Progress in Studies of Cryospheric Changes and Their Impacts on Climate of China

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ABSTRACT

The cryosphere is a prominent factor in and an indicator of global climate change. It serves one of the most direct and sensitive feedbacks in the climate system, and plays an important role in the earth's climate system. Cryospheric research has attracted unprecedented attention in the context of global warming, and is now one of the most active areas in studies of global change, sustainable development, and the climate system. This paper addresses recent and potential future changes in the cryosphere both globally and within China under the background of global warming. Particular attention is paid to progress toward understanding the impacts of the Tibetan Plateau and Eurasian snow cover, Arctic and Antarctic sea ice, and permafrost and glaciers on Chinese climate. The future development of cryospheric research in China is also discussed.

Key words: cryosphere, climate effect, climate system, global warming

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1. Introduction

The volume of water that exists in solid form at and below the surface of the earth is called the cryosphere. The cryosphere consists of ice sheets, glaciers, snow cover, permafrost, sea ice, lake ice, river ice, and solid precipitation. Currently, 75% of the earth's fresh water supply is stored in the cryosphere. Approximately 10% of the land surface is covered by ice sheets and glaciers, and 7% of the ocean surface is covered by sea ice. About half of the land surface experiences winter snow cover, and the permafrost area is even larger (IPCC, 2007).

The cryosphere plays an important role in the earth's climate system due to high albedo, the latent heat associated with phase changes of snow and ice, and the sheer volume of ice reserves. Rapid changes in the components of the cryosphere have profound influences on the energy balance, atmospheric circulation, ocean circulation, water cycle, changes in sea level, sources and sinks of carbon, and socio-economic development (Qin et al., 2006). Changes in ice and snow can alter regional and global climate dynamics through their influences on the energy balance and water cycle. Changes in ice volume can affect the ocean circulation by altering distributions of salinity and temperature. Changes in permafrost not only influence the climate system by altering exchanges of water and heat between land and atmosphere, but also influence the global carbon cycle via changes in the permafrost carbon pool. Cryospheric change also contributes significantly to sea level rise (IPCC, 2013): recent increases in sea level can be attributed primarily to melting of the cryosphere and thermal expansion of the ocean (Cazenave et al., 2008, 2009).

China has the largest cryospheric area among the

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countries in mid and low latitudes. Glaciers, permafrost, and snow cover are widespread, with significant effects on climate, the environment, water resources, and ecological processes. The cryosphere is fundamental to maintaining oasis economies in arid areas and ecosystem stability in cold regions, and is therefore of great significance for strategic development in western China (Ding and Qin, 2009; Qin and Ding, 2009).

Cryospheric research has attracted unprecedented attention in recent years due to high sensitivity of the cryosphere to climate change and its important role in climate feedbacks. Cryospheric research is now one of the most active fields in climate system studies, and an important element of research programs on global change and sustainable development (Allison et al., 2001; Xiao, 2008; Qin and Ding, 2009). In this paper, we review recent findings on changes in the global and Chinese cryosphere and summarize recent studies of the impacts of cryospheric changes on Chinese climate. We conclude with an outlook for future cryospheric research in China.

2. Changes in the global cryosphere

The global cryosphere has undergone significant changes in recent decades. Almost all of the elements of the cryosphere have lost mass under global warming. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) Working Group I (IPCC, 2013) provided a comprehensive assessment of current understanding of changes in the global cryosphere (Fig. 1).

The AR5 reported that the Greenland and Antarctic ice sheets have lost mass over the last two decades. The Greenland ice sheet lost mass at an average rate of 34 (–6 to 74) Gt yr^{-1} between 1992 and 2001, while the Antarctic ice sheet lost mass at an average rate of 30 (–37 to 97) Gt yr^{-1} over the same period. These rates have accelerated, with the Greenland ice sheet losing mass at a rate of 215 (157 to 274) Gt yr^{-1} and the Antarctic ice sheet losing mass at a rate of 147 (72 to 221) Gt yr^{-1} since 2002. Glaciers have shrunk effectively worldwide. The average rate of global ice loss from glaciers was 226 (91 to 361) Gt yr^{-1} over the period 1971–2009.

Arctic sea ice extent decreased substantially between 1979 and 2012, at a rate of 3.5%–4.1% per decade for the annual mean and 9.4%–13.6% per decade for the summer season. By contrast, the annual mean Antarctic sea ice extent increased at a rate of 1.2%–1.8% per decade over the same period. These changes are regionally heterogeneous, with sea ice extent increasing in some regions and decreasing in others.

