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POSSIBLE CONTRIBUTION OF A TROPICAL CYCLONE TO SHORT-TERM CLIMATE ANOMALIES IN EAST ASIA VIA SNOW COVER ON THE TIBETAN PLATEAU

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Abstract: Snow cover on the Tibetan Plateau (TP) has been shown to be essential for the East Asian summer monsoon. In this paper, we demonstrate that tropical cyclone (TC) 04B (1999) in the northern Indian Ocean, which made landfall during the autumn of 1999, may have contributed to climate anomalies over East Asia during the following spring and summer by increasing snow cover on the TP. Observations indicate that snow cover on the TP increased markedly after TC 04B (1999) made landfall in October of 1999. Sensitivity experiments, in which the TC was removed from a numerical model simulation of the initial field, verified that TC 04B (1999) affected the distribution as well as increased the amount of snow on the TP. In addition, the short-term numerical modeling of the climate over the region showed that the positive snow cover anomaly induced negative surface temperature, negative sensible heat flux, positive latent heat flux, and positive soil temperature anomalies over the central and southern TP during the following spring and summer. These climate anomalies over the TP were associated with positive (negative) summer precipitation anomalies over the Yangtze River valley (along the southeastern coast of China).

Key words: tropical cyclone; snow cover anomaly; short-term climate anomalies
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1 INTRODUCTION

Tropical cyclones (TCs) in the northern Indian Ocean and particularly the Bay of Bengal (BOB) strongly have impact on the weather over the Tibetan Plateau (TP) and southwestern China (Duan et al.[1]; Lv et al. [2]). Convective cloud clusters from the BOB associated with these storms bring extremely heavy rainfall to the low-latitude parts of the plateau (Lv et al.[2]; Li et al.[3]; Xu et al.[4]). In addition, the convergence of cold air (mainly in conjunction with a southerly trough) with clouds from TCs in the Northern Indian Ocean can produce snowstorms over the TP (Zou and Cao[5]; Wang et al.[6]; Suo and Ding [7]). Storms over the BOB are a major cause of strong snowstorms over the TP (Zou and Cao [5]). A recent study (Lin et al.[8]) reported that the Indian low pattern (also called the tropical storms over the BOB pattern) is the most common (accounting for 23% of all cases) of five general circulation patterns that has led to heavy snowfall over the TP from 1980 to 2010.

Snow cover anomalies over the TP have been shown to be related to the climate anomalies associated with the Asian monsoon (Wu and Qian[9]). Barnett et al.[10] found that Eurasian snow cover affected regional and even global climate based on its impacts on the energy and water budgets of the land surface and atmosphere. Excessive snow accumulation during winter can affect wintertime ground temperatures by reflecting more incoming solar radiation (Groisman et al.[11]); it can also affect ground temperatures during the following spring and early summer through hydrological processes (Stieglitz et al. [12]). Snow cover over the TP is a major component of the total Eurasian snow cover; it has a considerable effect on rainfall associated with the South Asian and East Asian summer monsoons because of its long-lasting influence on surface thermal conditions (Hsu and Liu[13]). Anomalously low ground temperatures over the plateau induced by excessive snow accumulation during the early summer can reduce the land-sea thermal gradient, thus postponing the onset of the Indian summer monsoon or even weakening the monsoon itself. Anomalously low ground temperatures also cool the overlying atmosphere in the mid-troposphere, inducing a westward extension of the subtropical high in the western Pacific. Because this is an important component of the East Asian summer

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monsoon system, the consequence of these anomalies is a modification of the monsoonal wind path (Zhang et al.[14]).

Previous studies have shown that tropical cyclones that make landfall in the northern Indian Ocean may contribute to heavy snowfall processes over the TP. Given that snow cover on the TP plays an important role in East Asian climate, it is possible that a cyclone in the northern Indian Ocean could cause increased snow cover over the TP and thus short-term climate anomalies. However, no previous studies have examined the effects of TC-induced snowstorms over the TP on climate anomalies over the TP during later seasons, and thus East Asian monsoon circulation and Asian rainfall. In this study, we use observations and sensitive numerical model simulations to investigate whether a TC that makes landfall can induce short-term climate anomalies over the TP and the surrounding area by changing snow cover over the TP. We chose TC 04B in 1999 as a case study. The datasets, methods, and the numerical model are introduced in section 2. Section 3 outlines the evidence for increased snow cover in October of 1999 after the landfall of TC 04B, based on observations and model sensitivity simulations. Section 4 presents the results of short-term climate numerical modeling with different initial amounts of snow cover on the TP. Finally, we present conclusions in Section 5.

2 DATA AND MODEL SENSITIVITY EXPERIMENTAL DESIGN

In this study, the TP was defined as 25°—40°N and 70°—103°E, which roughly delimits the area with a height exceeding 3,000 m (Chen et al.[15]).

