ONE PLANET POLAR SUMMIT

Scientific Statement on Cryosphere of the Paris Call for Glaciers and Poles

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Science of the state of the cryosphere calling for international stewardship

INTRODUCTION

The cryosphere of mountain and polar regions bears a critical importance for the energy balance of the planet, the water cycle, climate feedbacks, biodiversity and human societies. But with continued global warming, ice sheets and glaciers are shrinking, sea-levels are rising, permafrost is thawing, snow covers are decreasing, sea-ice is melting, and the polar oceans are warming. Two billion people and two thirds of irrigated agriculture depend on runoff contributions from mountains, often originating from glaciers. By 2050, one billion people in the low-lying coastal zones will be exposed to consequences of sea level rise generated in a large part by melting ice sheets of Greenland and Antarctica.

The last IPCC reports and follow-up scientific studies highlight the role of the cryosphere as early warning system of global warming, show gaps in risk assessments, and in global and local mitigation and adaptation, notably through water management. The loss of cryosphere components is accompanied by local hazards and amplified regional and global extremes. The consequences are not yet included in estimates of the social cost of carbon emissions or insurability. It is imperative to keep the cryosphere in balance and prevent self-reinforcing processes with cascading impacts that cannot effectively be halted or reversed.

Thus, cryosphere scientists call for international stewardship in risk management. 2023 saw an exceptionally low cover of winter sea ice around Antarctica (-17% in June 2023 compared to average), leading to failure of reproduction of emperor penguins. Disturbances related with wildfires have increased in the Arctic compared to the mid-20th century. In 2021-2022, based on 37 reference glaciers, glacier mass loss was around 20% higher than the average of the last decade, with particular extremes in the European Alps, high-altitude regions of Asia, the North American west, South America and parts of the Arctic. New studies reveal that today's 1.2°C warming could trigger a slow by certain loss of part of the West Antarctic ice sheet over coming centuries, even with no additional warming beyond current temperatures. Such observations call for immediate action and coalitions to combat the risks of melting ice on our planet.

The following statements[1] on glaciers, sea ice, polar oceans and permafrost summarize the perspectives of international science as discussed at the One Planet – Polar Summit, November 8th and 9th, 2023. The scientists call for urgent political and socioeconomic action, and for new ambitious international and interdisciplinary approaches to reduce uncertainties and tackle unknowns in feedback mechanisms between the cryosphere and planetary health:

- **Glaciers, water cycle and sea level**

With the loss of glacier masses over continents, global sea level will inevitably pursue its increase with a pace particularly depending on poorly constrained processes at the interface between the austral ocean and huge ice shelves floating on the ocean. Mountain glaciers are major sources of water in downstream regions. With their loss, billions of people face the risk of lack of important water resources for agriculture during the dry season, with a risk of increased tensions or conflicts.

- **Sea ice, ocean, life and atmosphere**

As the world's largest carbon and heat sink, the polar oceans play a vital role for Earth's biogeochemical cycles, ecosystems and the livelihood of millions of people. The loss of sea ice strongly impacts the energy balance between the Earth and outer space, reducing its thermostat effect and amplifying the ongoing warming. It also impacts unique polar ecosystems (in addition to other stressors such as plastics and persistent chemicals), bringing in particular existential threat to many indigenous communities in the North or impacting biodiversity in the South.

- **Permafrost and georisks**

Boreal and Arctic permafrost contains about twice as much carbon as in the current atmosphere. There is low confidence in the timing, amount, trend and partitioning between CO_2 or CH_4 greenhouse gas fluxes being caused by its future thaw, in a context where wildfire disturbances have increased. Permafrost thaw in polar and high-altitude environments poses increasing geo- and biohazards, affecting infrastructures, people, heritage sites and wildlife.

[1] The exact content of the statement may slightly evolve based on feedbacks from the scientific community obtained during the scientific sessions of the One Planet – Polar Summit.

