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Key Viewpoint of Cryospheric Human-sociology: Function and Service

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Abstract

The cryosphere is closely related to human society. As a result of climate warming and corresponding cryosphere shrinkage, the cryosphere functions (CFs) and their associated services and hazards are undergoing profound changes. On the one hand, the cryosphere hazards become more and more frequent with heavily extreme events; on the other hand, the overall cryospheric service (CS) capacity has been deteriorating and would continue or be eventually lost. This article introduced the concepts of CFs, CSs, and their value on the basis of summarizing the human and social characteristics of the cryosphere and its affected areas. Then, taking the importance of world's "water towers" and changes in polar systems as examples, we illustrated the changes in CSs and their impact. Finally, the resilient pathway of cryosphere-affected socio-ecological systems was further discussed.

Keywords

cryospheric human-sociology; cryospheric functions; cryospheric services; water tower; polar system; service valuation; resilience

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Key Viewpoint of Cryospheric Human-sociology: Function and Service

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Abstract: The cryosphere is closely related to human society. As a result of climate warming and corresponding cryosphere shrinkage, the cryosphere functions (CFs) and their associated services and hazards are undergoing profound changes. On the one hand, the cryosphere hazards become more and more frequent with heavily extreme events; on the other hand, the overall cryospheric service (CS) capacity has been deteriorating and would continue or be eventually lost. This paper introduced the concepts of CFs, CSs, and their value on the basis of summarizing the human and social characteristics of the cryosphere and its affected areas. Then, taking the importance of world's "water towers" and changes in polar systems as examples, we illustrated the changes in CSs and their impact. Finally, the resilient pathway of cryosphere-affected socio-ecological systems was further discussed.
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The cryosphere is a subzero temperature zone where water bodies of the earth system are frozen, including mountain glaciers and polar ice caps, permafrost and seasonally frozen soil, snow cover, sea/river/lake ice, ice shelves, icebergs and frozen water bodies in the atmosphere, which are mainly distributed in the poles of the earth and alpine regions [1,2]. The cryosphere, as one of the five major spheres of the climate system, has a pivotal role in the climate system and climate change; the cryosphere, serving as an important element of the earth's surface environment, has been closely related to the human society [3,4]. In recent decades, with climate warming and under the promotion of sustainable development, the cryospheric science has developed rapidly and its scientific connotation has been continuously enriched; the research scope covers the formation, evolution and internal mechanism of cryospheric elements, as well as the interaction between the cryosphere and other spheres of the climate system, but expands to the interdisciplinary areas of science and humanities studying the impact and adaptation of the cryosphere on human society [1,2].

Human evolution and advancement have always been accompanied by ice and snow, but with perseverance. Looking back at the long process of human evolution, migration and socio-economic changes, the cryosphere has played an important role. The ice bridges in cryosphere, as transportation channels, have promoted remote migration of human at early stages; meanwhile, the cryosphere once fixed a large amount of seawater on the land through adjusting the global water distribution during the ice age, which greatly lowered the sea level, and led to the exposure of the "bridges," for example across the Bering Sea and between southeastern Pacific islands, thus making it possible for modern Homo sapiens to migrate to America and Oceania from Africa and Eurasia, and facilitating their global dispersal.

In 2015, Chinese scientists proposed a theoretical framework for cryospheric functions (CFs) and services (CSs) for the first time to systematically study the direct/indirect, material/spiritual benefits that the cryosphere can contribute to the human society [3,4]. For instance, the cryosphere has long been providing climate regulation services for mankind. On the one hand, it has created suitable climatic conditions to make the temperate zone a most advanced and fastest-growing region of human civilization; on the other hand, alternating of warm and cold temperatures has also helped human beings adapt to nature, objectively promoting the progress and development of human society. In addition, the cryosphere can also provide valuable fresh water resources for production and living of the residents in cold and arid areas. Especially in the high-altitude areas of Asia centered on Qinghai-Tibet Plateau, there are abundant cryospheric water resources, forming the birthplaces of the Yangtze River, Yellow River, the Ganges River, the Indus River, Tigris River, and Euphrates River cultivating the Chinese civilization, Indian civilization, and Mesopotamian civilization. In the cryosphere and the affected areas, the religions/totems related to glaciers and snow-capped mountains have developed into unique cultural forms as important parts of cultural diversity of the world.