2.1 *Data selection and availability*

Northern Hemisphere EASE-Grid Weekly Snow Cover data (Armstrong and Brodzik[16]) from 1981 to 2006 were obtained from the U.S. National Snow and Ice Data Center (NSIDC). The data were provided for the Northern Hemisphere with a spatial resolution of 25 km, an equal-area grid and a temporal resolution of one week. The data have been shown to be reliable in the Northern Hemisphere on a continental scale (Ke and Li[17]). We also used daily accumulated snowfall observations from 39 meteorological surface stations in the southern part of the TP.

National Centers for Environmental Prediction Reanalysis 1 (NCEP Reanalysis 1) and National Centers for Environmental Prediction Final Operational Global Analysis (NCEP FNL) data were used to analyze TC-induced increased snow and the climate anomalies caused by increased snow cover. The track of TC 04B in 1999 was obtained from the Joint Typhoon Warning Center (JTWC). Satellite infrared brightness temperature data from cloud imaging are from Japan's Geostationary Meteorological Satellite (GMS-5) Series. The cloud image data covers the area from 70°N—70°S and 70 °E—150 °W; it has a resolution of 1/4 degrees and 560× 560 pixels. The image data were provided by Weather Home of Kochi University (http://weather.is.kochi-u.ac.jp/archive-e.html). Monthly 0.25° × 0.25° merged Tropical Rainfall Measuring Mission Project (TRMM) precipitation data for 2000 were used to verify the precipitation results from the short-term climate numerical model. These data can be accessed from http://disc.sci.gsfc.nasa.gov/datacollection/TRMM_3B43_V7.html.

2.2 *Design of sensitivity simulation*

The Weather Research and Forecasting (WRF) model version 3.2 (Skamarock et al.[18]) was used to verify the contribution of TC 04B (1999) to snow cover on the TP and short-term climate anomalies in East Asia during the spring and autumn of 2000. NCEP FNL data were used for the initial and lateral boundary conditions of the Remove TC (RT) experiment and the short-term climate (SC) experiment. Both the RT and SC experiments used the same single model domain (Fig.1a), with a horizontal resolution of 45 km (on a 181° × 131° grid) and 35 vertical levels. We used WSM6 microphysics, Grell-Devenyi cumulus parameterization (Grell and Dévényi[19]), the Noah land surface model (Chen and Dudhia [20]) and the MYJ planetary boundary layer (Janjic [21]). The integral time and initial conditions for the RT and SC experiments are shown in Table 1.

In the RT experiment, the TC Bogus Scheme was used to remove TC 04B (1999). In the TC Bogus experiment, the center of the removed TC was over 13.0° N, 87° E at 0000 UTC on October 14; The maximum radius was set to 100 km (http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3.1/users_guide_10.htm#tc_bogus).

The SC experiments were designed to examine the influence of TP snow cover on the atmosphere during the following months. Three control experiments (SC_con_1, SC_con_2 and SC_con_3) were initialized using the NCEP FNL data at 0000 UTC on November 1, 2, and 3, 1999, respectively. Three sensitivity experiments (SC_sen_1, SC_sen_2 and SC_sen_3) were created using the same initial conditions and lateral boundary conditions as SC_con (Fig.1b), except that the initial snow water equivalent on the TP was set as the mean from 1999 to 2011. Snow water equivalent (SWE) is a measurement of the amount of water contained in the snowpack. It can be considered as the depth of water that would result if the entire snowpack instantaneously melted (http://disc.gsfc.nasa.gov/hydrology/data-holdings/parameters/snow_water_equivalent.shtml).

The initial SWE for SC_con was greater than for SC_sen over the central and southern TP (Fig.1c). All SC_con and SC_sen experiments ended at 1800 UTC on August 31, 2000. The average values of the three control (sensitivity) experiments were used as the final results of SC_con (SC_sen).

