

Low-frequency snow changes over the Tibetan Plateau

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ABSTRACT: Snow change over the Tibetan Plateau may exert a large influence on climate variability in the surrounding regions. However, the characteristics of snow changes at different time scales and the factors for these changes are still not clear. The present study documents linear trends in snow cover and snow water equivalent over the Tibetan Plateau and their relationship to surface air temperature changes during 1979–2006 based on satellite data. The long-term snow variations display a remarkable regional difference and an obvious seasonal dependence. A significant decreasing trend is observed in the western part for snow cover and snow water equivalent in summer and fall and in the southern part for snow cover in all the four seasons. A significant increasing trend is identified in the central-eastern part for snow cover in fall, winter, and spring and in the eastern and far western parts for snow water equivalent in winter and spring. The relationship between snow and surface air temperature changes features regional disparity. The temperature increase is accompanied by snow cover decrease in the southern and western parts, but by snow cover and snow water equivalent increase in the central-eastern part. The reasons for the snow changes vary with the season. The increase in snowmelt following the temperature increase may be the reason for the snow cover decrease in the western and southern parts in summer. The snowfall change induced by vertical motion change appears to be a factor for the snow water equivalent increase in the far western part and the snow cover decrease in the southern part in winter. The increase in snowfall induced by the increase in atmospheric moisture following the temperature increase and the enhanced upward motion may contribute to the snow increase in the eastern part in winter.

KEY WORDS Tibetan Plateau snow; low-frequency change; surface air warming; regional feature; seasonal dependence

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1. Introduction

Snow is an essential component in the climate system. Snow may change the energy cycle of the earth surface through altering surface albedo, modulating sensible heat exchange between the land surface and atmosphere, consuming latent heat during snowmelt, and modifying long-wave radiation from the surface (Barnett *et al.*, 1989; Cohen and Rind, 1991; Yasunari *et al.*, 1991). The snowmelt has an immediate influence on the water cycle, especially in mountain, arid, and semiarid regions (Barnett *et al.*, 2005). Snow change may affect atmospheric circulation and regional precipitation (Bamzai and Shukla, 1999; Chen and Wu, 2000; Zhang *et al.*, 2004; Dash *et al.*, 2005; Wu and Kirtman, 2007; Zhao *et al.*, 2007; Wu *et al.*, 2010; Si and Ding, 2013; Wu *et al.*, 2014a, 2014b; Zhu *et al.*, 2015).

The Tibetan Plateau exerts a large impact on East Asian and global climate variability through its dynamic and thermal effects (Flohn, 1957; Ye, 1981; Yanai and Wu,

2006; Wu *et al.*, 2007; Wang *et al.*, 2008). The snow cover may modulate the thermal state of the Plateau surface and in turn the thermal contrast with the surrounding regions (Blanford, 1884; Zhao and Moore, 2004; Wu and Kirtman, 2007; Liu *et al.*, 2014; Wu *et al.*, 2016). While many studies have been made about the impacts of the Tibetan Plateau snow on regional climate variability, the plausible causes for snow changes in this region have been rarely addressed. In particular, the long-term changes of snow over the Tibetan Plateau is often considered as a factor for interdecadal rainfall variability over East Asia, but what caused the snow change has not been investigated. It is important to identify the features and the plausible factors of snow variations over the Tibetan Plateau for a better understanding of their effects.

Previous studies about the Tibetan Plateau snow variations are mostly based on station observations that are mainly located in the eastern part. The station observations suggest that the snow depth in March–April and the number of days covered by snow in April–May both declined after 1980s (Zhao *et al.*, 2007; You *et al.*, 2011; Si and Ding, 2013; Zhu *et al.*, 2015). Satellite observations show that the western part is covered by snow in summer (Pu *et al.*, 2007; Wu *et al.*, 2016) which may pose an impact on summer climate variability (Liu *et al.*, 2014; Wu *et al.*, 2016). A decrease in summer snow cover was detected

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in the western part in the late 1990s based on satellite observations (Wu *et al.*, 2016). The seasonal dependence of snow cover trends has been detected in other regions. The snow cover over Eurasia and North America displayed a significant decline in spring, but an increase in fall during the period 1972–2006 (Déry and Brown, 2007). Estilow *et al.* (2015) showed that the Northern Hemisphere snow cover experienced a decrease in spring and summer and an increase in fall and winter during the period 1981–2010. A question is whether the snow variations over the Tibetan Plateau display seasonal dependence and regional features.

Temperature is a principal factor influencing snowfall and snowmelt (Karl *et al.*, 1993; Hantel and Hirtl-Wielke, 2007; McCabe and Wolock, 2010) and in turn the snow-covered area and snow mass. In general, snow tends to decrease in response to surface warming (Karl *et al.*, 1993; Dai *et al.*, 2012). Brown *et al.* (2010) indicated that air temperature is an important element for the Arctic spring snow cover decrease during 1967–2008. The decrease of spring snow cover and snow water equivalent over the mid-high latitude Eurasian continent in the late 1980s is associated with the surface air temperature increase induced by atmospheric circulation changes (Ye *et al.*, 2015). Station observations show warming over the eastern Tibetan Plateau in recent decades (Wang *et al.*, 2008; Rangwala *et al.*, 2009; Duan and Xiao, 2015; Duan *et al.*, 2015; You *et al.*, 2015). On the other hand, the station snow depth over the eastern Tibetan Plateau increased in the late 1970s and decreased in the late 1990s (Zhang *et al.*, 2004; You *et al.*, 2011; Ding *et al.*, 2013; Zhu *et al.*, 2015), both of which correspond to surface warming. This indicates the complexity of the relationship between snow and temperature changes. Wu and Chen (2016) detected that the relationship between surface air temperature and snow water equivalent variation during spring displays differences in western and eastern Eurasia, depending on the amount of snow mass. A question to be addressed is what is the relationship between snow and air temperature variations over the Tibetan Plateau. Does the warming lead to snow decrease over the whole region?

In the following, we describe the datasets and methods in Section 2. We document annual mean snow cover and snow water equivalent changes along with the relationship to annual mean surface air temperature changes in Section 3. Section 4 focuses on the seasonal character of snow and surface air temperature changes and their relationships. In Section 5, we discuss plausible reasons of the snow changes and the relationship between snow and temperature changes. Summary and discussions are provided in Section 6.

2. Data and methods

The snow cover and snow water equivalent data were obtained from the National Snow and Ice Data Center (NSIDC) (available at <http://nsidc.org/data/>). The original snow cover data are the Northern Hemisphere Weekly Snow Cover that were derived from the Advanced Very

High Resolution Radiometer (AVHRR) version 4, the Geostationary Operational Environmental Satellite System (GOES), and other visible wave band satellite data (Brodzik and Armstrong, 2013). The weekly snow cover data are converted to monthly mean values for this analysis. In the conversion, the same value of the weekly snow cover frequency in a specific week, which is a binary value (0 or 1), is assigned to all the days in that week and the monthly mean value is obtained simply by averaging the daily values in the specific month. The global snow water equivalent data were originated from Scanning Multichannel Microwave Radiometer (SMMR) (1978–1987) and selected Special Sensor Microwave or Imagers (SSM/I) (1987–2007) (Armstrong *et al.*, 2005).

The original snow cover and snow water equivalent data are on the Equal-Area Scalable Earth Grid (EASE-Grid) with a spatial resolution of 25 km. The snow cover data span the period from October 1966 to June 2014 and snow water equivalent data cover the period from November 1978 to May 2007. All those data were converted to the $1^\circ \times 1^\circ$ regular longitude-latitude grids before analysis. The value at a latitude-longitude grid point is assigned by the value at the nearest EASE grid in the conversion. The maximum distance between a latitude-longitude grid and the nearly EASE grid is $\frac{25\sqrt{2}}{2}$ km. As snow cover data before 1975 show overestimation over the Tibetan Plateau (Robinson *et al.*, 1993), the present study analyzes the data after 1975.

The monthly mean surface air temperature and precipitation data were acquired from the University of East Anglia Climatic Research Unit (CRU) version ts3.23 with a spatial resolution of $0.5^\circ \times 0.5^\circ$ and covering the period 1901–2014 (Harris and Jones, 2015) (available at <http://www.cru.uea.ac.uk/data/>). The global elevation data were obtained from the National Aeronautics and Space Administration (NASA) (available at <http://reverb.echo.nasa.gov/reverb/>) and regridded to the $1^\circ \times 1^\circ$ grids.

