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Opportunities and threats of cryosphere change to the achievement of UN 2030 SDGs

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The cryosphere plays a critical role in maintaining the stability of the social-ecological system, but rapid cryosphere changes have been and are wide-ranging and have a profound affect, even threatening the achievement of the UN's 2030 sustainable development goals (SDGs). In the study, we review the opportunities and threats caused by cryosphere changes in achieving the SDGs. The results reveal that cryosphere changes are significantly related to the supply of sustainable fresh water (SDG 6), alpine hydropower (SDG 7), and climate action (SDG 13). In addition, they favorably support life on land and below water (SDG 14-15), and effectively affect the livelihoods (SDG 1-5), agricultural development (SDG 2), snow/ice tourism (SDG 8), infrastructure (SDG 9), regional inequality (SDG 10), and cities and communities (SDG 11), as well as affecting Arctic shipping routes (SDG 16). Long-term cryosphere threats far outweigh their contributions to the SDGs. The cryosphere contributes little to human emissions, but it is significantly affected by climate change. Areas affected by cryosphere changes need to strengthen resilience and enhance the ability to adapt to the influences of cryosphere changes (SDG 1-17) via financial transfer, multilateral international cooperation, and other practical policies.

Introduction

The cryosphere is a sphere on the Earth's surface with a certain thickness, within which temperature is continuously below the freezing point. The cryosphere can be divided into three components—continental, marine, and aerial—consisting of components such as glaciers, ice sheets, ice shelves, frozen ground, snow cover, sea ice, and river/lake ice. The cryosphere is the most direct and sensitive sphere in the climate system (Qin et al. 2018). Ice and snow surfaces affect the Earth's energy budget by reflecting solar radiation. For example, the Arctic forcing on the atmosphere through the loss of sea ice and land snow is increasing (Overland and Wang 2018). Cryosphere changes also affect the oceanic transport zone and the strength of ocean currents, and they affect the global climate. Projected cryosphere changes in response to past and present emissions of human-induced greenhouse gases and continued

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global warming include climate feedback, inevitable changes over decades to thousands of years, abrupt thresholds, and irreversibility (IPCC 2019).

There is high confidence that almost all of the components of the cryosphere are melting or thawing, with mass loss from ice sheets and glaciers; reductions of the snow cover extent, the extent of Arctic sea ice, and the extent and thickness of river/lake ice; and increased permafrost temperatures over the last several decades, especially in the late 20th and early 21st centuries. The predicted cryosphere retreat trend for 2015–2100 is also significant (See Supplementary Information) (IPCC 2019, 2021; AMAP 2021). Projected cryosphere changes in response to continued global warming include climate feedback, inevitable changes over decades to thousands of years, abrupt thresholds, and irreversibility (IPCC 2019). Synthesizing paleoclimate, observational, early warning signals, future model projections, underlying theory, and existing assessments, a revised shortlist of global "core" tipping elements and regional "impact" tipping elements and their temperature thresholds are provided based on the IPCC's confidence rating system. These inevitable changes and tipping points (Atlantic Meridional Overturning Circulation, the abrupt loss of Barents sea ice, collapse of Boreal permafrost, the abrupt thawing of boreal permafrost, the expansion of boreal forests, the loss of mountain glaciers, the collapse of the Antarctic and Greenland ice sheets) (Armstrong McKay et al. 2022) are or could soon affect human health and well-being, water and food security, and socioeconomic development; these are closely related to the UN's 2030 sustainable development goals (SDGs) (United Nations 2015).

The cryosphere is significantly related to water resources, the ecological environment, and the social system, upon which human beings depend. Furthermore, the cryosphere is not only an important material basis for the SDGs but is also the main factor influencing the achievement of the SDGs, such as the disaster causing body. The cryosphere region scarcely contributes to global climate warming but is severely affected by global change. In view of the inconvenient location conditions and its relatively backward economic level, optimizing cryosphere services and mitigating and preventing risks related to cryosphere changes remains the main pathway for achieving the SDGs.

Linkages between cryosphere changes and SDGs

Cryosphere change has different dimensions, such as mass, salinity, hydrology, stability, hydrothermal, freeze-thawing change, as well as the change of extent, duration, scale and intensity. Different dimensions of cryosphere change have different impacts on the human system. Cryosphere create both opportunities and challenges, which occur on the local, regional, international, and even global scales. As an important part of the Earth's system, the cryosphere's resources and environment is closely related to the human system and interacts with the SDGs. Overall, the threats posed by cryosphere changes to the realization of the SDGs outweigh the opportunities it provides (Figs. 1 and 2).

The cryosphere contributes the most to the achievement of clean water and sanitation (SDG 6) and poses the greatest threat to climate action (SDG 13). SDG 6 has the greatest synergistic relationships with other goals (Fader et al. 2018), and its implementation could make it easier to implement other SDGs. Progress on SDG 13 would reduce the risks to aspects of sustainable development that are fundamentally linked to the cryosphere and the services it provides. In addition, cryosphere changes also affect services such as clean energy development (SDG 7), sustained ice and snow tourism (SDG 8), efficient use of water resources (SDG 12), and life below water (SDG 14) and on land (SDG 15). Moreover, they influence infrastructure (SDG 9), regional inequality (SDG 10), and the sustainability of cities and communities (SDG 11). In this context, the cryosphere affects the realization of other SDGs in the future (Figs. 1 and 2).

As a water body, cryosphere changes have directly reduced the level of global water stress (SDG 6), increased the clean energy potential (SDG 7), and improved the livelihood level (SDG 1-2). The increase in ice/snow meltwater is beneficial to the development of alpine hydropower and for increasing the supply of agricultural irrigation water, so it has a positive effect on regional clean energy use (SDG 7.1-2) and drought-resistant agricultural development (SDGs 2.4, 1.4, 6.1-4, 6.6) (Masiokas et al. 2006). Conversely, when the decrease in glacier runoff exceeds a certain threshold, there is a potential threat to the achievement of these goals. In addition, the cryosphere water cycle directly affects life below water (SDG 14). For example, ice sheet mass loss has contributed a large amount of fresh water to the ocean, resulting in a reduction in seawater salinity and sea temperature; this affects the structure and function of underwater ecosystems (SDG 14.2) and fishery production as a result (SDG 14.7). Furthermore, sea level rise (SLR) caused by cryosphere melting poses comprehensive threats to coastal and low-lying island states (CLISs) and the achievement of SDGs 1–17, especially SDGs 3c, 7b, 9a, and 10b.

As a climate system, rapid cryosphere changes plays an important warning role in mitigating climate change (SDG 13) and implementing green development and consumption patterns in the future (SDG 12). For example, permafrost degradation exacerbates the release of frozen soil carbon and viruses, which affect climate change (SDG 13.3) and human health (SDG 3.9). Warning signs (e.g., tipping points) of rapid cryosphere changes (Armstrong McKay et al. 2022) help governments at all levels to deepen their understanding of the impacts of climate change (SDG 13.3) and to incorporate climate change mitigation measures into their policies and plans (SDG 13.2). Through climate action, the resilience and adaptive capacity of areas affected by cryosphere changes would be enhanced (SDG 13.1).

As economic resources (alpine hydropower, snow/ice sculptures, ice lantern art, and ice-snow-related industries), the cryosphere has effectively promoted clean energy development (SDG 7.1-2), sustainable use of ice/snow melt water (SDG 12.2), and sustained growth of snow and ice-related goods and industries (SDGs 8.9, 4.4, 4.7, 12.b), and it has improved the standards of related infrastructures (SDGs 9.1, 9.4, and 11.2). Ice/snow-related economies and industries are of great significance to the sustainable goals of eradicating poverty (SDG 1), improving livelihoods and well-being (SDG 2-3), improving quality education and learning opportunities (SDG 4), achieving gender equality (SDG 5), and decreasing regional inequality (SDG 10). Decreased snow cover even affects snow and ice tourism industries (SDG 8.9) and traditional cultural structures in high mountains and permafrost areas (SDG 11.4).

