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Developing Cryospheric Remote Sensing, Promoting Scientific Programme of Earth's Three Poles

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Abstract

Remote sensing of cryosphere, as an important branch of cryospheric science, is a new interdiscipline, involving the knowledge of both cryospheric science and remote sensing techniques. This paper overviews the objects and basic methods of cryospheric remote sensing, introduces the progresses by using representative case studies, and especially, describes the research status of Chinese cryospheric remote sensing. Finally, we propose several recommendations for the development of remote sensing of cryosphere. In particular, we discuss the potential paths to the scientific programme of Earth's three poles.

Keywords

cryosphere; remote sensing; Earth's three poles; scientific programme

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Developing Cryospheric Remote Sensing, Promoting Scientific Programme of Earth's Three Poles

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Abstract: Cryospheric remote sensing, as an important branch of cryospheric science, is a new interdiscipline, involving the knowledge of both cryospheric science and remote sensing techniques. This paper overviews the objects and basic methods of cryospheric remote sensing, introduces the progress by using representative case studies, and especially, describes the research status of Chinese cryospheric remote sensing. Finally, we propose several recommendations for the development of cryospheric remote sensing. In particular, we discuss the potential paths to the scientific programme of Earth's three poles. **DOI:** 10.16418/j.issn.1000-3045.20200323001-en

Keywords: cryosphere; remote sensing; Earth's three poles; scientific programme

The cryosphere, as one of the five major layers of the Earth's climate system, is composed of glaciers (including ice sheets), frozen soil, snow cover, river ice, lake ice, sea ice, ice shelves, and icebergs, as well as ice crystals, supercooled water clouds, snowfall, hail, and graupel in the atmosphere. The cryospheric changes are closely related to the changes in climate, water cycle, and ecosystems. It directly affects the changes in global climate, sea level, lakes, and rivers and also affects the ecological environment and sustainable economic and social development. Therefore, cryospheric science plays a special role in geoscience and human science [1].

The cryospheric science mainly studies the followings: the formation, development, and evolution of the elements of the cryosphere under natural background conditions and processes of interaction between various elements; the interplay and mutual transformation of the various elements and the entire cryosphere with other layers of the climate system; the relation between the cryosphere and sustainable economic and social development, especially the adaptation to, mitigation of and countermeasures against global and regional cryosphere changes [2].

The elements of the cryosphere are mainly distributed in high-latitude and high-altitude areas, making it hard to perform ground observation and deploy a high-density observation network. Therefore, remote sensing observation has become an indispensable method for cryospheric research. Cryospheric remote sensing refers to the technology for obtaining the geometric, material, and energy characteristics of elements of the cryosphere through noncontact observation. At present, cryospheric remote sensing methods cover visible light/near-infrared, thermal infrared, microwave, laser, radio, and gravity measurement remote sensing methods. The remote sensing platform is dominated by satellites, and aerial remote sensing and ground-based remote sensing are also important experimental means of cryospheric remote sensing. The unmanned aerial vehicle (UAV) remote sensing emerging in recent years has enriched the means of cryospheric remote sensing.

Cryospheric remote sensing, as an important branch of cryospheric science, learns from and promotes other branches of the cryospheric science system (such as cryospheric hydrology and cryospheric climatology), but also establishes its own system [3,4]. This paper introduced the basic research contents and methods of cryospheric remote sensing, further reviewed the relevant research progress of cryospheric remote sensing in China and other countries, analyzed the advantages and disadvantages of cryospheric remote sensing in China, and finally discussed the ways of cryospheric remote sensing to promote scientific programme of "Earth's three poles."

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1 Overview of cryospheric remote sensing

Cryospheric remote sensing is developed on the basis of the basic principles of remote sensing science, and its objects are cryospheric elements with special electromagnetic characteristics. For example, snow cover has high reflectivity at the visible light band and low reflectivity at the near-infrared band, which can make it easier to distinguish snow cover from other surface features by multi-spectral remote sensing; the dielectric constant of liquid water at the microwave band is about 80, which declines to 3 after it is frozen to ice crystals, providing scientific criteria for determining whether the soil or water surface is frozen via microwave remote sensing, which can be used in the research on the freezing and thawing of sea ice and the earth's surface. Therefore, compared with remote sensing of vegetation and land use, cryospheric remote sensing has its own special research methods.