Station daily mean surface air temperature, relative humidity, and surface pressure were obtained from the China Meteorological Administration (available at <http://data.cma.cn/>). We only choose 72 stations which are located in the region of the Tibetan Plateau with elevation higher than 2000 m and with continuous observations for the period 1975–2012. The station data are subject to a quality control to insure the reliability of the data (Feng *et al.*, 2004). Station-specific humidity is calculated based on station air temperature, relative humidity, and pressure.

The monthly mean vertical p -velocity at 500 hPa from the Japanese 55-year Reanalysis (JRA-55) (Kobayasho *et al.*, 2015) is used to diagnose the vertical motion in this study. The horizontal resolution of JRA-55 reanalysis is 1.25° longitude-latitude. The JRA-55 reanalysis is available starting from 1958. The JRA-55 data were obtained via ftp at [ds.data.jma.go.jp](ftp://ds.data.jma.go.jp).

The snow mass change is determined by snowfall and snowmelt. There are no available observations of snowfall and snowmelt. To understand the change in snow, we estimate snowfall and snowmelt based on empirical formula established in previous studies. The amount of snowfall

was calculated according to the snowfall model established based on the method of monthly water balance (Hylckama, 1956; Tarboton *et al.*, 1991; McCabe and Wolock, 2010). The input data are monthly temperature and precipitation. The snowfall model is as follows:

$$S_f = \begin{cases} P & , \text{if } T \leq T_{\text{snow}} \\ P \left(\frac{T_{\text{rain}} - T}{T_{\text{rain}} - T_{\text{snow}}} \right) & , \text{if } T_{\text{snow}} < T < T_{\text{rain}} \\ 0 & , \text{if } T \geq T_{\text{rain}} \end{cases} \quad (1)$$

where S_f is monthly snowfall, P is monthly precipitation in mm, T is monthly surface air temperature, T_{rain} is a threshold of monthly temperature above which all precipitation in that month is rain, and T_{snow} is a threshold of monthly temperature below which all precipitation in that month is snow. When monthly surface air temperature is between T_{rain} and T_{snow} , the partition of precipitation between snow and rain depends on the linear relationship of temperature. In this study, the T_{rain} is 7°C and T_{snow} is -4°C following McCabe and Wolock (2010). The snowmelt model uses degree day approach to calculate the amount of snowmelt (Gottlieb, 1980; Hock, 2003), which is as follows:

$$S_m = \begin{cases} \mu (T - T_{\text{snow}}) d & , \text{if } T > T_{\text{snow}} \\ 0 & , \text{if } T \leq T_{\text{snow}} \end{cases}, \quad (2)$$

where S_m is the amount of monthly snowmelt in mm, μ is the melt rate, and d is the number of days in a month. We set the melt rate as 0.47 following McCabe and Wolock (2010).

Based on the snowfall model, the change in snowfall is determined by both temperature and precipitation. When the temperature remains about T_{rain} , there would be no snowfall. In such case, the precipitation change has no effect on the snowfall. When the temperature remains below T_{snow} , all the precipitation change would be the snowfall change. In such case, the factors contributing to the precipitation change would act on the snow change. When the temperature fluctuates between T_{rain} and T_{snow} , the snowfall change would depend upon both the precipitation change and the temperature change. In such case, the partition of the precipitation change to the snowfall change would depend on the mean temperature.

The Gaussian low pass filter with a half power frequency period of 9 years was used to extract the decadal variability. The F -test was applied to examine the significance of trends. Gaussian filter is widely used in obtaining low frequency signal in atmospheric science. It is based on the Gaussian function in the form:

$$f(x) = ae^{-\frac{(x-b)^2}{2c^2}},$$

where a , b , and c are arbitrary real constants, respectively, that determine the curve's peak of the height, location of the peak center, and the standard deviation.

Here, we offer some descriptions of the characters of different snow quantities used in this study and their relationships for facilitating understanding of the results presented in the following sections. Snow depth is the thickness of the snow layer. Snow water equivalent is the amount of

water contained within the snowpack. The snow depth is approximately the snow water equivalent divided by the density of snow. The snow cover is the percentage of area covered by snow. The relationship between snow cover and snow water equivalent changes depends upon the snow mass. When the snow mass is large and the snow layer is thick, the snow water equivalent change may not be accompanied by snow cover change (Wu and Chen, 2016). In contrast, when the snow mass is small and the snow layer is thin, the snow water equivalent change is likely to be accompanied by the snow cover change. Snowfall is the amount of precipitation falling from the sky and snowmelt is the amount of snow that is melted. Snowfall and snowmelt together determine the accumulation of snow and thus the change in snow water equivalent.

3. Changes in annual mean snow cover and snow water equivalent

In this section, we analyse annual mean snow cover and snow water equivalent distributions and long-term changes. The annual mean surface air temperature changes are analysed and compared to unravel the relationship between long-term snow and air temperature changes. The snow and air temperature changes and their relationships based on seasonal stratification will be presented in the next section.

The annual mean snow cover over the Tibetan Plateau displays two high value regions, one located in the western part and the other in the southeastern part (Figure 1(a)). The region in the western part has values higher than 70% in the center and extends southeastward and northeastward. The distribution of annual mean snow water equivalent is similar to that of snow cover with large values located in the western and southeastern parts (Figure 1(b)).

The annual mean snow cover changes during 1979–2006 display notable regional difference. Significant decrease is observed in the western and southern parts, whereas a remarkable increase is detected in the central and eastern parts (Figure 2(a)). The linear trend reaches 10% per decade in some regions. The annual mean snow water equivalent shows an increase in the eastern Tibetan Plateau (Figure 2(b)), similar to that in snow cover. The linear trend there reaches 1 mm decade^{-1} . In other regions, the snow water equivalent trends are less obvious and display smaller scale features compared with the snow cover trends. The difference appears to suggest that the snow cover is more likely influenced by the climate change.

In view of the remarkable regional character in snow cover changes, we choose three regions to examine and compare the trends among different regions. These regions are determined based on annual mean snow cover trends. The three regions are, respectively, the west region ($31.5^\circ\text{--}40.5^\circ\text{N}$, $69^\circ\text{--}80^\circ\text{E}$), the south region ($26.5^\circ\text{--}29.5^\circ\text{N}$, $80^\circ\text{--}97^\circ\text{E}$), and the east region ($29.5^\circ\text{--}35.5^\circ\text{N}$, $92^\circ\text{--}101^\circ\text{E}$) as denoted by the boxed areas in Figure 2(a). The regional mean is calculated based on values at grids (with the elevation above 2000 m) only.

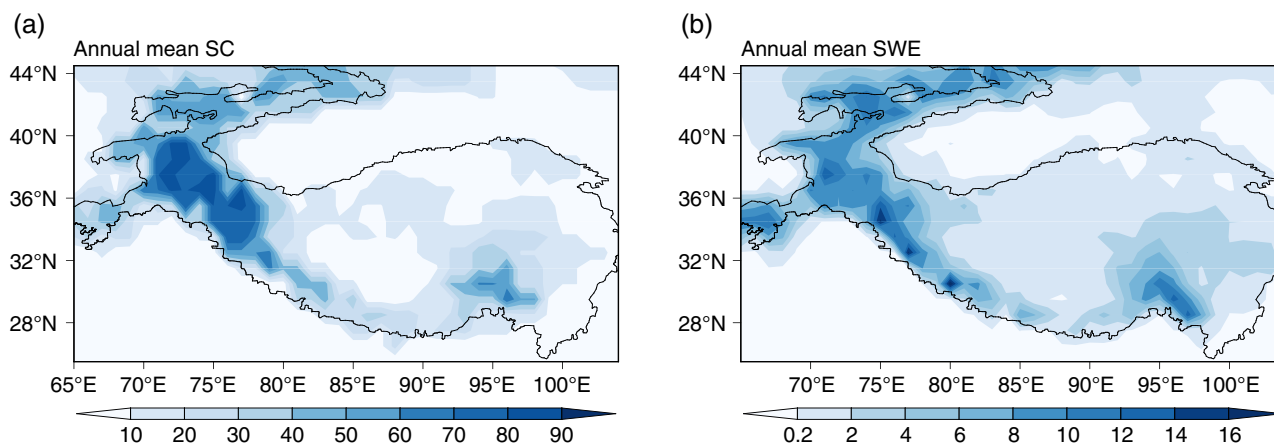


Figure 1. Climatological annual mean (a) snow cover (%) and (b) snow water equivalent (mm) for the period 1979–2006 based on the NSIDC data. Black curves denote the 3000 m elevation (same in other figures). [Colour figure can be viewed at wileyonlinelibrary.com].

