

Review

# Cryosphere Services and Human Well-Being

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**Abstract:** Cryosphere services (CSs) refer to various benefits that humans directly or indirectly obtain from the cryosphere, which makes significant contributions to human well-being (HWB). To facilitate such research, we first present a classification system for conceptualizing, monitoring and assessing CSs based on the current process-based understanding of their nature and sustainability. Specifically, the CSs are grouped into five major categories (provisioning, regulating, cultural, bearing and supporting services) and 18 sub-categories. Then we provide a detailed overview on formation, current status and anticipated future changes of the identified types of the services, and their impact on HWB. Finally, the spatio-temporal scales, the links of the services with HWB and climate-dependence are further discussed. The research of CSs adopt interdisciplinary approach to address the formation mechanisms of CSs and their dynamic relationships with HWB, which is poised to provide a better understanding of the cryosphere's role in human society and help enhance socio-ecological sustainability and HWB over cryosphere-affected areas. Notably, most CSs have been deteriorating under global warming and cryosphere shrinkage, further leading to negative impacts on associated HWB. Therefore, great attention should be paid to the changes in CSs and their cascading risks.

**Keywords:** cryosphere; cryosphere services; cryosphere functions; human well-being; classification system; socio-ecological systems; sustainability

## 1. Introduction

Deriving from the Greek 'kryos', the term 'cryosphere' is generally defined as all parts of the Earth's surface system where water is in solid form, such as mountain glaciers, ice sheets, permafrost and seasonally frozen soil, snow cover, icebergs, sea ice, river ice and lake ice [1–5]. Over the past decade, research on the cryosphere, ranging from changes to impacts and adaptation, has received worldwide attention. As a result, the field of Cryosphere Science has seen rapid development [5].

The cryosphere makes significant contributions to human well-being (HWB) directly or indirectly and materially or spiritually, providing a wide array of benefits. All kinds of benefits that the cryosphere provides for humans can be considered cryosphere services (CSs) [6,7]. In prehistoric periods, early human evolution, migration out of Africa and occupation of the Tibetan Plateau have been closely linked to major environmental changes that the cryosphere has supported [8–10]. Later, important ocean "bridges" formed, for example across the Bering Sea and between southeastern Pacific islands, as the cryosphere fixed oceanic water in continental ice sheets and ocean shelves were exposed in the Ice Age [11]. These bridges (examples of cryospheric "bearing services") greatly facilitated migrations across continents and the global dispersal of modern *Homo sapiens*. However, the most

important human benefits (HBs) from the cryosphere is probably its ongoing involvement in the creation and regulation of suitable climatic conditions for human habitation [6]. In extensive cold and arid regions of the world, human socio-economic development strongly depends on freshwater resources that the cryosphere provides, which can be widely used for ecosystem integrity, agricultural irrigation, developing hydropower, domestic and industrial activities. It also lends important environmental support for animal and plant habitats, and unique natural resources are generated in cryosphere-dominated regions. In addition, it provides crucial load-bearing services for diverse types of infrastructure required for numerous human activities in cold regions. Moreover, elements of the cryosphere provide aesthetic, cultural, spiritual and recreational benefits for people living around it and far away that cannot be obtained elsewhere [6].

Although there is a wealth of studies on cryospheric processes and mechanisms, the interaction between the cryosphere and other spheres, and the cryospheric disaster risk, the systematic research on CSs is still in its early stage [5,7,12]. Some previous studies have also investigated polar or mountainous ecosystem services (ESs) [13–17], which generally take cryosphere as a component of large ecosystems that functionally supports the formation of ESs [18]. But CSs and their relatively direct contribution to HWB have received less attention [19,20]. Eicken et al. [18] considered the Arctic sea ice, one of the basic elements of the cryosphere, as a relatively independent system and identified its services categorization with a purpose of providing detailed and effective information for stakeholders perceiving and using sea ice. Taking all elements of the cryosphere into account, Xiao et al. [6] presented a preliminary classification and value evaluation method for CSs. Since 2017, the National Natural Science Foundation of the People's Republic of China has launched a research project series entitled *Determination of cryosphere service function and methods for service value evaluation and Formation Process of Chinese Cryosphere Service Functions and Integrated Regionalization*, the major objectives of which are to elucidate relationships between cryospheric processes and CSs in detail and promote sustainable regional development. Up to now, the main relevant achievements include but are not limited to [21–30]. Also, recently, based on the CSs concept, Mukherji et al. [7] reviewed the contributions of the cryosphere to mountainous communities across the Hindu Kush Himalaya.

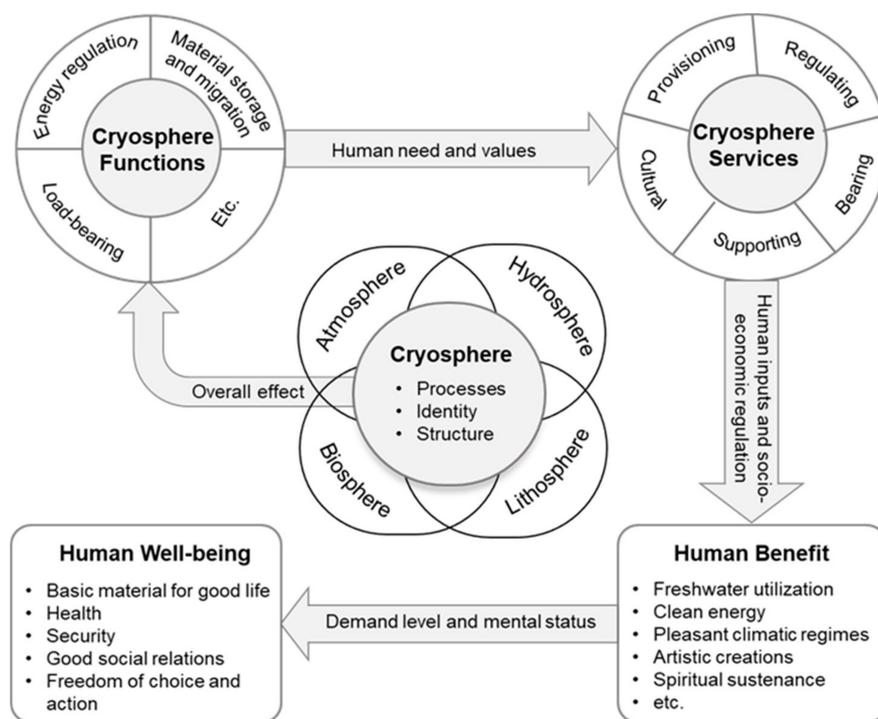
To make the concept of CSs more specific and feasible, there needs to be a more systematic classification to enable conceptualization, assessment, valuation and policymaking; there also needs to be a detailed understanding from the formation processes of various CSs to their linkages with HWB. To address these needs, we first propose a classification system based on descriptions of the processes involved in the formation of CSs and their links with HWB, and discussions of basic principles for an effective typology. Then we review the formation, current status and anticipated changes of the various types of the services and their links to HWB in detail. Finally, the spatio-temporal scales, the linkages between CSs and HWB, and climate-dependence are further discussed.