From the perspective of objects, cryospheric remote sensing can be roughly divided into terrestrial cryospheric remote sensing, ocean cryospheric remote sensing, and atmospheric cryospheric remote sensing. Terrestrial cryosphere mainly includes snow cover, glaciers (including ice sheets), frozen soil, river ice, and lake ice, and it has the most abundant research contents and methods; ocean cryosphere mainly involves sea ice, ice shelves, and icebergs; atmospheric cryosphere mainly involves ice crystals, supercooled water clouds, snowfall, hail, and graupel in the atmosphere. Table 1 lists most of the contents of cryospheric remote sensing and the corresponding remote sensing techniques. It can be seen that visible light/near-infrared methods and synthetic aperture radar (SAR) can monitor the most parameters, and the same parameter can be monitored by different remote sensing methods. However, different methods have different advantages. Taking the remote sensing inversion of snow depth as an example, SAR and microwave radiometer are both able to invert the snow depth. Although the microwave radiometer has a low spatial resolution, the daily change of snow cover can be obtained. Therefore, the corresponding technical means should be selected according to the research objectives. Additionally, since each remote sensing method has its own advantages and disadvantages, multi-source remote sensing data are often combined for monitoring. Taking the area of snow cover as an example, visible light remote sensing can accurately get the area of snow cover, but a lot of surface data would be lost as affected by the clouds, so microwave remote sensing with penetrability can be used to supplement data of snow cover under the clouds.

2 Research progress of cryospheric remote sensing

2.1 Research progress of cryospheric remote sensing techniques

Cryospheric remote sensing was initiated in 1961, but it began to rapidly develop till 1990 with the bloom of the earth observation techniques. Especially since the 21st century with the emergence of new and advanced sensors as well as the successful launch and operation of satellites special for cryospheric research, such as ICESAT (National Aeronautics and Space Administration of the US, NASA) and CryoSat (European Space Agency, ESA), cryospheric remote sensing has made great progress. The satellite observation programs available for cryospheric remote sensing are summarized in Figure 1.