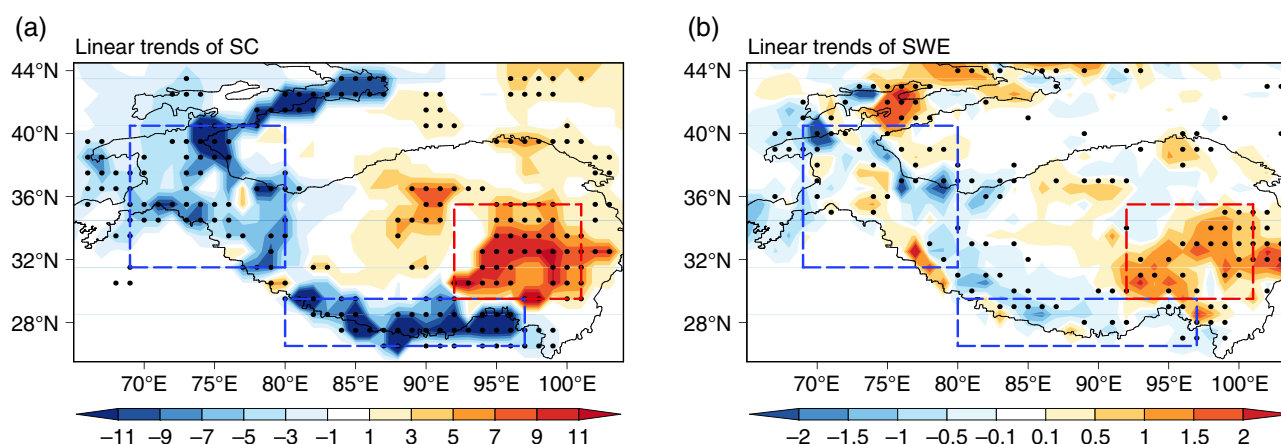


Figure 2. Linear trends of annual mean (a) snow cover (% decade⁻¹) and (b) snow water equivalent (mm decade⁻¹) for the period 1979–2006 based on the NSIDC data. Dotted regions denote trends significant at the 95% confidence level (same in other figures). Three box covered areas in (a) denote the domains of the west region, the south region, and the east region in calculating area-mean values (same in other figures). [Colour figure can be viewed at wileyonlinelibrary.com].

During the period 1979–2006, while the mean snow cover in the west region (Figure 3(a), red line) and the south region (Figure 3(a), blue line) shows a notable decrease, that in the east region (Figure 3(a), orange line) experiences an interdecadal increase in the mid-1990s. The trend of the snow cover averaged over the whole displays a decreasing trend (Figure 3(a), black line), following closely that in the west and south regions. The trends in the snow water equivalent during 1979–2006 are not clear in the west and south regions and the whole (Figure 3(b)). The snow water equivalent in the east region, however, displays a notable increase in the late 1990s, which is consistent with that of snow cover. After entering the 21st century, the snow water equivalent in the east region turned to decrease.

To compare the snow cover variations at different elevations, we calculate area-mean snow cover in the three regions based on the elevation ranges as follows: 2000–2999, 3000–3999, 4000–4999, and above 5000 m. In the west region, the snow cover variations show a similar downward trend at different elevations

(Figure 4(a)). In comparison, the trend is larger at 2000–2999 m and smaller at 4000–4999 m. In the south region, the downward trend is observed at all elevations below 5000 m with the magnitude increasing with the elevation (Figure 4(b)). Above 5000 m, the interdecadal change appears to be more prominent. In the east region, the interdecadal increase in the mid- to late-1990s is observed at all elevations (Figure 4(c)). The decrease after entering the 21st century is observed above 4000 m, but not between 2000 and 4000 m.

The snow change is often linked to surface air temperature variation. Higher surface temperature leads to more snowmelt, reducing the snow mass. Lower air temperature favours more snowfall, contributing to snow accumulation. Meanwhile, the snow albedo feedback and consumption of latent heat during snowmelt affect local air temperature. Here, we analyse the low-frequency variations in annual mean surface air temperature to identify whether they are related to annual mean snow cover and snow water equivalent changes. The annual mean surface air temperature trend during 1979–2006 is dominated

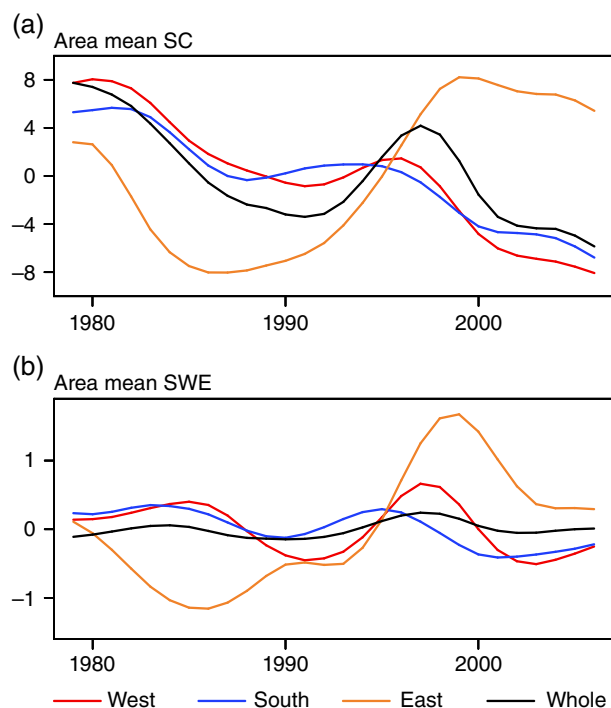


Figure 3. Time series of area-mean annual mean (a) snow cover (%) and (b) snow water equivalent (mm) anomalies based on climatology for the period 1979–2006 in different regions based on the NSIDC data. The area-mean values are calculated by averaging values at grid points with elevation above 2000 m. All lines are obtained by a 9-year Gaussian filter (same in other figures). [Colour figure can be viewed at wileyonlinelibrary.com].

by positive values, which is consistent with previous studies (Duan and Xiao, 2015; You *et al.*, 2015; Duan *et al.*, 2016). The largest increasing trend is observed in the central-western part where the trend reaches over $0.5^{\circ}\text{C decade}^{-1}$. The trend is relatively small in the southeastern part. The increasing trend in temperature is observed in the surrounding regions, indicating that the Tibetan Plateau temperature increase is part of broad scale warming. Comparison of Figures 2 and 5 indicates a complicated relationship between low frequency snow and surface air temperature variations.

4. Changes in seasonal mean snow cover and snow water equivalent

The snow distribution may vary with season. The relationship between snow and temperature change may also depend upon the season. In this section, we examine the low frequency snow changes in different seasons and their relationships to surface air temperature changes. Before that, we present climatological mean snow distributions in the four seasons: spring (March–April–May, MAM for brevity), summer (June–July–August, JJA for brevity), fall (September–October–November, SON for brevity), and winter (December–January–February, DJF for brevity).

The snow cover and snow water equivalent have a distinct seasonal cycle. The snow cover is the largest

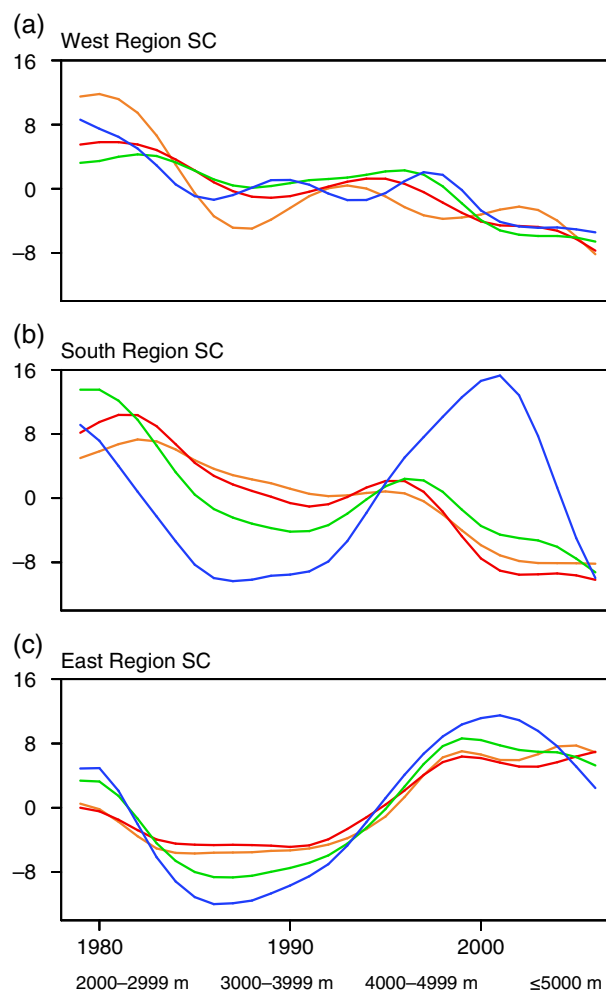


Figure 4. Time series of area-mean annual mean snow cover anomalies (%) based on climatology for the period 1979–2006 in the (a) west region, (b) south region, and (c) east region averaged for grid points with different elevations based on the NSIDC data. [Colour figure can be viewed at wileyonlinelibrary.com].

