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LUO Yong
Department of Earth System Science, Tsinghua University, Beijing 100084, China

See next page for additional authors

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Abstract

Since the 1980s, the establishment and development of modern climate system theory have promoted the cross integration of cryospheric science and climatology, thus giving birth to a new branch of cryospheric science-cryospheric climatology. The formation and evolution of cryosphere are closely related to the earth's climate. Now it is generally recognized that cryosphere is not only the product of climate under certain conditions, but also its changes affect the weather and climate, and affect the social economy and sustainable development of human beings. Cryospheric climatology is a science that studies the interaction between cryosphere and atmosphere and its physical mechanism. Starting from the introduction of the development history of cryospheric climatology, this paper systematically explains its basic concepts and subject characteristics. Cryospheric climatology focuses on the role of cryosphere in the formation and anomaly of weather, climate, and general atmospheric circulations, the process and mechanism of interaction between cryosphere and atmosphere, the development of climate system model and cryosphere models, the projection of change in climate and cryosphere, and the service function of cryospheric climatology to social economy. We will continue to deepen the understanding of interaction process and mechanism between the cryosphere and the atmosphere, and promote the development of parameterization schemes for the processes of terrestrial cryosphere, marine cryosphere, and atmospheric cryosphere towards refinement, quantification, and complexity. In particular, we will focus on considering the spatial-temporal scales of nonlinear effects among different components and elements of the cryosphere. The development of global and regional climate system model coupled with cryosphere processes is the future trend of cryospheric climatology.

Keywords

cryospheric climatology; climatology; cryospheric science; interdisciplinary; climate system; climate change

Authors

LUO Yong, QIN Dahe, ZHAI Panmao, MA Lijuan, ZHOU Botao, and XU Xinwu

Corresponding Author(s)

QIN Dahe [2,3*]

2 State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China

3 China Meteorological Administration, Beijing 100081, China

QIN Dahe Academician of Chinese Academy of Sciences (CAS) and the World Academy of Sciences for the advancement of science in developing countries (TWAS).He has long been engaged in the research on Cryosphere Science and sustainable development.He is now the Chief Scientist of the Key Project "Study on the Formation Process and Comprehensive Regionalization of China's Cryosphere Service Function" (41690140) sponsored by National Natural Science Foundation of China, and the PI of Innovation Research Group "Cryosphere and Global Change" (41421061) also sponsored by National Natural Science Foundation of China.E-mail:qdh@cma.gov.cn

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Cryospheric Climatology: Emerging Branch of Cryospheric Science

LUO Yong[1], QIN Dahe[2,3], ZHAI Panmao[4], MA Lijuan[5], ZHOU Botao[6], XU Xinwu[3,7]

1. Department of Earth System Science, Tsinghua University, Beijing 100084, China;
2. State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China;
3. China Meteorological Administration, Beijing 100081, China;
4. Chinese Academy of Meteorological Sciences, Beijing 100081, China;
5. National Climate Center, China Meteorological Administration, Beijing 100081, China;
6. School of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China;
7. College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: Since the 1980s, the establishment and development of modern climate system theory have promoted the cross integration of cryospheric science and climatology, thus giving birth to a new branch of cryospheric science—cryospheric climatology. The formation and evolution of cryosphere are closely related to the earth's climate. Now it is generally recognized that not only cryosphere is the product of climate under certain conditions, but also its changes affect the weather and climate, and further the social economy and sustainable development of human beings. Cryospheric climatology is a science that studies the interaction between cryosphere and atmosphere and its physical mechanism. Starting from the introduction of the development history of cryospheric climatology, this paper systematically explains its basic concepts and subject characteristics. Cryospheric climatology focuses on the role of cryosphere in the formation and anomaly of weather, climate, and general atmospheric circulations, the process and mechanism of interaction between cryosphere and atmosphere, the development of climate system model and cryosphere models, the projection of changes in climate and cryosphere, and the service function of cryospheric climatology to social economy. We will continue to deepen the understanding of interaction process and mechanism between the cryosphere and the atmosphere, and promote the development of parameterization schemes for the processes of terrestrial cryosphere, marine cryosphere, and atmospheric cryosphere towards refinement, quantification, and complexity. In particular, we will focus on considering the spatial-temporal scales of nonlinear effects among different components and elements of the cryosphere. The development of global and regional climate system model coupled with cryosphere processes is the future trend of cryospheric climatology.
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With the proposal and development of climate system theory since the 1980s, the scientific circle has broken the boundary between traditional cryospheric science and other related disciplines, and revealed the exchange mechanism of energy, mass (such as water), and momentum between the cryosphere and the atmosphere. Cryosphere, as a product of climate, is very sensitive to temperature and precipitation. The climate conditions determine the life span and elements of cryosphere. The differences of climate conditions and topography make the development, distribution, and change of cryospheric elements vary greatly. Cryosphere has the fastest and most significant impact on global climate change, and it is highly sensitive to climate change. Using a uniform underlying surface to explain the terrestrial cryosphere and marine cryosphere that occupy a large part of the earth surface ignores the change characteristics and internal differences of cryospheric elements, which will limit the development of research on climate system and climate change [1].