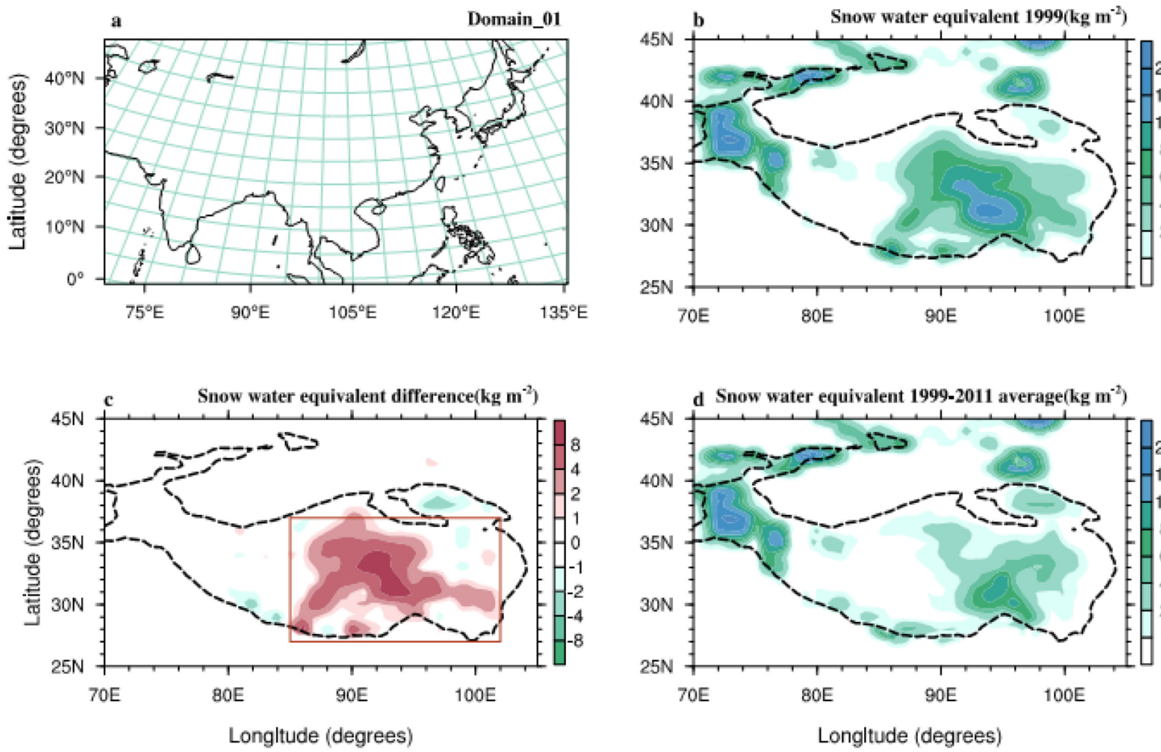

Figure 1. Model domain for the RT and SC experiments (a) and (b) the distribution of SWE for the mean of the three SC_con and (d) of the three SC_sen experiments and (c) the difference between the two. The black dashed line indicates the TP.

Table 1. Settings for the RT and SC experiments.

Experiment		Initial time	End time	Initial conditions
RT	RT_con	0000 UTC, Oct. 14, 1999	0000 UTC, Oct. 22, 1999	NCEP FNL
	RT_sen	0000 UTC, Oct. 14, 1999	0000 UTC, Oct. 22, 1999	NCEP FNL with TC removed
SC	SC_con_1	0000 UTC, Nov. 1, 1999	1800 UTC, Aug. 31, 2000	NCEP FNL
	SC_con_2	0000 UTC, Nov. 2, 1999	1800 UTC, Aug. 31, 2000	
	SC_con_3	0000 UTC, Nov. 3, 1999	1800 UTC, Aug. 31, 2000	
	SC_sen_1	0000 UTC, Nov. 1, 1999	1800 UTC, Aug. 31, 2000	NCEP FNL with the snow water equivalent over the TP replaced
	SC_sen_2	0000 UTC, Nov. 2, 1999	1800 UTC, Aug. 31, 2000	
	SC_sen_3	0000 UTC, Nov. 3, 1999	1800 UTC, Aug. 31, 2000	

3 CONTRIBUTION OF TC04B(1999) TO SNOW COVER ON THE TP

3.1 *Observations*

Observations were used to assess the influence of TC 04B (1999) on snow cover on the TP (Fig.2). Panels (a1)- (a3) of Fig.2 show that the center of TC 04B was close to 85°E at 0000 UTC on October 17, 1999, when the associated clouds reached the eastern part of the TP. At the same time, the India-Burma trough (thick orange line) was located northwest of the TP at 500 hPa (Fig.2 (a1)). TC 04B was further north at 0000 UTC on October 18 and the India-Burma trough northwest of the TP intensified and merged with TC 04B (Fig.2 (a2)). On October 19, the TC continued to move towards the north and most of the eastern TP was covered by clouds (Fig.2 (a3)). A heavy snowstorm occurred over the central and southern TP on October 18 and 19 (Fig.2 (b1)- (b3)). Weekly snow cover frequency over the western and southwestern TP was higher than over the central and eastern TP, where snow cover frequency was below 20%—40% for weeks 41—43 from 1981 to 2006 (Fig.2 (c1)-(c3)). However, snow cover increased dramatically over the central and southern TP during week 42 (October 18—24) of 1999, after TC 04B made landfall.