Northern Hemisphere snow cover extent decreased between 1967 and 2012 at mean rates of 1.6% (0.8%–2.4%) per decade for March and April and 11.7% (8.8%–14.6%) per decade for June. Permafrost temperatures have increased in most regions since the early 1980s, with observed warming of up to 3℃ in parts of northern Alaska (the early 1980s to mid 2000s) and up to 2℃ in parts of the Russian European North (1971–2010). This warming has coincided with a considerable reduction in permafrost thickness and areal extent.

As global climate continues to warm in the future, Arctic sea ice will continue to melt, and global glacier volume, Northern Hemisphere spring snow cover and permafrost extent will continue to decrease. By the end of the 21st century, Arctic sea ice extent is projected to decrease by 43%–94% in September and 8%–34% in February relative to the 1986–2005 mean. Global glacier volume is projected to decrease by 15%–85%, the area of Northern Hemisphere spring snow cover is projected to decrease by 7%–25%, and the extent of near-surface (upper 3.5 m) permafrost at high northern latitudes is projected to decrease by 37%–81%.

3. Changes in the Chinese cryosphere

The Chinese cryosphere consists mainly of glaciers, frozen ground, and snow cover. China contains 46377 glaciers with a total area of 59425 km^2 and an ice volume of 5600 km^3 (Shi, 2005). Over 70% of the land area is covered by frozen ground during at least part of the year. Permafrost regions account for 23% of the total land area, while seasonally frozen regions account for about 50% (Zhou et al.,

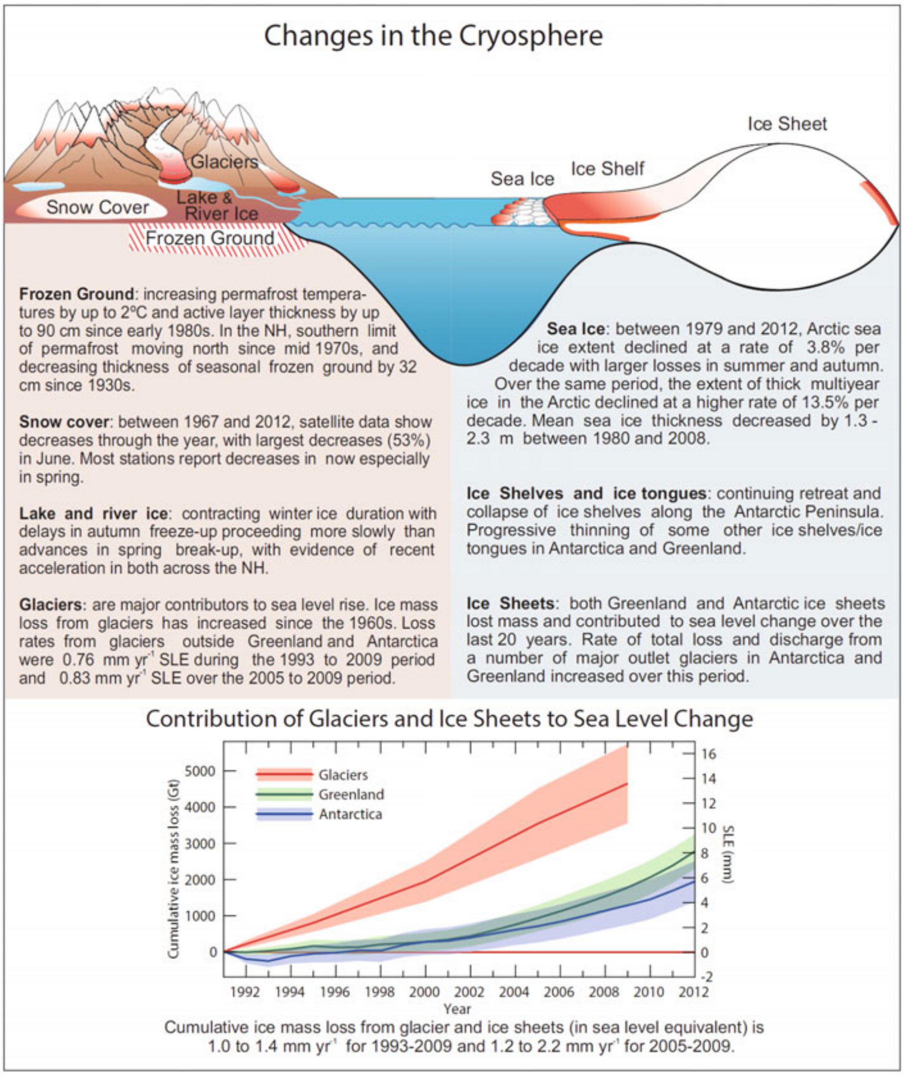

Fig. 1. Schematic summary of the most prominent changes in the observed cryosphere. [From IPCC, 2013]

2000). Snowfall occurs over more than 90% of the Chinese land surface. The area of China with stable snow cover (more than 60 snow days per year) is 3.4×10^6 km^2, while the area with unstable snow cover is 4.8×10^6 km^2 (Che and Li, 2005).