Nowadays, it has been realized that the research on the processes of the earth system should not be limited to single independent disciplines, such as cryospheric science, atmospheric science, hydrology and ecology. A complete scientific research system can only be formed by the integration of physics, chemistry, biology, and economic and social influences. The cross integration of cryospheric science and climatology gives birth to a new branch of cryospheric science—cryospheric climatology [2].

1 Definition and development of cryospheric climatology

Cryospheric climatology is a science that studies the interaction, influence, and feedback between cryosphere and atmosphere, and serves for the sustainable development of society and economy. It is an interdisciplinary science com-

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posed of cryospheric science and climatology and involves many other disciplines. The interaction between the cryosphere and the atmosphere and its physical mechanism are the key focuses of cryospheric climatology.

Prior to the 1980s, climatology and cryospheric science developed independently, whereas people have already noticed the extensive and profound relationship between them. As early as in 1939, the Soviet geographer Kalesnik pointed out that glaciers are the products of climate under certain conditions. With the in-depth study and understanding of the complexity of the response, scientists have gradually found that each element of cryosphere should be regarded as a nature climate-meter. That is, the elements of cryosphere are very sensitive to the changes of climate variables, such as temperature and precipitation. The German climatologist and botanist Wladimir Köppen categorized six major climate types, among which highland, polar and microthermal climate types are related to cryosphere [2].

Cryospheric climatology originated from the establishment of the concept of climate system in the 1980s. Modern climatology introduces the concept of climate system, which considers that climate is one of the main factors determining the formation and development of cryosphere, and climate change affects the evolution of cryosphere. Cryosphere can regulate climate, and the change of cryosphere influences the energy balance and radiation balance of the atmosphere, as well as the key process and feedback of atmospheric circulation. Climate change is not controlled only by the various processes within the atmosphere, instead, it is controlled by both climate system (involving atmosphere, hydrosphere, cryosphere, biosphere, and the surface layer of lithosphere) and human social and economic activities (anthroposphere). Contemporary climate change refers to climate system change. The change of any one of the five spheres is regarded as climate change.

The theoretical basis of cryospheric climatology is classical physics which mainly involves dynamics and thermodynamics. At present, cryospheric climatology has developed rapidly from single-point observation experiment, process description, and statistical analysis to mechanism analysis and mathmetical simulation of climate system. It focuses on the physical process and feedback mechanism of interaction between the atmosphere and the cryosphere, quantitative evaluation of the role of cryosphere in global and regional climate change, and the prediction of the future climate and cryosphere change.

2 Research content of cryospheric climatology

2.1 The role of climate in the formation and evolution of cryosphere

Cryospheric elements are formed and evolve under suitable temperature, precipitation, and terrain conditions. From the perspective of cryospheric climatology, cryosphere is a continuous sphere with a certain thickness, which is an irregular hollow ellipsoid. Due to the effects of altitude and latitude, the lower boundary of cryosphere is located in the area with the highest altitude near the equator, such as the Kilimanjaro Glacier, with an altitude of 5 963 m. The height of the lower boundary of the cryosphere gradually decreases with the increase in latitude from the equator to the south and the north respectively, and drops to sea level or even below in high-latitude area, such as the permafrost developed in the Arctic Ocean seabed.