3.2 *Comparison of snowfall between RT_con and RT_sen*

Previous studies have shown that heavy snowstorms occur when the moisture carried by TC encounters a favorable weather system, such as the Indian low or the India-Burma trough (Lin et al.[8]; Suo and Ding [7]). Fig.2 (a1)- (a3) shows that an encounter between the India-Burma trough and the TC may have

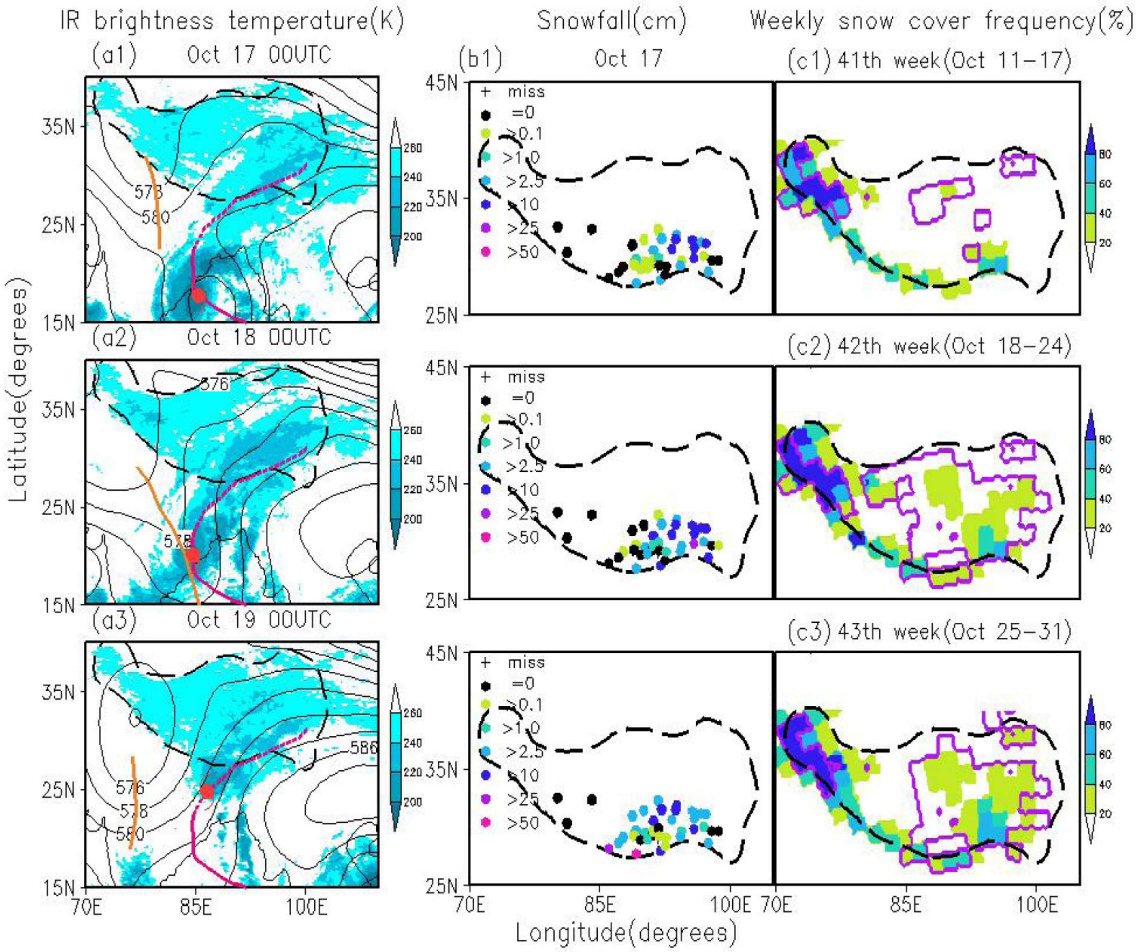

Figure 2. Weather observations over the TP during the lifetime of TC 04B (1999). Panels (a1)-(a3) show the 500 hPa geopotential height (thin solid lines), the infrared brightness temperature (shading), the best track of the TC (thick purple line) and the India-Burma trough (thick orange line), and the residual circulation center of the TC (purple dotted lines). Panels (b1)-(b3) show the daily snowfall observations from 39 meteorological stations in the southern TP. Panels (c1)- (c3) show the EASE-Grid weekly snow cover area (purple solid lines) after TC 04B (1999) made landfall and the snow cover frequency (shading) on the TP from 1981 to 2006. The black dashed line in all panels indicates the TP.

contributed to snowfall over the TP during week 42 of 1999. It is also clear that snow cover over the TP exceeded the climatological mean following the landfall of TC 04B (1999) (Fig.2 (c1)- (c3)). To verify the contribution of TC 04B (1999) to the snowfall over the TP during week 42 of 1999, we conducted a Remove TC sensitivity experiment (RT_sen) and compared the results with RT_con.

In RT_sen, we removed the TC. Fig.3 shows the cyclonic circulation wind fields were removed compared with the control run. The simulated precipitation results show that the greatest snow accumulation occurred on the central and southern TP for RT_con (Fig.4a); this result is generally consistent with the observed distribution of snowfall (Fig.2b) and snow cover (Fig.2c). However, the maximum snow accumulation occurred on the western and northern TP in the RT_sen experiment (Fig.4b). In addition, the total accumulated snowfall over the TP from October 14—21 in RT_sen was approximately 50% of the total in RT_con. Thus, the RT experiments suggest that TC 04B (1999) affected the distribution and the amount of snow over the TP.