As habitats, global cryosphere supports favorably life on land and below water (SDGs 14–15) in the polar and high mountain areas (HMAs). Today, about 4 million people live permanently in Arctic cities and communities (SDG 11), 10% of whom are indigenous peoples. The mountain population in the cryosphere is at least 1 billion (IPCC 2022). Climate-driven cryosphere changes are affecting the travel, hunting, fishing, and gathering practices of indigenous people. This also has implications for their livelihoods (SDGs 1–4), health (SDGs 3.3 and 3.9), cultural practices (SDG 12.b), economies (SDGs 8.3–5, 8.9), and self-determination. Degradation of permafrost increases the moisture content of the active layer, which is beneficial to the growth of ecological vegetation (SDG 15.1). However, the replacement of tundra with taiga or shrubs has limited the Arctic reindeer industry, thereby changing traditional cultural structures (SDG

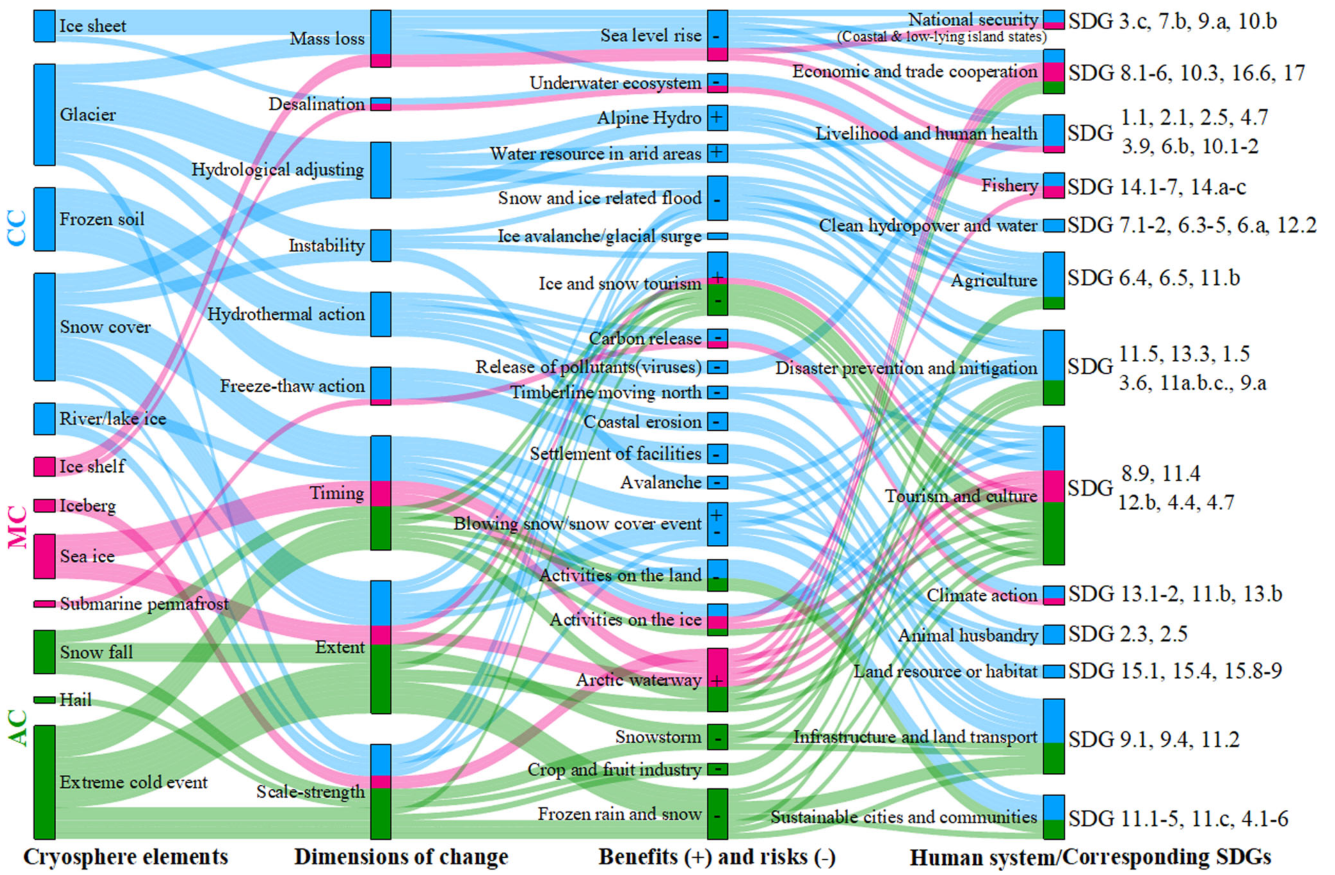

Fig. 1 Cryosphere, dimensions of change, and benefits and risks to the human system (SDGs). CC, MC and AC represent Continental cryosphere, Marine cryosphere and Aerial cryosphere, respectively. Alpine Hydro represents Alpine hydropower, GLOF represents Glacier Lake Outburst Flood. + represents benefit, while − represents risk. The heights of the columns of the different elements in the four columns do not represent the importance.

11.4). The reduction or loss of Arctic sea ice and the intensification of permafrost freezing and thawing have accelerated the erosion rate of Arctic coastal permafrost, which in turn affects the livelihoods of coastal indigenous peoples (SDGs 1.1, 1.4–5), infrastructure (SDG 9.1), residential facilities (SDG 11.1-2), habitats (SDG 15.5), and cultural heritage (SDG 11.4). In addition, erosion of coastal permafrost results in a massive loss of land resources, but there are no corresponding SDGs.

As a public territory (Antarctica and Arctic high seas), it offers opportunities for international collaboration of polar science research (SDG 17). The reduction in the Arctic sea ice extent (SIE) makes it possible to open up Arctic shipping routes and allows greater access to coastal fisheries (SDG 14.7) and offshore energy and mineral resources on land (SDG 12.2). The increase in Arctic shipping has significant socio-economic and political implications for the trade structures and economies of global and northern countries, which are closely linked to traditional shipping corridors (SDG 16). Certainly, Arctic (broad ocean) and Antarctic cryosphere changes constantly affect multi-party cooperation in fields such as the global economy, trade, tourism, and scientific research (SDGs 10 and 16).

As natural hazards, cryosphere events (ice/snow avalanche, ice and snow related flood, frozen rain and snow, snowstorm, freeze thawing, etc.) and related disasters affect the livelihood, lives, and property of people (SDGs 1–5), residences, infrastructure (SDGs 9.1, 9.4), transportation (SDG 11.2), and community safety (SDG 11) to some extent. For example, the instability of glaciers and the intensification of freezing and thawing increase the probability of the occurrence of ice avalanches, glacial surges, snow/ice floods, coastal erosion, and disasters related to the settling of facilities. In contrast, the decreases in the snow cover extent and extreme cold events (hail, snowstorms, freezing rain, and snow) reduce the occurrence of avalanches, blowing snow, snowstorms, frost, frozen rain, and snow-related disasters (SDGs 1.5, 11.5) and are beneficial to aviation safety, resident travel, and crop and fruit growth (SDGs 2.3–4, 8.2) (Figs. 1 and 2).

Cryosphere change-related opportunities to achieve SDGs

With climate warming, some opportunities presented by cryosphere changes to realize the 2030 SDGs have been significantly enhanced, these include the alpine hydropower potential, the increase in irrigation water resources in arid areas, the growth of ice and snow tourism income, and the improvement of Arctic economic trade and international cooperation.

Alpine hydropower potential. Glacier and snow cover are important and potential resources for hydropower, which is known to be a power source for economic development that is characterized by low carbon emission, reliability, and cost-effectiveness in the long term (See Supplementary Information). At the same time, ice and snow-supplied hydropower have great significance for preventing ice and snow meltwater floods and optimizing water resource allocation.

