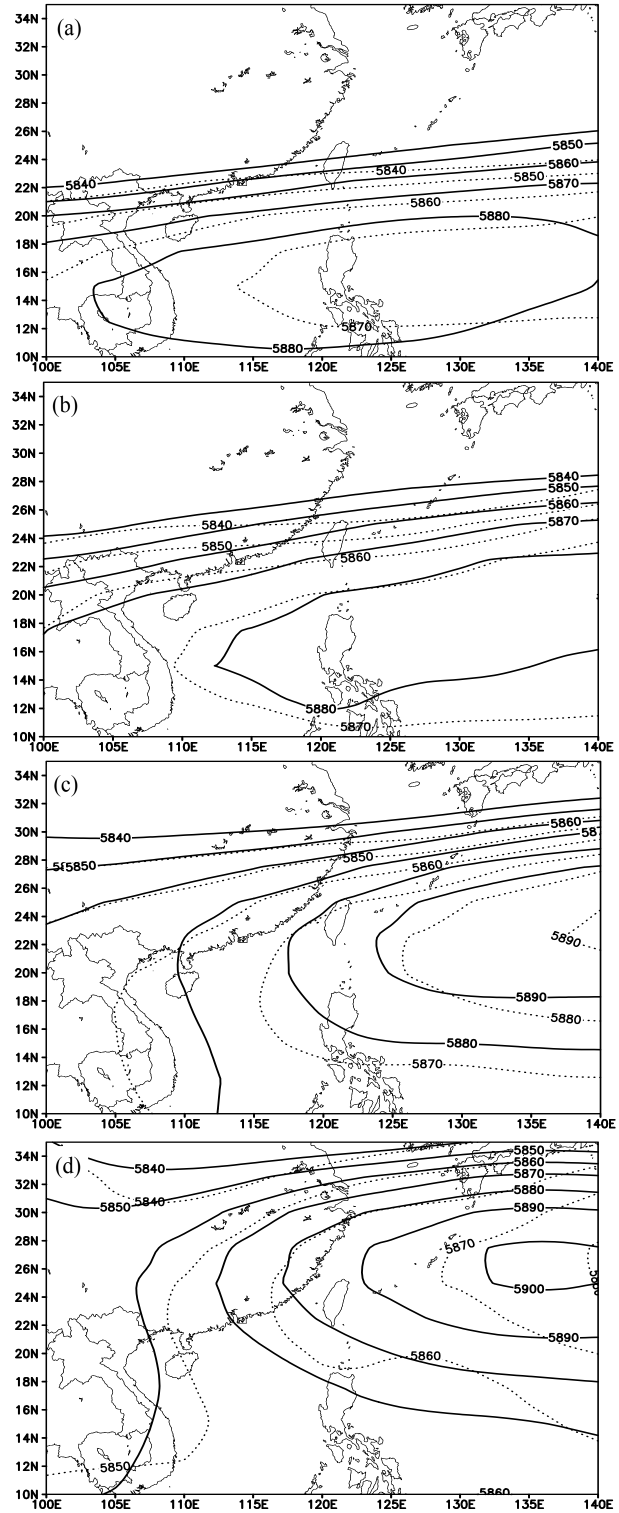

Fig. 9. Variation map of the subtropical high over the West Pacific in 1999 (dashed line) and 1991 (solid line) (a) April, (b) May, (c) June, (d) July.

1999 and 1991 (Fig. 8) show that the precipitation patterns of the two years are generally the same as the correlation patterns obtained above. In 1999, the thawing of seasonal frozen soil is early, July precipitation is above normal in South China and below normal in the middle-lower reaches of the Changjiang River; on the contrary, in 1991, the thawing is late, July precipitation is below normal in South China and above normal in the middle-lower reaches of the Changjiang River. The analyses of the July circulation patterns in 1999 and 1991 also suggest that the July circulation patterns of the two years are completely the same as those of the early and late thawing years, respectively, except anomalies in the typical cases are more remarkable (figure omitted).

Figure 9 shows the temporal evolution of the WPSH from April to July in 1999 and 1991. The seasonal frozen soil thaws early in 1999, and it has basically thawed in April, while the seasonal frozen soil thaws late in 1991, and it completely thaws in June. This difference results in the WPSH from April to July in 1999 being weaker than in 1991 (Figs. 9a–d), but the difference in the WPSH is not obvious in August (figure omitted). The 5880 m contour appears and extends west to land in April in 1991, but it does not appear in 1999. The area of the 5880 m contour in 1991 is much larger than in 1999. The 5880 m contour does not appear in May in 1999 as well. The area of the 5880 m contour in May in 1991 decreases a little, so the difference between 1991 and 1999 is reduced. The 5880 m contour appears in June in 1999. The area of the 5880 m contour in June in 1991 decreases sequentially, and the difference between 1991 and 1999 is reduced as well. The subtropical ridge over the West Pacific in June in 1999 is a little south compared to 1991. The difference of the 5880 m contour in July between 1999 and 1991 is a little larger than in June. The subtropical ridge over the West Pacific in July in 1999 is more south than in June. The difference becomes very small after July.

To sum up, after removing the influence of snow cover, the impact of the (early/late) thawing of seasonal frozen soil becomes more evident than in composite analyses. The impact starts to appear in April, reaches its maximum in July, and becomes very small in and after August.

5. Summary

(1) The frozen soil thawing date becomes earlier and earlier in the years from 1980 to 1999 in the Tibetan Plateau, which is consistent with the warming trend of global average temperature.

(2) When the frozen soil thaws early, the summer precipitation is greater in South China, which follows the type III rain pattern, but when the frozen soil

thaws late, the summer precipitation is greater in the Changjiang River and Huaihe River and valleys, which follows the type II rain patterm.