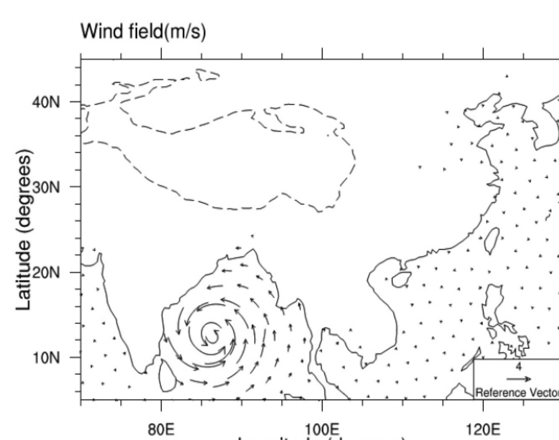

Figure 3. Difference in the wind fields for 1,000 hPa initial conditions between RT_con and RT_sen (RT_con minus RT_sen).

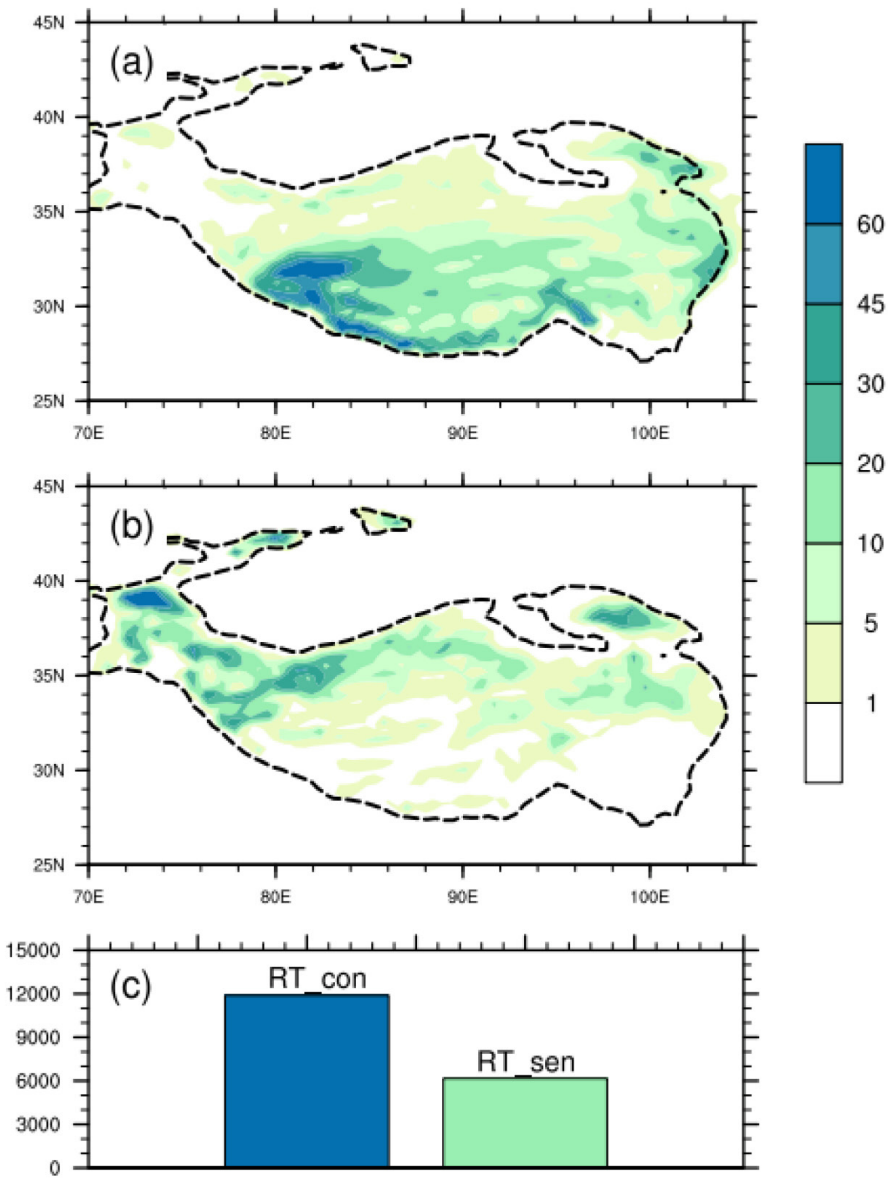

Figure 4. Simulated total grid-scale snow and ice accumulation (units: mm, from October 14–21, 1999) on the TP for (a) RT_con, (b) RT_sen, and (c) the total accumulated snowfall over the TP for (a) and (b).