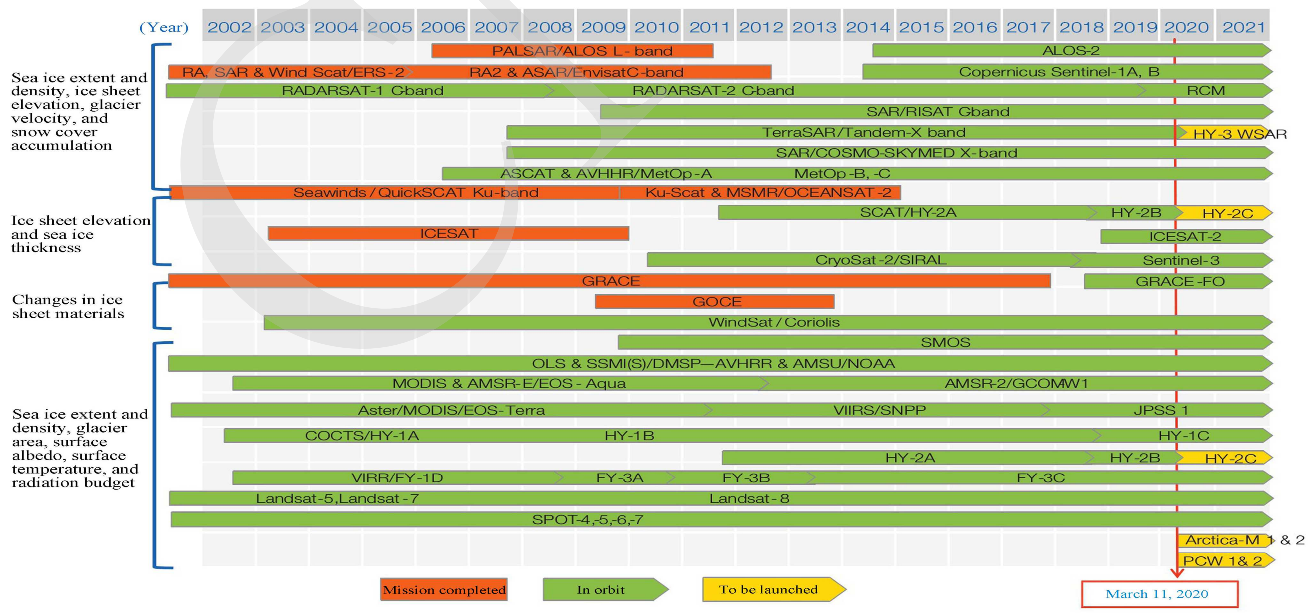

Figure 1 Satellite programs related to cryosphere in the past 20 years

Revised and updated according to the Global Cryosphere Watch (GCW) (https://globalcryospherewatch.org/satellites/overview.html).

Table 1 Cryospheric remote sensing contents and corresponding available remote sensing techniques

		Content	Visible light/ near-infrared	Thermal infrared	Microwave radiometer	Microwave scatterometer	SAR	Coherent interferometric radar	Laser radar	Radar altimeter	Radio wave
Terrestrial cryospheric remote sensing	Remote sensing of snow cover	Area of snow cover	√		√		√				
		Albedo of snow cover	√								
		Particle size of snow cover	√								
		Snow surface temperature		√							
		Snow depth and snow water equivalent			√		√	√	√		
		Density of snow cover					√				
		Humidity of snow cover				√	√				
	Remote sensing of glacier and ice sheet	Glacier area	√				√				
		Glacial terrain						√	√	√	
		Glacier thickness									√
		Subglacial terrain									√
		Snow line	√				√				
		End of glacier tongue	√				√				
		Ice sheet front	√				√				
		Surface temperature		√							
		Supraglacial lake and grey ice cave	√				√				
		Crevasse	√				√		√		
		Glacier surface moraine	√				√				
	Remoting sensing of frozen soil	Remoting sensing of frozen soil			√	√	√				
		Surface freezing and thawing state	√	√			√	√			
		Frozen soil deformation						√			
		Periglacial landform mapping	√	√			√	√			
		Active layer									√
	Remote sensing of river ice and lake ice	Density and area	√			√	√				√
		Lake ice thickness			√		√		√		√
		Lake ice phenology	√		√	√	√				
		Ice surface temperature		√							
		Ice jam, ice flood, and lake outburst	√				√				
Ocean cryospheric remote sensing	Remote sensing of sea ice	Sea ice extent and type	√		√	√	√				
		Sea ice density	√		√	√	√			√	
		Sea ice thickness	√		√		√		√	√	
		River between ice	√		√		√			√	
		Ice surface temperature	√	√							
		Sea ice phenology	√	√	√	√	√				
		Albedo	√								
	Remote sensing of ice shelf	Grounding line	√					√			√
		Iceberg calving rate	√				√				
		Iceberg identification and tracking	√			√	√				
Atmospheric cryospheric remote sensing		Ice crystals	√								
		Supercooled clouds	√				√				
		Snowfall			√		√				
		Hail and graupel	√								

√ indicates that the technique has been applied in the corresponding research field.

The remote sensing techniques used for cryospheric observation mainly include the followings: ① Visible light/infrared remote sensing. At present, it is developing toward the observation capabilities of long time sequence, hyperspectrum, high spatial and temporal resolutions, large width, and three-dimensional information acquisition. ② Microwave remote sensing. SAR, as the core sensor of active microwave remote sensing, has developed rapidly. Satellites using this technique and subsequent radar satellites programs mostly have the capabilities of two-station/or constellation coordinated observation, polarization interferometry, 3D/4D information acquisition, high-resolution wide-range data acquisition, or ultra-high resolution observation, and can realize high-precision, large-scale, and time-continuous monitoring and evaluation with respect to the surface dynamic process of the cryosphere. ③ Laser, gravity, and other new remote sensing techniques. Laser radar satellites have developed from single-point observation to point cloud observation. The existing gravity satellites have made innovative progress in large-scale material balance. In the future, such techniques will make breakthroughs in improving spatial resolution, and other new techniques (such as low-light-level remote sensing) will also be used for the extraction of cryospheric elements.