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CSs are based on CFs, with orientations towards human needs and values. Specifically, the cryosphere meets human's material and spiritual needs, thereby contributing to human well-being. They also form a process improving human well-being based on the demand for cryospheric resources and utility of resources to humans (Fig. 1) [4,5]. CSs are expected to benefit human beings in a maximized and optimized manner. In contrast, the cryosphere may also produce many negative effects on human society. The hazard effects include all losses to human society and economic development caused by changes in cryospheric elements, such as torrential flood, glacial debris flow, snow-bearing wind, snow avalanche/glacier avalanche, glacier surging, frost heaving and thaw collapse [6,7]. The hazard effect can reveal the exposure and vulnerability of human to the cryosphere, and the resulting disaster risks (Fig. 1). A method is expected to be established to minimize the risks, and avoid potential negative impacts on society, environment and economy.

The impact of the cryosphere on human society is closely linked to the cryospheric changes. As a result of climate warming and accelerated shrinking of cryosphere, the CFs and CSs have shown the signs of weakening in some areas, and this retreat may continue to intensify as estimated to result in further decline and lose of CFs (Fig. 1). At the same time, as cryosphere melting is accompanied by extreme or abnormal processes such as the release of energy, water and carbon, the cryospheric disasters will be intensified. Besides, with the increase in population and economy in the cryosphere and its affected areas, major and profound changes have taken place in the hazards to human society [6]. Compared with the frequent and obvious cryospheric disasters, the decline and loss of the CSs will be a long process with potential irreversible consequences, so special attention should be attached.

Cryospheric human-sociology aims to explain the relation between the cryosphere and human society, define the social, economic, cultural, and political attributes of the cryosphere and its affected areas, and reveal and quantify the actual and potential impacts of cryospheric changes on human society through analysis from the perspective of human-sociology (mainly sociology and economics). Through objectively predicting the impacts and risks of cryospheric disasters, and declines in CFs and CSs, we expect to find a path to minimize risks, maximize and optimize services for adaptation, restoration and transformation of the regional social-ecological system, thus providing a basis for decision-making of sustainable development in the cryosphere and its affected areas. This paper focused on introducing the contents of CSs based on the cultural and social characteristics of the cryosphere-affected areas.

1 Humanistic and social characteristics of the cryosphere and its affected areas

The cryosphere is mainly distributed in the high-latitude Antarctic and Arctic regions, and low- and mid-latitude alpine regions, but the impacts of the cryosphere on social economy are not only limited to the core area of the cryosphere, but the related processes will also radiate to the areas surrounding the cryosphere (the cryosphere-affected areas). The core area of the cryosphere is harsh in environment, and sparsely populated with primitive and simple economic industries, underdeveloped transportation, and information delay. Some areas are closed and independent public territories/sea areas, where a variety of ethnic groups and religions, languages and cultures, as well as unique legal systems and ethnic regional autonomy systems have been formed. The impacts of the cryosphere can extend to all regions around the world. The main affected areas, such as coastal zones and lower reaches of rivers, are generally highly developed in society, economy and culture, and some have even become political, economic and cultural centers in some countries or regions.

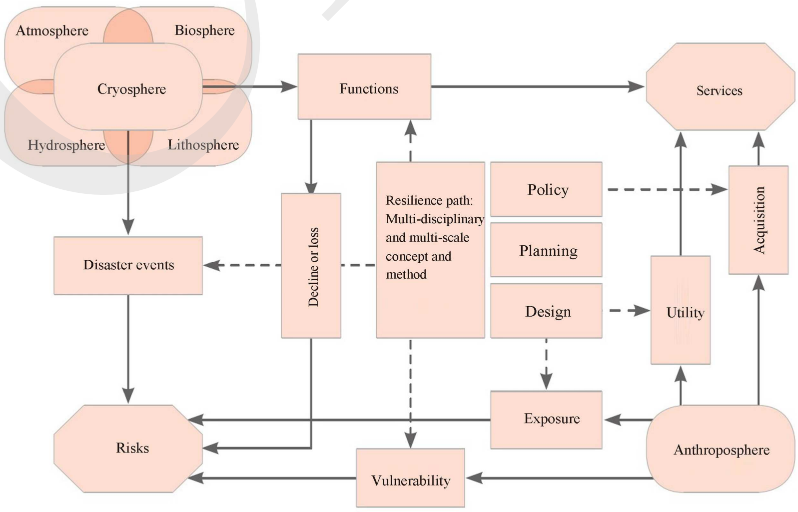

Fig. 1 Schematic diagram of the relation between cryosphere and human society [6]