4 SHORT–TERM CLIMATE SIMULATION

Autumn snow cover over the TP may provide a seasonal climate signal that persists in the circulation during the subsequent winter and spring. This is because solar energy melts the snow and causes evaporation rather than heating the ground directly(Zuo et al.[22]). More importantly, snow cover over the TP affects the land surface energy and moisture budgets during the late spring and early summer. High (low) snow cover on the TP during the winter and spring is associated with weaker (stronger) sensible heat fluxes (Zhao et al. [23,24]) and colder (warmer) surface temperatures. However, it is difficult to detect this sequence of climate anomalies following the snow cover signal over the TP purely from observations because other weather processes can affect regional climate in similar ways. Numerical models offer a way of simulating the effects of varying snow cover over the TP. Thus, we conducted short-term climate (SC) numerical experiments to determine the effects of snow cover anomalies over the TP on atmospheric climate anomalies in eastern China.

4.1 *Verification of SC_con runs*

The simulated daily mean precipitation during March and April reaches maximum values in southern China (Fig.5 (b1)), where a similar maximum in precipitation is observed in TRMM data (Fig.5 (a1)). The simulated precipitation distribution and amounts in May—June and July—August are generally consistent with TRMM observations in East Asia (Fig.5 (b2)-(b3)). One exception is the distribution of precipitation in the East China Sea. These results indicate that the SC_con numerical experiment is reasonable.

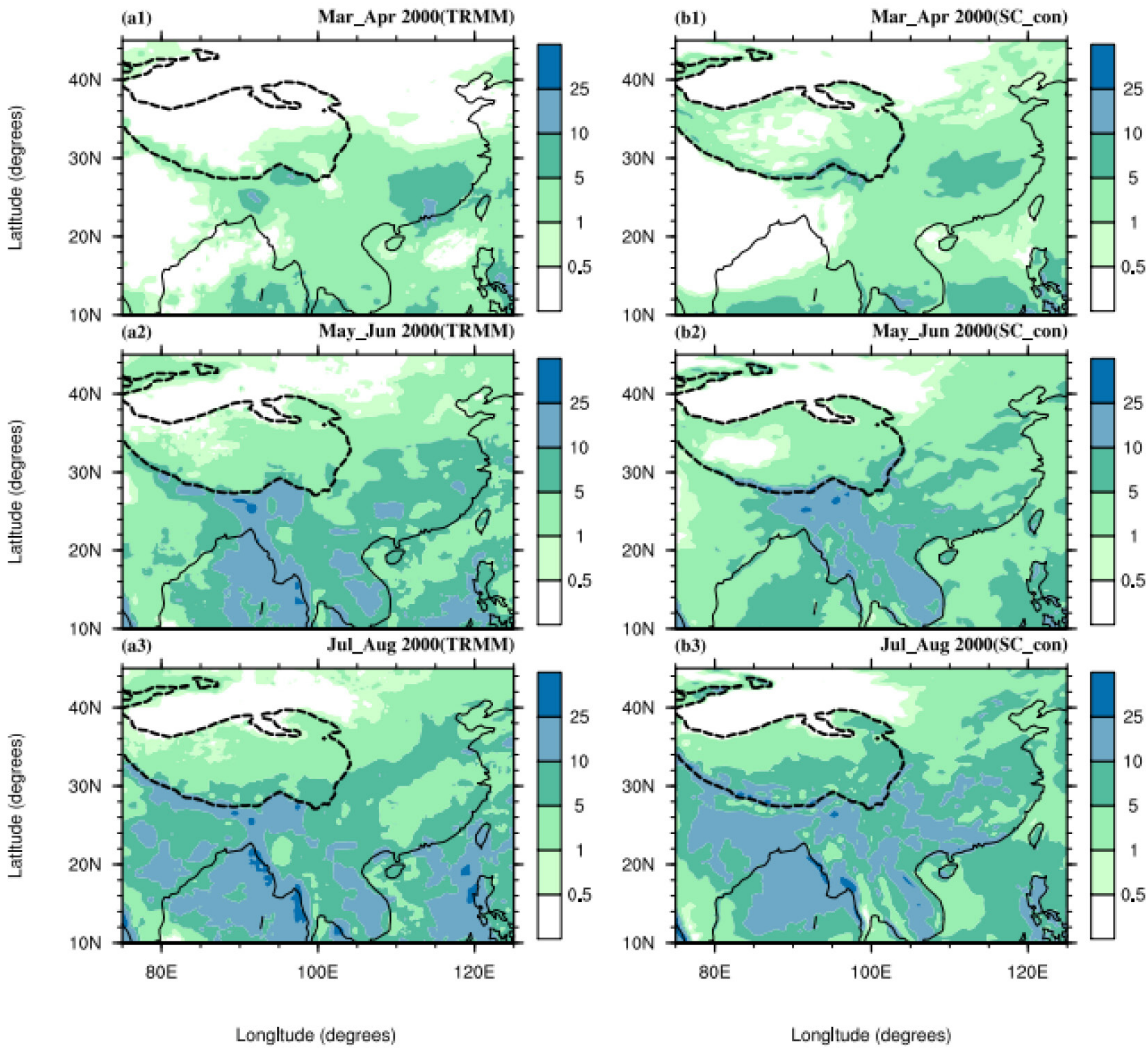

Figure 5. Daily mean precipitation from (a1)- (a3) monthly merged TRMM data and (b1)- (b3) simulated precipitation from the SC_con experiment. Panels (a1) and (b1) show the mean values in March to April; (a2) and (b2) those of May to June; (a3) and (b3) those of July to August. The black dashed line indicates the TP.

