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REVIEW

Key Issues on Cryospheric Changes, Trends and Their Impacts

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Abstract

On the basis of analyzing the importance of cryospheric researches in China and current status of cryospheric sciences in the world, this paper addresses key issues and main contents of present cryospheric sciences in China. The key issues currently addressed are: i) mechanisms of different types of glaciers in response to climate change and the scale-conversion in water resources assessments; ii) modeling of water and heat exchanges between frozen soil and vegetation; iii) parameterization of physical processes in cryosphere as well as coupling with climate models. To gain full clarification of these key issues, works of the following three aspects should be highlighted, i.e., cryospheric processes and responses to climate change, influences of cryospheric changes, and adaptation strategies for cryospheric changes.

Keywords: cryosphere; climate change; impact; water resources

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1 Introduction

Cryosphere collectively describes the portions of the Earth's surface where water is in solid form, including mountain glaciers, polar ice caps, snow cover, frozen soil and sea ice. Because of high sensitivity and important feedbacks to climate, it receives much attention. Along with atmosphere, hydrosphere, lithosphere (land surface) and biosphere, cryosphere is considered to be one of the five spheres of climate system. Glaciers, frozen soil and snow cover, which are widely distributed within China, not only have important effects on climate, but also maintain oasis economy development in arid areas and ensure the stability of water sources of ecosystem in cold regions. The climatic effects, environmental effects, resource effects, and ecological effects, which are deduced by cryospheric changes, are becoming more and more significant in China. The future cryospheric changes are considered to have wide and profound impacts on the ecological and environmental security and sustainable use of water resources in western China.

At present, studies on cryospheric changes and their impacts are paid unprecedented attention, and thus have become one of the most active research areas in international studies. Furthermore, the internal processes, mechanism and laws of cryosphere, linkages and feedbacks with other

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spheres, and the establishment of cryospheric science system are also part of joint research directions in cryosphere and related disciplines. Therefore, China's cryospheric research is not only of scientific importance, but also demonstrates the urgency to meet the needs of national strategic requirements.

2 International research status and trends

2.1 *Dynamic processes, trends and impacts of cryosphere*

Cryosphere has an extremely sensitive response to climate change. Ranges of snow and sea ice show large seasonal variations. Monitoring by satellite remote sensing shows that snow cover has maximum extent of 45.5×10^6 km^2 and minimum of 3.3×10^6 km^2 in the Northern Hemisphere. In the Antarctic, the areas of sea ice are 17×10^6–20×10^6 km^2 in late winter and only 3×10^6–4×10^6 km^2 in the end of summer. Correspondingly, the areas of sea ice in the Arctic are 14×10^6–16×10^6 km^2 and 7×10^6–9×10^6 km^2, respectively [*Allison et al.*, 2001]. In centurial and decadal scales, glaciers and permafrost are also sensitive to climate change. The total amount of glaciers in the Alps decreased by 35% from 1850 to 1970 and by 15% from 1970 to 2000 [*Zimov et al.*, 2006]. The area covered by glaciers on Mount Kilimanjaro in Africa decreased by about 80% from 1912 to 2000 [*Cullen et al.*, 2006]. Since 1950, the largest areal extent of seasonally frozen soil in winter decreased by about 7% in the Northern Hemisphere while decreased by 10%–15% in China [*Qin*, 2004].

The international scientific community is extremely concerned of the major impacts of cryospheric changes on the global environment. If the glaciers in the world melt completely, sea level would rise by 60 m from present level. The coastal cities and lowlands would submerge. The Fourth IPCC Assessment Report concluded that the total annual rate of sea-level rise is 2.7–3.5 mm from 1993 to 2003, of which 30%–60% are contributed by changes in cryosphere. Studies showed that rapid melting of Arctic ice, which results in a large number of freshwater flows into ocean, has led to a slow-down or even stagnation of the thermohaline circulation in the North Atlantic Ocean [*Stouffer et al.*, 2007], and thus has major impacts on global climate. Amounts of restrained greenhouse gases in Siberian permafrost are 75 times higher than those which are emitted into atmosphere due to the annual burning of fossil fuels. With the continuous warming and degradation of permafrost, those greenhouse gases might be gradually released into atmosphere and affect the global climate [*Zimov et al.*, 2006].