in winter (Figure 6(d)) and reduces somewhat in spring (Figure 6(a)). The snow coverage is smaller in summer and fall (Figures 6(b) and (c)) than in winter and spring. In summer, snow cover is limited to the western and southern parts (Figure 6(b)). The snow water equivalent experiences seasonal variation analogous to the snow cover (Figures 6(e)–(h)). However, the highest value in snow water equivalent is observed in spring, in particular in the western and southeastern parts (Figure 6(e)). This differs from the snow cover that has the largest value in winter. This difference is confirmed by a comparison of climatological mean spring minus winter snow cover and snow water equivalent (figures not shown). In the western part, snow water equivalent increases, whereas snow cover shows a relatively small change from winter to spring. In the central and eastern parts, both snow cover and snow water equivalent decrease from winter to spring. The different change in the western part is likely due to the dependence of snow cover change on snow mass. The snowfall may exceed snowmelt in late winter and early spring in high elevation regions with low temperature, which leads

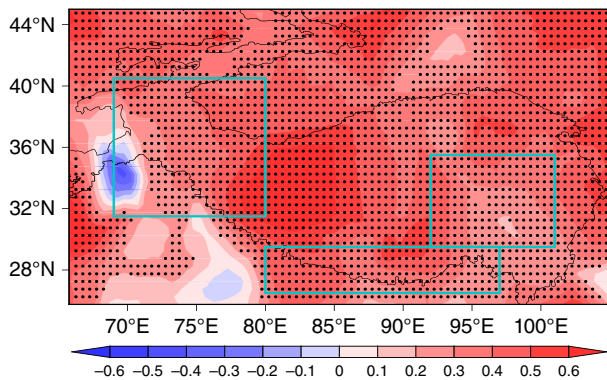


Figure 5. Linear trends of annual mean surface air temperature ($^{\circ}\text{C decade}^{-1}$) for the period 1979–2006 based on the CRU ts3.23 data. [Colour figure can be viewed at wileyonlinelibrary.com].

to further accumulation of snow amount from winter to spring. However, due to the presence of deep snow layer, there is little change in snow cover.

The linear trends of snow cover display an obvious seasonal dependence. In the western part, a significant decrease is observed in summer and fall (Figures 7(b) and (c)) and the trend in winter and spring is small and displays scattered feature (Figures 7(a) and (d)). The area-mean trend in summer and fall reaches -8.01 and -5.59% decade^{-1} , respectively (Table 1). In the southern part, decreasing trend dominates in summer, fall, and winter with area-mean trend of -6.77 , -5.54 , and -9.42% decade^{-1} , respectively (Table 1). In spring, the downward trend still dominates in most regions though small-area increasing trend is imbedded in the region. In the eastern part, significant increasing trend is observed in fall, winter, and spring with area-mean trend of 6.37 , 4.80 , and 9.37% decade^{-1} , respectively (Table 1). A significant increase is also detected in the central part in fall and spring.

The snow water equivalent trends display seasonal change as well. In the eastern part, the snow water equivalent displays an increase in spring, fall, and winter (Figures 7(e), (g), (h)) with area-mean trend reaching 1.51 , 0.68 , and 0.97 mm decade^{-1} , respectively (Table 1). In the far western part, an increasing trend is detected in spring and winter (Figures 7(e) and (h)), whereas a decreasing trend dominates in summer (Figure 7(f)). In the southern part, the trends are small although decreasing trends are present in summer and fall (Figures 7(e) and (g)).

The snow cover and snow water equivalent trends display both consistency and differences. The increasing trends in the eastern part are consistent. The decreasing trends in the western part during summer and fall are observed in both snow cover and snow water equivalent, but are more obvious in snow cover. The increasing trends in the western part during winter and spring are observed in snow water equivalent, but not in snow cover. In the southern part, the snow cover change is more obvious than the snow water equivalent change.

The above consistency and difference between snow cover and snow water equivalent trends may be explained by the dependence of snow cover change on the depth of

snow layer. We have examined the scatter plots of snow cover trends with respect to climatological mean snow water equivalent in the four seasons (figures not shown). The results indicate that snow cover trends tend to be small when mean snow water equivalent is large, whereas large snow cover trends tend to appear when mean snow water equivalent is small. In the eastern region where mean snow water equivalent is small, indicative of a relatively shallow snow layer, snow water equivalent increase is accompanied by snow cover increase. The situation is the same in the western region in summer and fall except that the trends are opposite. Somewhat similar situation is present in the southern region. In the western region in winter and fall, mean snow water equivalent is large, indicative of a deep snow layer, a change in snow water equivalent does not affect the snow coverage.

In order to further show the regional and seasonal dependence of the snow change, we compare seasonal mean snow cover trends in the three regions noted above. In the west region, the decreasing trend is obvious in spring, summer, and fall, with the trend in summer most remarkable (Figure 8(a)). In winter, the snow cover displays a dip in the late 1990s. In the south region, all the four seasons experience a decreasing trend and the trend in summer is most remarkable (Figure 8(b)). In the east region, except for summer, the other three seasons display a significant interdecadal increase in the mid- to late-1990s (Figure 8(c)). In summer, two peaks are observed, one in the late 1970s and the other in the early 2000s.

We have examined the snow cover changes at different elevations in the four seasons (figures not shown). The obtained main features are similar to those of annual mean snow cover variations. For example, in the west region, the decreasing trend is larger at 2000–2999 m in spring, summer, and fall; in the south region, decreasing trend dominates below 5000 m and obvious interdecadal changes are observed above 5000 m in all the four seasons; in the east region, there is an obvious increase at the mid- to late-1990s at all the elevations in spring, fall, and winter and above 5000 m in summer.

The surface air temperature trend is dominated by warming in the four seasons with some differences in the magnitude of the trend (Figure 9, Table 1). The warming is most prominent in winter with the trend above $0.5^{\circ}\text{C decade}^{-1}$ over most of the Plateau (Table 1) with larger trends in the southern part (Figure 9(d)). In spring and summer, the temperature increase in the central-eastern part is larger in the north than in the south (Figures 9(a) and (b)). In fall, the trend over the northeastern Plateau is relatively small (Figure 9(c)). In the far western Plateau, a relatively small trend is observed in summer (Figure 9(b)).

The relationship between seasonal mean snow and surface air temperature trends features prominent regional dependence. Table 2 presents correlation coefficients of regional mean snow and surface air temperature variations in the three regions and four seasons. Two different types of relationships are detected based on a comparison of the spatial distribution between the snow and surface air temperature trends (Figures 7 and 9) and correlation