Hydropower represents a significant source of revenue for mountainous regions and comprises close to 100% of electricity generation in many mountainous countries (Gaudard et al. 2016). In some countries, more than 90% of the electricity comes from hydropower, and glacier runoff is the main source of electricity (Iceland: 91%, Norway: 15–20%). Notably, 70% of Austria's electricity comes from hydroelectricity, and many large facilities

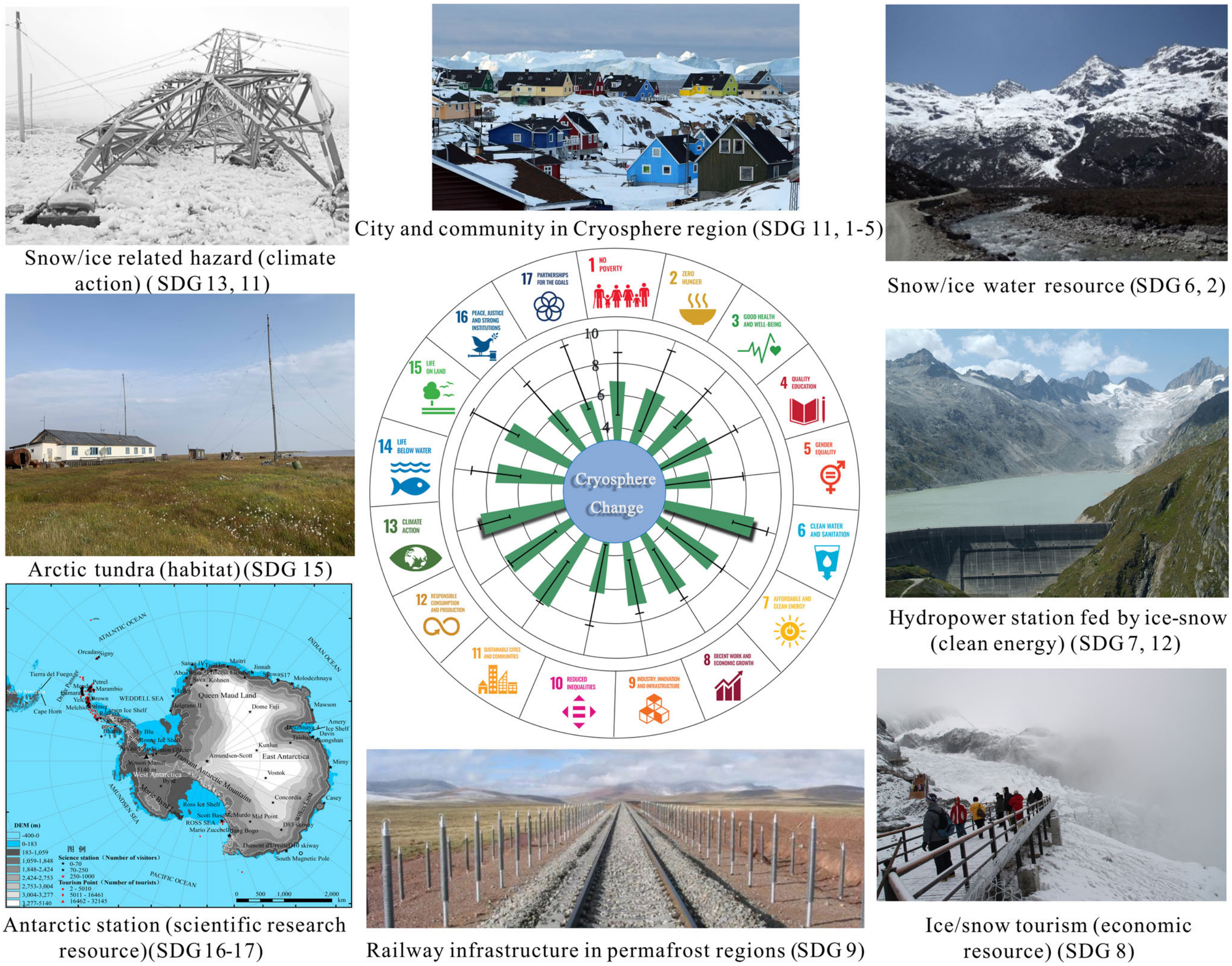

Fig. 2 Cryosphere changes and 2030 SDGs. The length of the green fan within the circle represents the relative importance of cryosphere changes to the realization of the SDGs. The upper middle photos are of Ilulissat City (taken by Chen Jian-en).

are supplied by glaciers. The Rhone River, which is fed by glaciers, has 19 hydropower stations that supply 25% of France's hydropower. 51.8% of Argentina's total hydroelectric generation in 2003 was based on the rivers flowing from the north Patagonian Andes (Farinotti et al. 2019). The Hindu Kush Himalaya (HKH) glacier-fed basins have some of the world's largest hydropower potentials, but the current utilization of these hydropower resources is still small.

The estimated results for roughly 185,000 glaciated sites worldwide are as follows: a theoretical maximum total storage of $875 \pm 260\,km^3$ and a hydropower potential of $1,355 \pm 515$ terawatt-hours per year (95% confidence interval) at present. Roughly 40% of this potential may be suitable for realization. Three quarters of the potential storage volume is expected to become ice-free by 2050, and the storage volume would be sufficient to retain about half of the annual runoff output of the investigated sites. The hydroelectric potential of the glacial basins in Nepal, Afghanistan, Bhutan, and Kyrgyzstan exceeds the current electricity consumption; however, this is partially due to the very low per capita demand. Other countries with high potential include Tajikistan (82% of current consumption), Chile (40%), Pakistan (35%), and Georgia (31%). These results also indicate that deglacierizing basins could make important contributions to the national energy supplies of several countries, particularly in High Mountain Asia (Farinotti et al. 2016) (Fig. 3).

Irrigation water resource. Snow and ice meltwater is not only a source of clean energy but is also important for agricultural irrigation in glaciated arid areas globally. More than a billion people depend on snow and ice meltwater and are affected by snow and ice resources in mountainous areas (Millan et al. 2022), most of which originate in the mountains in the Northern Hemisphere (Lievens et al. 2019; Pritchard 2019). Snow and ice meltwater has played an integral role in agriculture, drinking water, and other economic activities in arid areas (Fig. 3). Glacier and snow meltwater thereby modulates the seasonal patterns of river flow and groundwater and provides water when rainfall is scarce.

Asia's shrinking glaciers protect large populations from drought stress. About 800 million people partially depend on meltwater from the thousands of glaciers in HMAs in Asia (Pritchard 2019). In northern India, Butan, and Pakistan, most of the agricultural water comes from upstream ice and snow meltwater (Lutz et al. 2014). In the Indus, Amu Darya, and Syr Darya basins, the combined contributions of snow and glacier meltwater to annual streamflow are $69.1 \pm 1.7\%$, $84.5 \pm 1.3\%$, and $59.6 \pm 2.2\%$, respectively (Armstrong et al. 2019). In Wyoming, crop production to support the $800 million cattle industry is dependent on glacial meltwater, which provides a stable source of water during the growing season (Cheesbrough et al. 2009). In Alberta, agriculture is also dependent on meltwater from the