Changes in the Chinese cryosphere are largely consistent with changes in the global cryosphere. Most glaciers in China have receded under global warming. Approximately 82% of Chinese glaciers have receded or disappeared since the 1960s, resulting in the loss of more than 10% of the glacier area. Glacier recession has accelerated since the 1990s (Committee of the Second National Assessment Report on Climate Change, 2011). For example, the mean recession rate at the tail of the Rongbuk Glacier (Mt. Qomolangma) increased from 5–8 m yr^{-1} during 1966–1997 to 7–9 m yr^{-1} after 1997. Likewise, the mean recession rate of the Urumqi Riverhead No. 1 Glacier increased from 0.18 m yr^{-1} during 1981–2001 to 0.62 m yr^{-1} during 2001–2006 (Fig. 2).

Permafrost on the Tibetan Plateau has undergone significant changes over the past two decades. The changes may be summarized in two aspects. First, permafrost temperatures have warmed substantially. For example, the temperature of permafrost areas in the low and middle mountain ranges of the Tibetan

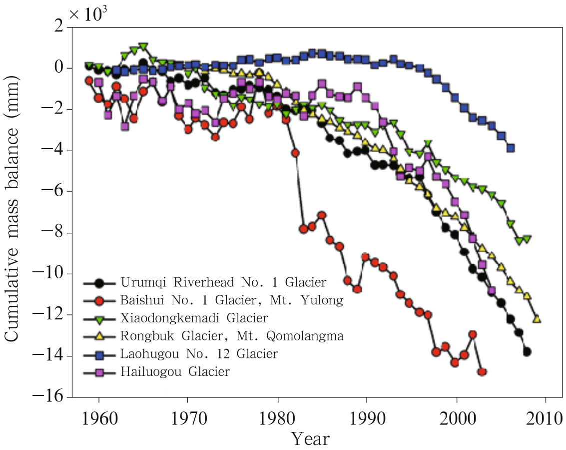

Fig. 2. Changes in the mass balance of selected glaciers over recent decades. [From Qin et al., 2012]

Plateau has increased from about –3°C to values of –3 to 1°C, while the temperature of permafrost in river valleys and basins has reached values between −1 and 0.5°C. The temperature of upper-layer permafrost has increased at a rate of 0.1°C yr^{-1}. Second, a substantial amount of permafrost has experienced direct degradation. Permafrost with temperatures lower than –3°C has mainly warmed without severe degradation. By contrast, many permafrost areas with temperatures higher than –1°C have receded. For example, the area of permafrost near Xidatan has been reduced by 12% since 1975, while the area of permafrost within 2 km to either side of the Anduo-Liangdaohe Road has been reduced by 35.6%. The thickness of seasonally frozen ground has also decreased. The maximum depth of seasonally frozen ground on the Tibetan Plateau thinned at an average rate of 3.3 mm yr^{-1} between 1961 and 2006 (Committee of the Second National Assessment Report on Climate Change, 2011).

The depth of snow cover over the Tibetan Plateau increased steadily over the latter half of the 20th century, but decreased significantly during the early part of the 21st century. The maximum snow depth in northern Xinjiang has increased at an average rate of 0.8% since 1961. The depth of snow cover in Northeast China—Inner Mongolia shows no obvious long-term trends, but the amplitude of interannual fluctuations has increased substantially since the 1990s (Committee of the Second National Assessment Report on Climate Change, 2011).

The Chinese cryosphere is projected to continue to decrease in both area and volume during the following decades. Smaller glaciers and glaciers that contact the ocean are projected to recede significantly. The thickness of the active layer of permafrost is expected to continue increasing, while the area and thickness of seasonally frozen ground are expected to continue decreasing. Changes in snow cover are projected to vary substantially among different regions (Qin et al., 2012; Yao et al., 2013).

4. Impacts of cryospheric changes on Chinese climate

4.1 Snow cover

Snow cover is a product of atmospheric circulation systems. Variations in snow cover can affect climate by changing the energy balance, the hydrologic cycle, and the atmospheric circulation, and thus play an important role in the earth's climate system. More than a century ago, Blanford (1884) and Walker (1910) proposed that winter snow cover over the Tibetan Plateau and precipitation of the Indian summer monsoon were out of phase. This hypothesis was later confirmed by multiple studies (Hahn and Shukla, 1976; Dey and Kumar, 1983; Dickson 1984; Parthasarathy and Yang, 1995).