2.2 *Development of climate models including processes of cryosphere*

Changes of cryospheric factors such as snow, ice and permafrost play an important role in climate system. The spatial and temporal changes of snow and ice, which both have high albedo, have significant influences on global energy balance and hydrological process. Through altering the dynamic processes of climate in regional or global scale, those changes of snow and ice affect climate. By means of oceanic circulation which results from changes of salinity and temperature, changes in global ice volume lead to an alteration of global climate patterns linking with fresh water flowing into ocean. Through altering water and heat exchange processes between land surface and atmosphere, changes of permafrost have influences not only on climate system, but also on the global carbon cycle and climate change.

Earlier studies show that the variation of snow cover in winter and spring in the Himalayan Mountains has effects on the subsequent Indian summer monsoon [*Dey et al.*, 1982]. Further studies also indicate that a complicated relationship exists between snow cover in different regions of Eurasia and monsoon [*Zhang and Tao*, 2001; *Fasullo*, 2004]. Compared to rapid variation of snow and sea ice, changes of glaciers and ice sheets are relatively small. However, the coupling of Ice Sheet Dynamic Models with Sea-ice Thermal Dynamic Models and Ocean-Atmospheric Models successfully explains the instability of glacial climate in the North Atlantic [*Schmittner et al*., 2002].

In view of the importance of cryosphere in climate system and the lack of research on the mechanism between cryosphere and climate system, the scientific scheme "Climate and Cryosphere" (CliC) was launched in 2001 by the World Climate Research Program [*Allison et al.*, 2001]. The main goals are: 1) to improve understanding of interaction, physical processes, and feedback mechanisms between cryosphere and climate system; 2) to improve models' abilities to describe the processes of cryosphere, and to reduce uncertainties of simulation and prediction; 3) to assess and quantify the impacts of climate change on components of cryosphere; 4) to strengthen observing and monitoring of cryosphere.

2.3 *Mechanism analysis and numerical simulation*

The construction of quantitative models on relationships between glacier and climate is a key issue to assess glacial changes under climate warming. Numerical simulation studies on changes of mountain glaciers responding to climate change started in the 1960s. At the end of the 20th century, glacier dynamic models came to maturity [*Van de Wal et al.*, 1995]. Based on dynamic models which describe changes of glacier responding to climate change, and observational data from 169 glaciers all around the world in recent 100 years, *Oerlemans* [2005] estimated global warming of 0.5℃ in the first half of the 20th century. To predict glacier changes using limited observational data, statistical models have also been developed. *Letreguilly and Reynaud* [1989] set up a linear statistical model to estimate the influences of changes in glaciers' lengths on glaciers' mass balance. *Wang and Yao* [1996] also established an equilibrium model to evaluate changes of mountain glaciers responding to climate change.

Studies on the simulation of changes in runoff at basin-scale are core issues in glacial hydrology and water resources researches. With conceptual models and water balance models, changes of glaciers in the Alps and the Tianshan Mountains in Central Asia were analyzed. The results showed that with further shrinkage, glacier's runoff tends to decrease [*Hagg et al.*, 2007; *Hagg and Braun*, 2005]. Recently, studies on simulation of changes in glacier responding to climate change and future scenario analysis in regional- or basin-scale also raised a number of new research ideas such as the geometrical model [*Raper and Braithwaite*, 2006], the grid-based glacier mass balance model, and sensitivity analysis method based on scale-conversion [*Gregory and Oerlemans*, 1998; *Van de Wal and Wild*, 2001]. Some studies which use the models mentioned above in the Tianshan Mountains in Central Asia, the Himalayas, and other regions, suggest that changes in glacial melting water have great impacts on river runoff in highly glacierized areas.