## 2. Cryosphere Services Classification System

### 2.1. The Formation of Cryosphere Services and Their Links to Human Well-Being

Each service the cryosphere provides to human society depends upon cryosphere functions (CFs), which refer variously to the cryosphere's environmental nature, structures and processes, as illustrated in Figure 1. The distinguishing feature of the cryosphere in relation to other environmental elements is the presence of water in the frozen state. Cryospheric processes cover cryospheric changes and their interaction with other spheres [5]. CFs include energy regulation, material (especially water) storage and migration, load-bearing, natural cooling capacity and release, and surface erosion or consolidation, etc. However, these functions are natural attributes of the cryosphere. Switching attention from CFs to CSs not only changes the research perspective, but also fundamentally extends the objectives, from solely considering the cryosphere's nature to addressing its relationship with human society. Specifically, CSs are based on CFs, with orientations towards human needs and values. That is, the cryosphere meets human's material and spiritual needs, thereby contributing to HWB, which

focuses on the positive effects of the cryosphere, in contrast with the negative effects (i.e., cryospheric disasters).



**Figure 1.** A cascade framework from cryosphere functions (CFs) to cryosphere services (CSs) and human well-being (HWB).

HWB has multiple constituents, but its core is quality of life [20,31]. According to the Millennium Ecosystem Assessment (MA), HWB has five constituents: basic material for good life, health, security, good social relations, freedom of choice and action [20]. All types of CSs have a positive impact on human' social, economic and spiritual needs, by definition, so they all contribute (directly or indirectly) to HWB. However, the linkages between CSs and HWB are also complex processes (Figure 1). Firstly, the links between supplies and consumptions of the services involve a great deal of investments of built and human capital together with appropriate socioeconomic regimes and value orientation [32]. Then there is spatial separation, and hence, complex nonlinear and hysteretic relationships between the services' supply and HBs from them (Ibid.). In some cases, their contributions to HWB may also be marginal, and dependent on levels of human demand or even mental status [33]. However, the essential issues are the dynamic relationships between CSs and CFs, which determine how, where, when and what benefits from the cryosphere can be used to improve HWB.

## 2.2. Principles of Cryosphere Services Classification

In attempts to categorize ESs, there have been great differences in the understanding and definition (implicit or explicit) of services, ranging from natural functions to actual HBs, which has caused confusion both theoretically and practically [32–34]. Failure to distinguish between intermediate processes and terminal services may lead to duplication of service values in auditing and monitoring programs. Moreover, if only the final benefits are considered, some potential services or indirect contributions may be neglected or underestimated. Thus, to accommodate the range and complexity of the services, the following perspectives and principles should be applied when classifying them.

Treat CSs as a specific class of ESs. The cryosphere is an essential component of both ecosystem and natural environment that supports a healthy human society, although the cryosphere's contributions have long been marginalized and received less attention. CSs should be treated as a specific class

of ESs and be valued to strengthen the understanding of the relationship between cryosphere and human system.

Apply systematic procedures. Links between cryospheric processes and their impacts on socio-ecological systems (SEs) and HWB are highly complex. When we classify CSs, we should take into account all of the cryosphere's contributions (potential, indirect, past and present) to HWB. In addition, the intermediate processes from terminal services must be distinguished to avoid duplicate classification and objectively reflect their contributions. The classification should also focus on the real, measurable and predictable measurable or predictable services, so human evolution service and some historical CSs are, therefore, not included.

Consider sustainability. Some CSs, such as major infrastructure-bearing services on frozen soil, contribute to HWB at the expense of huge socioeconomic input. Corresponding services in non-frozen areas may also yield more benefits with less investment. However, the Earth is clearly unsustainable with no or substantially less cryosphere. Thawing of frozen soil will bring on an unstable phase to the existing infrastructures and short-term building plans [35]. Even worse, thawing permafrost is very likely to be globally disrupting to the climate, especially through increased methane emissions [36]. Therefore, sustainability must be considered when discussing CSs.

### 2.3. Results of Classification

The formation pathways of CSs can be classified into three categories. First, the cryosphere is responsible for various provisioning, cultural and bearing services. Second, it provides regulating services through indirect interactions with other spheres. Third, it contributes to HWB by supporting or dominating the formation of natural environments, with unique biota, resources and geopolitical environments, which can be considered supporting services. In this study, after describing the formation processes of CSs and their links with HWB, and discussing the main principles for establishing CSs classification, we have divided the CSs into 5 major types and 18 subtypes (Table 1).

**Table 1.** Scientific facts of the cryosphere services.

Cryosphere Services	Functional Basis	Human Benefits (Examples)
1 Provisioning services		
1.1 Freshwater provisioning services	Freshwater storage (natural "reservoirs") and supply	Uses in agricultural irrigation, public systems, industrial activities, livestock husbandry, ecosystem integrity, etc. Historically used for cooling houses, making cold drinks and food, refrigerating food, treating ailments, etc. Current uses in thermal difference power plants, freezing plant seed banks, etc.
1.2 Natural "cold energy" provisioning services	Huge natural reserve and source of cold substances	Historically used for cooling houses, making cold drinks and food, refrigerating food, treating ailments, etc. Current uses in thermal difference power plants, freezing plant seed banks, etc.
1.3 Ice and snow material provisioning services	Physical properties (solidity, transparency, etc.)	Building igloos, creating fire, etc.
2 Regulating services		
2.1 Climate-regulating services	Weather and climate regulation	Creation of pleasant climatic regimes for human habitation
2.2 Runoff-regulating services	Regulation of water flows	Reduction of water resources' management costs
2.3 Ecological regulating services	Water conservation, and water and thermal regulation	Improvements in land productivity in frozen ground
2.4 Erosion-regulating services	Terrestrial surface-erosion and suppression of the erosion (surface protection)	Provision of material and nutrients for formation of environments in lower reaches of mountains, protection of coastal facilities and property, etc.

Table 1. Cont.

Cryosphere Services	Functional Basis	Human Benefits (Examples)
3 Cultural services		
3.1 Aesthetic services	Attractive landscape features	Aesthetic value and pleasure, alleviation of stress, etc.
3.2 Inspirational services	Distinctive natural features with inspirational value	Artistic creations (such as literature, photographs and paintings) and technological innovations etc.
3.3 Religious and spiritual services	Distinctive natural features with religious and spiritual value	Sense of belonging and cultural identity, emotional and spiritual sustenance
3.4 Knowledge and educational services	Distinctive natural features with scientific and educational value	Scientific research, popular science education, etc.
3.5 Tourism and recreational services	Distinctive landscapes with recreational uses	Sightseeing, skiing and skating, adventure tourism, etc.
3.6 Cultural diversity services	Distinctive landscapes supporting cultural diversity	Enrichment of human cultural diversity
4 Bearing services		
4.1 Passage services	Formation of “land bridges” after freezing	Early human migration across continents, passage of people, livestock and vehicles in cold regions, etc.
4.2 Facility-bearing services	Load-bearing capacity of solid ice	Infrastructural installations such as residential buildings, drilling rigs, research stations, oil pipelines and roads in cold regions
5 Supporting services		
5.1 Habitat-supporting services	Dominant environmental factor for endemic biota of cold regions	Provision of biological resources such as foods, medicinal materials, pasture, aquatic products and germplasm resources
5.2 Resource generation-supporting services	Important environmental conditions for the formation of distinctive natural resources	Provision of natural resources such as natural gas hydrate and wind energy
5.3 Geopolitics and military-supporting services	Distinctive physical properties create concealed environments, etc.	Provision of environmental defenses for specific political and military purposes

### 3. Scientific Facts of Cryosphere Services

Based on relevant published literature, here we provide a comprehensive overview of the formation of various types of CSs, their status, anticipated future changes and their effects on HWB.