Chinese scientists have carried out a number of studies examining how snow cover over the Tibetan Plateau impacts precipitation and the East Asian summer monsoon. Despite isolated discrepancies due to differences in snow cover data or analysis periods, most studies show negative correlations between winter–spring snow cover over the Tibetan Plateau and the East Asian summer monsoon (Guo and Wang, 1986; Chen et al., 1996; Fan et al., 1997; Chen et al., 2000; Zheng et al., 2000; Zhang and Tao, 2001; Qian et al., 2003; Wu and Qian, 2003; Zhao et al., 2007). The East Asian summer monsoon tends to be weaker or onset later when the Tibetan Plateau snow cover is above normal during winter and spring; it tends to be stronger or onset earlier when the snow cover is below normal. More snow cover over the Tibetan Plateau in winter and spring reduces solar absorption by increasing surface albedo, and decreases the transport of sensible and latent heat from the surface to atmosphere. These effects weaken the plateau heat source to the atmosphere. Melting snow absorbs heat and leaves the soil relatively wet. This "wet soil" can retain features of the snow cover anomaly and continue to interact with the atmosphere for a long time.

The most significant climatic effect of snow cover over the Tibetan Plateau is its influence on summer precipitation in China. First, winter–spring snow cover over the plateau is positively correlated with summer (June–August) precipitation in the Yangtze River valley and negatively correlated with summer precipitation in South China and North China (Chen and Song, 2000a; Chen and Wu, 2000; Wu and Qian, 2000; Zheng et al., 2000; Wu and Qian, 2003). Second, winter–spring snow cover over the plateau is positively correlated with early summer (May–June) precipitation in South China and negatively correlated with early summer precipitation over the Yangtze River valley (Chen, 1998; Wei et al., 1998; Cai, 2001; Zhao et al., 2007). Third, interdecadal variations in winter-spring snow cover over the plateau are associated with changes in the spatial pattern of summer precipitation in eastern China. Snow cover over the Tibetan Plateau in winter and spring was enhanced between the 1970s and the 1990s (Zhu et al., 2007; Ding et al., 2009; Song et al., 2011), resulting in a weaker summer monsoon (Zhang et al., 2004). This situation induced a "southern flood and northern drought" pattern in China (Zhao et al., 2007; Zhu et al., 2007; Ding et al., 2009).

Fewer studies have examined the impacts of Eurasian snow cover on Chinese climate, although this has begun to change in recent years. Interannual variations in winter–spring Eurasian snow cover are in phase with summer precipitation in Northeast China, eastern North China, and Southwest China (Chen and Song, 2000b; Chen and Sun, 2003) and out of phase with summer precipitation in the Yangtze-Huaihe River valley (Liu and Luo, 1990). Yang and Xu (1994) showed significant positive correlations between winter Eurasian snow cover and summer precipitation in South China and North China, and negative correlations with summer precipitation in the western, central, and northeastern parts of China. Ye and Bao (2005) indicated that summer precipitation in eastern China is negatively correlated with autumn Eurasian snow cover. Interdecadal changes in the spatial pattern of summer precipitation in eastern China have also been linked to interdecadal variations in spring Eurasian snow cover. Summer precipitation in southern China increased significantly after the late 1980s. This change may be associated with a reduction in spring Eurasian snow cover (Zhang et al., 2008, 2013). Wu et al. (2009a) showed that the Eurasian snow cover distribution between the late 1970s and the 1990s was characterized by a coherent negative anomaly over most of Eurasia but a positive anomaly over portions of the Tibetan Plateau and East Asia. This distribution can affect high latitude wave activity and stimulate atmospheric teleconnections. As a result, North China was covered by an anomalous high while South China was covered by an anomalous low. This led to positive precipitation anomalies over South and Southeast China and negative precipitation anomalies over the upper reaches of the Yellow River valley (Fig. 3). This mechanism explains the close relationship between the decrease in snow cover over Eurasia, the increase in snow cover over the Tibetan Plateau, and the "southern flood and northern drought" pattern that dominated China during the last 20 years of the 20th century.

Changes in Eurasian snow cover also significantly influence springtime precipitation over China. Wu and Kirtman (2007) showed that snow cover over western Siberia is positively correlated with precipitation in southern China during spring. Zuo et al. (2012a, b) showed that increases in springtime snow cover over Eurasia are associated with more precipitation in southeastern China and less precipitation in southwestern China, while decreases in springtime snow cover over Eurasia are associated with the opposite pattern. They argued that the significant decreases in springtime Eurasian snow cover since the 1980s are an important reason for the simultaneous decreases in precipitation over southeastern China and increases in precipitation over southwestern China.