The existing states and mutual transformation of water, ice and vapor in soil determine the characteristics of frozen soil. The one-dimension water-heat coupled model FROSTB, which was constructed by *Berg et al*. [1980], is initially used to calculate variations in soil freezing and thawing for frozen soil engineering practices, and is later applied to simulate water transfer in processes of soil freezing and thawing and permafrost responding to climate change. The simulation results have been proved with observational data. However, the exchange processes of water and heat flux between land surface and atmosphere (i.e., surface processes) are not taken into account in FROSTB model. By combining observational meteorological factors, soil moisture, and temperature in frozen soil with optimized methods, the permafrost surface parameters seem relatively feasible [*Yang et al.*, 2005]. The Simultaneous Heat and Water (SHAW) Model developed by *Flerchinger* [2000] is a one-dimensional model to simulate soil freezing and thawing. The model has ability to simulate heat and water movement through plant cover, snow, residue, and soil.

2.4 *Impacts of cryospheric changes becoming the general trends*

Recently, different studies and assessments pointed out that glacier melting in Central Asia, South Asia and the Qinghai-Tibetan Plateau might change runoff, flood disasters and supply of freshwater resources in the coming 50 years, and might be one of the most serious threats to human progress and food security in those areas, relating more than 2 billion people affected [*WB*, 2005; *UNDP*, 2006]. If the average summer (April to September) temperatures rise by 3℃ within the next 100 years, about 80% of glaciers in the Alps will melt. These indicate that cryospheric change has begun to threaten human socio-economic development.

Taking cryosphere as a whole, systematic and integral researches on cryosphere relating multidisciplinary, applying new techniques, and implementing significant projects at global scale, have become an international trend. The WCRP/CliC program [*Allison et al.*, 2001] focused on land-based cryosphere, hydrology and meteorology in cold regions, glaciers and sea-level change, marine cryosphere, and ocean-atmosphere interactions in high-latitude areas, and relationships between cryosphere and global climate change. The Third International Polar Year (IPY 2007–2008) Program (http://www.ipy.org/), which was cosponsored by the International Science League and the World Meteorological Organization, stressed to enhance awareness of relationship between the poles and the globe by establishing a sound observation system in polar areas through international cooperation and multi-disciplinary cross-cutting partnerships. The Global Land Ice Measurement from Space (GLIMS) Program (http://www.glims.org/) monitors dynamic changes of global glaciers through remote sensing, and assesses their impacts. The Asia CliC Program (http://www.jamstec.go.jp/iorgc/sympo/asiaclic2006/), which was jointly advocated by China and Japan aimed at dynamic changes of Asian cryosphere and their impacts on regional water resources, environment and human development.

From the point of discipline development, the concept of cryosphere science was first proposed in 2000 at the beginning stage of WCRP/CliC Programme [*Allison et al.*, 2001]. It integrates glaciers, ice caps, permafrost, sea ice, and snow cover into a unified system for integral researches and becomes an important symbol which indicates that cryospheric research is one of the hot spots of international global change research. It mainly aims at internal mechanism and processes of various components in cryosphere as well as interactions of cryosphere with other spheres. Though scientists from various countries attach great importance to the science, it is still in an initial stage at present.

3 Research progress and development trends in China

Study on cryosphere in China began in the late 1950s. With the joint efforts of Chinese Academy of Sciences, China Meteorological Administration, State Oceanic Administration, and relevant colleges and universities, great progress in research of glaciers, snow cover, permafrost, polar ice caps, periglacial landforms, and regional climate in China have been achieved. In recent years, the latest research progress and development trends are mainly manifested in the following four aspects.

3.1 *Glacial resources and characteristics of cryospheric changes in recent decades*

China's glaciers inventory began in 1979 and lasted for 24 years. Based on a large number of field investigations, and aerial and topographic maps in the 1960s and 1970s, the total number of glaciers, and ice reserves as well as distribution of various mountain glaciers are identified. The basic characteristics of glaciers and glacier classification system were defined. The glacial information system was accomplished. The glacial thickness estimation formula, which was widely used in survey of glacial resources in China and its neighboring countries [*Shi et al.*, 2008], was established by the applications of self-developed ice penetrating radar.

Based on the data of glaciers inventory, a large number of studies on glacier changes were carried out [*Liu et al.*, 2003; *Yao et al.*, 2004; *Ding et al.*, 2006]. The results show that the shrinking speed of glacier declines from oceanic glacier area to continental glacier area since the Little Ice Age. About 82% of the glaciers are retreating or vanishing since 1990s. The area of mountain glaciers decreases by 2%–18%.