#### 3.1. Provisioning Services

Cryospheric provisioning services refer to the various products or services that the cryosphere can directly provide to humanity, which can be divided into freshwater, natural “cold energy”, as well as ice and snow material provisioning services.

##### 3.1.1. Freshwater Provisioning Services

The cryosphere is considered as a huge solid reservoir, which stores 77% of the Earth’s freshwater [37]. The bulk of the freshwater in the polar ice sheets has not been available to humans, but glaciers and snow are irreplaceable suppliers of freshwater to humans, especially in extensive cold and arid regions of the Earth. The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) estimates the total volume of mountain glaciers is about 113,915~191,879 Gt [4]. Major glacierized drainage basins reportedly cover 26% of the Earth’s land surface (excluding Greenland) and provide water supplies for almost a third of the global population [38]. As an important source of runoff during spring, snowmelt provides about  $59.5 \times 10^{11} \text{ m}^3$  of freshwater annually on terrestrial land [39], ensuring water safety for production and life of 1.2 billion people [40].

The High-Asian region, also known as the Water Tower of Asia, is the source of many large Asian rivers (such as the Yangtze, Yellow, Ganges, Indus, Tigris and Euphrates) that have played major roles in the birth and development of Chinese, Indian and Mesopotamian civilizations. Cryospheric water provisioning services are crucial for human sustainability and approximately 800 million people, in part, rely on it [41,42]. Especially in arid and semiarid areas (such as the Indus Basin, Aral and Chu/Issyk-Kul

river basins, and the Xinjiang Uygur Autonomous Region and Hexi Corridor of China), glaciers and snow meltwater are considered “lifelines” of local SESs [43–46]. Hamish (2019) concluded that seasonal glacier meltwater can satisfy the basic needs of  $221 \pm 59$  million people in this region [42]. The huge cryospheric water resources and steep terrain also provide tremendous potential for hydropower generation in this region. Statistical analysis showed that the contribution of hydroelectricity to the total electricity supply is about 100% in Bhutan, 92% in Nepal, 74% in Myanmar, 33% in Pakistan, 17% in India [47]. There is no doubt that cryosphere meltwater takes a very important role.

In Europe, the Alps serve as water towers that account for 26, 34, 41 and 53% of total runoff in the Danube, Rhine, Rhone and Po basins, respectively [48]. In 2009, more than 400 MW of hydropower was generated in Germany and Slovenia, more than 2900 MW in Italy and Austria, and more than 11,000 MW (about 75% of total national electricity supplies) in Switzerland [49,50]. In the Scandinavian Mountains, especially in Norway, modeling indicates that cryosphere melting water can account for more than 50% of the annual discharge in the highly glacierized catchments, providing 15% of national electrical energy [51].

In north-western mountainous North America, such as Wyoming, glacial meltwater provides stable water for crop growth, and supports a cattle industry worth \$800 million [52]. In the lower Hood River watershed of the Oregon Cascades, glacier meltwater comprises 41–73% of the upper watershed flow, which have a potential impact on irrigation and agriculture [53,54]. In the Gulf region of Alaska, runoff from the glaciated part of the drainage basin (18% of 420,230 km<sup>2</sup>) accounts for about 47% of total runoff [55]. Agriculture in Alberta is also dependent on meltwater from the neighboring Peyto and Proximal glaciers in the Canadian Rockies [52].

In parts of the Andes of South America, at altitudes over 2500 m with an arid climate, most cities are highly dependent on glacial meltwater for water supplies [56]. In Quito, Ecuador, a considerable proportion of domestic water for a population of about 2 million comes from the Antizana and Cotopaxi glaciers [57]. In La Paz and El Alto, western Bolivia, 30–40% of drinking water for 2.3 million people originates from glacial melt in the surrounding mountains [54]. Similarly, about 40% of the Rio Santa River discharge comes from glacial meltwater during the dry season [52]. In Peru’s Santa River basin, glacier meltwater accounts for more than 66% of watershed flow during the dry season, and is crucial for the large-scale Chavimochic irrigation and agriculture project [54]. Andean countries are also highly dependent on water from cryosphere for hydropower, which accounts for 80% of the total national energy supplies in Peru and 50% in Ecuador [57].

Cryospheric meltwater is widely used for domestic water in the Arctic, and for both agricultural irrigation and hydropower generation in sub-Arctic regions [58]. It has also been exploited as a source of mineral water for sale around the globe because of its relatively low pollution levels and high contents of minerals and trace elements through directly contacting with rock powder from glacial erosion. Famous brands include Evian in France, Heidiland in Switzerland, Alaskan Glacier Water in USA, Eska in Canada, the 5100 Tibetan Glacier and Kunlun Mountains Mineral Water in China [6]. Another notable use of sea ice in China’s Bohai Sea (which is abundant and has low salinity) is the experimental desalination and application of for irrigation and improvement of saline-alkali soil in the Bohai region [59].

As the climate warms and cryosphere shrinks, runoff is expected to increase for a certain period of time, which can meet the demands for more water and bring opportunities for developing Alpine hydropower. However, after a “peak water”, supplies of glacial meltwater will decline until the glaciers disappear, which will have serious negative effects on regions that rely on cryospheric water resources and alpine hydropower [60,61], especially if they have insufficient access to alternative water and energy sources. A recent study showed that about half of the 56 global, large-scale glacierized drainage basins have already passed peak water, and that the glacial runoff in the remaining basins will continue to rise in the near future because of higher ice coverage. Moreover, by 2100, one-third of these basins might experience runoff decreases greater than 10% due to glacial mass loss during at least one month of the melt season, especially in central Asia and the Andes [38].

### 3.1.2. Natural Cold Energy Provisioning Services

Historically, natural cryospheric cold energy resources have been widely exploited. People have collected ice cubes during the winter and stored them for uses in the summer, such as cooling indoor temperature (“air conditioning”) and anticorrosion of food and wine (“refrigerator”). Natural ice cubes are also used to make cold drinks and food, and even for preserving corpses and treating certain ailments [62].

Currently, the improvement of living standard has met people’s demand for cold energy and refrigeration to a certain extent, but cryospheric natural cold energy resources (especially in polar regions and high mountains) have great potential for cold energy provisioning services because they are abundant and less costly to develop and exploit than other options. For example, in 2008, the Norwegian government built the famous “Doomsday” Seed Vault in Svalbard. This facility can store approximately 2.25 billion seeds of about 4.5 million crop varieties in a natural deep freeze to enable the continuation of agriculture following a global disaster such as extreme climate change or nuclear war [63]. It is highly significant for the protection of global crop diversity. However, as the climate warms, cryospheric temperatures are also increasing and thus continuously reducing cold storage capacity [64], which will reduce potential cold energy provisioning services.

### 3.1.3. Ice and Snow Material Provisioning Services

Because of the cryosphere’s unique physical properties (solidity, transparency, etc.), in some periods or areas, people make ice or snow materials to meet specific production and living needs. For example, the Inuit, living along the Arctic Ocean coast, use ice and snow to build igloos which are essential for their survival [65]. It is also said that natural ice has also been used as a “convex lens” to make fire in the alpine region, even though there are few beneficiaries. In addition, since freezing increases the volume of water by about 10% it can generate huge expansion forces, so people in some areas skillfully use this force for quarrying and obtaining stone more cost-effectively and safely than by blasting.

## 3.2. *Regulating Services*

Cryospheric regulating services are the benefits that humans derive from regulatory cryospheric processes and functions. These include various material and non-material benefits from cryospheric climate, runoff, ecological and erosion regulating services.