Thus, science calls for sustained coordinated action in order to avoid highly adverse and irreversible impacts of a disappearing cryosphere:

1. Strongly and urgently decrease global greenhouse gas emissions and close the gap to achieve the goals of the Paris Climate Agreement.

2. Address the cryosphere feedback mechanisms for physical, biological and social tipping points that pose risks to planetary and human health. This requires major collaborative efforts to monitor and evaluate the processes at work, to quantify and forecast them, and to inform policy-makers.

3. Include the socio-economical dimension of melting ice, to quantify and mitigate losses and damages by risk management. This must involve the perspectives of indigenous and other communities inhabiting high-altitude and high-latitude regions.

4. Accelerate the political processes enabling the protection of cryosphere ecosystems to reduce pressure on high latitude and high mountain ecosystems.

5. Support integrative international scientific initiatives and missions to improve cryosphere knowledge as developed by the scientific communities.

6. Improve the environmental footprint and sustainability of cryosphere observations, infrastructure and data sharing, for all communities working in polar and high-mountain environments.

Glaciers, water cycle and sea level

CONTEXT

The polar regions and mountain areas are the home to Earth's major ice fields, which are now responding to our increasingly warming climate. The polar regions, especially the Arctic, are warming up to four times the global average and are now the largest contributors to sea level rise. The Antarctic ice sheets hold close to 58 m (West Antarctic Ice Sheet ~6 m, East Antarctic Ice Sheet ~52 m) of potential global sea level rise, and the Greenland ice sheet ~7m.

The ice sheets also contain a rich store of past climate data on the response of the ice to past periods of climatic change. Bubbles of air captured in ice cores yield a unique record of CO_2 and other greenhouse gas fluctuations over the past 800,000 years. From this record we have established that CO_2 levels never rose above 280 parts per million during the past 800,000 years but since the 1800's carbon dioxide levels have risen way beyond this to our current level of more than 416 parts per million. This extraordinary record has provided us with important information about cycles of ice sheet behaviour in the past, and particularly about the pattern of decay of ice sheets in past periods of warmth. From this we can model projections of whether our ice sheets might decay gradually or in a more erratic pattern with intermittent catastrophic collapses.

Satellite observations indicate that the great ice sheets of Greenland and Antarctica are clearly responding to both atmospheric and oceanic warming. Ice shelves fringing Antarctica are vulnerable to warm ocean waters that are forced beneath them by strengthening winds, melting the ice shelves from below. The loss of ice shelves, which protect glaciers from the surrounding ocean, has already started to destabilise ice at the Antarctica Peninsula and in West Antarctica and this alone could cause 1.6 metres of global sea level rise by 2100 if climate warming persists unheeded. Similarly, Greenland glaciers that terminate in the Arctic Ocean are being impacted by warming Atlantic Ocean waters and surface melting, adding to sea level rise. Altogether, there has been a sixfold increase in the rate of ice loss from Antarctica and Greenland since the 1990s.

The Greenland and West Antarctica ice sheets are close to tipping points that could result in irreversible and self-sustaining changes that could continue for many generations, even if global warming is stopped or reversed. The massive East Antarctic Ice sheet, once thought to be stable for many years into the future, shows signs that some glaciers have thinned and retreated over the past few years.

Melting of the vast ice sheets in the polar regions is causing global sea level rise that will affect billions of people who live in coastal regions across the planet. Every centimetre of sea level rise brings an extra 2-3 million people into a state of annual flooding. More accurate forecasts of global sea level rise (rate and extent) are critical for risk evaluation and actions to protect people and their livelihoods, major cities and industrial supply chains, many situated in coastal regions. Better understanding of the processes affecting Antarctic ice sheet instability is required to more accurately forecast sea level rise; some models predict up to 2 metres sea level rise by 2100.

Even if the Paris 1.5°C temperature restriction is met, 30—60 centimetres of sea level rise due to ice loss is already committed and will continue to rise as further warming impacts the stability of the ice sheets in future. With higher sea levels, more frequent extreme weather events will cause greater damage to coastal zones and populated areas, with more coastal erosion, landslides, groundwater inundation, saltwater intrusion and contamination of aquifers.