By using a variety of data, *Li* [1993] analyzed the spatial distribution, seasonal variation, and inter-annual fluctuation characteristics of snow cover in western China. The results show that the periods with above normal snow cover include the late 1970s and mid 1980s while the mid l970s and early 1980s have below normal snow cover. The inter-annual fluctuations of snow cover closely link to ENSO events. Years with above normal snow cover occur mostly in El Niño years while years with less snow cover usually have La Niña events. Latest research [*Qin et al.*, 2005] showed that snow cover in western China has a slightly increasing trend, even under global warming.

With nearly half a century climate warming and increasing impacts of human activities, signs of degradation of permafrost (i.e., the rise of the lower boundary) are obviously observed. These include increasing ground temperatures, thickening of active layer, enlarging of non-convergence, and growth and expansion of unfreezing areas. The greatest and most significant thinning area of seasonal frozen depth is found in the hinterland and the northeastern part of the Qinghai-Tibetan Plateau with thinning about 20 cm. In the northwestern and southeastern parts of the Qinghai-Tibetan Plateau, the thinning depth is about 5–6 cm, which takes up 8%–10% of the total frozen depth [*Zhao et al.*, 2004].

3.2 *Interaction between cryosphere and climate*

As China has a well developed cryosphere in mid and low latitudes, cryospheric changes have significant impacts on climate of China and the surrounding regions. A number of researches are carried out in recent years on how changes of snow cover on the Qinghai-Tibetan Plateau as well as the Eurasian snow cover influence atmospheric circulation, monsoon and precipitation. The results show that snow cover changes in the Qinghai-Tibetan Plateau have significant effects on atmospheric circulation, Indian air pressure system, and tropical easterlies jet. A high (small) amount of snow cover on the plateau leads to weak (strong) summer monsoon and floods (droughts) in the Yangtze River basin in China [*Zhang and Tao*, 2001]. Additionally simulation of climatic effects on the plateau's snow cover was done by a regional climate model (RegCM2) [*Zheng et al.*, 2000]. Changes of snow cover in Eurasia show negative correlation with intensity of summer monsoon and precipitation in the flood season (April to September) in Hunan and in the Meiyu season (rainy season) in Jiangsu. It is worth noting that recent studies [*Xie and Luo*, 1999; *Chen et al.*, 1999] indicate that different spatial and temporal distribution patterns of snow cover in the Qinghai-Tibetan Plateau as well as in the Eurasian continent have different impacts on Asian monsoon system.

The soil structure, characteristics, and the relationship with atmosphere in the Qinghai-Tibetan Plateau are different from other regions. In the existing global and regional climate models, the description of the process, and the hydraulic and thermal parameters are not adequately precise. Rough description of freezing and thawing processes, which are mainly controlled by atmospheric circulation and the climate system of China and East Asia, restricts the parameterization of freezing and thawing processes in land surface models. Therefore, determination of hydraulic and thermal conductivity within frozen soil under different soil components appears to be more important and urgent.

3.3 *Impacts of cryospheric changes on hydrology, ecology and environment*

Glaciers are important water resources in arid areas in northwestern China. The variation of river runoff is closely related to glacial areas and to changes in glacierized basins. Stable and sufficient glacial melting water supplying in summer is the key function for glaciers in regulating river runoff. The size and coverage of glaciers determine the inter-annual and inter-decadal fluctuations of glacial runoff in river basins. Several studies show that glacial melting water has significant impacts on river runoff when the glacier coverage is over 5% of the basin-area [*Ye et al.*, 2003]. One third of the increasing amount in runoff on the southern slope of Tianshan Mountain is glacial melting water due to glacial retreat [*Liu et al.*, 2006]. China's glacial reserves decrease by 450–590 km^3 [*Liu et al.*, 2003] during 1960s–1990s which have significant impacts on water resources in arid regions of western China. It is estimated that over 5.5% of glacial melting runoff originates from the reduction of glacial reserves since the 1990s. Mountainous snow and frozen soil also have important implications on the variation of river runoff. Changes in snow and frozen soil result in changes of annual river runoff allocation [*Kang et al.*, 2000].