### 3.2.1. Climate Regulating Services

The cryosphere plays a crucial role in feedback and regulation of the weather and climate, thereby making an irreplaceable contribution to the formation of a good living environment. The cryosphere regulates the weather and climate at different spatio-temporal scales through complex processes and functions, such as the provision of huge cold storage and latent heat exchange capacities, high albedo, low thermal conductivity, driving thermohaline circulation and the effects of carbon sink [4,18,36,39].

Global warming and cryosphere shrinkage have profound impacts on both the global and regional climates. Cryospheric elements in polar regions are major “air conditioners”, and simulations indicate that losses of polar ice sheets and sea ice will have major effects on the Earth’s climatic zones, with disastrous impacts on human society [6]. Polar glaciers also play key roles in the healthy operation of ocean conveyor belts. However, due to the melting glaciers and increasing freshwater over certain Gulf streams, the upper ocean waters do not sink easily, which has caused the oceanic conveyor belt to weaken. If the conveyor belt stops, the North Atlantic warm current will not enter the Atlantic Ocean, and Europe will become much colder, potentially leading to a dramatic change of global climate [66–68]. Large flows of Arctic river water into the Arctic Ocean also regulate the structure of the ocean’s upper layers by hindering exchange of upper and lower layers and inhibiting sea ice ablation [69]. Loss of this regulatory effect of Arctic freshwater resources would likely strengthen the

surface water warming in the Arctic Ocean together with its cascading and spillover effects. In addition, permafrost regions have stored enormous amounts of organic carbon, but the frozen ground thaw will result in emissions of greenhouse gases such as CO<sub>2</sub> and CH<sub>4</sub>, which will likely further amplify global warming [36]. The economic losses of climate regulating services due to anticipated increases in permafrost organic carbon emissions and reductions in both sea ice and snow's albedo in the Arctic cryosphere are estimated to rise from \$7.5 to \$91.3 trillion between 2010 and 2100 [70].

### 3.2.2. Runoff Regulating Services

Glaciers, snow cover and frozen soil have a unique function of "peak shaving and valley filling" through the accumulation of large volumes of frozen water during cold or/and humid seasons and their ablation during hot or/and droughts seasons [38,55], which maintains the relative stability of river runoff on annual or seasonal scales and further facilitates utilization and management of regional water resources, especially in arid regions and droughts.

The average contribution of glaciers to the watersheds' runoff is relatively low, but in dry years glacial meltwater has important recharge effects on runoff, such as in the Indus Basin [71,72]. Snow cover, which is highly significant in regional agricultural production, is an important water resource for relieving spring drought, especially in arid regions [43]. For seasonally frozen soil, on the one hand, it thaws from late spring or early summer, which can increase runoff; on the other hand, it retains rainfall during the autumn and winter, thereby increasing water storage capacity. But for permafrost, because of permafrost's impermeability to water, the other water directly becomes runoff, and the groundwater makes little contribution to runoff in winter. Permafrost also retains a certain amount of water resources in the form of underground ice over centuries or millennia, which will be released if the permafrost thaws [73].

Global warming will cause cryosphere ablation, which will demonstrate as earlier snow and ice melt and commencement of the associated runoff, resulting in runoff regulating function increase for a certain period. However, when the "peak water" is exceeded, this function will be greatly weakened [38]. The degradation of frozen soil will also have a severely negative effect on runoff stability in associated basins.

### 3.2.3. Ecological Regulating Services

The cryosphere (especially frozen ground) regulates vegetation and its community's types, composition structure and distribution pattern, and also has a significant impact on the distributions of animals and microorganisms based on its functions of water conservation, and water and thermal regulation [74].

Permafrost is impervious to water and can prevent groundwater infiltration into the active layer (the upper layer that thaws in summer and freezes in winter), which can further reserve water in the active layer. To a certain extent, the moisture translocation caused by thickness changes in the active layer determines the types of surface ecosystem in permafrost regions [73]. In the tundra of the northern Arctic, the formation of polygonal tundra and associated vegetation and polygonal wetlands are closely related to their underlying permafrost properties. However, permafrost thawing has caused lakes and wetlands to dry in some areas and formed new wetlands in other places. In the Qinghai-Tibet Plateau, from the Kunlun Mountains to the Tanggula Mountains and its vast western areas, large areas of alpine meadow and alpine wetland ecosystems have developed due to the ecological regulation functions of the frozen ground, but as the frozen ground has degraded, the desertification area has increased [43,75].

As a good heat insulator, snow cover preserves heat on the earth's surface and prevents soil from excessively cooling. The snow depth also influences the distribution of tundra, and hence distributions of types of vegetation and winter conditions in habitats of many animals and plants [76]. In the alpine belt and Arctic regions of the northern hemisphere, the thickness and timing of snow melt strongly influence the composition of plant communities and ecotypes of the plants. For most vegetation types

in these regions, snow cover generally promotes increases in biomass and growth, although there are thresholds. Hence, changes in snow cover will have significant impacts on terrestrial ecosystems, including community structures and growing seasons of both plant and animal populations [77].

Sea ice also provides habitats for many microorganisms, especially planktonic microorganisms. The generation and ablation of sea ice also play an important role in population dynamics of other marine organisms, as described in more detail in the section on habitat supporting services.

#### 3.2.4. Erosion Regulating Services

Cryospheric erosion regulating services refer to the benefits humans obtain directly or indirectly from the CFs of surface-erosion and suppression of surface erosion (surface protection).

Firstly, when water freezes and covers the Earth's surfaces, it forms a barrier that protects it from external forces. Especially in high-latitude coastal areas, the frozen ground and sea ice stabilizes and prevents the seashore from erosion by ocean waves, thereby maintaining coastal socio-economic assets. However, shrinkage of frozen ground and sea ice is causing significant recession of Arctic coastlines and severe damage to coastal infrastructure [18,78]. For instance, extensive parts of the northern coast of Alaska are retreating by more than a meter per year, threatening many coastal communities and urgently creating the need for migration inland, which approximately causes millions of dollars of property loss per year [79].

Secondly, erosive cryospheric freeze-thaw processes and meltwater participate in the generation of gravel and finer sediments, and subsequent flushing of the sediments out of canyons and deposition on lowlands along margins of glacier-covered mountains. This provides important sources of material (particles and nutrients) for the formation of proluvial fans, oases, and plains, thereby creating production and living environments [52,54]. The erosion and material accumulation generated in this manner occurs in all piedmont areas influenced by the cryosphere and affect HWB via complex interactive processes. However, cryosphere changes would cause significant shifts in the processes involved in soil and water creation and related activities [52].

### 3.3. Cultural Services

Cryospheric cultural services are the non-material benefits that humans can obtain from the cryosphere, such as spiritual solace, aesthetic experience, development of cognitive abilities and promotion of mental health. Here, we further divide cultural services into six sub-types: aesthetic, inspirational, religious and spiritual, knowledge and educational, tourism and recreational, and cultural diversity services.

#### 3.3.1. Aesthetic Services

Natural environments are essential sources of humans' aesthetic experiences and pleasure, which contribute significantly to spiritual pleasure, comfort, happiness, alleviation of stress, and hence HWB [80]. Glacial and periglacial landforms, glacial relics, landscapes of ice sheets, ice shelves, sea ice, snow cover, glaze ice and their combinations are visually striking elements of the Earth's natural environments with unique aesthetic values. In these regions, cryospheric elements are often combined with blue sky, large mountains, clear rivers, flora and fauna, tranquil villages, stately temples and other aesthetically attractive features, both natural and cultural. These features give people a sense of reverence, freshness, pleasure and comfort. In combination with complex and ever-changing weather, they also induce wide-ranging emotional responses, from simple pleasure to awe. Therefore, the cryosphere's unique aesthetic values are highly significant for the promotion of HWB [6].