Mountain areas, such as the Andes and Himalayas, are losing their ice cover. These glaciers and snowfall provide meltwater during dry seasons, sustaining a sixth of the global population and a quarter of the GDP. Two-thirds of irrigated agriculture depends on runoff contributions from these ice masses. It is also one of the most sensitive parts of the ecosystem services to climate change. Over the next 30 years the Alps, Rockies, Andes and Himalayas are projected to lose 10-40% of their snow, equating to hundreds of cubic kilometres of water supply. By the end of the century, mountain glaciers will lose 20-60% of their ice.

This poses a global threat to secure water, food, energy and livelihood for hundreds of millions of people. However, how much water the mountain cryosphere provides and how its role will change remains remarkably uncertain. Although this is seen as a matter of greatest importance *(WMO high mountain call to action, 2019)* there has yet to be a global initiative to measure mountain water resources.

Ice covered areas in both polar regions and high mountains are shrinking, revealing newly exposed ground in which plant species are colonising and growth rates are increasing, even in Antarctic terrestrial sites. Extreme weather events, drier conditions and warming events are causing turnover in plant species such as mosses and lichens. Ice-free areas are also being increasingly colonised by sea birds and seals in polar regions. Non-native species have become established in some newly exposed areas in cold regions, although far more monitoring is needed to fully understand the changes in terrestrial systems as glaciated landscapes shrink. Are we losing glacial microbiomes that we still know little about?

Mountain glaciers and the seasonal snow cover in their surroundings are heritage sites of unparalleled scenic beauty, areas of intense tourism and winter sports use, guaranteeing financial resources and maintaining the local population's way of life. These assets are already suffering the impact of glacier melting and retreat to higher elevations.

PRIORITIES

1. **Sea level projections.** The major threat from melting polar ice sheets is the rise in global sea levels and the impact on coastal populations and infrastructures. It is crucial and urgent that forecasts of sea level rise are improved, both in terms of timing and amount. The management of sea level rise impacts and risks for coastal communities, plus actions to address challenges from migration of displaced populations from inundated low-lying regions all require more certainty in the forecast of sea level rise.

2. **Ice-ocean interactions.** To improve future projections of Greenland and Antarctic ice loss, it is necessary to understand better ocean-ice interactions, the melt rates below the ice shelves, the instabilities of the ice cliffs and the nature of the marine ice sheets. This requires both better observations with innovative technologies to monitor and measure changes in the field, sustained and enhanced satellite observations, and improved ocean-ice coupled computer / artificial intelligence models to provide more accurate forecasts of future sea level rise for policymakers.

3. **Past climates.** Ice sheets are important archives of past climates. Observations from these palaeoclimate records (ice cores) are urgently needed to help understand whether past ice sheet retreat was a gradual process or characterised by more erratic and intermittent events. This is needed to improve models of future projections of icesheet behaviour to aid long-term planning.

4. **Water resources.** Better understanding of the water supplies provided by ice and snow in mountain regions is needed, requiring more monitoring, field research, satellite observations and improved modelling. It is critical that this is undertaken in collaboration with local communities and policymakers to ensure urgent action.

5. **Hazards.** It is essential to monitor and evaluate the risk of natural disasters due to the melting of mountain glaciers, such as the rupture of glacial lakes.

6. **Ecosystems.** The impact of ice loss on ecosystems, both in high mountains, coastal regions and oceans, has yet to be fully understood. Newly exposed areas require monitoring to assess what and how new ecosystems develop in freshly exposed areas, which may need special management and protection from invasive species.

7. **Collaboration.** Working in remote and challenging polar and high mountain regions to undertake these observations is expensive, time-consuming and difficult. Research is most efficiently, effectively and safely undertaken through large multi-skilled research teams, sharing infrastructures and costs.