(1) Polar regions. The Arctic Region consists of parts of Russia, Canada, Alaska (the US), Iceland, Greenland (Denmark), Sweden, Finland, and Norway, with permanent residents of about 4 million, including 10% of aborigines in more than 20 ethnic groups [8]. The aborigines have been living in the cryosphere through hunting on the ice, and the Inuit live in igloos. The unique living modes and customs, as well as the resulting socio-economic structures, are closely related to the cryospheric environment. With the changes in the cryospheric environment, the improvement of the transportation network, and the introduction of foreign cultures, the traditional society, economy and culture of the Arctic region have been continuously impacted. The population has decreased, and the aging has aggravated. The Antarctic Region is covered by ice caps all year round, without any residents. It is a sensitive area of geopolitics and also an ideal place for scientific research and exploration. At present, the number of scientific expedition members from all over the world may reach 1 100–4 400 in winter and summer each year.

(2) Alpine regions. Alpine regions are praised as the "water towers" by virtue of the water resources provided by regional glaciers, frozen soil and snow cover. These "water towers" play an extremely important role in global water cycle, which can ensure the natural and human water demand in alpine regions and downstream regions [3,4,9]. In history, human beings living around water bodies facilitated the formation of unique watershed socio-economy and culture, especially in arid inland areas such as Central Asia, which is closely related to the cryospheric melt water. At present, 250 million people are living in Alpine regions and 1.6 billion (about 22% of the global population) in downstream regions, with the GDP accounting for 4% and 18%, respectively. The cryospheric water resources in Alpine regions play a vital role in the social and economic development of the relevant basins. The cryosphere in Alpine regions, the Alps for instance, can also provide unique and favorable conditions for the development of cryospheric tourism. In addition, the snow-capped mountains, the lakes and rivers supplied by melt water, and the animals and plants have been functioned as the natural carriers of religions and beliefs, thus producing a profound impact on cultural structure of the local society [8,10].

(3) Low-lying areas such as coastal zones and islands. These areas are indirectly affected by the cryosphere through affecting the rise and fall of the sea level. The population densities in such areas are high, especially those in coastal areas (the most densely populated areas), and 28% of the people (about 1.9 billion) live in coastal lowlands less than 100 km from the coastline with the altitude of less than 100 m. Seventeen of the metropolises with the population of more than 5 million are distributed in these areas. Due to the shrinkage of mountain glaciers and polar ice caps, and the influence of ocean warming-induced thermal expansion, the social-ecological system of coastal areas is under the threat of the rise of sea level and the related extreme weather events and will long remain so [8].

2 CFs, CSs and human well-being

2.1 Basic concept

CFs include energy regulation, material (especially water) storage and migration, load-bearing, natural cooling capacity and release, and surface erosion or consolidation, all of which are natural attributes of the cryosphere and independently exist in nature. CSs refer to the various benefits that the cryosphere can provide for the human society. The distinguishing feature of the cryosphere in relation to other spheres or environmental elements is the presence of water in the frozen state. The cryospheric process can reflect the cryospheric changes and the interaction with other spheres. CSs of the cryosphere are determined by CFs, which are the results of cryosphere's environmental nature, structures and processes [3,4] (Fig. 2). From CFs to CSs, the research perspective has changed, and the research objectives have been switched from solely considering the cryosphere's nature to relating to human society and economy.