2.2 Research progress of applications of cryospheric remote sensing

The greatest advantage of remote sensing is to obtain wide-range information of cryospheric elements, and the most notable achievement is that it can evaluate the global glacier material balance and its contribution to sea-level rise with multi-source remote sensing data [5]. The cryospheric remote sensing applied in the Antarctic, Arctic, and mountainous regions has different scientific problems and technical means. The research on cryospheric remote sensing in mountainous regions mainly involves mapping for glaciers, snow cover, and frozen soil and monitoring of changes, as well as the effects of the changes in these cryospheric elements on regional ecological environment and water resources [6,7]. In addition to the assessment of the material balance of the Antarctic ice sheet, the application research on the cryospheric remote sensing in the Antarctic mainly focuses on remote sensing monitoring of the ice shelf calving, grounding line, and sea ice. The mapping of the Antarctic is also an important scientific task. The long-term sea ice products obtained on the basis of the remote sensing data of passive microwave brightness temperature showed that the sea ice in the Antarctic, being different from the Arctic where sea ice was reduced rapidly, has not changed much in the past few decades, and even increased slightly [8].

In the Arctic, main scientific issues include the rapid melting of Greenland ice sheet, the rapid reduction of Arctic sea ice, and the impact of cryosphere shrinkage on the Arctic passage. Besides, attention has also been paid to the Arctic climate amplification effect, changes in snow cover in the Pan-Arctic region, and ecological and engineering effects of permafrost degradation. Many satellite-borne, airborne, and ground-based remote sensing observations have been carried out in the Arctic, which have increased the understanding of changes in the Arctic. At the same time, many international programs of Arctic observation have been initiated, including Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAiC), GCW, and Integrated Arctic Observation System (INTAROS). The Greenland ice sheet and the Antarctic ice sheet are negative in material balance, but there are certain differences in the melting mechanism. The active and passive microwave remote sensing data show that the surface melting of Greenland ice sheet is increasing year by year, which further reduces the albedo of the ice sheets to absorb more heat, thus accelerating the melting. As for the Antarctic ice sheet, it mainly melts on the edge, and its material loss is mainly reflected by ice-shelf calving. Actually, the increase in melting on the surface of the Antarctic ice sheet has also been observed in recent years. There is no doubt that the most noteworthy issue is the rapid decline in Arctic sea ice. Remote sensing techniques can not only monitor the reduction of sea ice but also identify the changes in sea ice types, and the size and number of melting ponds on the sea ice surface are becoming the key factors of the melting of sea ice [9].

To sum up, for regional cryospheric remote sensing, the Arctic region is currently considered the most crucial and hot spot region with the most projects and achievements. The cryospheric remote sensing in the Antarctic region is mainly carried out according to national strength and free exploration of scientists. In the mountainous regions, cryospheric remote sensing is generally independently carried out by different regions.

3 Progress of cryospheric remote sensing in China

3.1 Characteristics of cryospheric remote sensing in China

The research of cryospheric remote sensing in China is mainly carried out in the Qinghai-Tibet Plateau with great progress and rich achievements. The most representative work is reflected in glacier, snow cover, and frozen soil [10]. Figure 2 shows the latest results of the second Chinese glacier inventory, permafrost mapping and inversion of snow cover on the Qinghai-Tibet Plateau.

(1) Glacier remote sensing. The continuous maturity of glacier remote sensing has made important contributions to the completion of the first [11] and the second Chinese glacier inventories [12,13], involving the aerial remote sensing interpretation, massive application of land satellite data, development of automatic glacier classification methods, and

automatic extraction of glacier attributes. In recent years, Chinese scholars have made great achievements in extracting glacier material balance and glacier velocity on glacier surface [14,15].

