Decadal Change of the Spring Snow Depth over the Tibetan Plateau: The Associated Circulation and Influence on the East Asian Summer Monsoon*

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ABSTRACT

The decadal change in the spring snow depth over the Tibetan Plateau and impact on the East Asian summer monsoon are investigated using station observations of snow depth data and the NCEP–NCAR reanalysis for 1962–93. During spring (March–April), both the domain-averaged snow depth index (SDI) and the first principal component of the empirical orthogonal function (EOF) analysis exhibit a sharp increase in snow depth after the late 1970s, which is accompanied by excessive precipitation and land surface cooling. The correlation between SDI and precipitation shows a coherent remote teleconnection from the Tibetan Plateau–northern India to western Asia.

It is found that the increased snow depth over the plateau after the mid-1970s is concurrent with a deeper India–Burma trough, an intensified subtropical westerly jet as well as enhanced ascending motion over the Tibetan Plateau. Additional factors for the excessive snowfall include more moisture supply associated with the intensification of the southerly flow over the Bay of Bengal and an increase of humidity over the Indian Ocean. While the extensive changes of the circulation in Eurasia and the Indian Ocean are associated with a climate shift in the Northern Hemisphere after the mid-1970s, some regional factors such as the enhanced coupling between the sea surface temperature (SST) warming in the northern Indian Ocean/Maritime Continent and the tropical convective maximum (TCM), as well as local feedback of the land surface cooling due to excessive snow cover and the atmosphere may contribute to the regional circulation changes. The former enhances the western Pacific subtropical in the South China Sea–Philippine Sea through modulation of the local Hadley circulation and results in stronger pressure gradients and fronts in southeastern and eastern Asia.

A close relationship exists between the interdecadal increase of snow depth over the Tibetan Plateau during March–April and a wetter summer rainfall over the Yangtze River valley and a dryer one in the southeast coast of China and the Indochina peninsula. It is proposed that the excessive snowmelt results in a surface cooling over the plateau and neighboring regions and high pressure anomalies that cause a more northwestward extension of the western Pacific subtropical high in the subsequent summer. Additionally, the increased surface moisture supply provides more energy for the development of the eastward-migrating low-level vortex over the eastern flank of the Tibetan Plateau. Both factors lead to a wetter summer in the vicinity of the Yangtze River valley.

1. Introduction

More than a century ago, Blandford (1884) and, later, Walker (1910) documented an inverse relation between the winter snow cover over the Tibetan Plateau and the subsequent Indian summer monsoon rainfall. Their results are supported by several studies using the satellite-derived Eurasian winter snow cover data (Hahn and Shukla 1976; Dey and Bhanu Kumar 1982, 1983; Dickson 1984; Parthasarathy and Yang 1995; Yang 1996). The related physical processes have also been investigated with the help of the general circulation models (Barnett et al. 1989; Yasunari et al. 1991; Zwiers 1993; Vernekar et al. 1995; Shen et al. 1998; Bamzai and Marx 2000; Becker et al. 2001). The relationship between the Eurasian–Tibetan Plateau snow cover and the East Asian summer monsoon has also been studied (Yang and Xu 1994; Chen and Wu 2000; Wu and Qian 2003) but the associated physical processes have not been clarified.

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As an elevated heating source in summer with an average altitude of about 4000 m, the Tibetan Plateau plays an important role in the development of the Asian summer monsoon. It is known that the onset of the Asian summer monsoon is closely related to the concurrence of a reversal of meridional temperature gradient in the upper troposphere south of the Tibetan Plateau and a warming over the Tibetan Plateau (Flohn 1957; Li and Yanai 1996; Wu and Zhang 1998). During the monsoon onset period, the sensible heating and the effects of increasing latent heat release give rise to the establishment of the upper-level anticyclonic circulation around the Tibetan Plateau and the development of the low-level cyclonic circulation (Yeh 1981; Luo and Yanai 1984). These have been considered to be closely related to the establishment of the Asian summer monsoon onset over the South China Sea (SCS) and Southeast Asia (Luo and Yanai 1983; Wu and Zhang 1998).

The anomalous snow cover may provide a seasonal climate signal of the circulation in the winter and spring, and more importantly, it affects the land surface energy and moisture budgets in late spring and early summer (Shukla 1984; Shukla and Mooley 1987; Yasunari et al. 1991). Two effects are involved in the land process. One is the albedo effect, in which the excessive snow cover may decrease the surface temperature by reducing the net solar radiation at the ground surface by increasing reflectance. The other is the snow-hydrological effect, in which the excessive snow accumulation in winter and spring gives rise to colder surface temperature since more solar energy is consumed to melt snow and evaporate water rather than to heat the ground directly; additionally, the soil moisture from the melted snow leads to the release of the surface latent heat flux. Shukla (1984) proposed that an excessive snowfall during the previous winter and spring seasons could delay the buildup of the reversal of the land–ocean temperature gradient. The numerical experiment conducted by Ose (1996) supports that the positive snow mass anomaly over the Tibetan Plateau could cause the anomalous atmosphere cooling in spring to early summer, which delays the seasonal transition of the atmospheric circulation from winter to summer.

The greatest uncertainty with regard to the snow cover–Asian summer monsoon relationship is insufficient observational snow data. In most of the previous studies (e.g., Hahn and Shukla 1976; Bamzi and Shukla 1999; Robock et al. 2003), the snow cover data [e.g., National Ocean and Atmospheric Administration's (NOAA's) satellite data] used for a grid point are in binary form (snow or no snow). They measured only the frequency of the occurrence of snow (snow extent), rather than estimating the local snow amount quantitatively. This leads to difficulty in properly estimating the Asian summer monsoon–snow cover relationship because the snow-hydrological effect could not be estimated. Additionally, this relationship may vary in different decades. A reversed snow cover–monsoon relationship in the recent decade has been reported by Robock et al. (2003).

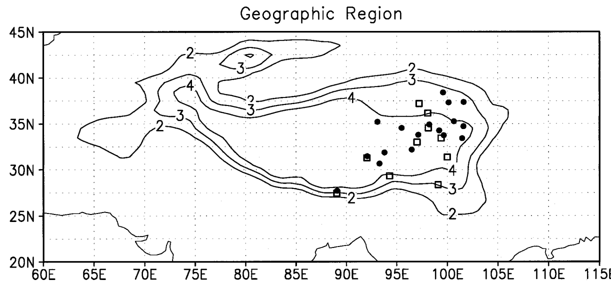

FIG. 1. Map of station distributions for snow depth (closed circles) and precipitation (open squares) data. The contours indicate the height of the Tibetan Plateau (in km).

In this study, long-term 32-yr station snow depth data observed over the Tibetan Plateau are used to document the interdecadal variations of snow cover over the Tibetan Plateau and its relationship to the east Asian summer monsoon. In this paper we particularly focus on the change of the large-scale circulation that links to the snow–monsoon relationship in the interdecadal time scale. In section 2, we described the dataset. In section 3, the relationship between the local snow depth over the Tibetan Plateau and the anomalies of rainfall in Eurasia and sea surface temperature (SST) in the Indian and Pacific Oceans are presented. The changes of the atmospheric circulation associated with the excessive snow depth after the late 1970s are investigated and a possible mechanism is proposed in section 4. Section 5 discusses the processes through which the excessive spring snow cover influences the east Asian summer monsoon. Finally, conclusions are given in section 6.