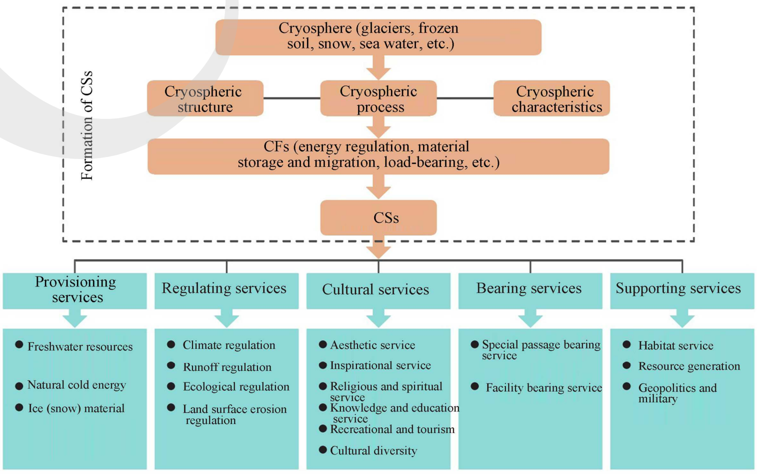

Fig. 2 The formation process and classification system of CSs

On the basis of the formation processes of CSs and their links with human well-being, a classification system of CSs has been proposed where CSs can be divided into five major categories (provisioning, regulating, cultural, bearing, and supporting services) and 18 subtypes (such as freshwater provisioning and nature cold energy provisioning) from the perspective of ecosystem services, and in accordance with the principles of systematicness and sustainability [4]. In addition to the "one-to-one" relation between CSs and CFs, there are more "many-to-one" and "one-to-many" relations (Fig. 2).

Human well-being, the healthy and happy life with abundant materials, is a multi-level system composed of multiple constituents, with objective and subjective connotations. Human well-being consists of five constituents, i.e., security, basic material for a good life, health, good social relations, and freedom of choice, and action according to the Millennium Ecosystem Assessment (MA) [11]. CSs are important contribution factors of human well-being. All types of CSs have, more or less, directly or indirectly, positive effects on human' social, economic and spiritual needs.

The linkages of CSs and human well-being are complicated processes. ① The processes from supplies and consumptions of the services require the investments of financial, human, construction and social capital, and will be affected by a series of socio-economic factors such as social regimes, market regulation, technological level, and value orientation. ② There may be spatial separation between supplies and consumptions, so there is a complicated non-linear and hysteretic effect between the actual benefits from CSs and service supplies. ③ The actual benefits from CSs also have a marginal effect on the contribution to human well-being, and may be affected by human needs and mental status [4].

As a result of global warming and accelerated shrinkage of the cryosphere, the CFs and CSs will continue to decline and even lose on a long view although some (such as water supply) may be enhanced in a short period of time [4,6], thus exerting a profound impact on regional sustainable development and human well-being.

2.2 Case analysis: CFs and CSs of global "water towers" and polar systems

The most critical services of alpine cryosphere are the water supply and runoff regulation; as for the polar cryosphere, the influences of the polar systems on climate regulation, the production and life of aborigines, and the economy and society of other hemispheres and even the whole globe are highly significant. Taking the importance of world's "water towers" and changes in polar systems as examples, this paper illustrated the changes in CFs and CSs and their impacts.

2.2.1 Importance of global "water towers"

The alpine cryosphere areas are known as "water towers," describing and emphasizing the water storage and water supply of alpine cryosphere in maintaining downstream production, life and ecological water demand. Compared with the downstream regions, the "water towers" can provide stable water supply for downstream regions by virtue of orographic precipitation and delayed release of water and lake reserves in the cryosphere. On the basis of the basins, global "water towers" have been divided into 78 basic units to determine the supply indices from four dimensions of the "supply" of mountainous areas (precipitation, snow cover, glaciers, and surface water reserve), and determine the demand indices from four dimensions of the "demand" of the affected areas (domestic water demand, industrial water demand, irrigation water demand, and natural water demand). The importance of the "water towers" has been evaluated with those indices [10].