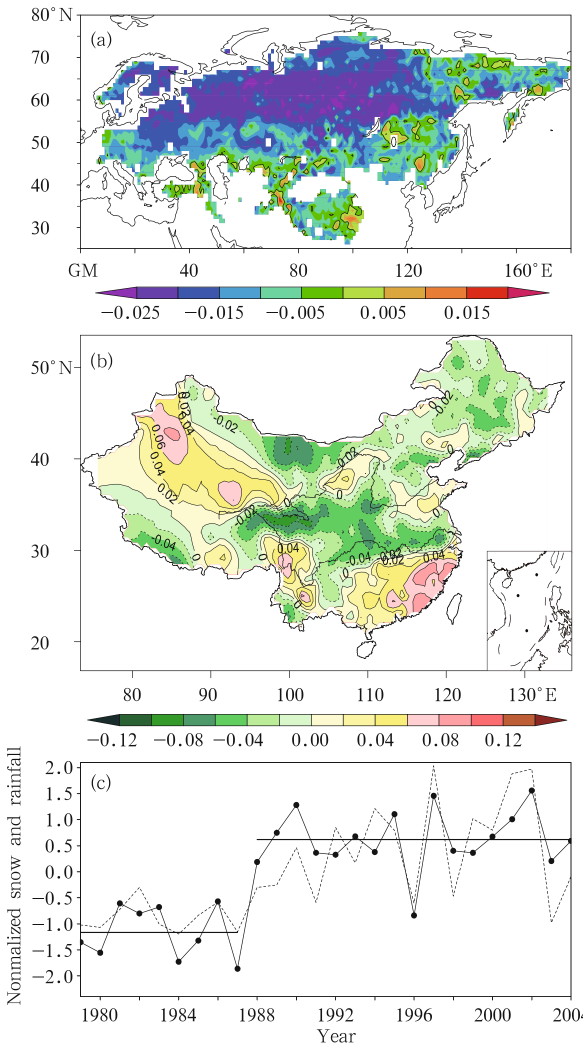

Fig. 3. Spatial distributions of the leading singular value decomposition modes of (a) springtime Eurasian snow water equivalent (SWE) and (b) summertime rainfall at stations in China. (c) Normalized time series of spring Eurasian SWE (solid line) and summer rainfall in China (dashed line). [From Wu et al., 2009a]

Mu and Zhou (2010, 2012) analyzed the impacts of changes in newly increased winter snow cover on summer temperature in China. They showed that winters with significantly increased snow cover over northern Eurasia are generally associated with anomalous low pressure over midlatitudes of East Asia during the following summer. This anomalous low causes cool summers over the eastern part of Inner Mongolia and western part of Northeast China. These summers are also characterized by a more intense East Asian westerly jet, while the western Pacific subtropical high strengthens and shifts northward and westward. This situation results in droughts and high temperatures south of the Yangtze River. The opposite changes are observed following the winters with marginally increased Eurasian snow cover.

4.2 Sea ice

Polar regions play important roles in global and regional climate. They have therefore been identified as key regions in many international scientific programs on global climate change. Chinese scientists have conducted a variety of studies examining how changes in polar environments (especially changes in temperature and ice) influence the atmospheric circulation over East Asia and the climate in China.

Recent warming in the Arctic has resulted in reductions of ice and snow, which have caused rapid changes in both ecosystem and climate (Committee on Emerging Research Questions in Arctic, 2014). Changes in Arctic sea ice can impact atmospheric and oceanic heat transport, as well as fluxes of heat between the ocean and atmosphere. Strong warming over the Arctic Ocean in autumn and winter is clearly associated with reduced sea ice extent during the past decades (Serreze and Barry, 2011). Studies have shown close relationships between sea ice changes in the Kara, Barents seas, and Greenland seas during winter and the Northern Hemisphere subtropical high, El Niño–Southern Oscillation (ENSO), and the East Asian winter monsoon (Fang, 1987; Huang et al., 1992; Fang and Wallace, 1994; Yang et al., 1994; Wu et al., 1997, 1999, 2001, 2004; Wu and Qian, 2000). Interannual and interdecadal changes in Chinese climate also appear to be closely related to Arctic sea ice extent.