2. Data

The data used in this study include the following sources:

1) The daily snow depth data archived by the Data Center of the Institute of Atmospheric Physics (IAP), the Chinese Academy of Sciences. Among the 56 stations, 17-station observations with missing rate less than 5% are selected from January 1962 to December 1993. The monthly data were derived from the daily data. The geophysical locations of the station are presented in Fig. 1 and Table 1.
2) The Chinese rainfall data collected from 336 observation stations from the National Climate Center, China Meteorological Administration. Among them, 10 stations over the Tibetan Plateau are selected and their locations are presented in Fig. 1.
3) Monthly mean National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) for the period 1962–93.
4) Monthly terrestrial air temperature and precipitation

TABLE 1. Spatial component of the first EOF (30.9%) for each station.

Station No.	Lat (°N)	Lon (°E)	Spatial component
52645	38.42	99.58	0.16
52754	37.33	100.13	0.20
52765	37.38	101.62	0.16
52908	35.22	93.08	0.13
52957	35.27	100.65	0.35
55299	31.48	92.07	0.30
55773	27.73	89.08	0.03
56021	34.55	95.48	0.21
56033	34.92	98.22	0.03
56034	33.80	97.13	0.30
56041	34.27	99.20	0.30
56046	33.75	99.65	0.29
56065	34.73	101.60	0.37
56067	33.43	101.48	0.32
56106	31.88	93.78	0.28
56125	32.20	96.48	0.15
56202	30.67	93.28	0.15

data. This 47-yr dataset (from 1950 through 1996) is provided by Climate Diagnostics Center (CDC). This archive is produced by using version 2 of the Global Historical Climatology Network (GHCN) and Legates and Willmott's (1990a,b) station records of monthly and annual mean air temperature and total

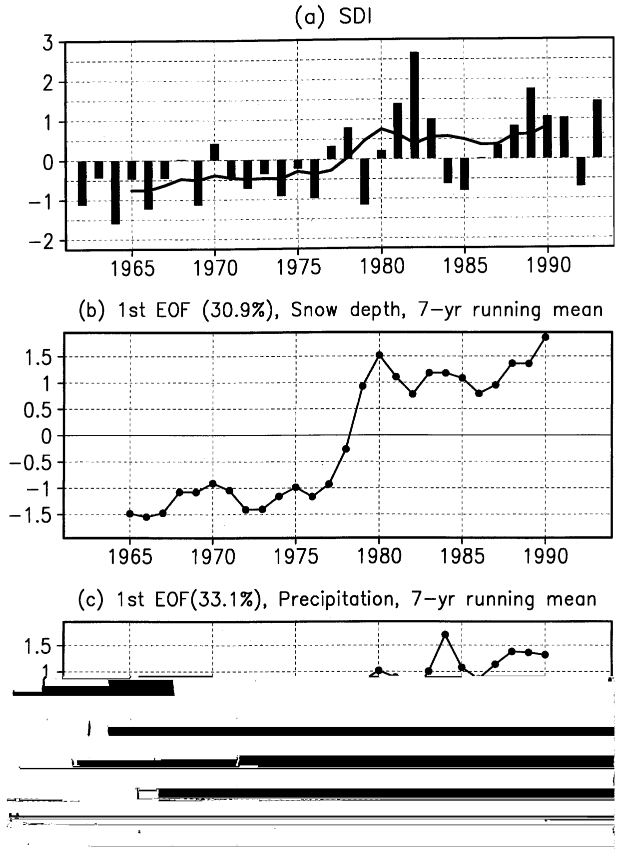

FIG. 2. (a) The normalized SDI for Mar–Apr obtained by averaging the 17-station observations during Mar–Apr. The bar denotes the interannual variation, and the solid line represents the 7-yr running mean. The 7-yr running mean of the first EOF principal component for (b) the snow depth and (c) precipitation for Mar–Apr over the Tibetan Plateau.

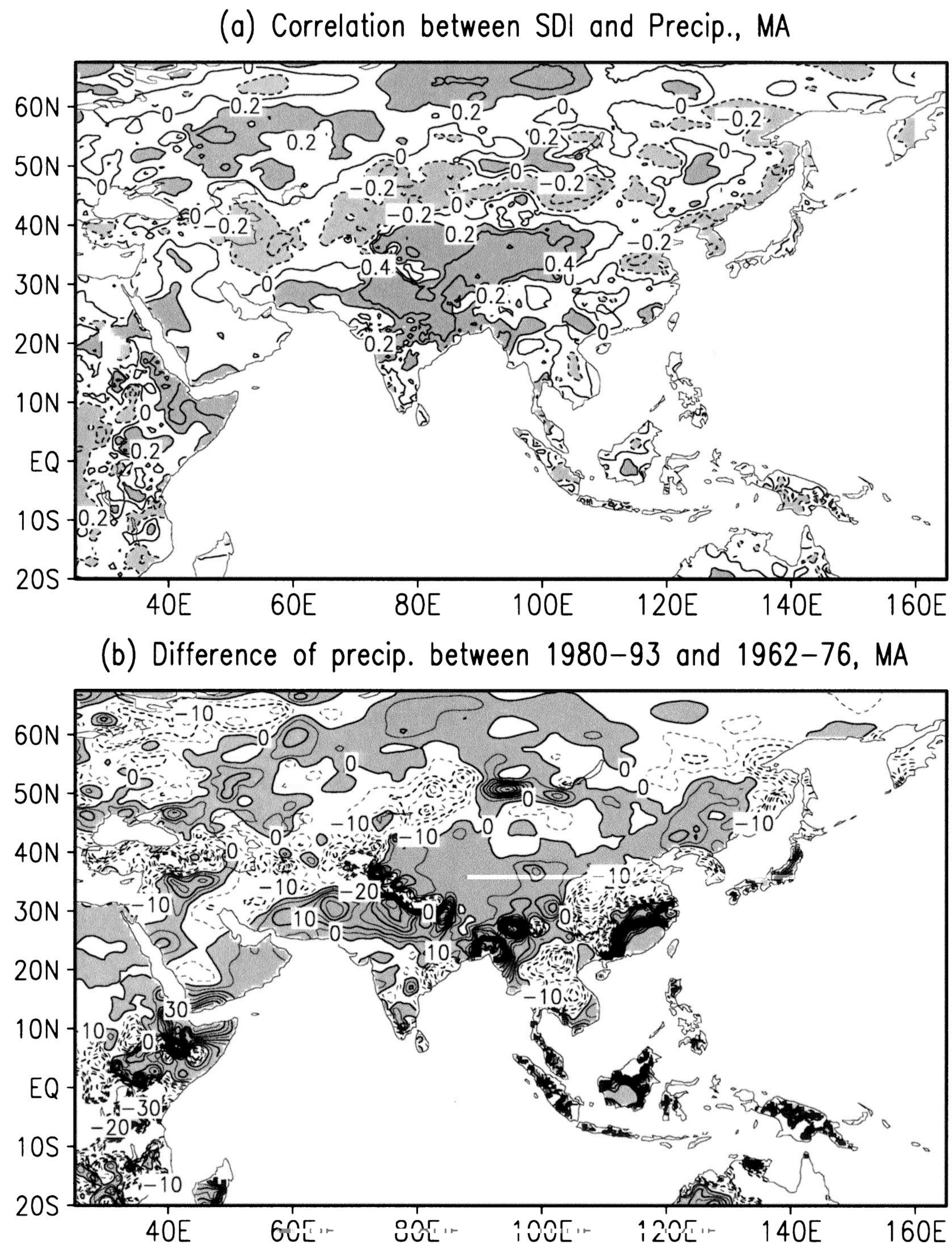

Fig. 3. (a) The correlation coefficient value between the SDI and precipitation during Mar–Apr. The contour interval is 0.2 with heavy shading indicating values greater than 0.2 and light shading denoting values less than −0.2. The 5% significance test of the correlation is 0.35. (b) The difference of the rainfall during Mar–Apr between 1980–93 and 1962–76. The interval is 5 mm and shading indicates the positive values.