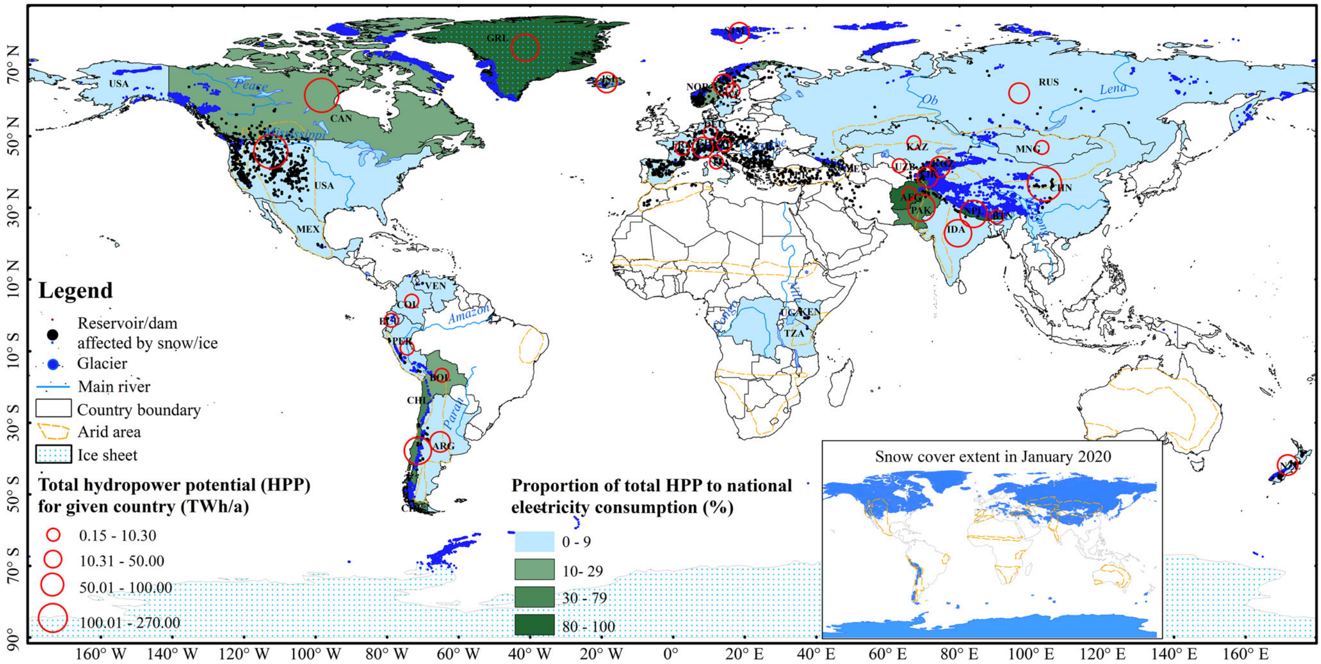

Fig. 3 Hydropower potential and reservoirs/dams affected by snow/ice meltwater. The countries are colored (green to light blue shading) according to the nationally aggregated hydropower potential based on sites with high development potential that are glaciated at present as a percentage of the present-day national electricity consumption. The pie charts show the maximum hydropower potential (pie slice size) (Data are from Farinotti et al. 2019). The reservoirs and dams that are significantly affected by snow and ice meltwater were selected (Global Reservoir and Dam Dataset, http://sedac.ciesin.columbia.edu/pfs/grand.html). The snow cover data for the Northern and Southern hemispheres were obtained from the IMS (Ice Mapping System) 4 km resolution and MERRA2 products of NOAA, respectively, and the coverage was calculated based on 50% and 1% coverage days in January 2020.

Peyto Glacier and proximal glaciers in the Canadian Rockies, which are predicted to lose 90% of their present volume by 2100 (Kehrl et al. 2014). In the Indus and Ganges basins, up to 60% of the total irrigation water during the pre-monsoon season comes from mountain snow and glacier meltwater, which contributes 11% to the total crop yield. Snow and glacier meltwater provides enough water to grow food crops and sustain a balanced diet for 38 million people (Biemans et al. 2019). In Bolivia, 27% of La Paz's water consumption during the dry season is supplied by glacial meltwater from the Cordillera Real; and 40% of the discharge of the Rio Santa, which drains the Cordillera Blanca in Peru, is from glacial runoff, providing extensive irrigated areas along the dry Atacama coast as well as 5% of Peru's electricity (Bradley et al. 2006; Chevallier et al. 2011). In the Shule River basin on northwestern China, a representative area of global glacier-covered arid areas, the existence of glacial meltwater reduced the basin water stress (freshwater withdrawal as a proportion of available freshwater resources) by an average of 0.71 during 2000 and 2030 (Wang et al. 2021).

Ice and snow tourism. Ice and snow resources not only provide essential resources/services in the form of water for human use and climate regulation but also support the ice and snow-related tourism industry and produce huge economic benefits (Schrot et al. 2019). The rapid cryosphere changes have increased the diversity of cryosphere landscapes, while the rapid decrease in sea ice extent has increased the travel time and travel scope in the Arctic. During 2000–2018, the number of skiers worldwide ranged from 300 million to 360 million (Fig. 4), of 400 million when indoor ski resorts are included (Vanat 2019) (See Supplementary Information). In Europe, the growth of alpine skiing and winter tourism after 1930 resulted in major economic growth and transformed winter sports into a multi-billion USD industry (Denning 2014). In the past few snow seasons (2000–2018), the La Plagne Ski Resort in southeastern France has been the ski resort with the highest number of skiers in the world, with an annual average of approximately 2.4 million skiers (Vanat 2019). For glacier destination, at present, more than 100 well-known mountain glacier resorts around the world serve as natural attractions. Some of these glacier tourist sites are World Heritage Sites or major attractions (See Supplementary Information). During the tourism season in 2018–2019, a total of 55, 489 people arrived in Antarctica. In China, glacier tourists in the Yulong and Gongga Snow Mountains exceeded 5.56 million in 2017, which is far greater than those of other glacial destinations (Wang et al. 2020a; Wang et al. 2020b).

With the improvement of infrastructure and the increase in leisure time, glacier tourism destinations have extended to include the Polar Regions. In recent years, the Arctic channel has opened earlier and traffic conditions have greatly improved as a result of global warming. In the next 30 years, it is likely for the Arctic to have ice-free summers. The increase in the number of tourists will greatly promote the economic benefits of the Arctic region, promote the employment of surplus labor in local communities, and have far-reaching significance for cultural dissemination and exchange. In 2017, the number of inbound visitors in the noted regions reached 66.37 million, of which Russia and Canada accounted for a large share of tourists, accounting for 68% of the total number of tourists visiting the Arctic (Wang et al. 2015). In 2017, the number of tourists in snow-covered Greenland, Svalbard, and Iceland (only cruise passengers) reached 50,000, 102,000, and 402,834 (AMAP 2019) (Fig. 4).

Arctic economic trade. Sea ice not only provides an essential habitat for polar species and supports the livelihoods of people in the Arctic, but it also aids or hinders energy and mineral resource development and international economic, trade, and tourism exchanges in Pan-Arctic regions (Nilsson and Larsen 2020). The

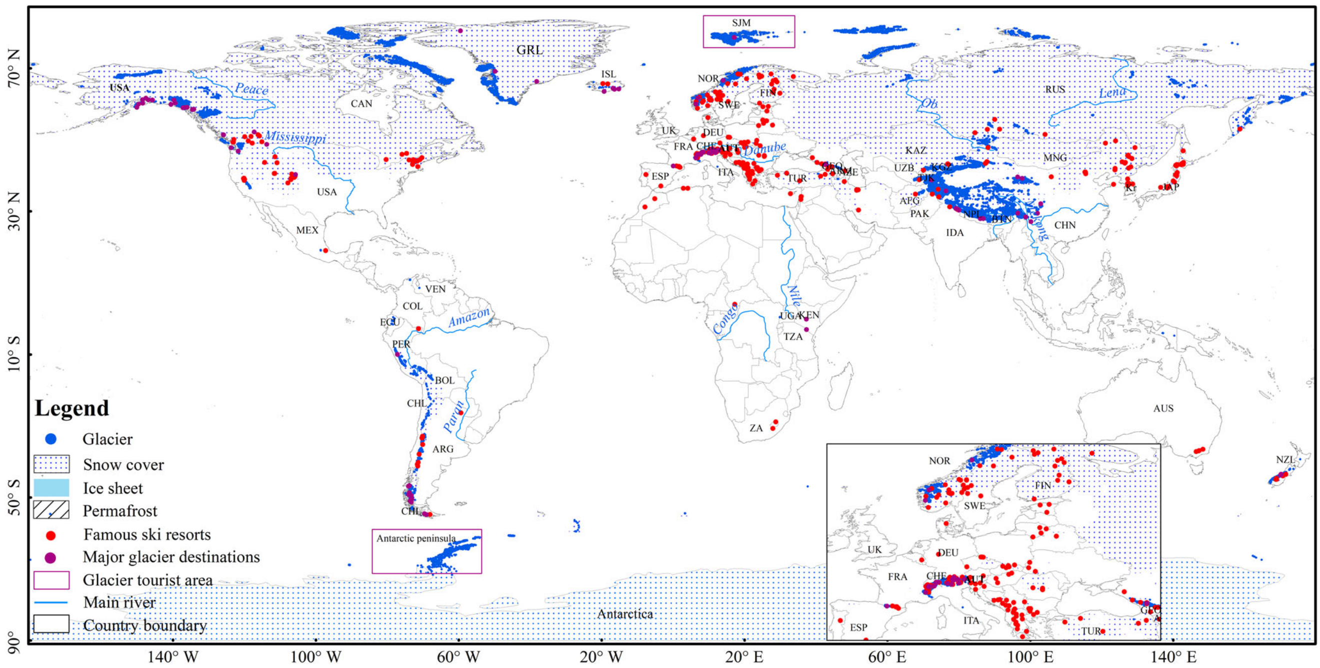

Fig. 4 Major ski resort and glacier tourist destinations around the world. The extent of snow cover was calculated based on 50% and 1% coverage days in January 2020.