8. **Action.** International action is key to tackling these major challenges; their urgency demands large teams of complementary expertise working together to collect new data sharing major infrastructures. Antarctica InSync is a new proposal that will bring together the polar community to plan and deliver a programme of synchronous measurements of many aspects of the Antarctic environment to understand how the continent and its ocean is being impacted by climate change and provide better forecasts that benefit the whole planet.

Ocean, sea ice, life and atmosphere

CONTEXT

Sea ice is an integral part of the high latitude oceans and a key Earth system indicator for climate change. Sea ice is frozen seawater, it expands during each hemisphere's winter; and melts in the summer. The white surface of sea ice reflects solar energy (albedo), cooling the planet. Sea-ice strongly influences ocean-air momentum, heat and gas exchange. When it melts, the darker ocean absorbs more heat, amplifying the cycle of melting sea ice. Sea ice is also a habitat to huge diversity of life, from microbes to whales, many of which are endemic. Increasing losses of sea ice, especially shelf and multi-year ice, are endangering polar life. Sea ice transports matter, builds a barrier against glacial ice loss, and protects coastlines against waves and erosion. It supports human mobilities and has been part of hominid expansion and culture even before the emergence of *Homo sapiens*, and remains a key element of human cultures and livelihoods today.

Polar oceans drive the ocean's conveyor belt. When cold polar water sinks, it brings oxygen and dissolved organic matter, but also pollutants to the deep-sea. Fluxes of radiative heat and freshwater from enhanced precipitation and melting sea ice and ice sheets are increasing, thereby enhancing surface stratification. The ocean warming has far-reaching climatic implications for melt of Greenlandic marine-terminating glaciers and Antarctic ice shelves and ice sheet, thereby enhancing sea level rise and possibly ocean overturning at lower latitudes. Complex and poorly understood processes include oceanic eddies, tropical-polar interactions, interior warming and stratification changes, and future ability to take up CO_2 by the physical and biological carbon pump.

At times present at much lower latitudes over Earth history, sea ice is conceivably a hotspot for evolution of microorganisms on Earth, and potentially harbours life on extraterrestrial ocean worlds. The role of sea ice as a major biome on Earth, and an integral part of polar ecosystem functioning remains to be understood. Establishing a baseline in the state of sea-ice related ecosystems constitutes a race against time in the face of the speed of transformations affecting the polar sea ice, particularly the oldest one. In losing old sea ice in the Arctic, we may lose our best analogue of conditions prevailing during past ice ages and in other ocean worlds.

As to polar ocean productivity, the lack of time series with adequate seasonal and regional resolution has limited our understanding as to the effect of warming. Satellite observations show mainly increases in phytoplankton biomass in the Arctic and Southern Ocean over the last 20 years, because the shrinking sea ice enhances light penetration. However, concurrent stratification changes, including increased air-sea momentum transfer enhancing ocean mixing, and it impacts nutrient supplies, thus future projections are highly uncertain. The key drivers of polar productivity, the diatoms get replaced by smaller algae as a result of ocean warming, changing the food web and potentially reducing the carbon pump. Loss of sea ice endangers marine mammals and seabirds as they find their prey there and use it as a platform to reproduce, leading to alarming massive breeding failure in emperor and Adélie penguin colonies. Loss of sea ice also affects microbial life and thereby the entire food web. While northward expansion of new species into the Arctic Ocean from the Pacific and Atlantic has been documented at all trophic levels, the actual causes (e.g. changes in water mass distribution, currents, seawater properties or sea ice dynamics) remain unclear, and therefore our capacity to make any prediction about marine ecosystems are terribly limited.