A simultaneous correlation between the SDI for March–April and precipitation over Eurasia shows a coherent wave train pattern projecting from northern India–northwestern China to western Asia (Fig. 3a). The anomaly patterns are tilted from southwest to northeast. The increase of the SDI is concurrent with excessive precipitation over northern India–northwestern China and western Asia and with drought over central Asia. Note that this correlation pattern is similar to the pattern of precipitation difference between 1980–93 and 1962–

(a) Correlation between SDI and Tsfc, MA

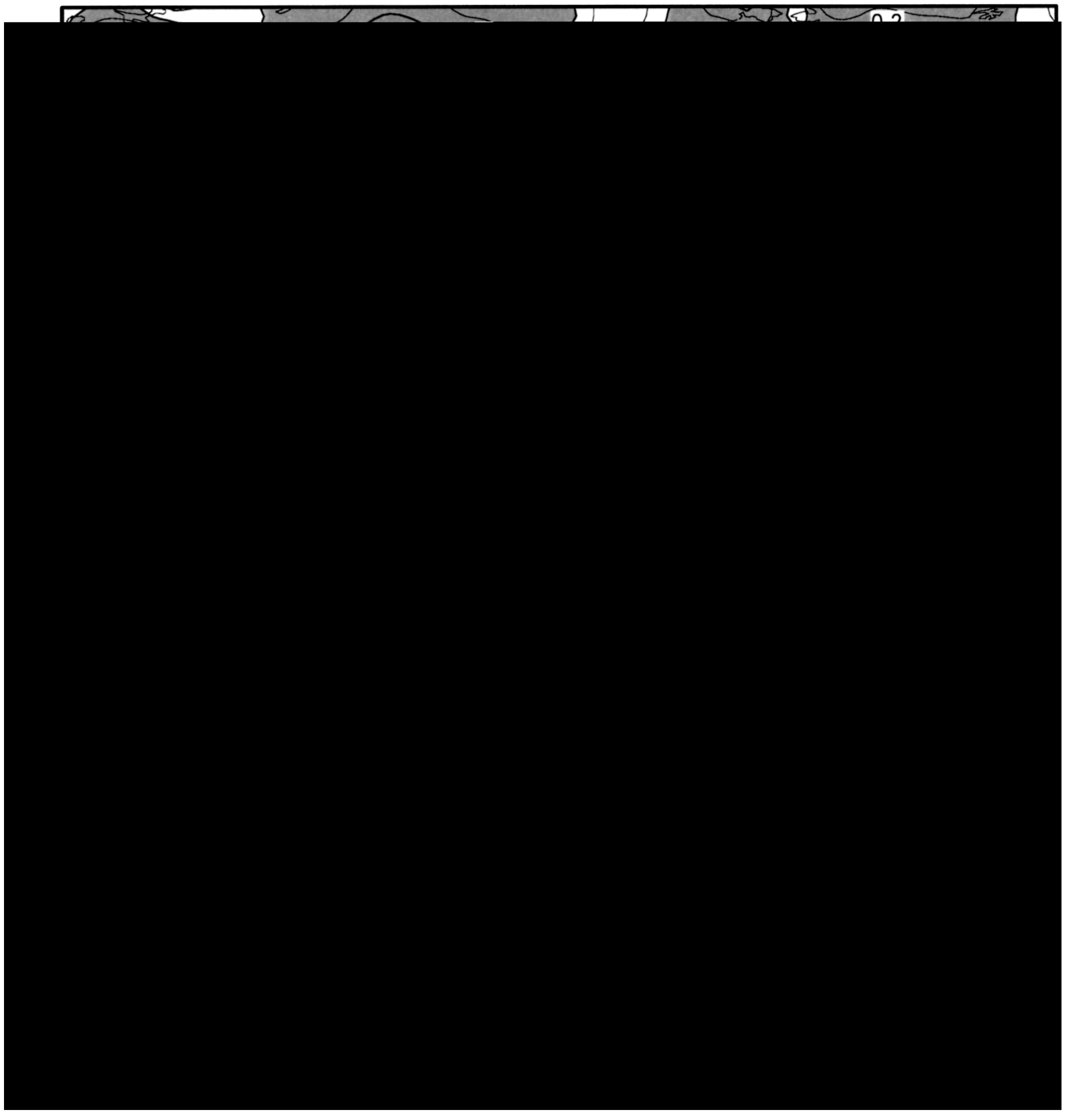

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FIG. 4. (a) Same as Fig. 3a, but for the skin temperature of NCEP–NCAR reanalysis, which indicates the surface temperature over land and the SST over ocean. Heavy (light) shading denotes the values greater (less) than 0.3 (-0.3). (b) The difference of the skin temperature during Mar–Apr between 1980–93 and 1962–76. Shading indicates the regions where the values pass the 5% significance level test.

76 (Fig. 3b). It indicates that the considerable regime shift of the snow also exits in the precipitation field.

To investigate the relationship between the snow depth change over the Tibetan Plateau and the anomalies of sea and land surface temperature, we performed the simultaneous correlation between the NCEP–NCAR reanalysis skin temperature and SDI for March–April. Figure 4a shows that the correlation between the SDI and SST in the Indian Ocean–Maritime Continent is highly positive with two maximum centers (greater than 0.4) appearing over the central Indian Ocean south of the equator and the eastern Maritime Continent. This warming accompanies the land surface cooling over the Tibetan Plateau and neighboring regions. To further confirm this, we also performed a correlation analysis between the SDI and terrestrial air temperature using an independent dataset (not shown). The correlation pattern over Eurasia is very similar to Fig. 4a, implying that cooling occurs not only over the land surface temperature but also in the air temperature.

In the midlatitude Pacific Ocean, the SST cooling south of the Aleutians is concurrent with the warming in the eastern Pacific near the coast of Baja California. This relationship reflects the anomalies associated with the Pacific–North American (PNA) pattern, which is a crucial part of the decadal mode exhibited by Latif and

Barnett (1994, their Fig. 10b). This is further confirmed by Fig. 4b, which presents the difference of the skin temperature between 1980–93 and 1962–76. The increase of the SDI in the latter decade is identified to be concurrent with the decadal SST warming in the Indian Ocean and subtropical eastern Pacific and with cooling in the North Pacific.

In summary, both the snow depth and precipitation over the Tibetan Plateau reveal an upward trend during spring after the late 1970s. This change is seen in phase with the simultaneous decadal SST changes in the Indian and Pacific Oceans and is indicative of the planetary-scale rainfall variations during spring in Eurasia.

4. Changes of atmospheric circulation associated with the interdecadal increase of spring snow depth and a possible mechanism

To investigate the atmospheric circulation changes associated with the increase of spring snow accumulation over the Tibetan Plateau after the late 1970s, we divided data into two decades, 1962–76 and 1980–93, and performed a composite study with respect to these two periods.

a. Change of the zonal wind

Figure 5 shows the difference of wind and height at 500 hPa in March–April between 1980–93 and 1962–76. Since a lot of other studies (e.g., Trenberth and Hurrell 1994; Kachi and Nitta 1997) have discussed the significant decadal changes happening in the Pacific, such as an deeper Aleutian low pressure system and the westerly anomalies in the equatorial western-central Pacific, we focus our attention on the phenomena in Asia and the Indian and western Pacific Oceans. In Fig. 5b, strong southwesterly and northwesterly anomalies are identified in southeastern and southwestern parts of the Tibetan Plateau, respectively. The former stretches from the Bay of Bengal to eastern China. This, along with the northeasterly anomalies identified in the western Pacific off the equator, indicates an intensification of the western Pacific subtropical high (WPSH) in the SCS–Philippine Sea. Meanwhile an anomalous cyclonic circulation occurs from the Tibetan Plateau to eastern China. Climatologically in March and April, a subtropical westerly jet stream prevails in this region, which is deflected by the Tibetan Plateau in the low to middle troposphere and thereby forms a trough in the India–Burma region (Yin 1949; Wu et al. 1996). The latter is termed the India–Burma trough. The anomalous westerlies around the plateau reflect the intensification of the westerly jet stream and the India–Burma trough in the later decade.