(2) Remote sensing of snow cover. Chinese scholars have developed long-term remote sensing products of snow cover area, snow depth, and snow water equivalent, which have been widely used [16]. In particular, the passive microwave brightness temperature based on the Fengyun meteorological satellite has promoted the development of the snow depth inversion algorithm in China [17]. In addition, Chinese scholars have also made special research contributions to the cloud removal by products for optical remote sensing of snow cover area [18]. The spatial and temporal changes in snow cover area and snow depth in the Qinghai-Tibet Plateau in the past 40 years are preliminarily explained [19]. Due to the influence from the factors such as the complex terrain of the Qinghai-Tibet Plateau, the spatial resolution of the remote sensing products for determining snow depth should be further improved, so as to meet the needs of research on hydrology and water resources.

(3) Remote sensing of frozen soil and periglacial environment. The comprehensive observation integrating multi-source remote sensing data has become an important method for frozen soil mapping. At present, Chinese scholars have obtained the distribution of thermally stable frozen soil of the Qinghai-Tibet Plateau and its long-sequence changes [20]. The Chinese active microwave remote sensing technique has also made rapid progress in surface deformation and active layer thickness inversion, especially in the aspect of interferometric SAR (InSAR) [7]. Typically, with the passive microwave brightness temperature, the decision tree algorithm was developed for the surface freezing-thawing state and the data of long-term surface freezing-thawing cycle process were prepared [21].

3.2 Arctic cryospheric remote sensing in China

In recent years, Arctic cryospheric remote sensing has been gradually conducted in China, and it currently focuses on Arctic sea ice monitoring and navigation capability research. The remote sensing research on Arctic sea ice mainly involves the inversion of the parameters such as extent, type, and density of sea ice and the relationship between sea ice and global climate change. Good progress has been made in studying the seasonal and inter-annual changes in sea ice of passage with remote sensing satellite data, analyzing the impact factors of navigation, and evaluating the navigation capability [22].

As mentioned above, in addition to sea ice remote sensing in the Arctic region, the Greenland ice sheet, river ice, lake ice, and snow cover are also involved. Chinese scholars have carried out several related research [23] mainly focusing on the analysis of remote sensing data and application of products.