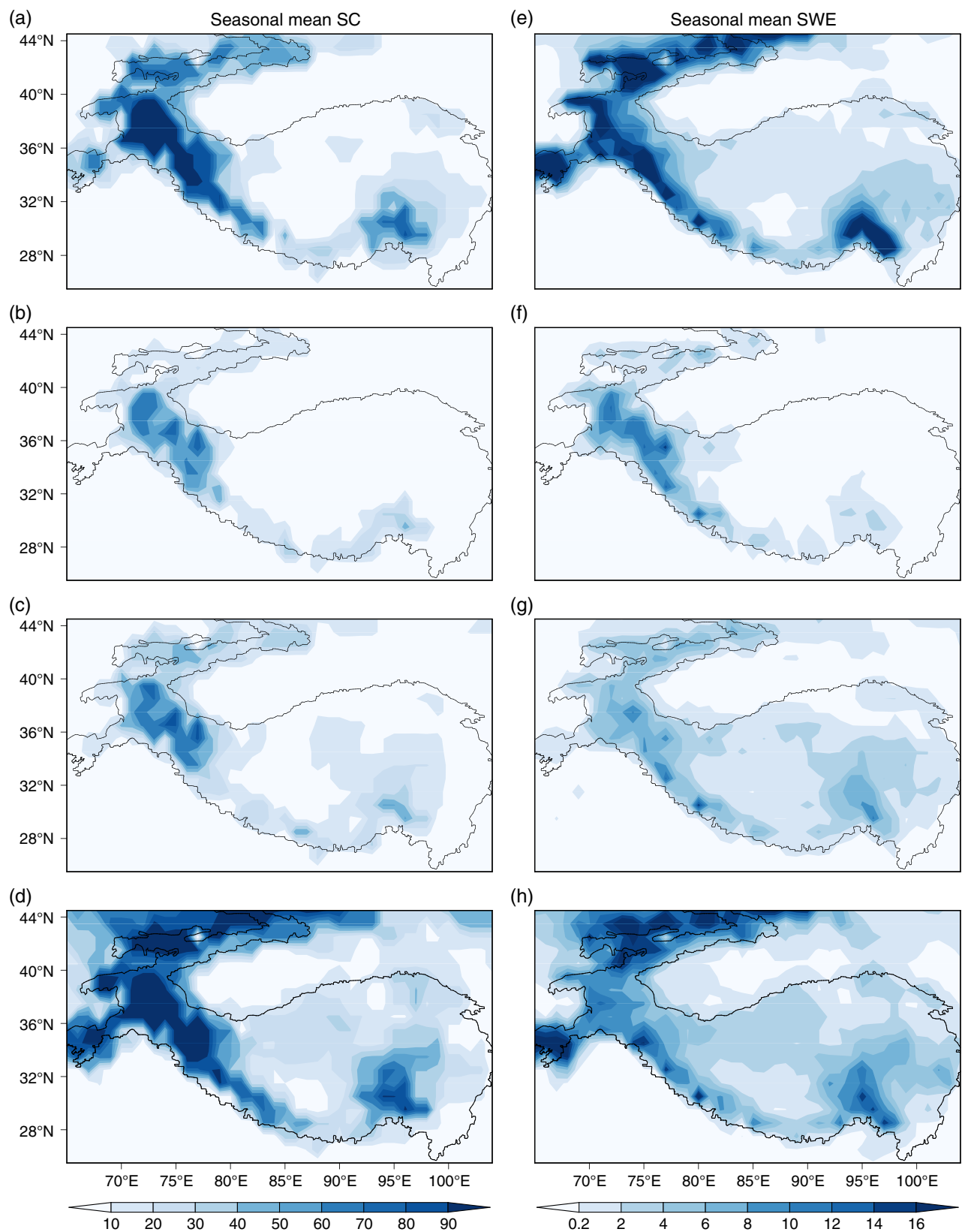


Figure 6. Distribution of climatological seasonal mean snow cover (left, %) and snow water equivalent (right, mm) in (a, e) MAM, (b, f) JJA, (c, g) SON and (d, h) DJF for the period 1979–2006 based on the NSIDC data. [Colour figure can be viewed at wileyonlinelibrary.com].

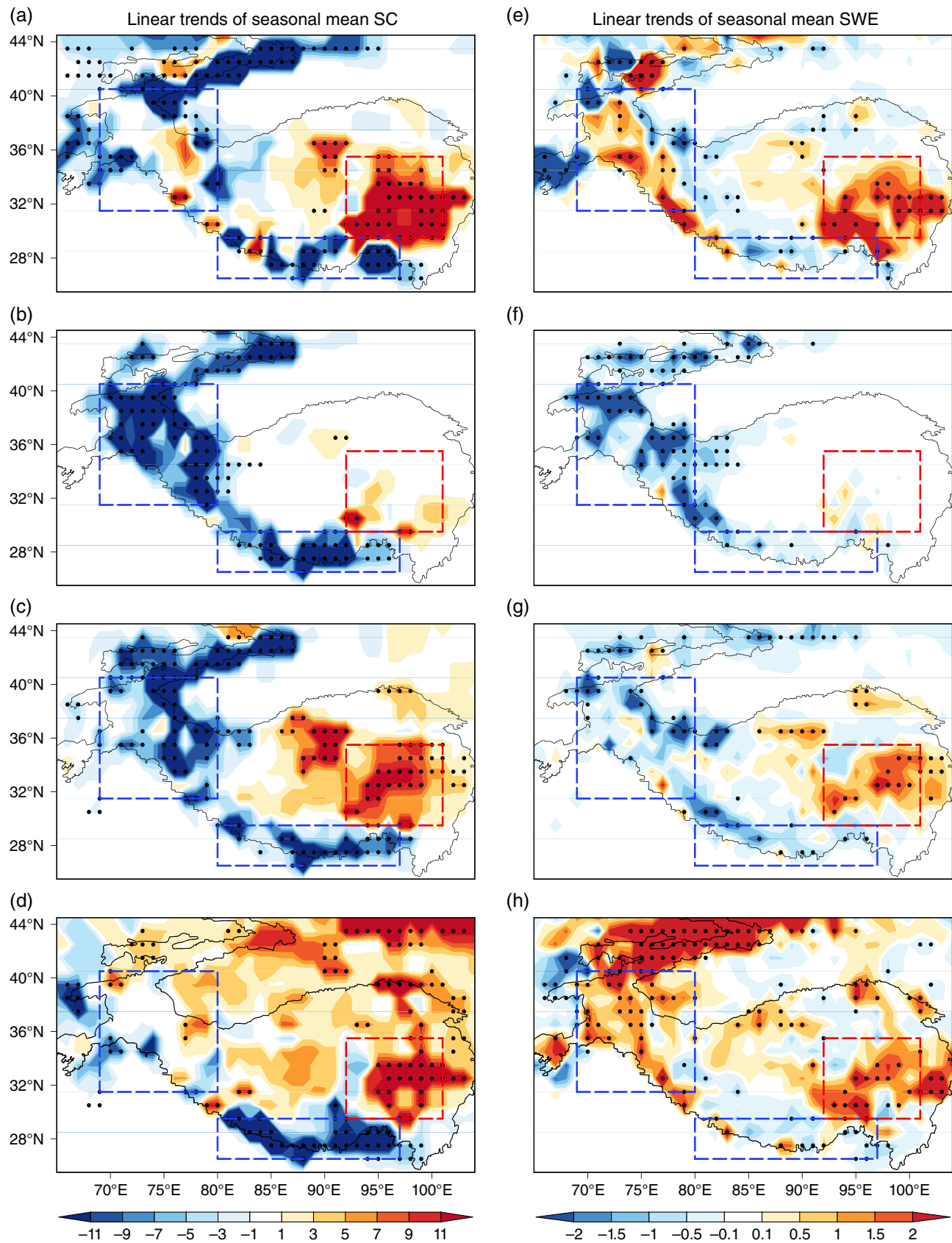


Figure 7. Linear trends of seasonal mean snow cover (left, % decade⁻¹) and snow water equivalent (right, mm decade⁻¹) in (a, e) MAM, (b, f) JJA, (c, g) SON and (d, h) DJF for the period 1979–2006 based on the NSIDC data. [Colour figure can be viewed at wileyonlinelibrary.com].

Table 1. The linear trends of snow cover (SC) (% decade⁻¹), snow water equivalent (SWE) (mm decade⁻¹) and surface air temperature (Ta) (°C decade⁻¹) in the west region, the south region, and the east region for the four seasons.

	SC			SWE			Ta		
	West	South	East	West	South	East	West	South	East
MAM	-4.57	-4.84	9.37	-0.11	-0.01	1.51	0.31	0.14	0.17
JJA	-8.01	-6.77	1.30	-0.94	-0.40	-0.03	0.32	0.27	0.38
SON	-5.59	-5.54	6.37	-0.54	-0.40	0.68	0.48	0.50	0.25
DJF	-0.92	-9.42	4.80	0.59	0.02	0.97	0.63	0.69	0.58

The bold font denotes the linear trends that are significant at the 95% confidence level.