As for the "supply," there is a considerable spatial difference in water supply capacity between the "water towers." In Asia, the Qinghai-Tibet Plateau is rich in ice and snow resources, and the plateau lakes also contain abundant water; in addition to abundant atmospheric precipitation, it possesses the highest water supply capacity. In Europe, the "water towers" in Islands of Arctic Ocean, Iceland and Scandinavia have abundant ice and snow reserves, especially in Iceland where there is the thickest glacier on earth with the water reserve of 15 times of annual precipitation in its "water tower" area. In Andean mountains in South America, there are also abundant water resources. Taking Chile as an example, the seasonal north-south changes in the south westerlies can bring plentiful topographic rain, and there are also large ice and snow reserves. In North America, the northwest region, Nunavut, Fraser, and Pacific and Arctic Coasts are critical "water towers." The water supply capacity of the northwest region and Nunavut is mainly related to abundant ice and snow resources and storage of surface water.

As for the "demand," water demand for irrigation is greatest in all continents. The river basins in Asia, especially the basins of the Indus, Amu Darya, Tigris, Ganges, Yarlung Zangbo and Tarim, are densely populated, with widely distributed irrigated agriculture. Additionally, there are relatively high industrial and domestic water demands. Therefore, the water demand index is the highest in these areas with high dependence on mountain water resources. Especially when the gap of water consumption should be filled by unsustainable groundwater, the water supply capacity of "water towers" is crucial to meeting demand and recovering the aquifer.

2.2.2 Recession risks of CFs and CSs of polar systems

The changes in polar systems can profoundly affect the local ecological environment and social economy, and produce hemispheric and even global effects through climate regulation services and waterway service. Taking the Arctic as an example, amid climate warming and cryosphere shrinkage, the polar system change has produced a significant impact on multiple sectors of local human society and economy, including commercial fishing, reindeer herding, livelihood system, tourism, non-renewable resource extraction, infrastructure, transportation, human health, and coastal communities. The Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) of IPCC systematically assessed the impact of climate changes on these sectors, and proposed the adaptation measures [8,12].

(1) Commercial fishing. Climate changes may cause varying degrees of alteration in abundance and distribution of fish in Arctic, and the marine ecosystem changes also affect fishery productivity. The resource background assessment should be conducted to resolve the problems of rights and interests, and adaptive management should be performed based on monitoring, research and public participation in decision-making.

(2) Livelihood system. Climate warming may result in changes in distribution and abundance of food in the Arctic, and may also affect traffic accessibility and safety, as well as crop production, storage and quality. The adaptive management system should be established to flexibly allocate food species, access methods and time, mobilize the public to participate in decision-making, and guarantee the right of production.

(3) Reindeer herding. Rain-on-snow① may result in a high mortality of the deer, and the thicketization of tundra pastures may reduce the quality of forages. The activity patterns of the herdsmen should be changed, and free herding policies should be prepared to ensure the land use right and strengthen food supply.

(4) Tourism. Open waters would be continuously formed under climate warming, bringing opportunities to the tourism, and allowing the public to seize the "last" opportunity of tourism. Polar tourism should be encouraged to increase the number of tourists and improve the quality of tourism services, and meanwhile, policies should be developed to ensure tourism safety, cultural integrity and ecological health.

(5) Non-renewable resource extraction in the Arctic. Amid the recession of sea ice and glaciers, there may be new opportunities for mining and development, but extreme hydrological events and permafrost degradation would bring certain impact on production and infrastructure. The following adaptive measures should be taken, such as carrying out climate change analysis and optimizing development methods.

(6) Infrastructure in settlements. The degradation of permafrost may affect the stability of foundation, and result in coastal erosion. New technologies should be developed to adapt to the thawing settlement of permafrost, and residential relocation should be carried out if necessary.

(7) Maritime transportation. Although the new waters can accommodate more ships and increase commercial benefits, the heavy traffic would result in negative effects on ecology and environment. The emergency response and control capabilities for hazardous waste, oil spills and safety accidents should be enhanced in addition to the increase in ships and promotion of tourism.

(8) Human health. Arctic system changes would affect food safety and physical and mental health of residents. The food safety research should be strengthened and human and financial resources should be invested to support public projects, and increase the public awareness in dealing with health problems.

The spillover effect of polar system changes would also affect the regions outside of the polar regions, even posing a global impact: The water retention function of the polar cryosphere (mainly ice caps and glaciers) would be weakened, increasing the global sea level; the carbon retention function of permafrost would be weakened, increasing the risk of warming due to the greenhouse effect; polar changes would make the polar atmospheric circulation turbulent and result in energy spillover, leading to frequent extreme weather and climate events in the affected areas. These large-scale effects can only be reduced and adapted through global actions of emission reduction and protection of climate.