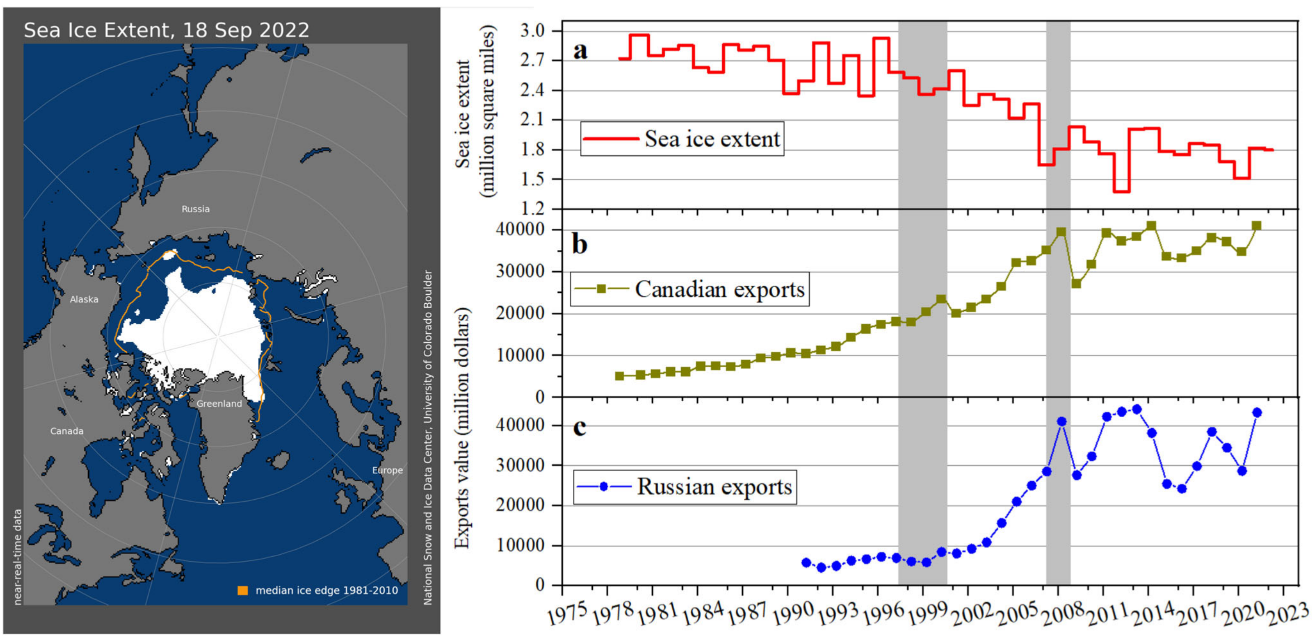

Fig. 5 Arctic sea ice and export trade change. Arctic sea ice on September 18, 2022 (https://Nsidc.org), average monthly September arctic sea ice extent, and average monthly September export value in Canada and Russia during 1979–2021 (Data source: Organization for Economic Co-operation and Development).

loss of sea ice means greater access to the Arctic for fishing, resource extraction, and transport and the potential for trans-Arctic trade (Bennett et al. 2020). Arctic sea ice likely reached its minimum extent for the year (1.80 million square miles) on September 18, 2022. The 2022 minimum was the 16th lowest in the nearly 44-year satellite record. The average monthly September Arctic sea ice extent exhibited a decline of 2.5% per decade during 1979–2022 relative to the 1981–2010 average (https://Nsidc.org) (Fig. 5). Arctic shipping routes are fully navigable by the end of summer (Smith and Stephenson 2013; Richter-Menge et al. 2019). Compared to the existing Suez Canal Route, Arctic shipping routes would be economically attractive, provide a viable opportunity for international trade in Western Europe and East Asia, and shorten the shipping distance from Asia to Europe by 40% (Lee and Kim 2015; Kim and Sur 2020), as well as reducing the distance between the east and west coasts of the United States. The increasing global demand for natural resources and the potential for the exploitation of Arctic resources have made Arctic shipping routes a focus of attention (Melia et al. 2016; USGS 2008). The seasonal thin ice and ice-free conditions determine the feasibility of waterways and seasonal roads (Mullan et al. 2017) as well as the timing of mineral and oil and gas exploration (Schaeffer et al. 2012). During 2013–2019, the Arctic shipping volume increased by 25%, and the total distance traveled increased by 75% (Masiokas et al. 2006).

Compared with the decrease in the sea ice extent, exports from Canada and Russia significantly increased during the same period (September), with a significant negative correlation. In particular, the correlation has become stronger since 2005 (Fig. 5). Over the last decade, the gross tonnage transported using the Northern Sea Route has increased by 79% (Babin et al. 2020), and ship traffic along Arctic shipping routes has tripled (Dawson et al. 2018). These trends are expected to continue as sea ice declines further, and a transpolar route directly across the Arctic Basin may even become a viable option by the middle of the century (Melia et al. 2016). For example, the relationship between the annual number of voyages (of all vessel types) and the sea ice extent over the northern routes in the Canadian Arctic region has a strong negative correlation coefficient ($r = -0.54$, $P = 0.01$). This relationship supports the hypothesis that sea shipping traffic has a negative effect on sea ice (Pizzolato et al. 2014; Hussain et al. 2021).

Threats posed by cryosphere changes to achieving SDGs

The greatest threats posed by cryosphere changes and their cascading effects on the achievement of the 2030 SDGs include livelihood, health and safety, cryosphere tourism and culture, land infrastructure and transportation, land resources, habitat, and homeland security.

Livelihood, health and safety. The indigenous peoples such as the Inuit-Aleutian in Alaska, Canada, and Greenland; the Sami in Northern Europe, the Nenets in Russia; and the Yakut, Chukchi, Native Americans, and Tibetans are distributed in the Arctic and HMAs (Larsen and Fondahl 2015). Their livelihoods, health, and safety are highly dependent on the cryosphere and its environment. Sea hunting, transportation, reindeer husbandry, hunting, fishing, gathering, and nomadism are their traditional means of livelihood. Rapid cryosphere changes are harming their livelihoods, drinking water, health and well-being, food security, and the safety of their lives and property (Yoo et al. 2021).

Winter activities on ice are a defining component of winter culture and identity in northern countries, contributing food through ice fishing, winter transportation on ice roads, and recreational activities, such as ice skating. However, poorer ice conditions and a longer open water season increase the likelihood of falling through the ice (Sharma et al. 2020), increase the risk of hunting, shorten the hunting period, and impact fishing options (Ford et al. 2019) and waterfowl hunting, resulting in a decline in traditional foods and a change in traditional lifestyles. Sudden reductions in food production and access, combined with reduced dietary diversity, have led to increased malnutrition among indigenous peoples (Masiokas et al. 2006). Melting ice, thawing permafrost, and degrading ice/snow may accelerate or release various pollutants and viruses such as persistent organic pollutants (POPs), polychlorinated biphenyls (PCBs), dichlorodiphenyl-trichloroethane (DDT), polycyclic aromatic hydrocarbons, microplastics, mercury, radon, and heavy metals, and even Mollivirus or Pithovirus sibericum (Van Oostdam et al. 2005; Ezhova et al. 2021), leading to safety issues regarding water quality and increased risk of waterborne disease transmission (Legendre et al. 2015; Schaefer et al. 2020; Bogdanova et al. 2021; Wu et al. 2022; Zhang et al. 2022). Indigenous peoples in cryosphere areas are facing dilemmas related to the risk of poverty and coping with environmental change (Ford et al. 2020; Huntington et al. 2021).