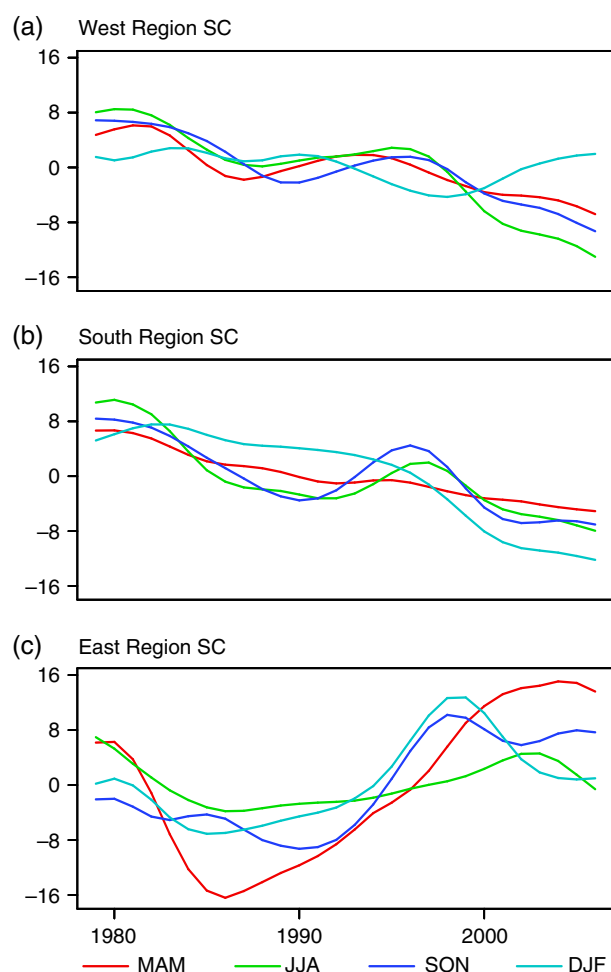


Figure 8. Area-mean snow cover anomalies (%) in different seasons based on climatology for the period 1979–2006 in the (a) west region, (b) south region, and (c) east region based on the NSIDC data. The area-mean values are calculated by averaging values at grid points with elevation above 2000 m. [Colour figure can be viewed at wileyonlinelibrary.com].

coefficients of snow and surface air temperature variations (Table 2) in the four seasons. The relationship displays seasonal preference as well. Those are described below in detail.

In the first type of relationship, snow cover decrease corresponds to surface air temperature increase, following the traditional relationship (Karl *et al.*, 1993). This type of relationship is observed over the southern part in all the four seasons and over the western part in

summer and fall. This type of relationship is further illustrated in Figures 10(a)–(c) that are scatter plots of area-mean summer snow cover in the west and south regions (Figures 10(a) and (b)) and winter snow cover in the south region (Figure 10(c)) versus surface air temperature in the same regions. In these cases, snow cover decreases with surface air temperature increase. The correlation coefficient for the period 1979–2006 is -0.49 in the west region in summer, -0.12 in the south region in summer, and -0.65 in the south region in winter. The correlation coefficient in the south region in summer increases to -0.41 when the period covers 1975–2013.

In the second type of relationship, surface air temperature increase is accompanied by snow increase. This is the case over the central-eastern part in spring, fall, and winter as well as over the far western part in winter and spring. This type of relationship is illustrated in Figures 10(d)–(f) that are scatter plots of area-mean winter snow cover in the east region (Figure 10(d)) and winter snow water equivalent in the west region (Figure 10(e)) and spring snow water equivalent in the east region (Figure 10(f)) versus surface air temperature in the same regions. In these cases, the snow increases with surface air temperature increase. The correlation coefficient for the period 1979–2006 is 0.12 in the east region in winter, 0.47 in the west region in winter, and 0.47 in the east region in spring. The correlation coefficient in the east region in winter is relatively small, indicating a weak relationship between winter snow cover and temperature changes in the east region.

5. Plausible reasons of seasonal mean snow changes

The snow changes are determined by snowfall and snowmelt. Thus, factors that affect the amount of snowfall and snowmelt can contribute to snow changes. The snowmelt is mainly controlled by surface temperature. The snowfall is determined by precipitation and temperature. The precipitation relies on both moisture and upward motion in the atmosphere. The moisture hold in the atmospheric column is related to air temperature. Thus, air temperature effects on the snow change include the partition of precipitation, the moisture, and the snowmelt. Overall, the snow changes are subject to both thermodynamic factors (temperature and moisture) and dynamic factors (vertical motion). Another factor to consider is the persistence of snow anomalies. The snow change in a specific season may be related to that in the

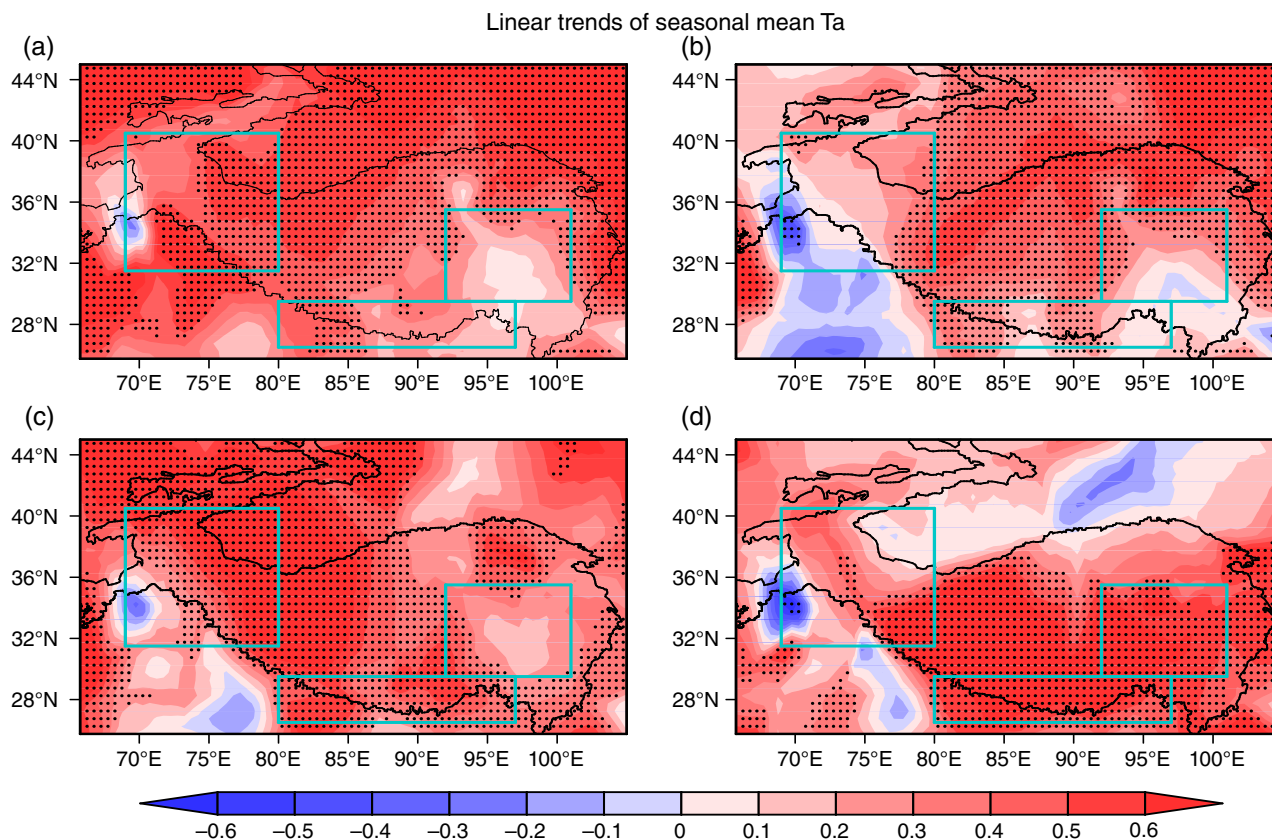


Figure 9. Linear trends of seasonal mean surface air temperature ($^{\circ}\text{C decade}^{-1}$) in (a) MAM, (b) JJA, (c) SON and (d) DJF for the period 1979–2006 based on the CRU ts3.23 data. [Colour figure can be viewed at wileyonlinelibrary.com].

Table 2. Correlation coefficients between snow cover (SC) or snow water equivalent (SWE) and surface air temperature (Ta) in the west region, the south region, and east region for the four seasons.

	SC-Ta			SWE-Ta		
	West	South	East	West	South	East
MAM	-0.41	-0.02	0.47	-0.23	-0.01	0.47
JJA	-0.49	-0.12	0.32	-0.52	-0.32	0.17
SON	-0.41	-0.44	0.15	-0.31	-0.34	0.01
DJF	-0.19	-0.65	0.12	0.47	-0.15	0.01

The bold font denotes the correlation coefficients that are significant at the 95% confidence level.

previous season. In this section, we examine the effects of different factors on satellite-derived snow changes over the Tibetan Plateau in different seasons and their relationship to surface air temperature changes.