#### 3.3.2. Inspirational Services

Inspiration refers to arousal (usually sudden) of artistic or scientific creativity. The natural environment provides infinite inspiration, and the cryosphere is no exception, as its unique lures have inspired (inter alia) myriads of literary works, films, TV programs, photographs, paintings,

sculptures, folklore, music, dance, national symbols, fashion, architecture and advertisements. In particular, most winter Olympics emblems and logos of ice- and snow-related festivals are inspired by cryospheric landscapes.

In addition, the cryosphere has provided important inspiration for innovation in natural sciences and technologies, such as the discovery of bubbles in ice cubes prompting research on ice cores and paleo-environments [81].

### 3.3.3. Religious and Spiritual Services

Humans derive from nature and seek their spiritual connections with the environment through personal reflection and more organized traditional rules (such as religious rules, rituals and traditional taboos) to understand their position in the universe. As a natural landscape, the cryosphere is closely related to human religious beliefs and spiritual values at both regional and local scales.

Some high mountains snow or ice covered and lakes and rivers they feed are regarded as physical manifestations of gods and spirits [82]. The Gangriboche, the beautiful, magical main peak of the Gangdese Mountains is a huge perpendicular slab of ice and horizontal rock layers that forms a Buddhist sign (taken as a symbol of spiritual strength, meaning that the Buddha Dharma is eternal) and attracts countless pilgrims [83]. The Kawagbo Peak, the main peak of the Meili Snow Mountains on the border between Yunnan province and Tibet Autonomous Region, is considered a manifestation of the war god and Tibetans forbid climbing of the mountain. In addition, the Muslim Kirghiz of western China believes that the snows of Muztagh Ata, one of the highest peaks in the Pamir, hide an earthly paradise that goes back to the time of the Garden of Eden [82]. Similarly, the Chagga people who live in the foothills of Mount Kilimanjaro oppose the climbing of the snow-covered peak (Kibo) because they believe it is inhabited by gods, such as the Cold God (Njaro), and they will sacrifice animals to appease them. In Ecuador, the natives associate the disappearance of the Mama Cotacachi glacier with local immoral behavior and a god's departure [84]. However, when even the glacier and snow retreat disappear, then local populations will view this as the product of their failure to show respect to sacred beings or a sign of social regression [85,86], which will undoubtedly have a serious negative impact on the local people's spiritual well-being.

Cryospheric landscapes have also been people's homes and the environmental foundations of their self-identity and spiritual values for a long time [85]. Hence, facing impacts of a globalization tidal wave, indigenous peoples (such as the Arctic Inuit and Sami peoples) have intensely striven to protect their cultural traditions [87].

### 3.3.4. Knowledge and Educational Services

Cryospheric knowledge and educational services refer to the socio-economic development and improvement in HWB enabled by cryospheric scientific research, popularization of cryospheric knowledge, and training cryospheric scientific and technological talents [6]. Most cryospheric knowledge comes from scientific cryospheric research. However, traditional knowledge derived from the experience of indigenous inhabitants during their adaptation to cold environments should not be ignored, such as the Inuit building igloos for protection from the cold. Thus, mining and summarizing traditional knowledge can make exceptional contributions to the human knowledge base.

Disseminating cryospheric knowledge to the public and cultivating cryospheric talents through popularization, education and tourist activities, etc., are important for promoting social, economic, cultural and technological development, as well as the improvement of HWB. However, as the cryosphere shrinks, the potential extent of cryospheric knowledge is constantly threatened [78].

### 3.3.5. Tourism and Recreational Services

Cryospheric tourism and recreational services refer to the spiritual benefits that people gain by participating in various cryospheric tourism and recreational activities. Depending on tourists' purposes, cryospheric tourism can be divided into sightseeing, winter sports, adventure tourism

and cultural tourism. Cryosphere tourism and recreational services cover fitness, leisure, experience, adventure and education, which can provide unique and multiple spiritual benefits for people.

The purpose of cryospheric sightseeing tourism is to appreciate cryospheric landscape features, the surrounding natural scenery and social customs, integrating experience, exploration, education and recreation [39]. Cryospheric aesthetic values, which link people and landscapes, are important motives for cryospheric sightseeing tours.

Winter sports are unique forms of cryospheric tourism and recreational services, which provide opportunities for people to develop fitness, and engage in diverse competitive or non-competitive, professional or amateur, activities and experiences. They include (inter alia) various kinds of skiing, skating, snowboarding, sledding and snowshoeing. Skiing can occur over extensive areas while skating sports in natural environments are limited to frozen water bodies such as rivers or lakes. Winter sports have become economic growth sectors in various regions, including Western Europe, North America, Eastern Europe, Central Asia and East Asia [88].

Challenging one's self-limits and exploring cryospheric mysteries have long attracted the interest and attention of cryospheric adventure enthusiasts [39], which include alpine and polar expeditions, and ice climbing. Cryospheric adventures are often associated with risks of injuries or fatalities caused, for example, by avalanches, falls into ice crevices, storms, low temperatures, and/or lack of oxygen. Accessibility of the alpine, plateau and polar regions affected by the cryosphere is low, but the unique phenomena in the "White World" strongly attract adventurers from all over the world to experience cryospheric activities such as ice climbing and mountaineering, or more leisurely activities.

Cryospheric cultural tourists seek to experience and understand social and cultural phenomena related to the cryosphere in cold regions, including national history, religion, customs, culture, art and social organization. For example, some tourists go to Arctic regions to experience the lives of indigenous Inuit or Sami people [89].

Modern cryospheric tourism began with mountaineering, adventure and pilgrimage in the early 19th century, and rapidly developed in the 20th century with the popularity of leisure- and experience-based tourism activities since the 1980s [39]. Owing to rises in living standards and leisure time, cryospheric tourism is playing an increasingly important role in many countries, enriching people's spiritual lives, enhancing regions' connotations and popularity, and promoting regional socio-economic development [6]. However, with global warming, the retreat of the cryosphere will affect various types of cryospheric tourism services, which on the one hand is seriously affecting tourists' sightseeing and experience, and profoundly affecting the livelihood of some local communities that economically rely on tourism [89]; on the other hand, it increases the marine tourism opportunities because of reduction in sea ice and increase in accessibility across the Arctic [90].

### 3.3.6. Cultural Diversity Services

The social culture in a cryosphere-affected area is an important element of the world's cultural diversity, with formats based on the cryosphere-related environment and reflected in arts, crafts, entertainment, politics, family life, social relations, education, religion, festivals, etiquette and other aspects of society. Respecting and protecting the cryosphere-related culture or cultural heritage in cold regions is essential for promoting the development of human civilization. For example, indigenous people in the Arctic region have lived in ice- and snow-dominated environments for a long time, so they have developed unique cultures [91,92]. Their unique clothing, food, shelter and transportation provide valuable information and evidence regarding humans' adaptations to the cold and harsh natural environments. However, globalization and global warming are severely impairing the cultures of the cold regions [87].

### 3.4. Bearing Services

Natural solid ice on land and ocean surfaces can provide load support for human travel and migration, material transportation and engineering construction in cold regions, namely cryospheric bearing services.