Wu et al. (2011) showed strong negative correlations between the intensity of the Siberian high during winter and sea ice concentrations in the eastern Arctic and along the northern coast of Eurasia during autumn and winter. They proposed that increases in sea ice near the eastern Arctic and the Greenland-Barents-Kara seas and negative SST anomalies (especially in the northern North Atlantic) during autumn and winter can cause a decrease in winter sea level pressure over northern Eurasia and the northern North Atlantic. This acts to weaken the Siberian high and enhance westerly winds in the mid-high latitudes of Eurasia. Increases in autumn–winter sea ice extent are also associated with negative temperature anomalies in the Arctic that enhance the atmospheric temperature gradient between the Arctic and the mid-high latitudes of Eurasia. This enhances westerly winds in northern Eurasia. These enhanced westerlies prevent cold air at high latitudes from breaking out toward the south, and therefore result in warmer surface temperatures over the high latitudes of Eurasia and East Asia. Decreased sea ice extent results in the opposite changes, so that the high frequency of severe winter weather over Eurasia in recent years may be closely linked to reductions in autumn–winter Arctic sea ice extent (Honda et al., 2009; Petoukhov and Semenov, 2010; Liu N. et al., 2012).

Changes in Arctic sea ice extent affect not only climate variability in winter, but also the prevailing meteorological regime and the intensity and frequency of extreme weather over Eurasia (Wu et al., 2013a). The decline in autumn Arctic sea ice extent since the late 1980s favors the frequent occurrence of blocking highs over northern Eurasia. Blocking highs over northern Eurasia are associated with colder temperatures over the middle and northern parts of the Asian continent during winter (Fig. 4). Liu J. P. et al. (2012) showed that the decrease in autumn Arctic sea ice extent is related to the occurrence of extreme temperature and snowfall events during winter in the mid-high latitudes of the Northern Hemisphere. Wide reductions in summer Arctic sea ice extent and delays in the autumn–winter recovery of Arctic sea ice may cause anomalous winter atmospheric circulations that include more frequent blocking events in mid-high latitudes. These changes increase the extent of open water in the Arctic, which can increase the flux of water vapor from the ocean to the atmosphere. Arctic warming also increases the amount of water vapor that the atmosphere can hold.

The effects of changes in winter Arctic sea ice extent on the atmospheric circulation and climate over Eurasia can persist into the following summer via SST anomalies in North Atlantic (Wu et al., 2013b). Changes in spring Arctic sea ice are also linked to summer precipitation in China. Reductions in spring Arctic sea ice extent are associated with increases in summer precipitation over Northeast China and the Yangtze–Huaihe River valley, and decreases in summer precipitation over South China. Wu et al. (2009b, c) suggested that the Arctic dipole might act as a bridge linking spring Arctic sea ice and summer precipitation over China. Zhao et al. (2004) showed that decreases in spring sea ice extent in the Bering and Okhotsk seas inhibit the northward movement of the East Asian

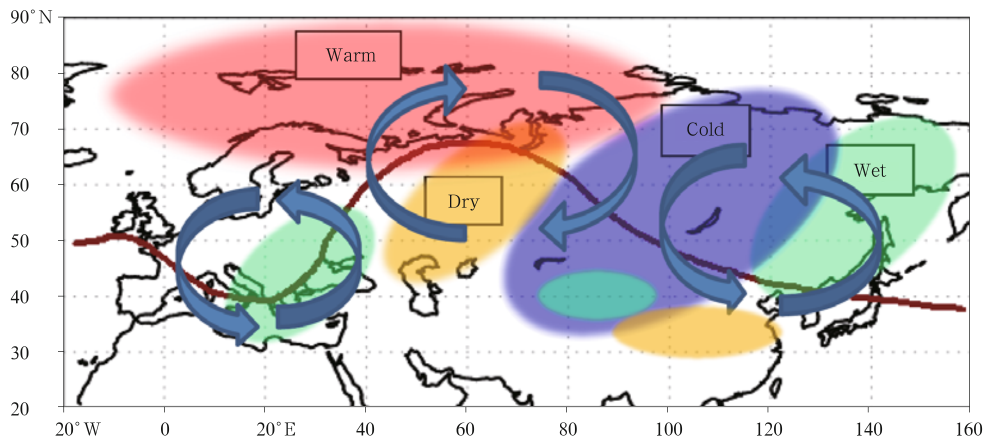

Fig. 4. Schematic diagram illustrating how reduced Arctic sea ice affects winter surface air temperature (SAT) and precipitation in Eurasia. Arrows show the typical locations of anomalous anticyclonic and cyclonic circulations in the lower troposphere associated with the negative phase of the tripole wind pattern. The brown line represents an isoline of geopotential height at 500 hPa. The yellow and green areas indicate decreases and increases in precipitation, respectively, while the red and purple areas indicate positive and negative SAT anomalies. [From Wu et al., 2013a]

summer monsoon, thereby resulting in increases in summer precipitation over southeastern China. Sea ice changes in the Bering and Okhotsk seas can also affect the frequency of typhoons over the western North Pacific through their influences on the tropical atmospheric circulation (Fan, 2007; Zhou and Cui, 2008; Zhou and Wang, 2008). A larger winter–spring sea ice extent in North Pacific corresponds to fewer typhoons in the western North Pacific.