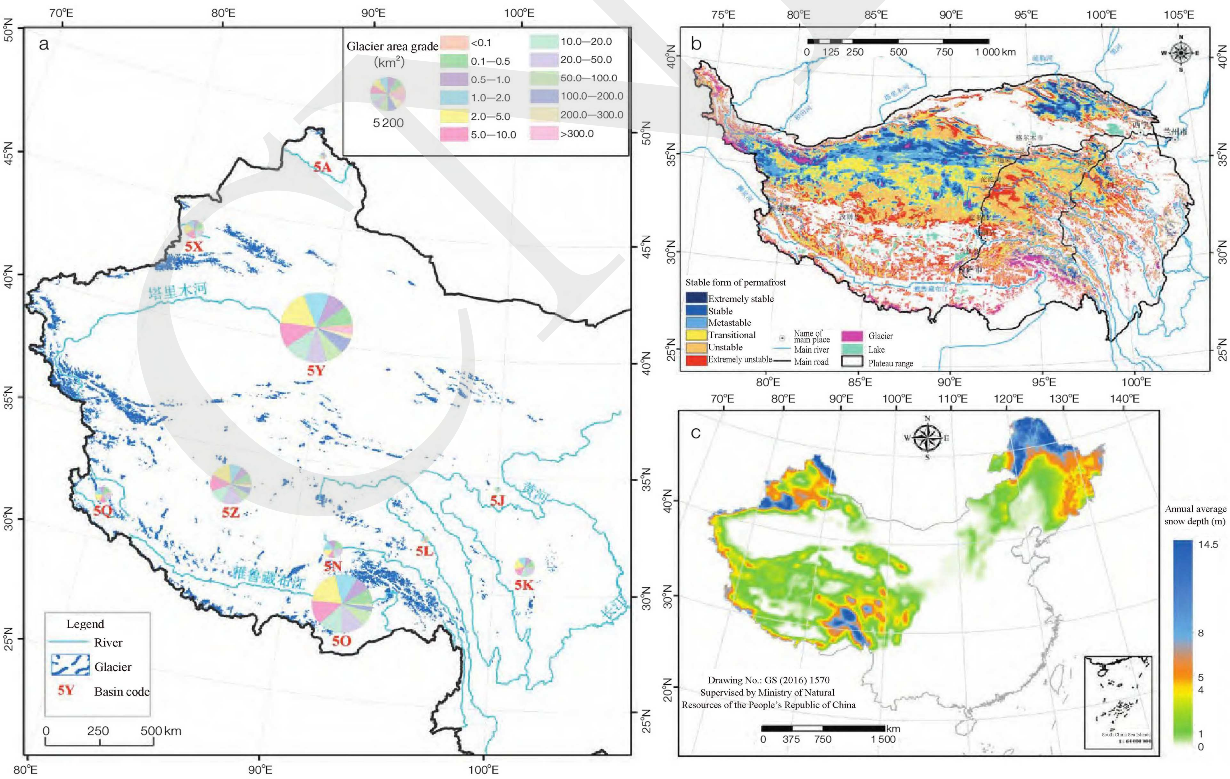

Figure 2 The second Chinese glacier inventory (a) [13], frozen soil map of the Qinghai-Tibet Plateau (b) [20]and snow depth distribution map (c) [16]

However, only a few studies have been conducted in terms of remote sensing mechanism and inversion method. With the introduction of the "Ice Silk Road" Initiative and the release of the white paper *China's Arctic Policy*, the Arctic will become a hot spot of cryospheric remote sensing research in China.

3.3 Characteristics of the Antarctic cryospheric remote sensing in China

Since China's joining in the Antarctic Treaty in 1983, Antarctic surveying, mapping, and remote sensing have realized good development. Antarctic cryospheric remote sensing mainly involves polar surveying and mapping, remote sensing monitoring of sea ice, ice sheets, and ice shelves. In terms of polar surveying and mapping, China has successively completed the surveying and mapping of large-scale topographic maps for typical areas, and the surveying and mapping of subglacial topography and seafloor topography are conducted in recent years [24]. In terms of remote sensing of sea ice, China has many research achievements in remote sensing monitoring of the extent, type, density, and surface albedo of Antarctic sea ice [25]. In terms of remote sensing monitoring of Antarctic ice sheet and ice shelves, substantive research has been carried out on topography, glacier velocity, material balance, grounding line, ice surface characteristics, surface freezing and thawing, and subglacial lake, especially the contribution of ice-shelf calving to material loss of the Antarctic ice sheet [26]. The glacier velocity product with the highest resolution has been developed with land satellite images and satellite altimetry data (Figure 3). Moreover, the sustained mass loss of the glacier of Wilkes Land in East Antarctica has been discovered for the first time, and the warming of the circumpolar ocean current may be the main reason causing accelerated melting of the glacier [27]. With the implementation of China's Antarctic aerial exploration programme and the launch of multiple remote sensing satellites made in China, the remote sensing of the thickness of the Antarctic ice sheet and its subglacial topography and subglacial lake as well as the application of satellites made in China in remote sensing in the Antarctic, is expected to be a new research hotspot.