#### 3.4.1. Special Passage Services

People can cross rivers or lakes by using natural ice bodies as bridges in cold regions. During migrations of modern *Homo sapiens* before the Holocene, sea levels were much lower than today, partly due to global re-allocation of water to the cryosphere. Hence, many land bridges were exposed (across the Bering Sea and between Southeast Asian islands for example), providing bridges for human migration [11]. Around 10,000 years ago, Mongolians in central and eastern Asia gradually moved north due to warming, and some remained in Siberia, but others migrated to Alaska across the “Bering Ice Bridge” [87]. In the Arctic, sea ice trafficability has a profound impact on people’s daily activities such as travel and hunting [93]. However, as the climate warms sea ice becomes thinner, loses volume and recedes from the coast, making its use for travel and transport more dangerous. Earlier spring warming leads to earlier snowmelt and splits of river ice, hindering Arctic communities’ use of snowmobiles to get to their hunting and fishing camps [94]. At high latitudes, river/lake ice also provides important passages in poor areas with under-developed transportation facilities, “ice bridges” provide convenient corridors and crossing points for people, animals and vehicles.

#### 3.4.2. Facility-Bearing Services

Facility-bearing services refer to the benefits provided by the cryosphere (especially frozen ground and sea/river/lake ice) bearing infrastructure such as residential buildings, drilling rigs, research stations, oil pipelines and roads.

Firstly, the cryosphere provides crucial bearing services for polar facilities such as houses, buildings and scientific research stations. For example, in the Arctic, sea ice or ice sheets provide indispensable load-bearing services for indigenous peoples’ residential infrastructure. Without the cryosphere, it may be difficult or very expensive to place facilities on the ocean. However, global warming and cryosphere thawing will seriously affect the stability of facilities in polar regions.

Secondly, people can directly place work facilities on ice surfaces in drilling operations. For example, drilling rigs can be placed directly on the ice surface when extracting oil or gas in polar regions, without using other equipment. In addition, during freezing periods geologists can install rigs directly on ice for drilling cores of lakebeds in cold regions. In the future, as demand for resources increases due to economic development, the abundant resources in cryospheric areas may be increasingly exploited and the cryospheric facility-bearing services may increase accordingly. However, the services will also be reduced by global warming.

Thirdly, the cryosphere provides bearing services for the construction and operation of oil pipelines and transport infrastructure (roads, railways etc.) in cold regions, because they are generally built on frozen ground [95]. Railways have played major roles in promoting regional development and maintaining prosperity in remote parts of regions such as western China, eastern Russia and western Canada [96]. Similarly, oil pipelines such as the Trans-Alaska pipeline in Alaska, Nadym-Pur-Taz natural gas pipeline network in Siberia, and Sino-Russian crude oil pipeline in Northeast China, make important contributions to regional and national economic development [97]. However, global warming will inevitably reduce foundations’ bearing capacities and the strength of connections between the foundations and soil, thus impairing the infrastructure’s stability and reduce the cryosphere’s facility-bearing service [35,98].

### 3.5. Supporting Services

Cryospheric supporting services are the benefits that humans derive from the environments supported or dominated by the cryosphere. They can be divided into three sub-categories. First, in most cold regions the cryosphere is an important environmental factor for the growth of specifically adapted biological communities, which provide food and other biological resources, namely habitat-supporting services. Second, the cryosphere provides important environmental conditions for resource generation services, i.e., formation of natural resources such as wind energy, gas hydrates and thermoelectric power. Third, the cryosphere's unique physical properties can also create some special environments (such as concealment etc.), and hence provide natural defenses for specific political and military purposes, which can be considered as geopolitics and military supporting services. It should be noted that cryospheric supporting services strongly differ from ecosystem support services, conceptually. Cryospheric supporting services are generated by the cryosphere's interactions with other environmental factors and thus contribute to HWB, while ecosystem supporting services are functional foundations for ecosystems' formation of other services (provisioning, regulating and cultural services), the final contributions of which, to HWB, are reflected in other services [32,80].

#### 3.5.1. Habitat Supporting Services

Ecosystems in cold regions are strongly influenced by the cryosphere, which provides unique habitats for animals, plants and microorganisms, and thus valuable biological resources such as medicinal materials, pasture, aquatic products, germplasm and food. Cryospheric habitat supporting services are more pronounced in polar regions, where the cryosphere has an important dominance over ecosystems.

In the polar region, the cryosphere provides habitats for diverse ice-associated organisms, including (inter alia) bacteria, fungi, microalgae, unicellular animals, birds and mammals, which photosynthesize, forage, reproduce and grow in cryospheric habitats and form unique food chains [6]. These organisms live in distinct biogeographical niches, provide abundant germplasm resources with high potential value, and some are sources of food, medicinal materials or foundations for food chains supporting fisheries. In particular, microbes in frozen soil are important components of cold ecosystems, play important roles in biogeochemical cycles of the frozen soil and are sensitive indicators of global climate change [39].

However, global warming is seriously impairing habitats in cold regions, thereby posing serious threats to associated organisms' populations and indigenous people's livelihood and well-being [58,99]. For example, the continuous decline of Arctic sea ice has increased the water area, resulting in severe threats to the habitats of Arctic animals such as polar bears, seals, and walruses. Moreover, extension of the ice-free period has caused shortages of food for polar bears, so their average weight and birth rate have declined, threatening their survival. The contraction of sea ice is also forcing Arctic animals such as walruses to migrate northwards. The thawing of the Arctic permafrost may lead to more fires and pests, reduce forests, induce expansion of lakes, grasslands, swamps, and habitats of aquatic birds and mammals, but exacerbate losses of habitats of Arctic reindeer, birds and mammals. Because of the warming of the waters, fish growth rates, the abundance and distributions are also changing [94].

The cryosphere also provides habitat services by interacting with the ocean. Cryospheric meltwater flowing into the ocean promotes circulation of cold and warm currents at high latitudes, through complex interactions involving thermohaloclines and upwelling of seawater that bring nutrients to the surface of the ocean in some places. This induces high growth rates of plankton, thus providing abundant food for fish, which generates world-class fishing grounds, such as the Hokkaido fishery in Japan, North Sea fishery in the UK and Newfoundland fishery in Canada [6].

### 3.5.2. Resource Generation Supporting Services

#### Natural Gas Hydrates

Natural gas hydrates, are ice-like crystalline materials generated by natural gas and water under low temperature and high-pressure conditions. They are mainly found in permafrost zones, seabed sediments in continental margins and deep-water sediments in inland lakes. The estimated amount of global natural gas hydrate resources is  $2.1 \times 10^{16} \text{ m}^3$ , which is twice the total estimated amount of coal, oil and natural gas resources [100,101]. Natural gas hydrates have enormous potential for development as they are clean, extremely abundant and have high utilization efficiency.

Permafrost plays an extremely important role in the generation of natural gas hydrates by providing the required pressure, temperatures and enclosed conditions for preventing upward migration and aggregation of free gas [96]. Currently, the estimated total amount of natural gas hydrates in permafrost regions is  $10^{13} \sim 10^{16} \text{ m}^3$ , mainly in high-latitude frozen ground surrounding the Arctic Ocean [96,101], the continental margins of Antarctica ( $\sim 0.97 \sim 1.63 \times 10^{13} \text{ m}^3$ ) [102] and some high-altitude areas such as the Qinghai–Tibet Plateau ( $\sim 1.2 \times 10^{11} \sim 2.4 \times 10^{14} \text{ m}^3$ ) [103].