Figure 6a illustrates the difference of the latitude–vertical profiles of zonal wind averaged over 90°–100°E between the two periods. It shows that the intensification of the westerlies over the southern slope of the Tibetan Plateau, of which the maximum axis is overlapped with the core of the westerly jet stream, is evident in the whole troposphere.

b. Change of the geopotential height

In the geoptential field (Fig. 5a), in contrast to the seesaw variation over the Tropics and middle Pacific, a teleconnection pattern occurs in the Asia–Indian Ocean regions, with an anomalous high pressure center appearing over the eastern equatorial Indian Ocean–Maritime Continent and an anomalous low pressure zone occurring around 30°N. The latter extends from the Tibetan Plateau to East Asia. Between those high–flow pressure centers, a strong pressure gradient is evident along the southern slope of the Tibetan Plateau, which is associated with the acceleration of the westerlies over the southern slope of the Tibetan Plateau.

c. Change of the vertical motion

The change of the vertical motion over the Tibetan Plateau is also remarkable (Fig. 6b). In the later period, 1980–93, a strong anomalous ascending motion is identified over the northern part of the plateau that passes a 5% significance test. This is dynamically consistent with the intensified trough and westerly jet stream in the region.

d. Change of the meridional wind

Figure 6c shows the meridional wind difference between the two periods. A significant feature is the increase of the meridional wind south of the Tibetan Plateau in the later period. The maximum center appears over 20°–25°N around 700 hPa. The enhancement of the meridional wind in the eastern Tibetan Plateau is associated with the intensification of the India–Burma trough. The enhanced southerly along the trough results in greater moisture supply from the tropical Indian Ocean, which is favorable for the excessive precipitation over the Tibetan Plateau.

e. Change of the atmospheric humidity

One of the factors that may lead to increased precipitation over the Tibetan Plateau in the later decade is the increase of humidity in the lower troposphere as a result of the warming SSTA over the Indian Ocean. This is validated by Fig. 7, which shows the difference of the specific humidity between 1980–93 and 1962–76 at 700 hPa. A greater increase of the humidity is seen over the northeastern Indian Ocean, where it is concurrent with the enhanced southwesterly.

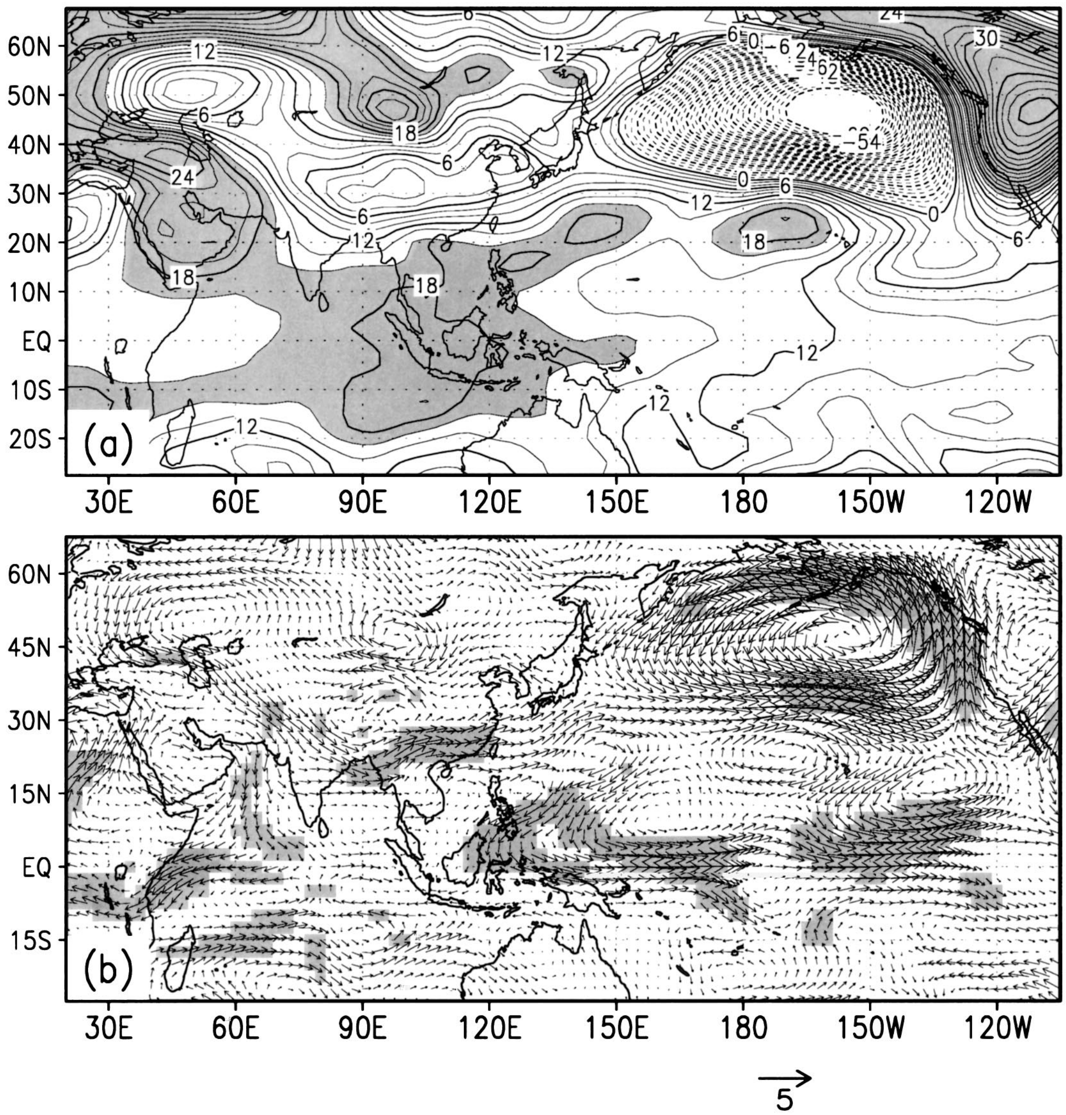

FIG. 5. The difference of (a) the height and (b) the wind vector (m s^{-1}) at 500 hPa for Mar–Apr between 1980–93 and 1962–76. Shading denotes the regions where the values pass the 5% significance level test in (b) and values larger than 17 m in (a). The contour interval in (a) is 1 m.

f. Discussion: The possible local physical processes responsible for the increase of the spring snow cover over the Tibetan Plateau

The data shown in Figs. 3–5 implies that the increased spring snow accumulation over the Tibetan Plateau since the late 1970s is closely associated with a vast environmental circulation change of the climate shift in the Northern Hemisphere (changes in the Pacific have been documented by a lot of studies; e.g., Latif and Barnett 1994; Trenberth and Hurrell 1994; Kachi and Nitta 1997) whereas this phenomenon in Eurasia and the Indian Ocean is seldom studied. To give a conclusive explanation of how the changes in the land–ocean–atmosphere coupled climate system give rise to the extensive changes in the stationary planetary waves over Eurasia seems impossible if a modeling study is not conducted whereas they contribute considerably to the changes of the local weather over the plateau and neighboring region. Here we only discuss the physical processes that locally contribute to increased snowfall over the plateau after the late 1970s.