Climatic influences of changes in Antarctic sea ice are observed not only in the Southern Hemisphere (e.g., the Antarctic Oscillation, the Mascarene high, and the Australian high) (Gao et al., 2003; Xue et al., 2004), but also over East Asia (Fu, 1981; Yang and Huang, 1992; Xue et al., 2003; Ma et al., 2006, 2007). Changes in Antarctic sea ice extent are negatively correlated with Meiyu rainfall in the Yangtze River valley (Fu, 1981). Decreases in sea ice extent are associated with a later end of the following Meiyu season, while increases in sea ice extent are associated with an earlier end. Xue et al. (2003) showed that increases in Antarctic sea ice during boreal spring and summer are associated with increases in summer precipitation over North China and decreases in summer precipitation over South China and Northeast China. This pattern of precipitation changes reflects a change in the East Asian summer monsoon circulation. Changes in Antarctic sea ice also affect the polar vortex, equatorial SST, the western Pacific subtropical high, and typhoon activities (Peng and Wang, 1989; Zhao and Ji, 1989; Bian et al., 1996).

4.3 Permafrost

Interactions between permafrost and global climate have attracted increased attention in recent years (Zhang et al., 1999; Qin and Ding, 2009). Early studies of these interactions were mainly limited to the effects of climate change on permafrost due to the complexity of permafrost hydrothermal processes (Jin et al., 2000; Cheng and Wu, 2007; Wu and Zhang, 2008; Zhao et al., 2010; Guo and Wang, 2013). Relatively few studies have focused on how changes in permafrost affect regional climate, especially in China.

The available studies (Li et al., 2002; Tanaka et al., 2003; Guo et al., 2011a, b) have demonstrated that the Tibetan Plateau permafrost plays an important role in surface heat flux changes. The freezing and thawing of plateau soils can enhance the exchange of heat between the land and atmosphere, and significantly influence atmospheric circulation patterns (including the South Asian high, the western Pacific subtropical high, and the Indian low). Hydrothermal changes resulting from freeze-thaw processes over the Tibetan Plateau appear to have important influences on East Asian climate (Wang et al., 2003), with significant implications for precipitation in eastern China (particularly during the flood season). Gao et al. (2005) showed that the thaw date over the plateau is positively correlated with summer precipitation over the mid-lower reaches of the Yangtze River valley.

Land-atmosphere coupled models are important tools for studying interactions between the land surface and atmosphere. These models provide a means of quantifying the impacts of permafrost changes on global and regional climate. Although permafrost simulations are still in their infancy, some progress has been made. Several studies have investigated the influence of freeze-thaw processes in the Tibetan Plateau permafrost on atmospheric circulation and regional climate of East Asia (Wang et al., 2002; Zhang et al., 2003; Wang et al., 2008; Li et al., 2011; Xin et al., 2012). For example, Wang et al. (2008) showed an increase in the consistency between simulated and observed summer precipitation over the Yangtze River valley after incorporating a new permafrost parameterization into CCM3 (Community Climate Model 3). The model's ability to simulate the East Asian atmospheric circulation is also greatly improved. Li et al. (2011) indicated that improving the permafrost parameterization scheme in CAM3 (Community Atmosphere Model 3) significantly enhanced the simulated heating of the atmosphere above the Tibetan Plateau. Surface temperatures in East Asia during winter and summer have also changed substantially. Xin et al. (2012) analyzed the response of East Asian climate to changes in permafrost by introducing non-frozen water processes into CAM3. Their simulations indicated a weakening of the East Asian winter monsoon and a strengthening of the East Asian summer monsoon. Summer precipitation increased over the southern Tibetan Plateau, the middle part of the Yangtze River valley, and Northeast China, and decreased over South China and Hainan Island. The results of these studies highlight the important role that permafrost plays in numerical simulations of East Asian climate.

4.4 Glacier

Glaciers are an important water resource for the arid regions in Northwest China. Variations in runoff from mountainous watersheds are tightly related to the evolution of glacier area within the basin. Glaciers have two main impacts on water resources in China: to supply water, and to regulate river runoff by reducing peak flows and supplementing insufficient flows. Glaciers regulate river flow according to the following mechanism. Enhanced precipitation during high flow years reduces temperatures in the glacial areas of high mountains. Lower temperatures decrease glacial ablation, so that less glacial melt water enters the rivers. This mechanism limits the increase in runoff that results from the increase in precipitation. Conversely, when precipitation in the basin decreases, the relatively high temperatures in the glacier area cause an increase in glacial melt that supplements the river flow (Ding and Qin, 2009; Committee on the Second National Assessment Report on Climate Change, 2011).