Global warming is likely to eliminate the temperature and pressure conditions that generate natural gas hydrates, and thus cause the decomposition and release of large volumes of the substances. This may transform the hydrates from promising sources of energy and associated economic benefits, to major contributors increasing atmospheric carbon and drivers of further climate change [104].

#### Wind Energy

Wind energy is generated from the large fluxes of air across the Earth's surfaces. Thus, the amount of wind energy resources depends on near-surface wind speeds, and ultimately on atmospheric circulation at various scales [105]. Clean and abundant, the development and utilization of global wind energy resource will mitigate climate warming to some extent [106].

The cryosphere's contribution to wind energy resources is still unclear. However, it probably plays an important role in their generation. On regional scales, it probably contributes significantly to the formation and enhancement of horizontal wind-generating pressure gradients through its functions such as significant cold storage and high albedo. For example, cryosphere distributed in the polar regions, is likely to strengthen strong polar easterly winds and winter monsoons by exacerbating the difference in air pressure between high and low latitudes. The strong Tibetan Plateau monsoon may also be closely relevant to regional cryosphere. At a local scale, since the temperature above glaciers is always lower than the temperature of the free atmosphere in front of them, air consistently flows downward from glaciers at night, forming glacier winds. These winds are not generally strong or extensive, but in areas with appropriate terrain and favorable weather systems, they may be sufficient for exploitation [107]. A notable aspect of wind is that during glacial periods strong winds can massively increase concentrations of atmospheric dust, creating thick loess [108].

With further global warming, wind speeds in mid-latitude regions of the northern hemisphere such as North America, Japan, Mongolia and the Mediterranean are expected to slow as increases in Arctic temperatures weaken their temperature differences with the equatorial region. Thus, wind energy resources in these regions are expected to decline. In contrast, in the southern hemisphere, differences between land and ocean temperatures are expected increase, because of the larger ocean area, resulting in significant increases in wind energy resources in Brazil, West Africa, South Africa and Australia [109].

### 3.5.3. Geopolitics and Military Supporting Services

Due to its unique natural properties, the cryosphere also provides services that support specific human political and military aims and activities. For instance, during the Cold War, Arctic sea ice provided a natural barrier for concealing nuclear submarines [110]. However, the Arctic sea ice's crypticity will be greatly weakened by warming of the Arctic [78], which will strongly reduce

cryospheric military supporting services theoretically. Another typical example is the Siachen conflict between India and Pakistan in the Eastern Karakoram. The high altitude and extreme climate in the vicinity of the Siachen glacier, on the one hand, create a hostile environment that has caused by far the most casualties and imposed tremendous costs on both sides; on the other hand, it has provided a natural laboratory and training ground for high altitude warfare for the Indian Army [111]. In addition, protection provided by cold ice and snow may partially explain why Inuit and Sami peoples of the Arctic have survived and retained their ethnicity and culture during periods when others were slaughtered or dispossessed by European colonists. Similarly, during large-scale wars in cold regions, such as the Battle of Moscow, local troops and soldiers have often been better adapted to the natural environment than intruding enemies, which provided major advantages.

## 4. Discussion

### 4.1. Spatio-Temporal Scales of Cryosphere Services

Spatio-temporal scales of CSs are determined on the basis of temporal characteristics and spatial extent of benefits that humans gain from the cryosphere. It is essential to consider the services' supply and consumption, as well as human input, comprehensively. However, in order to reduce the complexity, here we do not consider cross-border trade and remote transmission of the services.

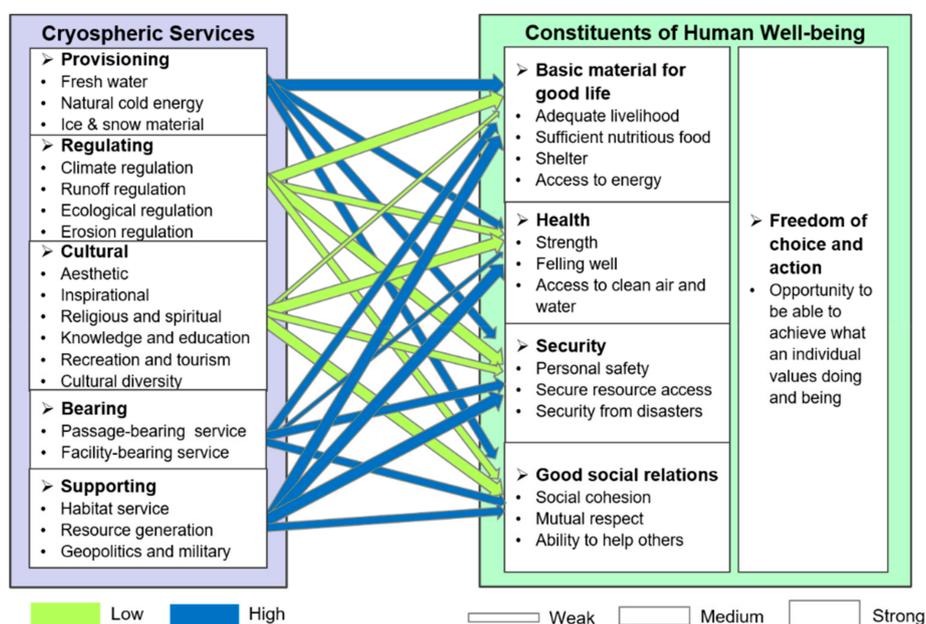
The temporal scales of CSs are characterized by sporadic, seasonal, year-round, short-term and long-term due to the differences in regional climate regime and their change, the historical stage and development level of socio-economy. On the whole, most CSs have long been associated with human history, except that human evolution and cross-continent migration mainly sporadically occurred in a specific prehistoric period. But some services are short-term for two reasons: one is the changes in socio-economic conditions, such as collecting ice for keeping things cold mainly occurs at a lower level, but the development and utilization of some bearing, resource generation-supporting and natural "cold energy" provisioning services are mainly at a higher level; another is climate-related cryospheric changes as stated above. These short-term and long-term services are also seasonal or year-round. Seasonal characteristics of the climate regimes determine the seasonality of many cryosphere services, typically such as various bearing services, skiing/ice sports, water supply and runoff regulation at lower latitudes. But others can bring benefits to humanity throughout the year, such as culture services, as well as some services at higher latitudes.

The spatial scale of CSs ranges from local to regional and global. For example, scales of freshwater provisioning services are mainly regional or local, while scales of cold energy and ice or snow material provisioning services are mainly local. Ranges of regulating services are very diverse as climate-regulating services create a suitable climatic environment for the world at global scale, while scales of runoff-, ecological- and erosion-regulating services may be regional and local. Scales of major infrastructure-bearing services are generally regional, while those of other bearing services are local. Scales of cryospheric supporting services are mostly regional. In addition, cultural diversity services are oriented towards the entire HWB, while other cultural services' beneficiaries are scattered and may be found anywhere in the world, although they are usually supplied and consumed locally or regionally.

### 4.2. Linkages between Cryosphere Services and Human Well-Being

As already stated, HWB can be divided into five constituents and both environmental and socioeconomic factors (including economic, social, cultural and technological) can influence HWB [20]. Compared with ESs, CSs contribute less to HWB, but they can nonetheless affect all aspects of HWB. Of course, there are variations in the intensity of linkages between CSs and HWB. Socio-economic factors also have different potential to mediate all types of services, for instance, if it is easy to purchase a substitute for a degraded CS, then there is a higher potential for mediation. Based on the scientific

facts reviewed above, as well as expert judgment, we here preliminarily assess the relationship between CSs and HWB (Figure 2).