4.2 *Climate anomalies*

The SC_sen experiments were used as a climate reference; climate anomalies were defined as the difference between SC_con and SC_sen. The SWE was greater in SC_con than in SC_sen on the central and southern TP (Fig.1c). Compared with SC_sen, SC_con simulated a lower bimonthly mean sensible heat flux, higher latent heat flux and higher surface air temperature (Fig.6). Furthermore, SC_con simulated a negative temperature anomaly that persisted over the TP until June of 2000. Another important effect of snow cover is the variation in soil moisture. The initial positive snow cover anomaly is associated with abundant soil moisture that persisted until the summer of 2010 (Fig.6(d1)-(d4)). The sensible heat flux anomaly on the TP is a "strong signal" that can be used to predict flood or drought in the middle and lower reaches of the Yangtze River (Bai et al.[25]). The soil moisture during May and June can act as a bridge, linking snow anomalies during the spring with the subsequent summer monsoon (Zhao et al.[24]).

The difference in simulated accumulated precipitation during the warm season (March to August) between SC_con and SC_sen indicates a change over East Asia (Fig.7). Fig.7 shows the difference in precipitation between SC_con and SC_sen. Compared with SC_sen, SC_con has much more warm season precipitation over the Yangtze River valley, the Sichuan Basin and the southern TP; it has less precipitation along the northern and southeastern coast of China (Fig.7).

A clear positive correlation between winter snow on the TP and rainfall during the following summer over the middle and lower reaches of the Yangtze River valley in central China has been noted previously (Wu and Qian [9]). Additionally, a close relationship has been proposed between the interdecadal increase in snow depth on the TP from March to April and more summer