As an impermeable layer, changes in permafrost have significant impacts on the hydrological processes in cold regions. Climate change, which influences the water table within the active layer and the freezing-thawing zone of permafrost, has direct impacts on hydrological processes in the permafrost area [*Yang et al.*, 1993]. During the formation of frozen soil, a large number of solid water is stored. Thus, soil water storage increases [*Chang et al.*, 2001]. At the same time soil evaporation and the generation of soil inflow above the frozen layer are suppressed [*Liu et al.*, 2002; *Wang et al.*, 2001]. The average soil water content within 10 m depth in the Qinghai-Tibetan Plateau permafrost region is 18.1%. It is estimated that an annual average of 50×10^8–110×10^8 m^3 [*Pan et al.*, 2005] liquid water resources, which is equivalent to 1/6–1/3 of annual runoff of the Yellow River at Lanzhou station, is transformed from underground ice due to the changes in permafrost. It is obvious that the hydrological effect induced by changes in permafrost is enormous.

Changes in permafrost have crucial impacts on the ecology and the environment. The relationships between ecology and environment, and permafrost have been widely recognized [*Wang et al.*, 2001]. Studies on the impact of permafrost on degradation of vegetation along the Qing-Kang Highway, the southern section of the Qinghai-Tibetan Highway and Liangdaohe-Nierong Highland at the southern foot of the Tanggula Mountain indicate that the degradation of vegetation in the plateau follows a gradual transformation series of swamp, swamp meadow, meadow, grassland, desert steppe, and desert [*Wang et al.*, 1999; *Wang and Zhao*, 1997; *Yuan et al.*, 1997]. Ecological and environmental problems in the source areas of the Yangtze River and the Yellow River have widely received concerns since the mid 1990s. Recent studies show that there are close correlations between hydrological processes in the source areas and permafrost, and typical alpine meadows [*Wang et al.*, 2006; *Yang et al.*, 2006].

It is obvious that current studies do not adequately explain the physical processes and feedbacks of cryospheric impacts on regional hydrology, ecology and environment, and do not give enough systematic understanding on the effects of cryospheric changes. In the course of climate warming in the next 50 years, the cryosphere will undergo tremendous changes [*Li et al.*, 1999; *Shi and Liu*, 1999; *Nan et al.*, 2005], which are bound to have significant impacts on water resources, ecology and environment in China as well as neighboring regions.

It should be noted that snow and frozen soil disasters which result from cryospheric changes, will become important topics of cryospheric impacts study. Frozen rain and snow disasters in southern China in early 2008, the avalanche disaster in the Sichuan-Tibetan Highway in early 2009, and the vast extent of drought in 2009, which are related to snow cover in northern China, probably are related to cryospheric changes.

3.4 *Integration of cryospheric research and cryospheric science*

China's cryospheric researches are developed as a scientific system. This system is mainly represented as follows: 1) the application of remote sensing, geographic information systems, geo-positioning systems, automatic field monitoring system, and computer simulation have been enhanced; 2) more attention is paid to the establishment and application of different models; 3) the climatic effects of underlying surfaces such as glaciers, snow cover and permafrost are concerned; 4) studies on cryospheric impacts on hydrology, water resources, ecology and environment due to glacial changes or permafrost changes become the main focus in cryospheric research; 5) adaptation measures to cryospheric changes are achieved through comprehensive assessments [*Qin*, 2002; *Qin et al.*, 2005; *Shi*, 2003].

Many studies accomplished a good basis and comprehensive breakthroughs in the field of cryospheric research in China. Based on the existing research, adequate studies on impact of cryospheric changes are urgent issues for Chinese scientists.

4 Key scientific issues and future focus

4.1 *Key scientific issues*

Based on the national and international scientific studies, and the actual needs of national development in China, researches on cryospheric changes will be achieved in the following three key issues.