In particular, cryosphere disasters affect the lives, livelihood, and property of indigenous peoples in the Arctic and local peoples in HMAs at middle-low latitudes (Haeberli and Whiteman 2021; Wang et al. 2022). In February 2012, Eurasia experienced extreme cold and heavy snow, and the extreme weather killed more than 300 people. On February 7, 2021, a catastrophically large glacial and rock avalanche caused widespread damage and severely damaging two hydropower projects, over 200 people were killed or are missing in the Chamoli region of Uttarakhand, India (Wang et al. 2022). Past glacial lake outburst flood (GLOF) disasters have directly caused at least seven deaths in Iceland, 393 deaths in the European Alps, 5745 deaths in South America, and 6300 deaths in Central Asia (Carrivick and Tweed 2016). During 2012–2016, at least 350 people were killed by avalanches in Badakhshan Province in northeastern Afghanistan. In late June 2013, heavy rains and the rapid melting of alpine snow caused flooding in Alberta, Canada. More than a dozen cities declared a state of emergency, more than 100,000 residents were evacuated from their homes, five people died, and the related economic losses amounted to $6 billion (Pomeroy et al. 2016). Future climate change could lead to increased flooding in high mountains and the Arctic (IPCC 2019), which could put the livelihoods of about 10% of the world's population (living in the region) at great risk.

Cryosphere tourism and culture. Cryosphere is an important resource for developing tourism, such as ice and snow landscapes and their culture created by cold environment for a long time (Wang and Qin 2015; Motschmann et al. 2020). Out of a total of 247 World Heritage natural sites recognized for their outstanding universal value, 46 sites contain glaciers within their boundaries, and the presence of glaciers is stated among the principal reason (five sites) or secondary reason (28 sites) for World Heritage Site designation (Bosson et al. 2019). Overall, the impact of climate change on the cryosphere is much smaller than the benefits from cryosphere tourism.

The most significant impact of ice and snow changes is the decline in the landscape quality and even the disappearance of these landscapes (Omoto and Ohmura 2015; Huss et al. 2021; Salim et al. 2021; Vuille 2013; Falk 2016). In September 2018, white sheets were installed at the lower glacier margin to protect an ice tunnel for tourists (Huss et al. 2021). Several studies have also taken glacier tourism as a symbol of last-chance tourism due to glacier retreat worldwide (Salim et al. 2021). Bolivia's Chacaltaya Glacier, the world's highest ski resort, has completely disappeared, and its summer skiing function was lost in 2009 (Vuille 2013). Glacier recession, broken ice surfaces, insufficient snow, snowstorms, and snow and ice avalanche hazards lead to a decline in ice and snow tourism activities, changes of ice climbing and ice hiking routes and can even cause disasters in ice and snow tourist areas (Mourey et al. 2019). The skiing industry is highly sensitive to weather and climate change, and rapid warming directly affects the amount of snowfall, snow depth, artificial snowmaking, and length of the ski season (Steiger et al. 2019). During the 38 years from 1982 to 2020, the snow cover extent and duration exhibited overall negative trends of $-3.6\% \pm 2.7\%$ and -15.1 days ± 11.6 days, respectively, in global mountainous areas (Beaudin and Huang 2014). Some ski resorts have closed due to unfavorable snow conditions brought about by climate change and/or the associated need for large capital investments to increase their snowmaking capacities (François et al. 2023). The number of ski resorts in Norway (currently 110 alpine ski resorts) would be cut almost in half in the 2030 s, and the ski season is

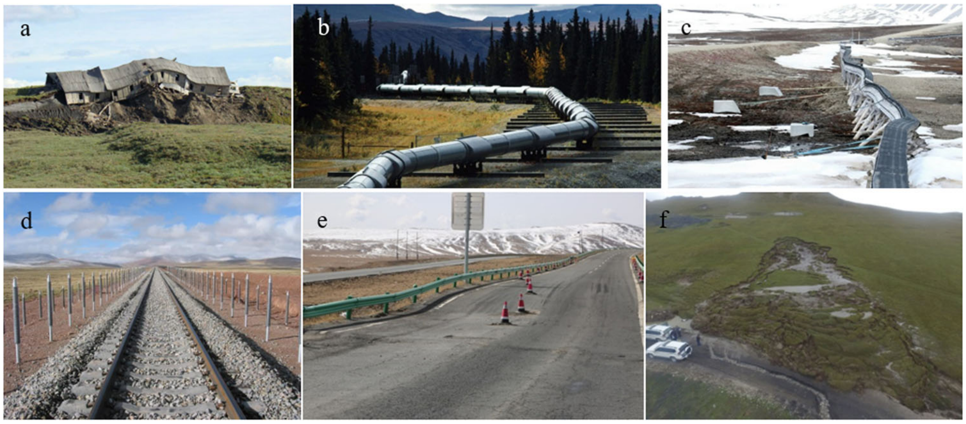

Fig. 6 Different types of infrastructure damages due to permafrost degradation. **a** Damaged army barracks on the Yenisei River, Russia (photo by Zhang Ze), **b** damaged roads in northern Canada (photo by Zhang Ze), **c** Trans-Alaska pipeline, Alaska, in the Arctic (photo by Kwaisi France), **d** the Qinghai-Tibet Railway, **e** highway and other roads at risk of land subsidence (photo by Tai Bowen), **f** thaw slumping on the QTP (photo by Luo Jing).

expected to be significantly reduced. Substantial shortening of the ski season (up to 40 days) would begin in the 2050 s under a high-emission scenario (Scott et al. 2019). Without snowmaking, 53% and 98% of the 2,234 ski resorts studied in 28 European countries are projected to be at very high risk for snow supply under global warming of 2 °C and 4 °C, respectively (François et al. 2023).

Climate change has had dramatic impacts on cryosphere cultures. There is high confidence that glacier retreat is negatively affecting cultural beliefs and practices in HMAs (medium evidence, high agreement) (Mukherji et al. 2019). In the Peruvian Qullqipunqu Mountains, thousands of pilgrims gather to celebrate the Snow Star Festival (World Intangible Cultural Heritage) each summer and worship their sacred glaciers. Permafrost degradation has led to shrub invasion on the tundra, which has reduced the grassland suitable for reindeer grazing and the reindeer population. This has affected the traditional food structure and cultural and social relationships of indigenous peoples (Bogdanova et al. 2021). Permafrost degradation and coastal erosion have also endangered monuments and ruins. A decline in snow and ice and an increase in intangible harm to people from snow- and ice-related hazards has accelerated the loss of cultural values in snow-covered mountainous regions (medium confidence) (Allison 2015). Rapid changes in sea ice are directly affecting the mental, cultural, and social well-being and the values of Arctic Inuits, whose lifestyles (e.g. access to culturally significant places) often rely on sea ice (Baztan et al. 2017; Rosales and Chapman 2015). Moreover, unsafe ice conditions have a great impact on the eating habits, hunting style, and social style of local residents. In order to fight for living space and human rights, the Inuit people have urged the eight Arctic countries on different occasions to actively promote climate change mitigation actions to enhance climate resilience (Watt-Cloutier 2005).

Land infrastructure and transportation. Cryosphere changes often threaten land infrastructure (e.g., railways, highways, oil/gas pipelines, power transmission, and transformation projects, optical cables, ports, drilling platforms, buildings, ports, airports, and ice load) and transportation safety on different temporal and spatial scales (AMAP 2021; Melnikov et al. 2022). Glacier surging, ice/snow avalanches, glacier floods, and GLOFs mainly affect reservoirs, hydropower stations, and roads downstream. Freeze–thaw events mostly affect the structure and stability of aboveground structures in permafrost areas. Sea ice mainly affects ports, ice engineering and offshore drilling platforms, farming facilities, and wind power equipment (Jin et al. 2021). Snowstorms often affect air transport and safety (Coleman and Schwartz 2017), and blowing snow affects land transportation and safety. Freezing rain and snow mostly affect electric power lines and transportation (Ohba and Sugimoto 2020). Among these events, freeze-thaw events have the greatest and most extensive impacts on infrastructure (Biskaborn et al. 2019).