3 Valuation and estimation of CSs

Valuation of CSs is an important means to measure all benefits obtained by human from the cryosphere, and an important constituent of cryosphere economics. Its accounting is related to the comprehensive description of the resource supply, circulation and consumption in the cryosphere. The valuation is also an important basis for improving decision-making. For example, an effective decision on the protection of the cryosphere and coordinated social and economic development requires the quantitative expression of CSs, so as to realize comprehensive balance of all demands and maximize the environmental and social benefits.

CSs can reflect the output value, which can be expressed as the sum of the value of benefits provided at specific time and space for human, namely the total economic value (TEV). Similar to ecological services, CSs can provide several types of benefits (Fig. 3). The TEV can be divided into use value (UV) and non-use value (NUV). UV refers to the value generated by the access to CSs for meeting consumption or production purposes; these services can be used

① Rain-on-snow refers to the precipitation falling on snow in high-latitude or high-elevation regions, and it is closely related to temperature, precipitation pattern, snow range and thickness. In a warmer climate, although the snow cover and thickness may decrease, the frequency of liquid precipitation would increase, thus increasing the frequency of rain-on-snow. Such events may have an important impact on regional climate systems, ecosystems, and human production and life.

directly or indirectly at present, or provide potential use value in the future. UV involves direct use value (DUV), indirect use value (IUV) and option value (OV). NUV refers to the value determined by people based on the awareness of a certain cryospheric resource (even if it will never be used), including patrimony value (PV) and existence value (EV).

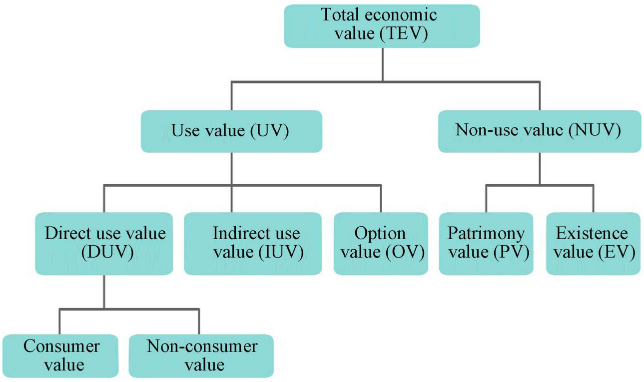

Fig. 3 Composition of value of CSs

The value evaluation of CSs is similar to that of ecosystem services. Considering the characteristics of CSs and referring to the valuation and evaluation methods of ecosystem services, the value system of CSs is demonstrated in Table 1 [3]. In the estimation, the uncertainty brought by subjective influence makes reasonable evaluation of the cryosphere value an urgent problem to be solved. Recent studies tend to separate the value of cryospheric resources and CSs, and the value of CSs is deemed to be realized through inputting the cryospheric resources into the socio-economic system. The value of freshwater resources in the cryosphere can be evaluated by the market price method (MPM), but the service valuation is reflected in the socio-economic benefits created by services. The value of CSs will also depend on resource supply and service demand.

4 Building social-ecosystem resilience in the cryosphere and its affected areas

4.1 Irreversible changes in the cryosphere amid global warming

Since the Industrial Revolution, human activities have brought a global impact on climate and ecosystems; the Earth system has got out of the regular Holocene glacial-interglacial cycle, and entered into a new era of the "Anthropocene." If more greenhouse gases are emitted in the future, the ecosystem will continue to degenerate, thus making a "hothouse earth" crossing the planetary boundary (Fig. 4).

As Earth has entered a new geological epoch "Anthropocene," many subsystems of the Earth system are tending to have an irreversible migration after reaching a certain threshold, and it is hard to return to the previous state, thus causing serious negative consequences. These subsystems are called irreversible elements, also known as tipping elements. At present, the tipping elements and tipping points are gradually emerging [13,14] (Fig. 4).