The survival time of different cryospheric elements varies. The area and scope of cryosphere present obvious diurnal, seasonal, interannual, and interdecadal changes. (1) Terrestrial cryosphere. The Antarctic and Greenland ice sheets have the time scales ranging from hundreds of thousands to millions of years. The ice of mountain glaciers melts and flows from the accumulation area to the glacier terminus, and its time scale varies from several decades to thousands of years due to the differences in glacier scale, nature, terrain, and climate conditions. The snow cover melts and runs away over time, forming spring floods in some mountainous areas. As the season changes (from winter to summer), the river ice and lake ice disappear. (2) Marine cryosphere. The sea ice changes with seasons, which forms in early winter and disintegrates and melts in early summer. In general, it exists for less than 12 months, while the ice in the Arctic Ocean can last for several years. The survival time of ice shelves varies from decades to thousands of years. The life span of icebergs varies from several months to hundreds of years, which is closely associated with atmospheric circulation, sea temperature, ocean current, as well as the size, location, and formation time of icebergs. (3) Atmospheric cryosphere. The survival time of frozen water body is on the scale of days or even hours, which is closely related to the specific climate conditions.

2.2 The role of cryosphere in the formation and variation of climate and atmospheric circulation

Cryosphere plays a role in the formation and variation of climate and atmospheric circulation. It affects climate not only on the global, regional, and local scales but also on the seasonal, annual, multi-year, and long-term scales.

Cryosphere, especially the snow cover on the Tibetan Plateau and the Arctic sea ice, profoundly influences the formation and anomaly of Asian monsoon. With the hydrologic and albedo effects of snow cover, the snow cover anomalies on the Tibetan Plateau and Eurasia in winter and spring can affect the interannual variation of precipitation in China in summer. On the interdecadal scale, the snow cover on the Tibetan Plateau in winter and spring has shown an increasing trend in the past five decades, resulting in the decrease of tropospheric temperature over the Plateau and the negative phase of the Asia-Pacific oscillation. As a result, the location of the Western Pacific subtropical high is southward.

Therefore, the rain belt in eastern China mainly stagnates in the south, resulting in southern flood and northern drought in the eastern region.

The Arctic is the source of cold air in winter. The Arctic sea ice blocks the heat exchange between air and sea, which regulates the cold air activities in the Arctic and Eurasia at high latitudes through the albedo feedback mechanism, thus affecting the cold wave and winter monsoon in East Asia.

2.3 The process and mechanism of interaction between the cryosphere and the atmosphere

The cryosphere and the atmosphere mainly interact with each other via the cryosphere-albedo feedback, energy balance, and water phase transition.

The cryosphere-albedo feedback is especially important and positive in high-latitude areas (Figure 1). In this process, the increase of near surface temperature will lead to the area reduction of snow or sea ice with high albedo, exposing the ground or unfrozen ocean with low albedo. As a result, more solar radiation can be absorbed by the ground and the ocean, leading to the melting of snow or sea ice. The cryosphere-albedo feedback mechanism can also work in reverse to amplify regional cooling.

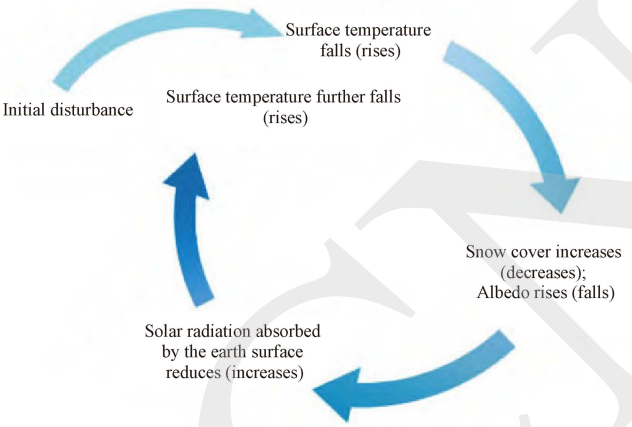

Figure 1 Scheme of cryosphere-albedo feedback

In terms of energy balance, the polar regions are the sink of atmospheric heat engine, and the heat flux is transported to the polar regions through the ocean and atmosphere throughout the year. Winter is characterized by the largest atmospheric heat transfer to the polar regions, large net radiation loss at high latitudes, and the largest temperature difference between the polar and tropical regions. In summer with the great decrease in temperature difference between the equator and the polar regions, the heat flux to the polar regions is small. Compared with those in the Northern Hemisphere, the mean ocean current and atmospheric circulation in the Southern Hemisphere show significant zonal distribution. The temperature difference from the equator to the pole in the Southern Hemisphere is 40% greater than that in the Northern Hemisphere, thus forming stronger mid-latitude westerly belt.