Freezing and thawing events often damage roads, lines, and pipeline network engineering, as well as buildings, in permafrost areas, leading to cracks, deformation, and the collapse of structures (Streletskiy et al. 2019). To date, Russia has built the most basic buildings in the Arctic permafrost region, covering an area of about 700 km^2, followed by Canada and Alaska (Bartsch et al. 2021), and approximately 70% of the infrastructure (residential, transportation, and industrial infrastructure) surrounding the Arctic is located in areas where the permafrost is projected to thaw by 2050 under representative concentration pathway (RCP) 4.5 (Hjort et al. 2018). In these areas, some communities have already begun to report the deformation of buildings and structures and the potential relocation of communities from these combined forces of erosion and permafrost thawing (Kotov and Khilimonyuk 2021). By 2050, these high-risk environments could encompass one-third of the existing Pan-Arctic infrastructure. Onshore oil and gas extraction and transportation in the Russian Arctic are at risk, and 45% of oil and gas production in the Russian Arctic is located in the most dangerous areas (Karjalainen et al. 2019). Even without further expansion of Russia's existing network, the total cost of road infrastructure maintenance due to permafrost degradation is expected to reach US $7 billion during 2020–2050 (Hjort et al. 2022). On the Qinghai-Tibetan Plateau (QTP), deformation or damage has occurred to roads, power transmission infrastructure, and oil pipelines in the permafrost region (Fig. 6).

There have been recent instances of severe reduction of the period when ice roads can be built and utilized due to unusually warm conditions in the early winter in northern Alaska and other regions of the Arctic (Gadeke et al. 2021). In particular, the degradation of permafrost has affected or threatened transportation accessibility in Russian Arctic settlements, and Building relocation, repair work, strengthening foundations, and jacking up of settled structures have to be conducted annually (Lytkin et al. 2022).

Land resources, habitats, and homeland security. The most serious impact of cryosphere changes is the loss of terrestrial habitats and national security due to the loss of national territory. Among them, the main dangerous factors causing the above two

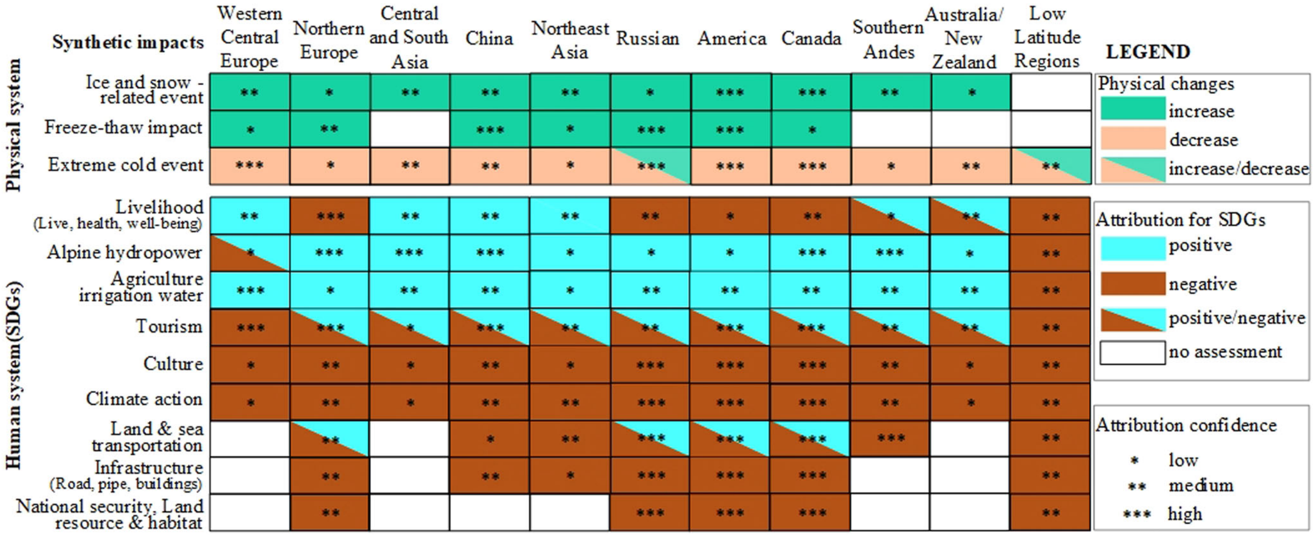

Fig. 7 Effects of cryosphere changes on achieving the SDGs on different spatial scales. Observations are only documented in scientific literature, but the impacts may also be experienced elsewhere. For the cryosphere changes, yellow and green denote increases and decreases, respectively, in the amount or frequency of the measured variables. For the impacts of cryosphere changes on human systems, blue and brown indicate positive (beneficial) and negative (adverse) impacts. The confidence levels with the asterisk refer to the confidence of the attribution to cryosphere changes (The larger the number of publications and the higher the consistency of the conclusions, the higher the reliability is). No assessment means: not applicable, not assessed at the regional scale, or the evidence is insufficient for assessment.

impacts are the erosion of coastal Arctic permafrost and SLR. Coastal permafrost erosion directly affects terrestrial resources, while SLR affects the national security of CLISs.

Arctic permafrost coasts account for 34% of Earth's coasts (Fritz et al. 2017). Rising temperatures thaw the permafrost, and the lack of sea ice increases exposure to storm waves, leading to rapid coastal erosion. The greatest impact of coastal erosion is the loss of land resources, followed by habitat loss and the destruction of communities and infrastructure, which eventually leads to the relocation of coastal communities (Hamilton et al. 2018; Schädel 2022). The current coastal erosion rates in the Canadian Arctic are six times greater than the average rate over the past 65 years, with qikiqtaruk-Herschel Island in the Canadian Arctic being eroded by waves at a rate of up to 1 m per day as a result of a warming climate that has extended the duration of coastal sea-ice free periods (Cunliffe et al. 2019). The mean erosion rate in the Arctic could roughly double by 2100 and very likely exceed the historical range of variability by the middle of the 21st century. The coastal erosion rate could increase from 0.9 ± 0.4 m/year during the historical period (1850–1950) to between 2.0 ± 0.7 and 2.6 ± 0.8 m/year by the end of the 21st century (2081–2100) (Nielsen et al. 2022).

Since the mid-19th century, the rate of SLR has been higher than the average rate over the past two millennia. Moreover, since 2003, the amount of meltwater in the cryosphere may exceed the thermal expansion of seawater and become the most important contributor to SLR. SLR has become the biggest threat to CLISs (Hallegatte et al. 2019). SLR preferentially affects the territorial integrity and habitability of CLISs. In addition, SLR may also cause storm surges to inundate the shore, affecting tourism activities, freshwater resources, agricultural resources, aquaculture, and residents' lives in CLISs. Moreover, flood disasters may increase, and events such as seawater intrusion are likely to occur. Low elevation coastal zones are the most affected by SLR, with more than 310 million people living in areas exposed to rising sea levels and suffering tens of billions of dollars in damages each year (Wahl et al. 2017). Roughly, 1.3% of the global population is exposed to once-in-a-century floods (Muis et al. 2016). In particular, SLR could also increase the risk of relocation for some small island states. In 2001, the leader of the Pacific island country Tuvalu issued a statement that failure in the fight against SLR could lead to the relocation of the entire country to New Zealand, and Tuvalu could become the first country to be relocated due to SLR (Walsh et al. 2012). The Pacific island countries of Kiribati, Tokelau, Anguilla, Nauru, Western Samoa, the Turks and Caicos Islands, and other island countries face the same fate.