Since the cryosphere is highly sensitive to climate warming, most of the above-mentioned tipping elements are closely related to the cryosphere, including Arctic sea ice, Greenland ice sheet, Antarctic ice sheet, permafrost and alpine glacier. Compared with other elements, tipping elements of the cryosphere are easier to reach the tipping point, and even get reversed within the temperature rise goal of 1.5 °C–2.0 °C. IPCC issued the Special Report on Global Warming of 1.5 °C (SR15) in 2018, which discussed the risk

Table 1 Typical CS value evaluation method [3]

CSs		Valuation method			Evaluation difficulty
		DUV	IUV	NUV	
Provisioning services	Freshwater resource	MPM			Easier
Regulating services	Climate regulation		RCM, WTP, HPM		Hard
	Runoff regulation		SEM		Hard
	Water conservation and ecological regulation		SEM, RCM, MPM		Hard
Cultural services	Aesthetic view and recreation service			WTP, TCM	Harder
	Scientific research and environmental education			RCM, CAM	Harder
	Religious spirit and cultural structure			RCM, WTP	Harder
Supporting services	Habitat service	OCM, CVM			Harder
	Clean energy	RCM			Harder

MPM: market price method; RCM: replacement cost method; WTP: wish to pay; HPM: hedonic price method; SEM: shadow engineering method; TCM: travel cost method; CAM: cost analysis method; OCM: opportunity cost method; CVM: contingent valuation method.

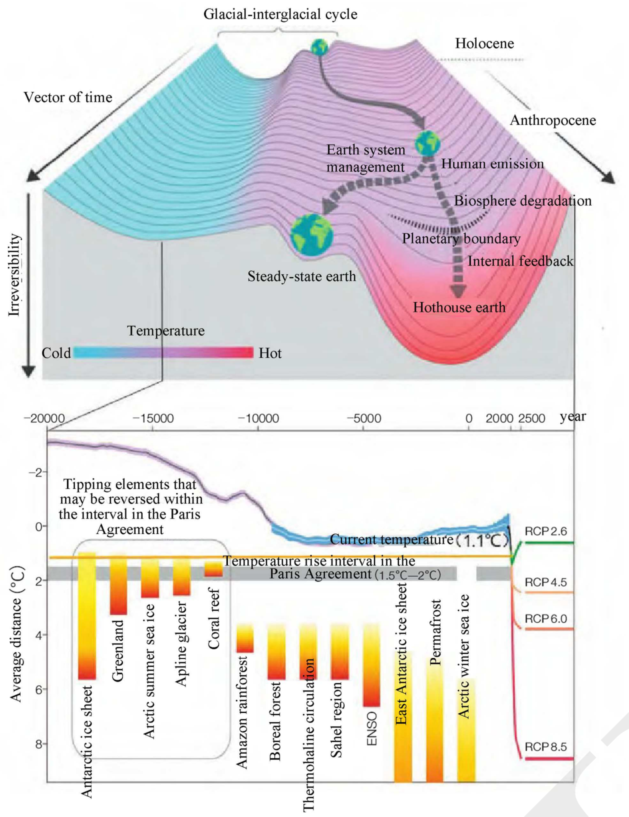

Fig. 4 Earth system evolution trajectory due to global warming and major tipping elements, as modified according to the literature [14,15]

The negative value of the abscissa indicates BC; RCP refers to representative concentration pathway.

of changes in 10 tipping elements under global temperature rise of 1.5 °C and 2 °C, including Arctic sea ice, tundra, permafrost, Asian monsoon, West African monsoon, Sahel, rainforest, boreal forest, heat waves and human health, key crop systems, and tropical and subtropical animal husbandry system, six of which are directly related to the cryosphere [15,16], and more have a cascade-correlation. If the tipping elements of the cryosphere are reversed, CFs and CSs will decline or even lose, and the potential irreversible changes in tipping elements of the cryosphere will be a huge threat to the socio-ecosystem and human well-being.

4.2 Socio-ecosystem resilient pathway of the cryosphere and its affected areas

In the context of global change, the rapid change of the cryosphere has brought wide and profound negative effects on the global socio-ecosystem, which are mainly reflected in the overall impact on the ice and snow tourism system, animal husbandry system in the cold region, oasis agriculture system in the arid area, disaster bearing area system in the cryosphere, major projects in cold areas, security of coasts and islands, and polar habitat system.