(1) Response mechanism and impact assessment

Response processes of glacier to climate change are complicated. In short, the response processes are achieved through the transmission of power waves. The transmission to the terminal of glaciers leads to the advancement or retreat of glaciers. To accurately understand the impacts of glacial changes on hydrology, it is necessary to establish climate response models, which are based on the dynamic processes of glaciers, to determine time-lag relations for glaciers responding to climate change, and thereby to analyze the quantitative affiliation of climate, glaciers and hydrology. As the response processes vary with characteristics, type and size of glaciers, typical studies on different type, size and spatial distribution of glaciers are essential to assess the impacts of glacial changes on water resources in river basins or at regional scale. On the other hand, how to transfer the relationship between single glacier and climate into basins scale or regional scale is key issue to evaluate the impacts of glacial changes on water resources. Therefore, using the correlation of glacier geometry, distribution characteristics of glaciers in the basin, and key climate-driven factors, response relationship between glacier and climate is diverted to estimate glacial melting water and its variation at river basin scale. Thus it provides scientific means to understand the impacts of glacial changes on water resources at watershed or regional scale.

(2) Accurate simulation of water and heat transfer between permafrost and vegetation

Impacts of permafrost change on ecosystem illustrate in two time scales. First, changes of water and thermal conditions in the active layer of permafrost directly affect the transfer processes of water and heat in the soil and water storage. Thereby it affects the stability of ecosystem. The time scale of this impact is relatively short, usually from season to decades. Second, under climate warming, the thickness of permafrost is decreasing, and the permafrost areas decline. The north-south boundary shifts and island permafrost disappears. Large amount of frozen water is released from permafrost directly, which alter the water and heat cycle between soil and atmosphere and the balance of water and heat budget of the surface. This influences the long-term stability of ecosystem. The time scale of those effects lasts 10 years to a century or longer. For better understanding of the impacts of permafrost changes on ecosystem, the impacts of changes in active layer on transfer processes of water and heat, as well as the impacts of changes in water cycle on ecosystem are taken into account. Therefore, it was necessary to construct water and heat coupling models which link atmosphere, soil (active layer), and permafrost together to quantify the mechanisms of water and heat transfer, the exchange between soil and vegetation, better simulating water and heat transfer processes, and to understand the time scales and spatial extent of their impacts on ecosystem.

(3) Parameterization and coupling of cryosphere and climate models

Among the various elements of cryosphere changes in snow cover and permafrost mainly contribute to the impacts of climate change in China. However, in studies on modeling and prediction of climate change, only the feedbacks of snow or frozen soil to climate change are considered. Complete coupling of physical processes of snow and frozen soil with climate models is yet not accomplished. Therefore, the third key issue is to couple the physical processes of snow cover and frozen soil into the global and regional climate models to reveal mechanism of cryosphere and to enhance the capacity of regional climate prediction. This issue is also highly concerned within the programme of WCRP/CliC.

4.2 *Focuses of future researches*

Future researches need to focus on three aspects, i.e. the mechanism of cryospheric changes, the impacts of cryospheric changes, and the adaptation measures to cryospheric changes.

(1) Cryospheric processes and response mechanisms

Researches on cryosphere at several levels should to be carried out as listed in the following. First, by using observational data from different types of glaciers, inter-linkages between glacier dynamics process and climate change are analyzed. Second, studies on responding mechanisms to climate change and impacts of snow cover and frozen soil are tightly integrated. Researches on responding mechanisms of snow cover and frozen soil to climate change need to enhance based on observations and models.

(2) Impacts of cryospheric changes

Impacts of cryospheric changes focus on water resources, ecology and climate. According to the principle of “limited objectives and highlighted key points”, studies on hydrological and water resources effects should be carried out in typical river basins in arid inland regions. Meanwhile, macro-evaluation of impacts of glacial changes on water resources in the Himalayas area should be prevalently concerned. Studies on ecological effects of cryospheric changes should focus on the relationships between ecology and frozen soil, and snow cover and in the source regions of the Yangtze River and the Yellow River. The studies on climatic effects of cryospheric changes should emphasize on regional impacts.

(3) Adaptation countermeasures

Macro studies on cryospheric changes in China in the past 50 years should be implemented to apprehend regional characteristics of cryospheric changes. Based on the characteristics of cryosphere, including natural, social, economic, and cultural factors, scientific evaluation guidelines should be put forward through the analysis of typical examples. Based on the scientific evaluation guidelines and models, by means of GIS and decision-supported systems, and comprehensive studies, an integrated analysis and vulnerability assessment system on cryospheric changes should be constructed to enhance adaptation measures on cryospheric changes in China.

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