**Figure 2.** Linkages between cryosphere services (CSs) and human well-being (HWB). Both environmental and socioeconomic factors (including economic, social, cultural and technological) can influence HWB. CSs is a subset of contribution to HWB, but they can affect all aspects of HWB. There are variations in the intensity of linkages between CSs and HWB. Socio-economic factors also have different potential to mediate all types of services. Green and blue arrows indicate low and high potential for socioeconomic factors, and their thickness indicates the strength of the links between the CSs and HWB.

The basic material for a good life refers to people's ability to obtain all they need for safe and adequate livelihoods without severe time constraints, including income and assets, adequate food and water, shelter, access to energy for warming and cooling, and access to goods [20]. All CSs influence the material elements of HWB, especially services like fresh water provision, ecological regulation, erosion regulation and habitat support, which make important contributions to maintaining the basic material life of local people. In today's society, substitute materials can be obtained through commodity trade. However, the potential for mediation by socioeconomic factors is relatively limited due to the low level of socio-economic development and traffic congestion in many cryosphere-affected areas. The cultural services also influence the material aspect of HWB by affecting other services, but relatively weakly.

The health aspect of HWB refers to access to adequate nutrition, energy for warming and cooling, clean water, clean air as well as freedom from disease [20]. The CSs such as freshwater provision, cold energy provision, ice and snow provision, climate regulation, habitat support and resource generation services can supply clean water, medicinal resources, clean air and energy, all of which contribute to the health element of well-being. Socio-economic conditions can moderately mediate the other services except climate regulating services. Cryospheric cultural services also make important contributions to regional human mental health, but socio-economic factors are difficult to mediate.

Safety aspects of HWB include personal safety, property safety, essential resources security and freedom from natural or man-made disasters [20]. Cryospheric provisioning, regulating, bearing and supporting services all contribute to the health element of well-being. Cultural services also have important effects on the safety by influencing social networks but are difficult to mediate. However, the others can be mediated moderately.

Good social relations refers to social cohesion, mutual respect and people's ability to help others and care for children [20]. In polar regions, people intensively depend on the natural cryosphere-dominated

environment. The cryospheric provisioning, regulating, bearing and supporting services make irreplaceable contributions to maintenance of good social relations through material, health and safety factors. Cultural services, especially religious and spiritual services, directly affect the quality of social relations. Similarly, socio-economic factors have some potential to mediate all types of services except cultural services.

Freedom of choice and action refers to individuals' abilities to control events that affect them, uphold their own values and realize their personal aspirations. It is influenced by the other four constituents of HWB (and, of course, other factors such as education) and is essential for access to other aspects of well-being (especially fairness and equality) [20]. The CSs also have important indirect effects on freedom of choice and action (such as food, shelter, transportation, education, etc.) by influencing other elements of HWB. In addition, spiritual factors such as religion in the cryosphere-affected areas profoundly affect people's value choices. Currently, socio-economic factors have relatively limited ability to mediate the well-being dimension of freedom of choice and action.

#### 4.3. Climate-Dependence of Cryosphere Services

The cryosphere is highly sensitive to climate change. Climate conditions and climate change directly affect the structure, processes and functions of the cryosphere, which in turn determines the potential of CSs.

Generally, cryospheric mass accumulates and potential available services increase when the temperature decreases and/or precipitation increases in cold regions. In contrast, if the climate continues to warm, potential supplies of various services will continue to decline and eventually disappear. However, patterns of changes will be specific for each type of service, it is not difficult to find that there are likely to be two main trajectories. Potential supplies of some (such as meltwater provisioning services) may initially increase and then weaken when a certain threshold is passed, while most other types of services will monotonously decline with warming.

The IPCC Special Report on Global Warming of 1.5 °C (SR1.5) was issued in October 2018 [112], which concluded that "human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, with a likely range of 0.8 °C to 1.2 °C; and global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate." SR1.5 also paid particular attention to the tipping elements of the Earth System and the climate change hotspots under different degrees of global warming [112]. The results showed that many of them are directly related to the cryosphere; and the risks for the cryosphere-related hotspots (such as Arctic sea ice, Arctic land regions, alpine regions and small islands, etc.) and tipping points (such as Arctic sea ice, permafrost, tundra and boreal forests, etc.) are projected to be higher for global warming of 1.5 °C than at the present, but lower than at 2 °C [112,113]. As a result, most CSs have been deteriorating and will continue to deteriorate, or be eventually lost, which can further lead to negative consequences for their associated SESs and HWB at regional or/and global scales [21]. Therefore, we must pay great attention to the changes in CSs and their cascading risks.

## 5. Conclusions and Prospects

### 5.1. Conclusion

In this study, we drew CSs as a parallel to ESs or environmental services, by describing the formation processes of CSs and their impacts on HWB using the cascading conceptual framework of "CFs-CSs-HBs-HWB". We also discussed the main perspectives and principles of establishing a classification system for CSs, that is, treating CSs as a unique set of ESs, systematically and with consideration of sustainability. On this basis, we divided the CSs into five major categories (provisioning, regulating, cultural, bearing and supporting services) and 18 sub-categories. There are differences in the formation processes of the various services and their impacts on HBs and WBs.

The temporal scales of CSs are specifically characterized by sporadic, seasonal, year-round, short-term and long-term due to variations in their associations with climatic and environmental regimes, and socio-economic development level. The spatial scale of CSs can range from local to regional and global.

CSs can impact all constituents of HWB. Cryospheric regulating services and cultural services are difficult to mediate by socio-economic factors because of the cryosphere's irreplaceability. Moreover, socio-economic factors have relatively limited potential to mediate the CSs partly because of the relatively low development level in most cryospheric-affected areas.

CSs are closely associated with the climatic regime and climate change. With global warming and cryosphere shrinkage, potential supplies of CSs have generally declined, mostly following one of two trajectories: initially increasing then declining or continually declining. The deterioration in CSs would further lead to negative consequences for their associated SESs and HWB.

## 5.2. Prospects

Research on CSs and HWB is very closely related to the concept of *Future Earth*. It can provide essential theoretical and practical foundations for extending understanding of cryospheric phenomena and enhancing social-ecological systems sustainability over cryosphere-affected areas. In this study, we have systematically addressed key scientific issues, with a view to laying theoretical foundations for further research on CSs. We propose that research on CSs in the future should focus on the following three scientific issues.

Deeply explore the relationships among CFs and CSs with four objectives. First, to further clarify the current status and future changes of CFs based on positioning observations, remote sensing and simulations. Second, to strengthen research on mechanisms linking CFs and CSs, and their future evolution through establishing coupled cryosphere and socioeconomics models and scenarios. Third, to investigate the trade-offs and synergies between different types of services. Fourth, to construct appropriate indicators of CSs in order to identify cryosphere-serviced regions of significant enhancement, relative stability, rapid decline and potential loss, to improve decision-making at national or local scales.

Conducting the evaluation of CSs for each cryosphere's element, each type of CS and functional regions to increase the public's awareness of the CSs and environmental protection, and improve government's comprehensive governance and appropriate decision-making.

Strengthen quantitative research on links between CSs and HWB based on in-depth surveys of demographic and socio-economic factors in order to provide an effective theoretical basis for improving regional HWB.

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