Water phase in the cryosphere also markedly impacts the atmosphere. The melting heat of glacier and the vaporization heat of water are respectively 80 times and 539 times of the heat required for the same volume of liquid water to rise by 1 °C. Therefore, the cryosphere plays a decisive role in the heat balance on the earth surface. Temperature inversion often occurs on the surface of ice and snow, and the vertical gradient of water vapor pressure on the surface of ice and snow is often lower than that in the low air layer. Therefore, the air will transfer heat and moisture to the surface of ice and snow (water vapor condenses on the surface of ice and snow). On windless days in spring, the temperature in the melting area is often dozens of degrees Celsius lower than that in the surrounding areas free of ice and snow.

2.4 Development of climate system model and cryosphere model

Climate system model is a mathematical-physical model established on the basis of the rules of dynamic, physical, chemical, and biological processes, which can quantitatively depict the state of each component of the climate system. It is solved by numerical method, and simulates and predicts the nonlinear complex behaviors and processes of climate system by high performance computing. The computer program of climate system model and its high performance computing are complex system engineering.

Climate system model is an efficient tool to reveal the climate change and its causes in the past, as well as the process and mechanism of the interaction between and within spheres in the climate system. In addition, it helps to predict the future climate change. Cryosphere model has become an important part of the current climate system model, which facilitates the study on the cryospheric process and the interaction between the cryosphere and the atmosphere.

Cryosphere model is a general term for the models of cryospheric components. Cryospheric components have corresponding models, such as glacier (ice sheet) model, frozen soil model, snow model, and sea ice model. Considering the physical properties of pure ice and non-pure ice material containing impurities, mathematical-physical equation can be used to simulate the macro changes of the cryosphere and predict the future changes of the cryosphere in different scenarios when the external physical conditions change. Sea ice model, as an independent element model, has been coupled with atmospheric model, ocean model, and land surface model. Snow model, frozen soil model, and river and lake ice model are generally important parts of land surface model. The dynamic models of glacier and ice sheet are still in development and have not been coupled with climate system model. The biogeochemical cycling model of cryosphere is now in development.

2.5 Prediction of climate change and cryosphere change

The prediction of climate change refers to the simulation of the responses of climate system to future emission or concentration scenarios of greenhouse gases and aerosols [3]. Two methods are available to predict the changes of elements in the cryosphere. (1) Global climate system model coupled with cryosphere model can directly predict the changes of cryospheric elements. (2) Global climate system model is used to predict the climate change first, and then the changes of cryospheric elements are predicted by cryosphere model in the climate change scenario.

The direct prediction method mainly relies on the Coupled Model Intercomparison Project (CMIP) for multi-mode integrated prediction. CMIP is a set of comparative plans for coupling climate system model, which aims to evaluate the model performance by comparing the simulation capability and provide a scientific basis for predicting the future changes [4]. Coupled Model Intercomparison Project Phase 6 (CMIP6) is currently in progress and will forecast the scenarios of future climate change and cryosphere change for the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [5].

The construction of future greenhouse gas emission scenarios and global socioeconomic scenario should involve population and socioeconomic development, especially changes in energy production and use, technological progress, land use and coverage, changes in environment and natural resources, policy and institutional management, and changes in living mode. The ongoing IPCC AR6 mainly adopts the combination of Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSPs) [6].

2.6 Service functions of cryospheric climatology to economy and society

The scientific basis and technical support provided by cryospheric climatology are indispensable for the management of cryosphere service functions in human society. Cryosphere can provide various products or benefits for human society in its action area and influence area. The survival and development of human beings in polar regions, high mountains and their adjacent areas are highly dependent on the climate regulation, runoff regulation, water source conservation, and ecological regulation of the cryosphere. As a special underlying surface, the cryosphere, with its high albedo and water cycle, makes the earth a planet with a livable climate and stable ecosystem structure for human beings.