In Fig. 5, the pressure and westerly anomalies indicate an enhanced subtropical westerly jet stream and a deeper India–Burma trough, which greatly affects the weather over southern and Southeast Asia. To further describe that, locations of the climatological trough/ridge of the stationary planetary wave at 500 hPa in the Northern Hemisphere is shown in Fig. 8a. It is seen that the southwest–northeast-tilted East Asian trough extends down from northeastern Asia to the India–Burma region,

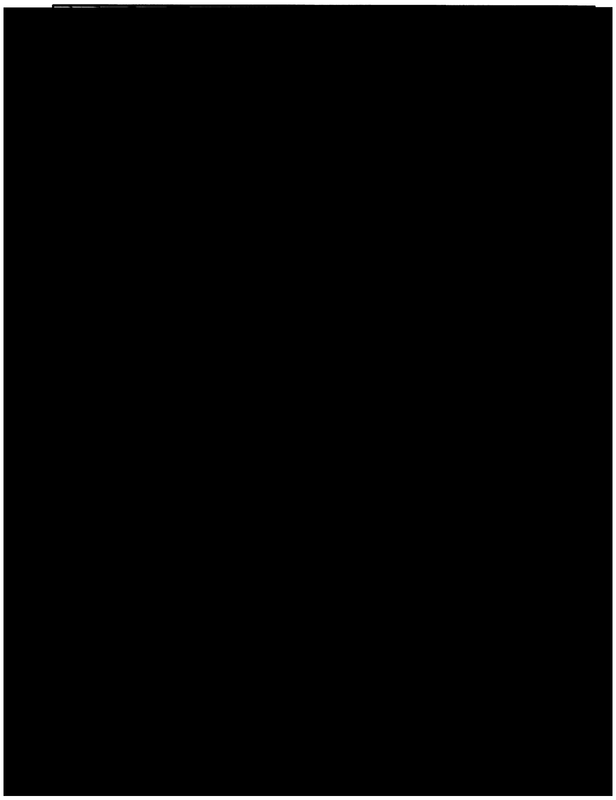

FIG. 6. The latitude–vertical profiles of the difference between 1980–93 and 1962–76 along 90°–100°E for Mar–Apr: (a) zonal wind, (b) vertical wind (omega), and (c) meridional wind. The contour interval in (a) and (c) is 0.25 m s^{-1}, and (b) 0.0025 Pa s^{-1}. Shading indicates the regions where the values pass the 5% significance level test.

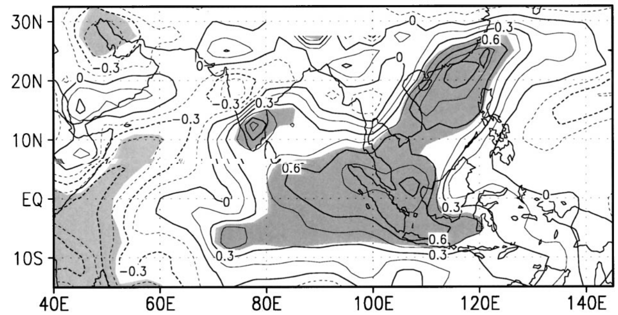

FIG. 7. Same as in Fig. 5, but for the specific humidity at 700 hPa. The interval is 0.15 g kg^{-1}. Shading indicates the regions where the values pass the 5% significance level test.

reaching the northern part of the Bay of Bengal and crossing southeastern part of the plateau. Therefore, more dramatical weather situation occurs in the region. Compared to Fig. 5a, the trough region in eastern China overlaps the relative low pressure anomaly zone (Fig. 5b) and the associated anomalous cyclone, indicating that the trough in India–Burma and eastern China is deeper in the later decade. Therefore, it is expected that the enhanced local cyclonic circulation will enhance ascending motion in the eastern Tibetan Plateau.

While the atmosphere has become more unstable in the recent decade, the vapor supply to the eastern plateau is likely more abundant than in the previous decade. In Fig. 5b, the southern part of the enhanced southwesterlies along the trough can be traced southward to the northern Bay of Bengal. This happened in the midlevel (700–500 hPa) due to the deflecting effect of the orography and the location of the western ridge of the WPSH, which occupies the Indochina peninsula and the SCS. Meanwhile, the humidity in the northeastern Indian Ocean is enhanced due to the underlying SST warming that occurred late in the decade. Therefore, more vapor supply resulting in more snowfall over the plateau is expected.

Figure 9 illustrates the possible physical processes that lead to more spring snowfall over the plateau. In Fig. 9, a forcing from the interdecadal SST warming in the Indian Ocean–Maritime Continent through enhancing the local Hadley circulation and an in situ feedback between the atmosphere and land surface cooling over the plateau are proposed. Even though it is not described in Fig. 9, the SST warming in the central-eastern Pacific is also considered as a remote forcing.

In Fig. 5, the neighbored cyclonic–anticyclonic circulation over the Tibetan Plateau–eastern China/SCS–Philippine Sea is evidenced by a seesaw pattern of the heightfield and enhanced pressure gradient along the southeastern slope of the plateau. The enhanced anticyclonic circulation in the SCS–Philippine Sea reflects intensification of the WPSH. In order to explain how an enhanced WPSH is forced, the distribution of the climatological seasonal change of OLR is plotted in Fig. 8b. Note that in the Tropics the minimum OLR centers represent the tropical convective maximum (TCM) and the ascending branch of local Hadley circulation. By comparing Fig. 4b with Fig. 8b, the location of TCM around the Maritime Continent confined to south of the equator is shown to overlap with the pronounced interdecadal SST warming (Fig. 4b). Thus, it is expected that there could exist a strong in situ coupling between the underlying SST warming and the intensified TCM while enhancing the ascending motion in the region. This postulation is confirmed by the enhanced precipitation and convergence at 850 hPa late in the decade from the NCEP–NCAR reanalysis (not shown), in the large SST warming regions, and what happened in the central-eastern Pacific as also documented by Kachi and Nitta (1997). Therefore, from the in situ feedback between the SST warming and TCM, the local Hadley circulation is modulated and the SST forcing propagates northward to the SCS–Phillipine Sea region and results in the intensification of the WPSH through enhancing the descending motion. The intensified WPSH enhances the pressure gradient over southern and Southeast Asia in its north and northwest, on the one hand leading to a more intense Asian subtropical westerly jet stream