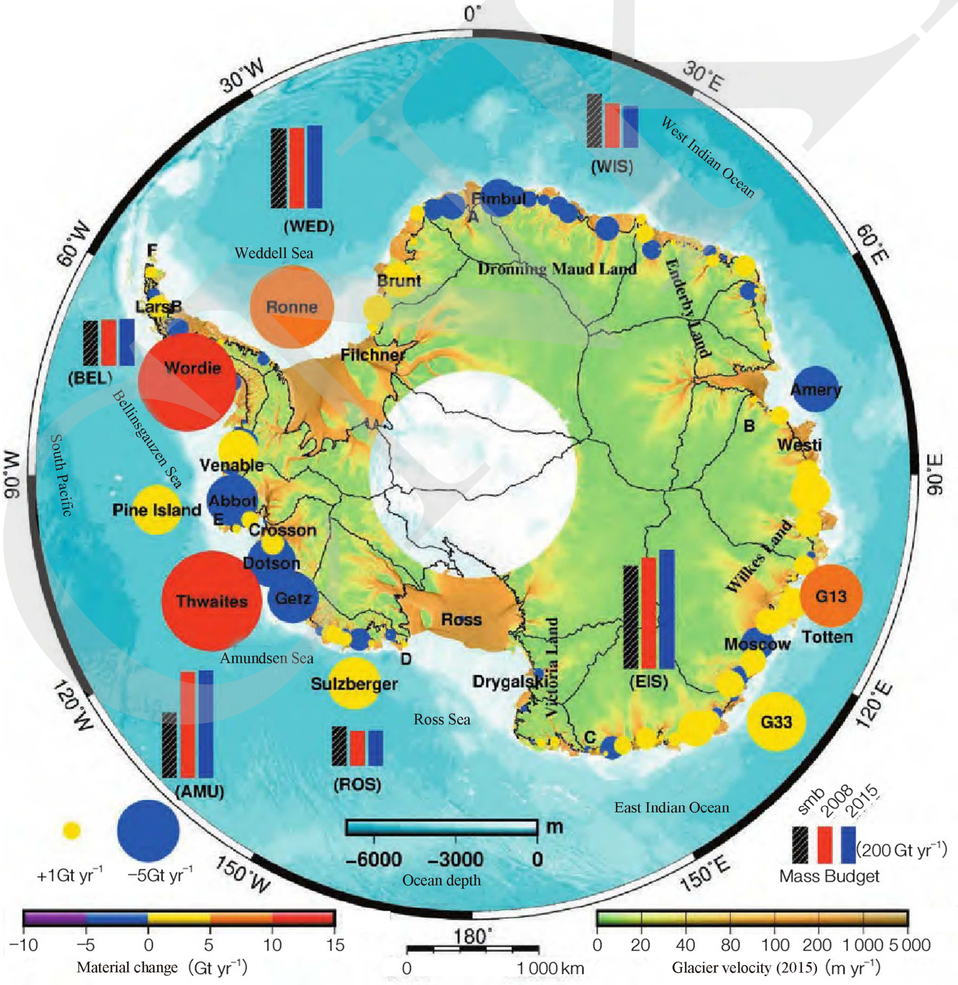

Figure 3 Antarctic glacier velocity (2015) and mass change (2008–2015) [27]

4 Prospect for the development of cryospheric remote sensing

4.1 Strengthening of the research on cryospheric remote sensing theory and application system

Cryospheric remote sensing is still an emerging discipline. With the emergence of many new remote sensing sensors, cryospheric remote sensing is facing new opportunities and demands. The understanding of electromagnetic scattering and radiation models of elements of the cryosphere, such as glaciers, frozen soil, snow cover, river ice, lake ice, sea ice, and atmospheric cryosphere, should be further strengthened from the perspective of the development of the discipline, so as to deeply understand the mechanisms and processes of remote sensing scattering and radiation of the elements of the cryosphere, thus providing theoretical support for remote sensing inversion of the elements. Special attention should be paid to the atmospheric cryospheric remote sensing for the research basis is relatively weak.

The cryosphere involves the related disciplines of ecology, hydrology, atmospheric science, oceanography, and catastrophology. Through strengthening the integration with these disciplines, the applications of the cryospheric remote sensing in cryospheric climate, hydrology, ecological environment, and disasters can be enhanced, making it play a greater role in solving scientific problems in these application fields. Meanwhile, the development of cryospheric science and different subject fields can provide new scientific problems and application opportunities for cryospheric remote sensing. For example, the development of photology, electronics, and materials science can provide advanced instruments for obtaining the cryospheric remote sensing data, thus promoting the development of cryospheric remote sensing.