Cryosphere is a vital supply source for rivers in the middle- and low-latitude mountainous areas and can naturally regulate river runoff, which is called “solid reservoir.” It has good performance of water source conservation. Especially because of the impermeability of frozen soil and water migration under temperature gradient, there is much underground ice near the upper limit of permafrost. Frozen soil plays an important role in maintaining ecosystem stability in cold regions. Without the water source conservation function and moisture and thermal effect of frozen soil, only desert, rather than the actual vast alpine meadow and alpine wetland, can be developed on the Tibetan Plateau. In the pan-Arctic region, typical polygonal tundra ecosystem and taiga ecosystem are developed, which are attributed to the huge moisture and thermal effect of permafrost.

Cryospheric climatology can provide scientific support for the forecast, prediction, and early warning of meteorological disasters. Meteorological disasters related to low temperature are one of the key fields of cryospheric climatology. For example, the freezing rain and snow disaster, caused by rain and snow weather on cold days, is often accompanied by low temperature, high humidity, and low wind speed. The composite ice accretion composed of glaze and silver thaw is formed on the surface of various carriers, which greatly increases the load of carriers and seriously affects or even destroys lifeline projects such as traffic, communication, and electric transmission lines. In the northern mountainous area of Xinjiang where there is abundant snowfall in winter, the warming of cryosphere has led to the spring flood in the mountainous area one month ahead of schedule in recent 30 years, as well as frequent snowmelt floods. Every year, dozens or even hundreds of people die of avalanches worldwide. The ice flood of rivers in spring is a threat to life and property.

3 Development trend of cryospheric climatology

With the progress of observation means, enriching observation data, and rapid improvement of computing conditions, earth observation, remote sensing, big data, artificial intelligence, and numerical model have developed rapidly. It is expected that cryospheric climatology will develop towards high cross, high resolution, and refinement. Particularly, the global and regional climate system model for coupling cryosphere process will be the general trend of the study on cryospheric climatology and global climate change.

At present, the global and regional climate system model is still rough in dealing with the physical process of cryosphere. Especially, the spatial-temporal scales of different components and elements of cryosphere in the climate system model may be a hot topic for a long period in the future. The development of regional climate simulation system and hydrological model with the land surface process model of cryosphere is a key to understand the water-heat process and environmental effect of the cryosphere.

The key to break through the limitation of parameterization in physical process of cryosphere is to deepen the quantitative research on the process and mechanism of cryosphere change. In order to improve the performance of simulation for the cryosphere process and the global and regional climate model, we must combine the analysis of massive observation results with the parameterization improvement.

Meanwhile, we should consider the energy, water volume, and material changes of cryospheric elements, and solve the constraints of different spatial-temporal scales of the non-linear physical process on coupling climate system model, so as to achieve substantial progress.

In conclusion, the understanding on the interaction process and mechanism of the cryosphere and the atmosphere should be deepened. Furthermore, it is necessary to strengthen the research on the process model and coupling test of terrestrial cryosphere and marine cryosphere, and foster the development of parameterization schemes for cryosphere process towards refinement, quantification, and complexity.

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LUO Yong, Deputy Director and Professor, Department of Earth System Science, Tsinghua University. He is mainly engaged in the research on climate change, water cycle, and meteorology for renewable energy. He is the CLA of Chapter 10 Asia of IPCC WGII AR6 and the PI of National Key Research and Development Program of China Project on Global Climate-Land Surface-Hydrological Process Interaction, Extreme Hydrological Event Risk and China's Adaptation Strategy. E-mail: yongluo@tsinghua.edu.cn

QIN Dahe, corresponding author, Academician of Chinese Academy of Sciences (CAS) and the World Academy of Sciences for the advancement of science in developing countries (TWAS). He has long been engaged in the research on Cryosphere Science and sustainable development. He is now the Chief Scientist of the Key Project "Study on the Formation Process and Comprehensive Regionalization of China's Cryosphere Service Function" (41690140) sponsored by National Natural Science Foundation of China, and the PI of Innovation Research Group "Cryosphere and Global Change" (41421061) also sponsored by National Natural Science Foundation of China. E-mail: qdh@cma.gov.cn