(3) When the frozen soil thaws early (late) in the Tibetan Plateau, it may cause the surface heat source to be weak (strong) and the ascending motion to be weak (strong) in summer in the Tibetan Plateau. The subtropical high over the West Pacific will be weak (strong) and shifted a little to the south (north). The summer precipitation will be more (less) in South China and less (more) in the middle-lower reaches of the Changjiang River and the lower reaches of the Huaihe River.

Acknowledgments. The authors would like to thank Profs. Wang Chenghai and Wei Li, Drs. Zhang Yu and Feng Guolin, and the anonymous reviewers for their helpful comments and suggestions. This work was supported jointly by the Key Innovation Project of the Chinese Academy of Sciences (Grant No. ZKCX2-SW-210), and the National Natural Science Foundation of the China (Grant Nos. 40375033 and 40175020), the Key National Natural Science Foundation of China (Grant Nos. 40231005).

REFERENCES

Chen Qianjin, Gao Bo, and Zhang Qiang, 2000: Studies on relation of snow cover over the Tibetan Plateau in winter to the winter-summer monsoon change. *Chinese J. Atmos. Sci.*, **24**, 477–492. (in Chinese)

Fan Guangzhou, Luo Siwei, and Lu Shihua, 1997: The preliminary numerical experiments of effect of anomalous snow cover over Plateau in winter on East and South Asian summer monsoon. *Plateau Meteorology*, **16**, 140–152. (in Chinese)

Feng Guolin, Cao Hongxing, Gao Xinquan, Dong Wenjie, and Chou Jifan, 2001: Prediction of precipitation during summer monsoon with self-memorial model. *Adv. Atmos. Sci.*, **18**, 701–709.

Gao Rong, Wei Zhigang, and Dong Wenjie, 2003: Interannual variation of the beginning date and the ending date of soil freezing in the Tibetan Plateau. *Journal of Glaciology and Geocryology*, **25**, 49–54. (in Chinese)

Guo Qiyun, and Wang Jiqin, 1986: The snow cover on Tibet Plateau and its effect on the monsoon over East Asia. *Plateau Meteorology*, **5**, 116–124. (in Chinese)

Li Guoping, Lu Jinghua, Jin Bingling, and Bu Nima, 2001: The effects of anomalous snow cover of the Tibetan Plateau on the surface heating. *Adv. Atmos. Sci.*, **18**, 1207–1214.

Luo Yong, 1995: Studies on the effect of snow cover over the Qinghai-Xizang Plateau in winter and spring on general circulation over East Asia in summer. *Plateau Meteorology*, **14**, 505–512. (in Chinese)

Ren Guangcheng, 1991: Effect of thermal regime over the Tibetan Plateau on South Asia High Activities. *Scientia Atmospherica Sinica*, **15**, 28–32. (in Chinese)

Slater, A. G., Pitman A. J., and Desborough C. E., 1998: Simulation of freeze-thaw cycles in a general circulation model land surface scheme. *J. Geophys. Res.*, **103**, 11 303–11 312.

Wang Chenghai，2002: The studies about the relation between the freezing-thawing processes of the Qinghai-Tibet Plateau and the atmospheric circulation over East Asia and the summer precipitation in China. Ph. D. dissertation, graduate school of the Chinese Academy of Sciences, 131pp. (in Chinese)

Wang Chenghai, Dong Wenjie, and Wei Zhigang, 2003: Studies on relationship between freezing-thawing processes of the Qinghai-Tibet Plateau and the atmospheric circulation over East Asia. *Chinese Journal of Geophysics*, **46**, 309–316. (in Chinese)

Wei Zhigang, Huang Ronghui, Chen Wen, and Dong Wenjie, 2002: Spatial distributions and interdecadal variations of the snow at the Tibetan Plateau weather stations. *Chinese J. Atmos. Sci.*, **26**, 496–508. (in Chinese)

Wei Zhigang, Luo Siwei, Dong Wenjie, and Li Peiji, 1998: Snow cover data on Qinghai-Xizang Plateau and its correlation with summer rainfall in China. *Quarterly Journal of Applied Meteorology*, **9**, 39–46. (in Chinese)

Yang Meixue, and Yao Tandong, 1998: A review of the study on the impact of snow cover in the Tibetan Plateau on Asian Monsoon. *Journal of Glaciology and Geocryology*, **20**, 186–191. (in Chinese)

Zhao Ping, and Chen Longxun, 2002: The climate characteristic of atmospheric heat source in Tibetan Plateau in current 35 years and the relation with precipitation in China. *Science in China D*, **31**, 327–332. (in Chinese)

Zhang Shunli, and Tao Shiyan, 2001: Influence of snow cover over the Tibetan Plateau on Asian Summer Monsoon. *Scientia Atmospherica Sinica*, **25**, 372–390.

Zhang Yan, and Qian Yongfu, 2002: Thermal effect of surface heat source over the Tibetan Plateau on the onset of Asian Summer Monsoon. *Journal of Nanjing Institute of Meteorology*, **25**, 298–306. (in Chinese)

Zhang Yu, and Lu Shihua, 2002: Development and validation of a simple frozen soil parameterization scheme used for climate model. *Adv. Atmos. Sci.*, **19**, 513–527.

Zhou Yushu, Deng Guo, Gao Shouting, and Xu Xiangde, 2002: The wave train characteristics of teleconnection caused by the thermal anomaly of the underlying surface of the Tibetan Plateau. Part I: Data analysis. *Adv. Atmos. Sci.*, **19**, 583–593.