The strengthening of the socio-ecosystem resilience building in the cryosphere and its affected areas is an important way to deal with the challenges of the decline of CFs and CSs, and achieve regional sustainable development (2). The overall goal of the socio-ecosystem resilience building is to reduce the vulnerability, maintain and develop the ability of the system to respond to external stresses and maintain stability from the perspective of system science, thus providing a practical framework for policy formulation and management of environmental issues [17]. IPCC AR5 defined the “climate resilient pathway” as the development trajectory that combines adaptation and mitigation to realize the goal of sustainable development [18], which effectively connects resilience to sustainable dynamic trajectories, and emphasizes the roles of adaptation and mitigation in the building of climate resilience [17]. The socio-ecosystem resilience building in the cryosphere and its affected areas should also organically combine mitigation with adaptation, to jointly deal with the changes in the cryosphere and the impact of other external pressures on regional society and ecology①.

(1) Due to the climate dependence of the cryosphere, slowing down global warming is a fundamental way to maintain the healthy CFs, ensure continuous and stable supply of CSs, reduce the risk of disasters in the cryosphere, and enhance the resilience of the cryosphere and its affected areas. If the critical value of the cryosphere under global warming and the effective supply of CSs are taken into consideration, we should take a stricter action against greenhouse gas emission than the Paris Agreement.

(2) In the context of continuous global warming and irreversible changes in most cryospheric elements, adaptation will be the main method for responding to cryospheric changes and their effects, and improving the resilience of the cryosphere-affected areas. Most cryosphere-affected areas have fragile natural environment and low socio-economic status. The international and national powers should raise more funds to strengthen the adaptive capacity of the cryosphere and its affected areas, including the development of local economy and education, improvement of infrastructure, and migration relocation.

(3) The establishment of a steady system for socio-ecosystem monitoring, evaluation, early warning and decision-making in the cryosphere and its affected areas is fundamental and crucial to strengthening the building of resilience, and it is extremely urgent at present. The specific plan and process should include the followings: ① Regularly carry out evaluation on cryospheric changes (including current status and expected future changes) based on positioning observation, remote sensing and model simulation; ② determine the dynamics of exposure and vulnerability of the cryosphere and its affected areas through socio-economic statistics, field survey and participatory interview; ③ further

① Su B, Xiao C D. Research and practice on resilience of cryosphere-affected areas: progress and prospect. Advances in Climate Change Research, 2020 (external review).

evaluate and discover problems through combining cryospheric changes with regional socio-ecosystem dynamics, so as to provide clearer system evolution information, including accurate early warning; ④ explore the potential solutions to strengthen the resilience building through discussion between different stakeholders; ⑤ comprehensively evaluate the costs and consequences of different plans, so as to make more reasonable planning and decisions; ⑥ continuously monitor and evaluate the system dynamics, including the implementation of the solution, and adjust the original plan in the case of any better solution.

5 Conclusion

The development of human society is inseparable from the benefits obtained from nature. The cryosphere, as a part of the natural system, is closely related to the human society. The analysis of CFs and CSs is an important approach to understand the global and regional human society and its development, and the basis of reasonable response to the impact of climate changes and sustainable use of cryospheric resources. This paper tried to build a bridge between the natural and social and humanistic attributes of the cryosphere from the aspects of the establishment of basic concepts, development of the theoretical framework, and application, so as to clarify the socio-economic effects of the cryosphere, especially the impacts on social development in the context of climate change, thus awakening the sense of crisis. Of course, our understanding is still not comprehensive, which should be improved in the continuous deepening research in the future.

The more systematic study conducted in the future should also include the following six aspects: ① the service function of the cryosphere in the human society; ② the relationship between CFs, CSs and human welfare; ③ cryosphere asset evaluation and valuation, as well as cryosphere economics; ④ zoning of CFs and CSs, the balance and synergy of various CSs; ⑤ resilience building and sustainable development in the cryosphere-affected areas; ⑥ the cryospheric geopolitics. The deepening research of the cryospheric human-sociology will serve sustainable development better and benefit all mankind.

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