The temperature is a factor determining the partition of precipitation in snow. Here, we examine the distribution of mean surface air temperature in the four seasons. In summer, mean surface air temperature is above 4°C in most of the Plateau (Figure 11(a)). The area-mean summer surface air temperature in the three regions is above 7°C (Figure 11(c)), the threshold for snowfall in the snowfall model. In winter, mean surface air temperature over the Plateau is below -4°C except along the slope and in the southeastern corner (Figure 11(b)). The area-mean winter air temperature is well below -4°C in the west and east regions and close to -4°C in the south region (Figure 11(c)). The mean surface air temperature in spring

and fall lies between -4 and 4°C in most regions (figures not shown). The area-mean spring and fall temperature displays a large range of variation with the month (Figure 11(c)).

In summer, due to the high surface air temperature over the Tibetan Plateau, it is inferred that there is little contribution to snow changes from snowfall. Thus, the snowmelt increase induced by surface air temperature increase is a dominant factor for snow cover decrease observed in both the west and south regions (Figures 7(b) and (c)). This explains the negative snow cover-temperature change relationship in the above regions in summer (Figures 10(a) and (b)). We note that there may be a positive feedback of snow cover decrease on the temperature increase via the snow-albedo effect.

In winter, according to the mean surface air temperature range, precipitation is mainly in the form of snowfall

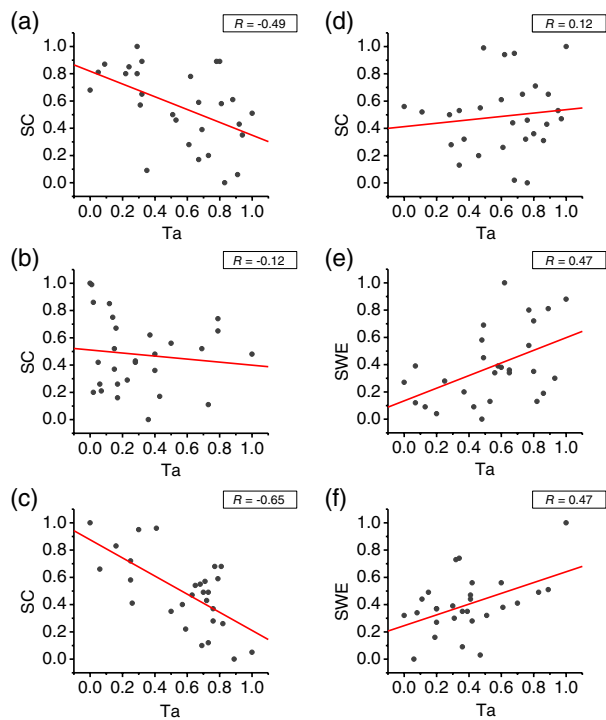


Figure 10. Scatter plot of area-mean snow cover and surface air temperature (a) in the west region in JJA, (b) in the south region in JJA, (c) in the south region in DJF, and (d) in the east region in DJF, and area-mean snow water equivalent and surface air temperature (e) in the west region in DJF and (f) in the east region in MAM during 1979–2006 based on the NSIDC and CRU ts3.23 data. The values shown are the difference of original values minus minimum values divided by maximum minus minimum values. The area-mean values are calculated by averaging values at grid points with elevation above 2000 m. The numbers on the top-right are the correlation coefficients. [Colour figure can be viewed at wileyonlinelibrary.com].

in the west and east regions and to a large part in the south region. It is inferred that the factors for precipitation change have a large effect on the snow changes. In the south region, winter precipitation shows a decrease (Figure 12(a)), which is related to suppressed upward motion (Figure 12(c)). The precipitation decrease leads to snowfall decrease (Figure 12(b)), which accounts for the snow cover decrease there (Figure 7(d)). There is an increase in snowmelt in relation to temperature increase, which has an additional contribution to the snow cover decrease in this region. These explain the negative snow cover-temperature change relationship in winter in the southern part (Figure 10(c)).

In the west region, winter precipitation shows a large increase (Figure 12(a)), leading to snowfall increase (Figure 12(b)), which accounts for the snow water equivalent increase in winter there (Figure 7(h)). The precipitation increase is related to enhanced upward motion that covers most of the west region (Figure 12(c)). The four available stations in the west region indicate an increase in specific humidity (Figure 12(d)), indicating an increase in moisture hold in the atmospheric column, which may contribute to the precipitation increase. This explains the positive snow water equivalent-temperature change

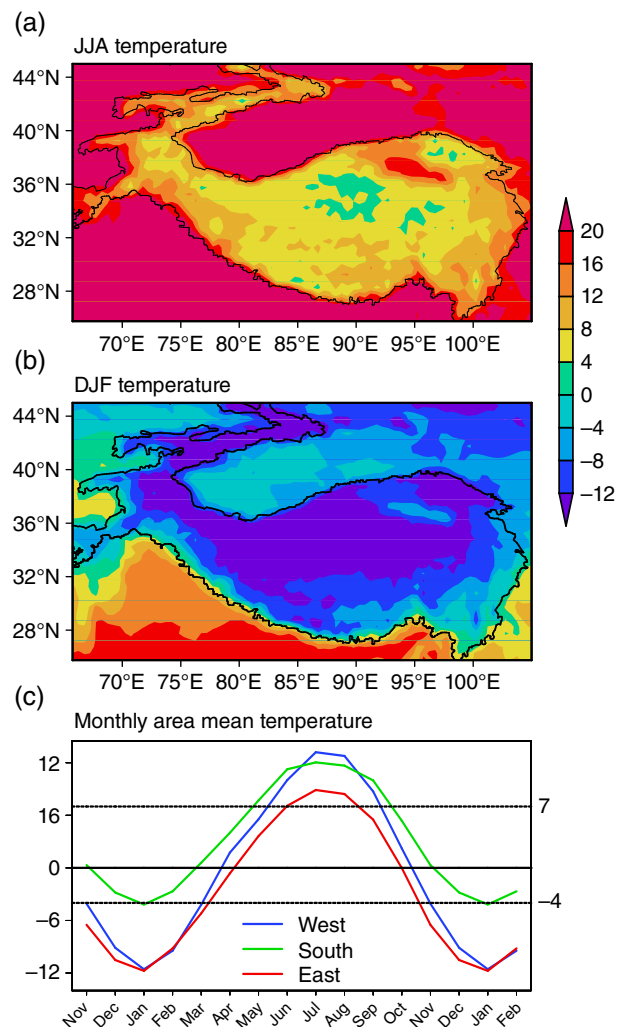


Figure 11. Climatological seasonal mean surface air temperature ($^{\circ}\text{C}$) in (a) JJA and (b) DJF for the period 1979–2006 and (c) area-mean surface air temperature ($^{\circ}\text{C}$) in the west region (blue), the south region (green), and the east region (red) based on the CRU ts3.23 data. The area-mean values are calculated by averaging values at grid points with elevation above 2000 m. The two dashed lines in (c) denote temperature of 7°C and 4°C . [Colour figure can be viewed at wileyonlinelibrary.com].

relationship in winter in the west region (Figure 10(e)). We note that the vertical motion-induced precipitation change contributes to winter snow changes in both the west and south regions. However, due to the opposite vertical motion changes, snow changes are opposite in the two regions, leading to an opposite relationship between snow and temperature changes.

In winter, precipitation increase covers northeastern part of the east region (Figure 12(a)). Thus, enhanced upward motion is a factor for snow increase in this region (Figure 12(c)). In addition, the temperature increase may lead to an increase in atmospheric moisture, contributing to precipitation increase. Indeed, station observations show an upward trend of specific humidity in the eastern part (Figure 12(d)). Thus, both dynamic and thermodynamic processes contribute to the winter snow increase in this region. This explains the positive snow-temperature change relationship there (Figure 10(d)). However, the