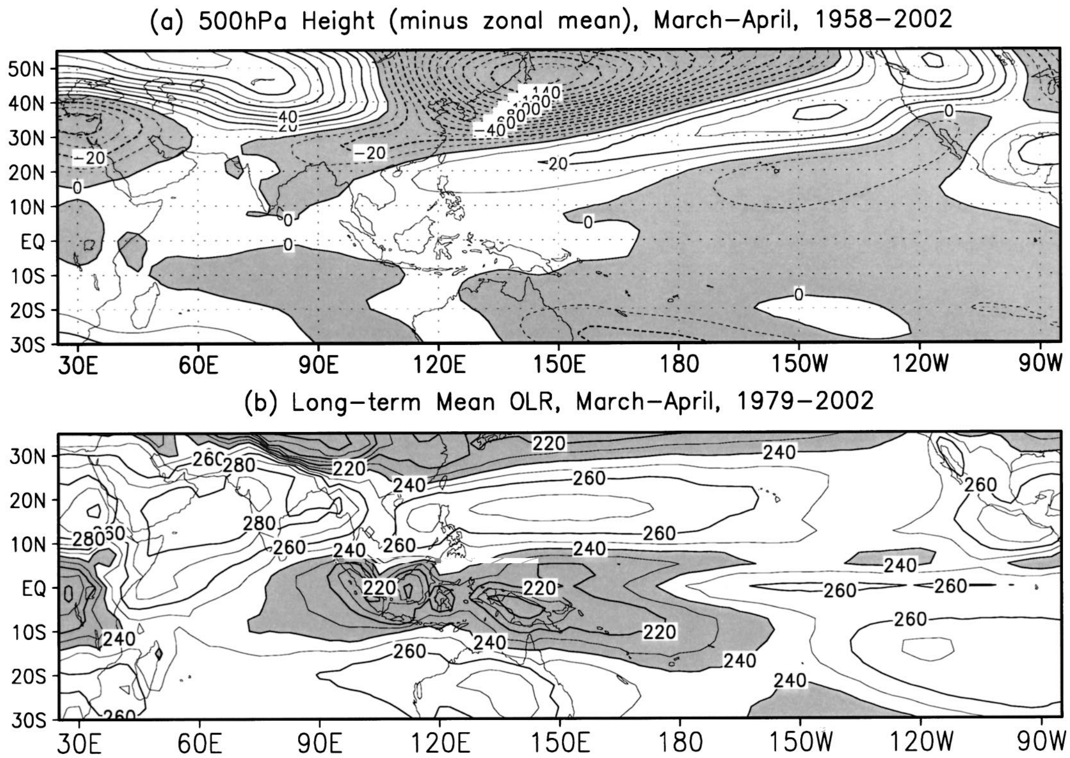

FIG. 8. (a) The climatological height (minus zonal mean) at 500 hPa during 1958–2002 and (b) OLR during 1979–2002 during Mar–Apr. The contour interval is 10 m in (a) and 10 W m^{-2} in (b).

over the southeastern Tibetan Plateau, and on the other hand resulting in a more intense extratropical front thereby enhancing the cyclonic circulation and reducing the pressure in extratropical East Asia. Through the above processes, the forcing of SST warming in the Maritime Continent south of the equator arrives in extratropical east Asia.

Besides the SST forcing in the Maritime Continent,

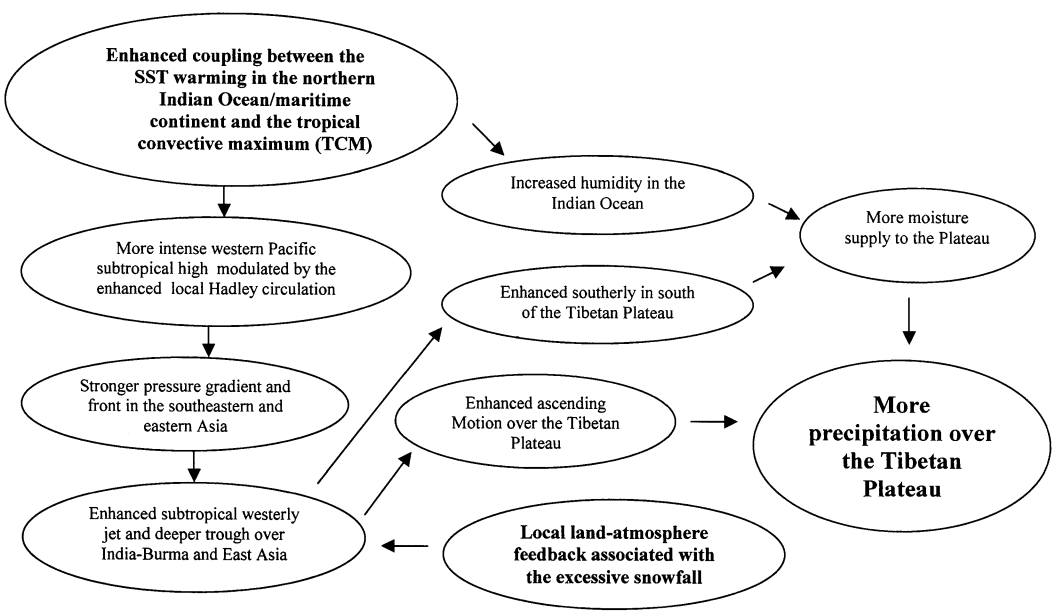

FIG. 9. Schematic diagram showing the processes responsible for the interdecadal change of snow depth in the Tibetan Plateau.

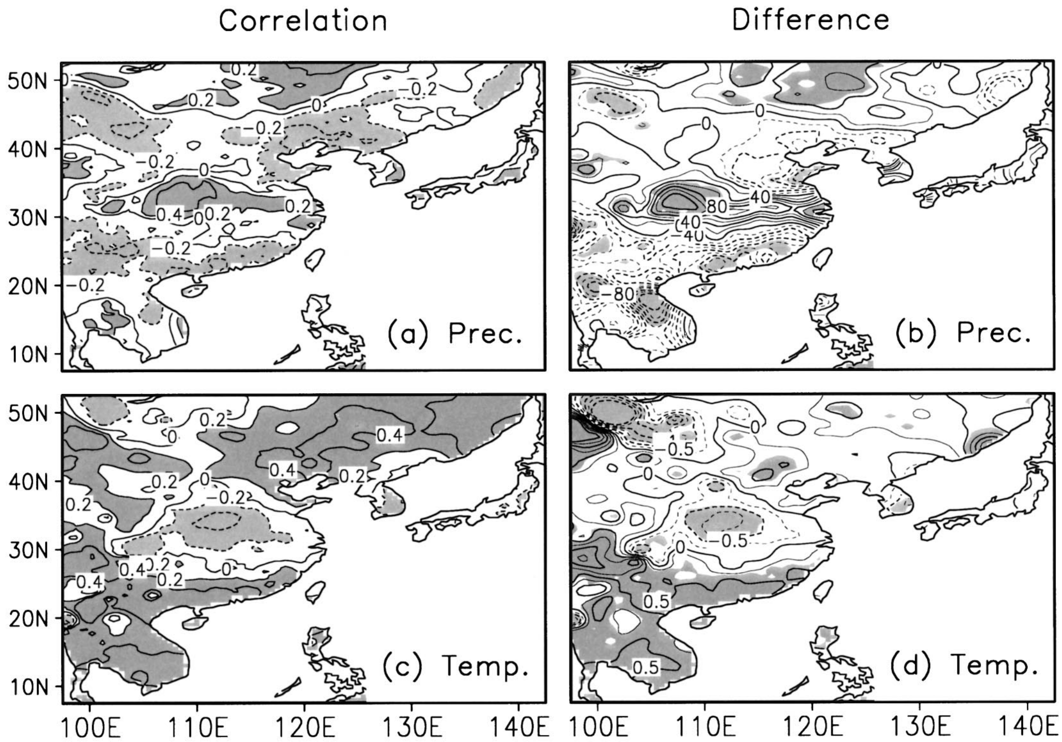

FIG. 10. Correlation between the SDI for Mar–Apr and (a) precipitation for JJA and (c) air temperature and the difference of (b) the precipitation in units of mm during JJA and (d) the air temperature in units of °C between 1980–93 and 1962–76. In (a) and (b), the contour interval is 0.2. Heavy (light) shading indicates the values greater (less) than 0.2 (−0.2). In (b) and (d), the shading indicates the regions where the value passes the 5% significance level test.

there is evidence that the remote forcing from the central-eastern SST warming might also be involved whereas it is too complicated to estimate. Associated with SST warming in the central-eastern Pacific, low-level westerly anomalies exist in the equatorial western-central Pacific (Kachi and Nitta 1997; not shown) indicating the weakening of the Walker circulation and thereby favoring the intensification of the WPSH. This is documented by Chang et al. (2000a) and Wang et al. (2000) for the El Niño years when the warming SST anomaly prevails in the eastern-central Pacific.

The other proposed process involves the local land–atmosphere feedback. The wind anomaly fields (Fig. 5a) show a strong anomalous cyclonic circulation over the plateau where strong underlying land surface cooling (Fig. 4b) is observed. The excessive snow cover can reduce the local land surface temperature due to increased reflectance of the solar radiation. Therefore, the enhanced cyclonic circulation over the plateau may result partly from the land surface cooling, and in turn dynamically results in more snowfall.