Interannual and interdecadal variations in the volume and extent of glaciers in the basin control the magnitude of glacier runoff. Glacial melt water can have a significant impact on river runoff if the glacier coverage in the basin exceeds 5% (Ye et al., 2003). Approximately 70% of the increase in runoff in the headwaters of the Urumqi River in recent years has been supplied by increases in glacial melt. About one third of the increase in runoff in Akesu can be attributed to increases in glacier runoff (Liu et al., 2006). Glacier melt water in the basin above Zhimenda hydrological station in the headwaters of the Yangtze River has increased by 15% over the past 40 years, even as river runoff has decreased by 14% (Liu et al., 2009). These increases in river flow due to glacial melt are beneficial at present, but it is worth noting that the associated loss of glacier mass will eventually result in rapid decreases in river runoff. Changes in snow and permafrost also have important effects on river flow. The influence of snow and permafrost on runoff processes can even lead to changes in the allocation of river water (Committee on the Second National Assessment Report on Climate Change, 2011).

5. Concluding remarks

The cryosphere plays an important role in the earth's climate system and is one of the most sensitive indicators of climate change. In this paper, we review recent scientific studies of changes in the global cryosphere, with particular focus on the Chinese cryosphere. We have summarized advances in understanding how snow cover over the Tibetan Plateau and Eurasia, Arctic sea ice, Antarctic sea ice, permafrost, and glaciers influence the atmospheric circulation over East Asia and the climate in China.

Changes in the cryosphere also have significant effects on ecological health, environmental systems, and resource availability, among others. The effects of cryospheric change in China have become increasingly pronounced under global warming, with significant impacts on regional climate, water resources, ecology, environment, and sustainable development. The regions directly affected by the cryosphere in China are both ecologically vulnerable and economically underdeveloped. The influences of cryospheric changes in these regions will increase the ecological and environmental pressures associated with economic development.

From the international perspective, cryospheric research is shifting from mechanistic and process studies focusing on single elements to holistic studies of the cryospheric system. The Climate and Cryosphere (CliC) Project developed by the World Climate Research Program focuses on the integrated interaction of the elements of the cryosphere with climate, hydrology, ecology, and environment, among others. The aim of the CliC project is threefold: 1) to improve understanding of the physical processes and feedback mechanisms that control the interactions between the cryosphere and other elements of the climate system, 2) to improve the representation of cryospheric processes in climate models and thereby reduce uncertainties in climate simulations and climate change projections, and 3) to assess and quantify changes in each component of the cryosphere during past and future climate change. Future cryospheric research will accordingly focus on physical mechanisms and impacts.

Both the international scientific direction and the national demand require that cryospheric studies in China should focus on the mechanisms of cryospheric change, the interactions between the cryosphere and climate, the impacts of cryospheric change, and strategies for adapting to current and future cryospheric change. We should conduct comprehensive interdisciplinary studies that build understanding of the complete cryospheric system. The mechanisms of cryospheric change are the foundation of cryospheric science. The interaction between the cryosphere and climate is a focus of current studies, which still needs to be strengthened. More and more attention is being paid to explore the impacts of cryospheric change, but the research base remains relatively weak. Examination of possible strategies for adapting to the impacts of cryospheric change is still in its infancy (Ding and Xiao, 2013).

Future cryospheric research should therefore address three mandates. First, we must continue basic research that deepens scientific understanding of cryospheric processes and their response to climate change. Important elements of this mandate include quantifying the relationships between glacial change and climate change and improving understanding of the responses of permafrost and snow cover to climate change. A deeper exploration of the physical processes and feedback mechanisms in the interaction between the cryosphere and climate will help to improve our ability to realistically simulate cryospheric processes in climate system models and quantitatively assess the role of the cryosphere in global and regional climate change. Second, we must strengthen studies that examine the impacts of cryospheric change. Particular attention should be paid to the influences and physical mechanisms of changes in different components of the cryosphere on climate, water resources, and ecology. Third, we must increase the resources allocated to studies of adaptation strategies. We should propose and develop scientific evaluation indices that are suitable for the Chinese cryosphere and are based on both the characteristics of cryospheric change and a comprehensive consideration of social, economic, and cultural factors. This could include the construction of a system for evaluating vulnerability to cryospheric change, proposing adaption pathways and strategies that address changes in the Chinese cryosphere and their impacts, and providing scientific support for sustainable economic development.

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