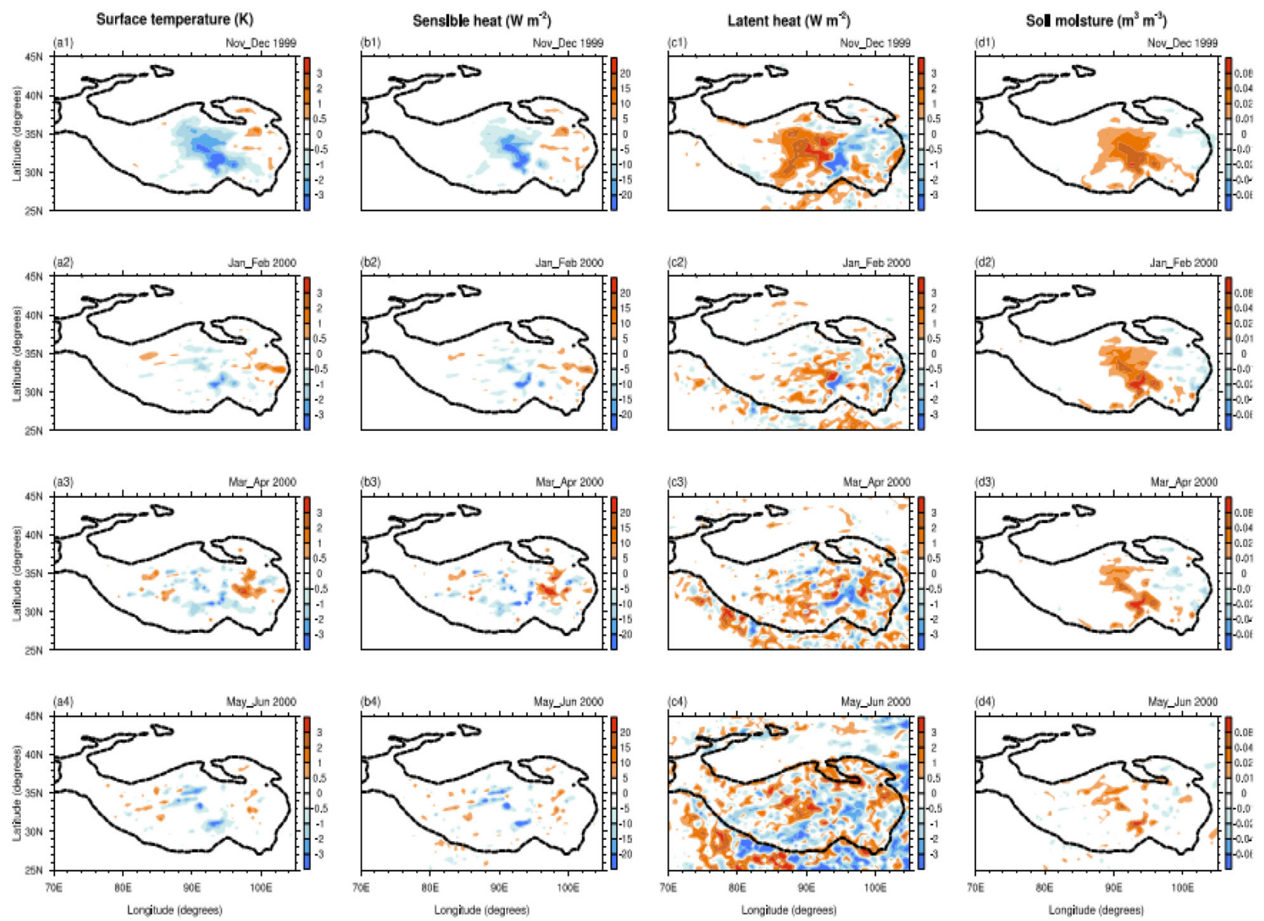

Figure 6. Difference between SC_con and SC_sen from November 1999 to June 2000 (bimonthly averages). Panels (a1)-(a4) show the surface skin temperature, (b1)-(b4) the sensible heat flux, (c1)-(c4) the latent heat flux, and (d1)-(d4) the soil moisture. Negative (positive) values indicate that the SC_con value was lower (higher) than the SC_sen value. The black dashed line indicates the TP.

rainfall over the Yangtze River valley, as well as aridity along the southeast coast of China and the Indochina Peninsula (Zhang et al.[14]). Heavier snowfall over the TP has also been associated with more summer precipitation in the middle reaches of the Yangtze River valley and Japan, and less summer precipitation in southern and southwestern China and southeastern Asia (Zhao et al. [24]). The precipitation anomalies (Fig.7) simulated in this study are consistent with these previous studies; our results indicate more summer precipitation in the middle reaches of the Yangtze River valley and less precipitation in southern China in 2000.

Zhang [14] suggested that two possible mechanisms could explain the correlation between snow cover on the TP and summer precipitation in eastern Asia; first, a northwestward extension of the western Pacific subtropical high during the subsequent summer could arise from surface cooling over the TP and neighboring regions and high-pressure anomalies due to excessive snowmelt. Second, the energy provided by increased surface moisture could lead to the development of an eastward-migrating low-level vortex over the eastern flank of the TP. Both mechanisms would lead to greater summer moisture over the Yangtze River valley. Based on the climate anomalies simulated in the SC experiments, excessive snow accumulation in SC_con causes lower ground temperatures (Fig.6 (a1)-(a4)) and lower sensible heat (Fig.6 (b1)-(b4)) by reflecting more

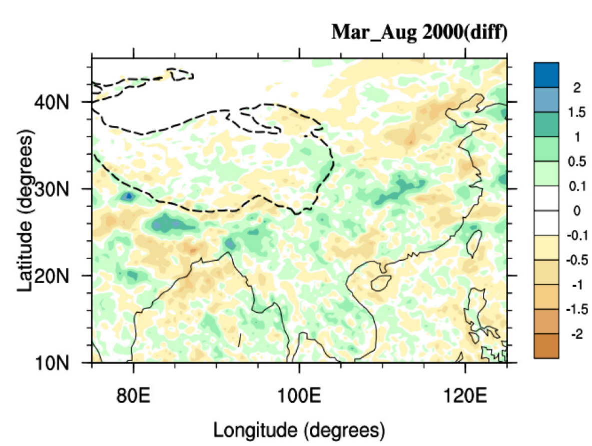

Figure 7. Difference in simulated daily mean precipitation from March to August in 2000 between SC_con and SC_sen (SC_con minus SC_sen). The black dashed line indicates the TP.

incoming solar radiation. Excessive snow accumulation also leads to higher latent heat and soil moisture during the following spring and early summer because of hydrological processes (Fig.6 (c1)-(c4) and (d1)-(d4)). The surface cooling and increased surface moisture caused by excessive snow accumulation would also favor precipitation anomalies over the Yangtze River valley and southeastern Asia.

5 CONCLUSIONS

Based on station snowfall and snow cover observations over the TP, as well as RT numerical experiments, we found that extreme snowfall over the TP during week 42 in 1999 was related to the landfall of TC 04B (1999), which carried moisture to the TP. Further SC experiments showed that the snow cover anomalies over the TP that followed the landfall of TC 04B (1999) caused regional short-term climate anomalies over the central and southern TP. These anomalies included higher latent heat flux and soil moisture as well as lower surface air temperatures and sensible heat flux. The anomalies persisted until the summer of the following year. At the same time, precipitation patterns over East Asia during the spring and summer of 2000 were also influenced by the excessive snowfall over the TP during the autumn of 1999. Our results show that more summer precipitation fell over the Yangtze River valley, while summer aridity increased along the southeastern coast of China.

Many studies have examined the effects of global climate change on local extreme weather and climate events. In this study, we show that an extreme weather event can also influence short-term regional climate. Here, the extreme event is anomalous snow cover over the TP. While our results are robust for this particular TC, they should be verified in additional cases.

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