5. Impact of the anomalous spring snow cover on the east Asian summer monsoon

Another interesting question in our study is whether and to what extent the excessive spring snow cover over the Tibetan Plateau has a delay impact on the Asian summer monsoon (ASM). To address this question, we calculated the correlation between the SDI for March–April and the summer [June–July–August (JJA)] monsoon rainfall. A close relationship is found only over the eastern Asian regions (Fig. 10). The increase of the snow depth is closely related to the excessive summer rainfall over the Yangtze River valley and the drought conditions in southeastern and northeastern China and the Indochina peninsula. A rainfall difference map between 1980–93 and 1962–76 (Fig. 10b) shows a similar pattern. This implies that the correlation map (Fig. 10a) presents a pronounced decadal variation. This is further supported by the decadal change of the air temperature shown in Figs. 10c,d. The wetter (drier) regions are concurrent with a cooler (hotter) summer (Fig. 10c). The air temperature increase (decrease) exceeds 0.4°C during the whole summer over these regions (Fig. 10d).

a. Change of the western Pacific subtropical high

Figure 10a shows the composite monthly 500-hPa geopotential height in the two decades, in which WPSHs are indicated by the 5850-, 5860-, 5870-, and 5880-m contours. It is seen that the strength and zonal extension of the WPSH differs greatly in the two decades. The 5850-m contour extends westward reaching west of

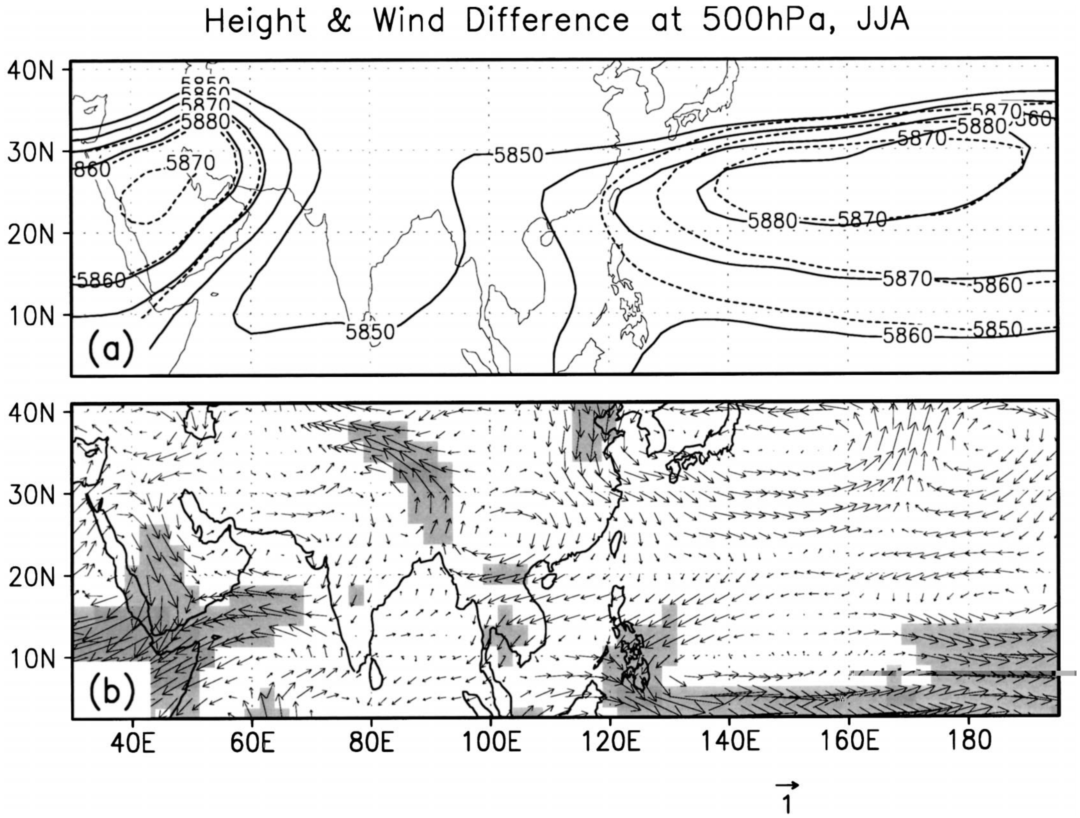

FIG. 11. (a) The composite summer (JJA) 500-hPa geopotential height, indicated by values larger than 5850 m for 1962–76 (dashed line) and 1980–93 (solid line). (b) The difference of the wind vector (JJA) at 500 hPa between these two periods (m s^{-1}). The shading in (b) denotes the regions where the values pass the 5% significance level test.

100°E in the later decade, while it is confined to east of 120°E in the earlier decade. This indicates that the WPSH is stronger and extends more northwestward in the later decade. Similar changes can be identified for the northern African subtropical high (NASH), which intensifies and extends eastward. The intensification of the WPSH and NASH is also illustrated by the occurrence of two anomalous anticyclones over the southeastern China/Indochina peninsula and the northern Arabian Sea, respectively, in the 500-hPa wind difference (Fig. 11b).

It is noted that the excessive rainfall belt over the Yangtze River valley occurs along the northern boundary of the WPSH while the southern drought belt is overlapped by the WPSH. This eastern Asian summer monsoon–WPSH relationship is similar to the one discussed by Chang et al. (2000a,b), who pointed out that the maintenance of the stronger WPSH in southeastern China modulates greatly the strength and duration of the subtropical mei-yu front. The WPSH, on the one hand, blocks the mei-yu front, thereby increasing the duration of the stationary rainfall. On the other hand, it enhances the pressure gradient to its northwest, resulting in a more intense front. Therefore, the heavy rainfall occurs over the northwestern boundary of the WPSH. Meanwhile, the anticyclonic circulation associated with the WPSH controls southeastern China and the Indochina Peninsula, leading to a remarkable decrease of southwesterlies (Fig. 11b), and a dryer and hotter summer over the regions.

A direct factor that affects the strength of the WPSH in the later decade is the SST warming in the Indian Ocean and Maritime Continent. Associated with the SST warming, more intense convective activities occur over the southern South China Sea and the Philippine Sea (not shown), resulting in more release of the diabatic heating. As discussed by Huang and Sun (1992), the more intense diabatic heating intensifies the local Hadley circulation and enhances the descending motion over the southeast coast of China, leading to the northward shift and intensification of WPSH.

Another factor for more westward extension of the WPSH in recent decades is proposed to be associated with reduction of sensible heating over the Tibetan Plateau and neighboring regions due to the excessive snow cover in spring. As we know, the elevated sensible heating of the Tibetan Plateau and the latent heating in southern and southeastern Asia are the primary reason for the breaking up of the subtropical high in late spring and summer in these regions (Liu and Wu 2002). The convection activity over southern Asia and the Bay of Bengal does not change much in later decades (not

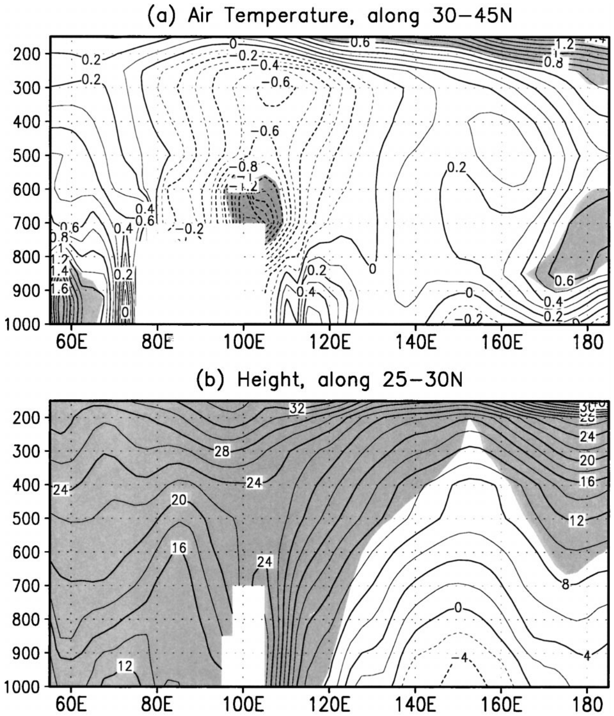

FIG. 12. The longitude–vertical profiles of the difference between 1980–93 and 1962–76 for JJA: (a) air temperature along 30°–45°N and (b) height along 25°–30°N. The contour interval in (a) is 2 m and in (b) is 0.1°C. Shading indicates the regions where the values pass the 5% significance level test.