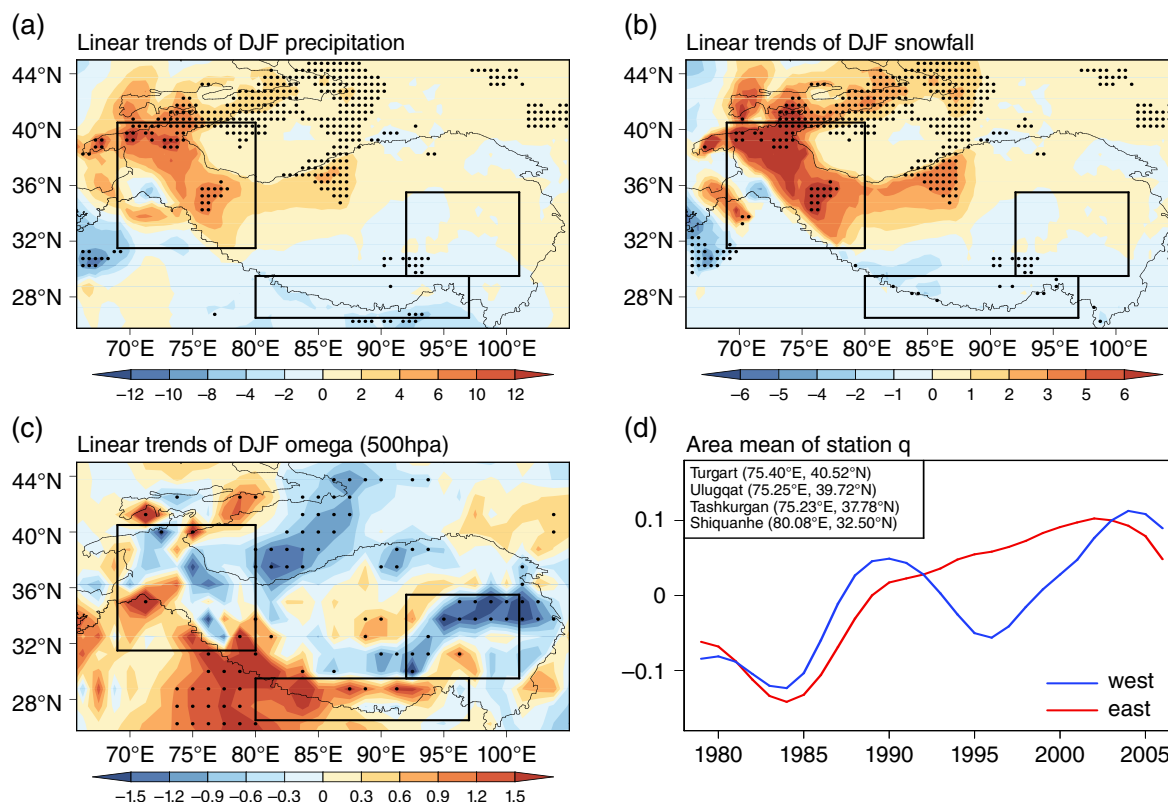


Figure 12. Linear trends of seasonal mean (a) precipitation (mm day⁻¹), (b) snowfall (mm decade⁻¹), and (c) vertical p -velocity (0.01 Pa s⁻¹) in DJF based on grid data for the period 1979–2006 and (d) area-mean specific humidity anomalies (g kg⁻¹) in DJF based on climatology for the period 1979–2006 in the east (red) and west (blue) region based on station data. The specific humidity in the east region is based on 28 stations and that in the west region is based on 4 stations. The name, longitude, and latitude of four stations in the west region are shown in the top-left of panel (d). [Colour figure can be viewed at wileyonlinelibrary.com].

snowfall increase is weak and covers only part of the east region, leading to a weak relationship. We note that there may be a negative effect of snow increase on the temperature change via the albedo change.

Given the range of surface air temperature variations in spring and fall, it is expected that the precipitation in the two seasons includes partly snowfall. This complicates the contribution of precipitation change to the snow change. In addition, changes in previous seasons may contribute to snow changes in spring and fall through the snow persistence. From Figure 7, it is quite obvious that the fall snow change tends to follow that in summer and the spring snow change tends to resemble that in winter. Thus, snow persistence may be an important element in explaining the snow change and snow-temperature change relationship in these transition seasons.

6. Summary and discussions

Previous studies mostly treated the Tibetan Plateau snow change as a factor for climate variability in the surrounding regions, such as the Indian and East Asian summer monsoon variability. Yet, it is not determined what may induce the Tibetan Plateau snow change at the first place. Based on snow data retrieved from satellite observations, this study investigates the low-frequency variations of

snow cover and snow water equivalent over the Tibetan Plateau and their relationship to surface air temperature changes.

6.1. Summary

The snow cover changes have remarkable regional differences. The snow cover displays a decreasing trend over the western part in summer and fall and over the southern part in all the four seasons. An interdecadal increase occurred at the mid-1990s over the central-eastern part in spring, fall, and winter. The snow water equivalent shows an increasing trend over the eastern part in spring, fall, and winter and over the far western part in winter and spring. In comparison, the snow cover change tends to be more obvious in regions and seasons with climatological mean snow small is small. The snow cover trends at different elevations tend to be consistent with each other with the magnitude varying with the altitude. One exception is the southern Plateau above 5000 m where the interdecadal variation is a dominant feature.

The reasons for snow changes depend upon the season. The snow decrease over the western and southern parts in summer and fall is mainly due to temperature increase that leads to increase in snowmelt. The snow cover decrease over the southern part in winter and spring is due to reduced upward motion that leads to decrease in snowfall. The snow water equivalent increase over the far western

part in winter and spring is related to enhanced upward motion that increases snowfall. The snow increase over the eastern part in fall, winter, and spring is contributed by the atmospheric moisture increase in response to the temperature increase and the enhanced upward motion. We note that the spring and fall snow changes may be partly related to the persistence of snow anomalies.

The relationship between snow and temperature trends displays remarkable regional dependence over the Tibetan Plateau. Two types of relationships are identified. The first type is characterized by opposite trends in snow and temperature. The first type of relationship is observed over the southern part in all the four seasons and over the western part in summer and fall, featuring temperature increase and snow cover decrease. The second type of relationship features increasing trends in both snow and temperature. This type of relationship is observed over the eastern part in fall, winter, and spring and over the far western part in winter and spring.

6.2. Discussions

The winter–spring station snow depths over the eastern Tibetan Plateau experienced a decrease around the mid-1990s (Zhao *et al.*, 2007; You *et al.*, 2011; Si and Ding, 2013; Ding *et al.*, 2013; Hu and Liang, 2013; Zhu *et al.*, 2015). This study showed an increase in snow cover and snow water equivalent in that region around the same time. The reason for the discrepancy between snow depth and snow water equivalent changes cannot be determined at this stage. Plausible reasons include biases in the satellite-derived snow water equivalent and the representation of station snow depth observations. Another plausible reason for this discrepancy is the snow density increase with the remarkable warming as discussed below. The topographic effect may be another factor contributing to the above discrepancy. Among the 71 stations over 2000 m, 6 stations are located at summit, 33 stations at valley, and 32 at flat terrain (You *et al.*, 2008).

The snow density is a quantity that may subject to large changes with time (Judson and Doesken, 2000; Chen *et al.*, 2011). Based on observations at Colorado, Judson and Doesken (2000) showed that the snow density declines largely with the temperature drop. Chen *et al.* (2011) observed that the fresh snow density in the Tianshan Mountain region increases drastically with the time with a quadruple increase in about 10 days. The weight of the upper layers of snow acts to densify the lower part of the deposit (Judson and Doesken, 2000). Because the snow density is extremely sensitive to local surface air temperature variations (Judson and Doesken, 2000; Dai *et al.*, 2012), an increase in surface temperature may increase significantly the snow density. Based on observations during 2009–2011 winters, Yang and Xue (2013) showed that the ratio of snow depth versus snowfall amount decreases with the temperature increase. Given the same snow amount, the snow depth is expected to decrease with increasing temperature.

The increase of snow amount with temperature has been noted in some previous studies. Li (1990) and Ke and Li

(1998) pointed out that the temperature increase leads to the snow increase over the Tibetan Plateau during 1960s through 1980s. Duan *et al.* (2016) noted that the snowfall over the eastern Tibetan Plateau increases corresponding to a temperature increase within the range of 0.8°–1.2°C. The accompanying temperature and snow water equivalent increase is observed over the Northern Hemisphere high latitudes during November through March (McCabe and Wolock, 2010). A similar relationship appears between snow water equivalent and temperature changes at the mid-1990s over the Tibetan Plateau according to this study.

The snowfall and snowmelt models used in this study were developed in previous empirical studies. The temperature thresholds were established by a method of exhaustive search calibration procedure based on satellite observations in March over the Northern Hemisphere (Hay *et al.*, 2002; McCabe and Wolock, 2010). Employing such thresholds to the Tibetan Plateau region may introduce some uncertainties that are hard to estimate. According to the snowmelt model, snowmelt may occur when monthly mean temperature rises above -4°C . This differs from reality in which snowmelt depends upon the weather condition and the daily temperature range. Further analysis is needed to validate the results derived based on these empirical models.

Given the fact that the snow changes over the Tibetan Plateau may be resulted from atmospheric thermodynamic and dynamic changes, caution is required when addressing the impacts of the Tibetan Plateau snow changes on climate variability over the Plateau and the surrounding regions. For a specific season, if the snow change is a result of atmospheric changes, treating the snow change as a forcing would be improper. Interpreting observations using results of numerical experiments with specified snow forcing needs to consider whether the model produced response is consistent with the observed relationship.

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