With the constant reinforcement of the effects of cryospheric changes on national and regional politics, society, economy, and sustainable development, the deficiency of personnel and institutions engaging in basic theoretical research of cryospheric remote sensing is obvious in China. Therefore, it is necessary to set up the relevant undergraduate and graduate courses in colleges, universities, and institutes, so as to enhance the public's understanding of cryospheric remote sensing and cultivate talents and teams who are willing to engage in cryospheric remote sensing.

4.2 Promotion of the scientific programme of "Earth's three poles"

The Antarctic, the Arctic, and the Asian alpine region mainly represented by the Qinghai-Tibet Plateau are deemed as the "Earth's three poles" and are also the core distribution area of the global cryosphere ①[28]. In addition to the most freshwater resources, they are also rich in oil and gas resources. Thus, they are potential strategic reserve areas of global resource and energy development and are of special significance to the future development, national interests, and security strategy of China. Meanwhile, the "Earth's three poles" are the regions most obviously affected by global warming, the typical areas of multi-layer interaction in the global climate system, and also the key and sensitive areas affecting global climate and environmental changes. They play important roles in global energy and water cycle. Therefore, the research on the "Earth's three poles" is the commanding height of the multi-layer coupling research of Earth system science and "Future Earth" natural-social sciences interdisciplinary research. Scientists from China and other countries are calling for implementing the scientific programme of "Earth's three poles."

As affected by the factors such as natural conditions and lagging social development, the ground observation ability for the ecological environment of the "Earth's three poles" is very limited, while remote sensing has unique advantages in obtaining ground observation data in spatial and temporal distribution. Although remote sensing has provided a large amount of cryospheric data for the "Earth's three poles," the existing remote sensing programs, except for ICESAT and CryoSat, are not designed for cryospheric observation. The priority of cryospheric observation and data acquisition capacity in the "Earth's three poles" are quite low. For example, the ESA plans to launch the BIOMASS satellite in 2021, which will take polar observation as the second priority in terms of scientific objectives. Although Japan and China have launched some small satellites specifically for polar observations in recent years, the lack of a polar observation system has not been changed. Therefore, in order to carry out the scientific programme of "Earth's three poles," the development of the cryospheric remote sensing observation system of air-space-ground integration should be strengthened. For special observation approaches and technical methods of cryospheric remote sensing, the research on the followings should be strengthened.

(1) Scholars should making full use of the existing satellite data to prepare the polar basic geographic information and ecological environment data sets. For example, the high-resolution remote sensing data can be used to figure out basic geographic environment data such as polar terrain, sea conditions, ice conditions, and vegetation; the remote sensing data of medium and low resolution but with long time series can be used to obtain the data of the changes in ecological environment and the cryosphere involving glaciers, ice sheets, snow cover, and sea ice in historical periods, thus providing basic data support for scientific research of the "Earth's three poles."

(2) The specialized satellite remote sensing technology

① Guo H, Li X, Qiu Y. Comparison of Global Change at Earth's "Three Poles" using Spaceborne Earth Observation. Science Bulletin.2020, 65, In Press.

should be developed for scientific research on the cryosphere. Penetrability is the advantage of microwave bands. Thus, the low-frequency band (such as P band) microwave radiometer or SAR satellite can be launched to detect the cryospheric elements undetectable before, such as the glacier thickness, tomographic structure of ice sheets, and thickness of the active frozen soil layer.

(3) As for the improvement of the polar environment observation revisiting period, double-satellite joint observation or satellite network observation can be conducted to realize the monitoring of the rapid changes in polar sea ice, glaciers, and ice sheets. The double-satellite joint observation or satellite network observation can also greatly improve the quality of the InSAR measurement data, thus monitoring surface topography and deformation of the cryosphere.

(4) Gravity satellites with high spatial resolution and communication satellites on large elliptical orbit are also important means for future research on polar cryospheric science. China is currently formulating and developing some satellite programs for cryospheric observations, which should be rapidly promoted.

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