FIG. 13. The difference of the vorticity at 850 hPa between 1980–93 and 1962–76 during JJA. The contour interval is 10^{-6} s^{-1}. Shading denotes the regions where the values pass the 5% significance level test.

shown), but a significant cooling of the air temperature occurs over the Tibetan Plateau (Fig. 12a) because the excessive snow cover consumes more solar energy during snowmelt. The cooling over the Tibetan Plateau results in anomalous high pressure around itself (Fig. 12b). This results in the more northwestward extension of the WPSH. On the other hand, the anomalous cooling around the Tibetan Plateau weakens the land–sea temperature gradient in the troposphere over Southeast Asia and may lead to the reduction of the southwesterly monsoonal flow. This causes less moisture supply and thereby intensifies the dry and hot conditions over the region.

b. *Role of eastward-migrating low-level vortices over the eastern flank of the Tibetan Plateau*

During the East Asian summer monsoon, the eastward-migrating low-level vortices frequently developing on the eastern flank of the Tibetan Plateau are another important heavy rain-producing and quasi-stationary phenomenon. These vortices migrate eastward along the mei-yu convergence zone and develop into severe weather systems that cause floods in the vicinity of the Yangtze River valley (Tao and Ding 1981; Ninomiya and Akiyama 1992). The generation of the vortices involves the interaction between the topographic effect and the large-scale flow (e.g., Wu and Chen 1985; Kuo et al. 1986; Wang 1987).

More intense activity of low-level vortices in the later decade is identified in the 850-hPa vorticity difference. There is a vorticity maximum center around 30°N, 115°E (Fig. 13). Increased vorticity is also found over the Tibetan Plateau at 500–600 hPa (not shown). Previous studies revealed that the energy for the vortex generation comes mostly from the release of the latent heat (Wu and Chen 1985; Kuo et al. 1986; Wang 1987; Wang and Orlanski 1987; Wang et al. 1993). Figure 14 presents the vertical distribution of the specific humidity difference between 1980–93 and 1962–76 along 30°N. In the later decade there is a significant increase of humidity on the eastern flank of the Tibetan Plateau around 105°E. While no significant moisture flux input is found from outside the region, it is likely that the increase of the humidity results from the increased local evaporation due to the melting of the excessive snow.

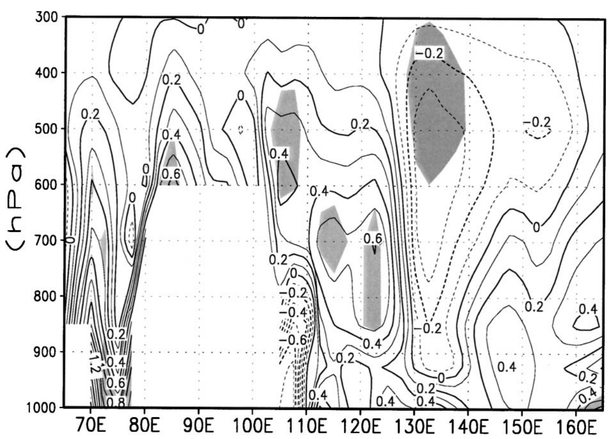

FIG. 14. The vertical profiles of the specific humidity difference between 1980–93 and 1962–76 along 30°N for JJA. The contour interval is 0.1 g kg^{-1}. Shading denotes the regions where the values pass the 5% significance level test.

This hypothesis is consistent with the results of the numerical experiments by Barnett et al. (1989) and Yasunari et al. (1991), who pointed out that the excessive snow cover could lead to more local evaporation. Increase of the local moisture causes the development of the cumulus convection, providing energy for the development and maintenance of the more intense vortices.

6. Summary and concluding remarks

In this work the interdecadal variation of the spring snow depth over the Tibetan Plateau and associated circulation changes are investigated using the station observational snow depth and precipitation data. The relationship between snow cover over the Tibetan Plateau during March–April and the subsequent East Asian summer monsoon is also examined. The major conclusions are summarized below.

1) The spring snow cover depth in the Tibetan Plateau undergoes a distinct decadal increase after the late 1970s, which is concurrent with excessive precipitation over this region. Simultaneous correlation between the snow depth index averaged from 17 stations over the Tibetan Plateau for March–April and precipitation over Eurasia shows a coherent wave train projecting from the Tibetan Plateau and neighboring regions to western Asia. The anomaly pattern is tilted from southwest to northeast, with a wetter-than-normal condition over northern India–northwestern China and western Asia, and a dryer-than-normal condition over central Asia. The increase of the snow depth is concurrent with the land surface cooling over the Tibetan Plateau and its neighboring region and the SST warming in the Indian Ocean and Maritime Content.
2) It is found that the increased snow depth is closely associated with the enhanced subtropical westerly jet and the ascending motion over the plateau as well as a deeper India–Burma trough. It is also linked to more sufficient moisture supply brought by the enhanced southwesterlies along the southeastern part of the plateau from the Bay of Bengal where the humidity is increased due to underlying SST warming. While the increased snow depth happened on the background of an extensive environmental circulation change associated with the climate shift in the Northern Hemisphere, there might be two local physical processes responsible for the phenomena involving the local land–atmosphere feedback and the SST forcing from the Indian Ocean–Maritime Continent. The latter, resulting in an intensified WPSH over the SCS–Philippine Sea through change of the local Hadley circulation by a stronger air-sea coupling between the TCM and underlying large SST warming, enhances the pressure gradient in subtropical Asia and thereby accelerates the westerly jet stream and enhances the subtropical front. The former involves the feedback of an enhanced upper-cyclonic circulation and underlying cooling of the land surface over the plateau that resulted from the increased reflectance of the solar radiation due to the increased snow cover.
3) Being concurrent with the decadal increase of the snow depth over the Tibetan Plateau for March–April, the change of the East Asian summer monsoon is identified by a wetter summer over the Yangtze River valley and a dryer summer in the southeastern China and Indochina peninsula. It is proposed that, in the later decade, the reduction of the surface sensible heating over the Tibetan Plateau, due to more solar energy being consumed to melt excessive snow cover, causes the, anomalous rising of the pressure in the region that in turn leads to a more intense and northwestward extension of the WPSH. The change of the WPSH, in turn, enhances the strength and duration of the pre-mei-yu and mei-yu fronts in the Yangtze River valley. In addition, more local moisture melted from the excessive snow mass provides a favorable condition for the generation of more intense local convection and thereby enhances the development of the eastward-migrating vortex in the eastern flank of the Tibetan Plateau. Both of the above factors lead to increased summer rainfall in the Yangtze River valley. The weaker southwesterly associated with the decrease of the land–ocean temperature gradient due to the cooling over the Tibetan Plateau and warming in the eastern Indian Ocean–Maritime Continent is another factor resulting in a dryer summer in southeastern China and the Indochina peninsula.

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