Synergy and trade-off between cryosphere change and the SDGs

The cryosphere provides great opportunities and services to human society in terms of habitat, freshwater, renewable energy, tourism, culture, and transportation for the human system; however, widespread cryosphere-related events are endangering human well-being and health in mid-to-high latitude and high mountain regions (Wang et al. 2022). Culture, land transportation, and infrastructure are negatively affected by cryosphere changes, while alpine water conservancy, hydropower, and irrigation water would benefit from cryosphere changes in the current stage. Regarding tourism and livelihoods, cryosphere changes present both benefits and risks. At spatial scales, the cryosphere environments around the Arctic region in Russia, Canada, Alaska, and Northern Europe are similar and have homogeneous types of social impacts. Cryosphere changes seriously affect Arctic indigenous peoples' livelihood, land transportation, infrastructure, land resources, habitats, traditional culture and socio-economic structure (Nilsson and Larsen 2020; Larson and Fondahl 2015), but they have increased the potential for alpine hydropower, irrigation water, and sea transportation. In particular, regional inequality within Arctic countries also needs to be improved. China, Central, and Southern Asia currently have a high dividend of cryosphere changes, which needs to be optimized to improve the economic and social benefits. The low latitude area is mainly affected by SLR, and the impact is omnidirectional. Opportunities (positive impacts) and threats (negative impacts) are often mixed and the achievement of the SDGs depend on future cryosphere change trend and our adaptive capacity (Fig. 7).

The benefits and risks of cryosphere changes to the achievement of the SDGs coexist, and there is a possibility of mutual transformation. Cryosphere changes provide certain opportunities in the short-term, such as providing clean energy in high mountains, agricultural water resources in arid regions, and tourism in cold regions. However, they could turn into threats in the long term. Similarly, the threats (especially cryosphere disasters) could become opportunities through reasonable early risk warning, prevention, and control. Ice-snow meltwater is an important water resource in arid areas and facilitates the water-food-energy nexus. Enhanced meltwater can increase the supply of irrigation water (SDG 6.4-5), increase the alpine hydropower potential (SDG 7.1-2), largely offset hydrological drought-like conditions, increase food production (SDGs 2.3–4), reduce fossil fuel use, and improve human livelihood and welfare. However, the increase in clean energy from meltwater could significantly reduce the amount of agricultural irrigation water and could thus affect food production. The decrease or disappearance of ice and snow meltwater could have major consequences and even cascading impacts on water availability for people and economies, contributing to an increase in tension and even conflicts (SDG 6.5) over water resources, especially in seasonally dry regions and international basins, such as the Andes, HKHs, and Central Asia, where the flows of many dry-season rivers depend on ice-snow meltwater (Rasul and Molden 2019; Haeberli and Weingartner 2020). Especially, the loss of Arctic sea ice has increased the length and extent of navigation, while also increasing the global geopolitical game around the Arctic.

In addition, permafrost degradation can affect people's livelihoods and health, infrastructure, transportation, cities and communities, habitats, and cultural structures (SDGs 1–5, 9, 11, 14–15). By 2050, in almost half of the 1,162 existing settlements, permafrost is likely to degenerate and then disappear altogether. This would drastically change the lives of more than three million people. Especially, more than half of the land on which oil and gas production, mining and similar activities take place is also at risk of permafrost degradation (GRID-Arendal 2023); meanwhile, coastal erosion in ice-rich areas has caused some mammoth fossils to be exposed, providing a business opportunity for local residents to collect new fossils (Doloisio and Vanderlinden 2020). Decreased snow cover reduces the probability of snow disasters (SDG 13.1) and the pressure of disaster prevention and mitigation (SDGs 9, 11). However, this increases the energy consumption and cost of artificial snow production (SDG 12.2), increases the pressure for climate action (SDG 13), and even affects cultural structures associated with snow (SDG 11.4). The beneficial aspect of sea ice reduction is that it increases access to food sources (SDG 2) and reduces the risk of productive activities on the ice (Huntington et al. 2021). However, the loss of sea ice has altered indigenous hunting and fishing cultures and diets to some extent (SDG 2).

Adaptation strategies

The changes in cryosphere may lead to both opportunities and threats. Using of advantages and avoiding of disadvantages of these changes are fundamental principles for adapting to the impacts of cryospheric change and promoting sustainable development in the future. In the scenario of current warming, some opportunities from the cryosphere will decrease and even turn into risks. Therefore, mitigating climate change is the only strategy. Action to mitigate climate change, such as carbon neutrality, is undoubtedly a long-term and effective response measure to address the impacts of cryospheric change (Huang and Zhai 2021). Of course, the following adaptive measures also need to be supplemented.

Enhance the applying value of alpine hydropower and irrigation resources from ice and snow. Ice and snow resources are important water sources for alpine hydropower and agricultural irrigation, which have played a huge economic benefits in the past. In the future, based on the changing trend of alpine ice and snow runoff, we should vigorously develop the hydropower resources of snow and ice, utilize the peak shaving and dry replenishment functions of alpine reservoirs, and enhance the hydropower value of alpine snow and ice.

Optimize the spatial layout of ice and snow tourism and strengthen the inheritance of cryosphere culture. Ice and snow tourism are mainly concentrated in the Alps, the Rocky Mountains and Japan, whereas rich cryosphere culture is located in the Northern Europe, the Russian and Canadian Arctic regions and the Tibetan Plateau. On the spatial scale, ice and snow tourism needs to be extended to more areas covered by cryosphere culture and other ice and snow resources. The fragile cryosphere culture needs to strengthen its cultural inheritance and development through ethnic autonomy and national policies.

Improve the welfare and health level of the people lived in the cryosphere area. Because industry in the cryosphere region is single, and the ability of the public to cope with the impact of the cryosphere changes is limited, increasing the welfare and health levels of the people in the cryosphere region is an important measure to enhance climate resilience, in which the poverty eradication has the strongest synergy with the UN 2030 SDGs goals (Bie et al. 2023).

Increase import and export trade in the Arctic Ocean and ensure safe land transportation. The retreat of the cryosphere is beneficial for Arctic maritime navigation, but unfavorable for Arctic land transportation. For maritime shipping, Arctic and non-Arctic countries need to reshape international economic and trade relations, utilize advantage of the benefits of sea ice decrease, and increase import and export trade. For land transportation in the cryosphere area, the main approach is to improve road levels through engineering measures for ensure safe transportation.

Adopt multiple engineering measures to reduce the coastal erosion rate of permafrost areas and the threat from sea level rise. On the one hand, changes in the cryosphere cause erosion of the permafrost coast around the Arctic, and on the other hand, changes in the cryosphere and ocean thermal expansion have led to sea level rise. Both will increase the reduction of coastal habitats, building facilities, and land resources. To reduce these threats, measures such as coastal reinforcement mode, relocation mode, land reclamation, flood protection and ecological restoration mode (coastal ecological restoration) need to be implemented in the long term.

Conclusions

The cryosphere contributes the least to climate change, but the cryosphere region is most severely affected by climate change. Global emission reduction is undoubtedly the best way to mitigate the impacts of cryosphere changes. Sustainable development paths in cryosphere regions need to be based on regional characteristics. The countries around the Arctic are not only developed but also have problems regarding the livelihood and health of the indigenous people. This development includes coordination of the imbalance in domestic and regional development (SDG 10). Financial transfer payments, technology transfer, and cooperation and exchange assistance are the main pathways for sustainable economic and social development in indigenous areas. As a global public domain, the implementation of the permanent validity of the Antarctic Treaty in future sustainable development is the basis for the peaceful use of Antarctica. Thus, it is necessary to strictly enforce Antarctic Treaty and Antarctic Environmental Protection Protocol and strengthen international multilateral cooperation for using peacefully and effectively Antarctic continent and the Southern Ocean (SDGs 16–17). The high mountain areas at middle and low latitudes outside Polar regions have fragile ecologies and singular industrial structures, cryosphere change events are more frequent, and the ability to deal with these changes is extremely limited. There is an urgent need to promote ecological protection and improve the welfare, education level, and health standards of local residents (SDGs 3, 4) through a series of ecological protection policies (SDG 15). In addition, it is necessary to strengthen disaster prevention and mitigation measures to mitigate global cryosphere disaster losses in high mountain areas to improve the capacity of cities and communities (SDGs 11, 13) to cope with disasters.

Currently, the melting of the cryosphere is significant, with frequent occurrences of cryosphere events, and its negative effects tend to intensify, seriously affecting the process of sustainable development. The conclusion of the impact and irreversibility of climate change and even cryosphere change is very clear. The most urgent task is to implement the implementation of carbon neutral, climate resilience and sustainable development policies and plans.

Data availability

Data will be provided by the authors upon request.

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