At the current level of global warming of 0.2°C per decade, sea ice loss in the Arctic observed since 1978 is 3% per decade in wintertime, and 13% in summertime. The majority of multiyear sea ice has been replaced with annual, thinner and more dynamic sea ice. There is a close relationship between changes in Arctic summer sea ice, cumulative CO_2 emissions, and global surface temperature - translating into around 3 square metre loss of Arctic sea ice for each ton of CO_2 emitted. In Antarctica, no significant sea ice trend was discernible from 1979 to 2020 (summer or winter), due to large internal variability and contrasting regional trends. It remains uncertain whether the exceptionally low cover in June 2023 (-17% compared to average) is an anomaly, or a response to climate warming. For Antarctica, the amplitude of warming is still poorly constrained due to the large decadal climate variability, but may be as much as twice the global average.

Human influence is the main driver of sea ice retreat. As greenhouse gas emissions and their atmospheric concentrations have continued to increase, the Earth heat content has also increased. 91% of this excess heat accumulates in the ocean, and half thereof in the Southern Ocean. 3% leads to cryosphere melt, 5% to land warming and 1% to lower atmosphere warming. Thus, the warming ocean will be an increasing threat to the future of sea ice. Several additional amplifying feedback loops act on sea ice and involve surface albedo, water vapor, clouds, snow precipitation, air-sea fluxes, altogether causing polar amplification. The extent to which negative feedback loops driven by physical and biological processes may dampen amplification is however not well constrained, adding to uncertainties. For instance, the production of climate active gases such as di-methyl sulfide, or aerosolized microbial ice nucleating particles, both favoring cloud production during newly ice-free areas, have been put forward. Long-range contaminants, notably black carbon transported from intensifying industrial regions at lower latitude, do contribute to reduction in sea albedo and, therefore, to melt.

Especially the Arctic shows a high sensitivity to global warming, of 4 times faster than the global average in 40 years. In scenarios and pathways assessed in IPCC reports, there is a risk already by 2030-2035 for a first ice-free (<15% ice-cover) summer for the Arctic Ocean, and at least once prior to 2050, linked to cumulative CO_2 emissions reaching 1000 gigatons. Recent variations are related to atmospheric circulation patterns, with persistent consequences due to a warmer ocean and possibly a new Antarctic sea ice state. Heat uptake in the Southern Ocean accounts for >50% of the global ocean heat uptake.

Gaps in scientific knowledge concern especially land-ocean, ice-atmosphere-ocean, ocean-glacier and sea-ice-life interactions. It is important to better understand the future of precipitations including snow, and the dynamics in atmospheric pressure patterns and winds. Changes in large scale water mass distribution, notably between Atlantic and Arctic Oceans, in the connection between fresh and cold surface waters and warm and salty deeper ones, including ocean mixing, and in sea ice growth/melt cycle and dynamics (advection, ridging, leads, melt ponds) further complexify the impact of global warming on polar icepacks. The lack of long-term time series with adequate regional resolution to achieve circumpolar assessments of change is critical and precludes reliable projections. Key problems are forecasts of the role of decadal dynamics and teleconnections of phenomena like El Nino, North Atlantic Oscillation and of the stability of the Atlantic Meridional Overturning Circulation, the Antarctic Circumpolar Current and their links to sea ice. The fate of sea ice directly and indirectly affects food-webs and biological interactions from microbial life to krill, fish, whales and birds, as well as to benthic life including the deep-sea. Gaps in knowledge remain large as to the total diversity of polar life and its dynamics, its interactions with ocean chemistry, i.e., aerosol formation, dissolved matter, particle fluxes, and its implications for economic development, human health and well-being.

IMPACTS AND RISKS

→ Polar oceans are experiencing climate change impacts with large magnitudes and will be profoundly different by 2050.

→ The impacts of shrinking polar sea ice may be felt globally, including in weather patterns.

→ Sea-ice loss, warming and acidifying oceans reduce habitat options for many polar marine species, including many shellfishes, fish species and marine mammals, while opening the way to invasive boreal species. Exposure to new stressors such as plastics and persistent chemicals could worsen the negative effects for polar marine species.

→ Sea ice decline leads to more opportunities but also growing risks from expanding and intensifying shipping, fisheries, tourism, resource development, and other industries - including intensification of geopolitical tensions and debate.

→ Sea-ice loss and extreme events arising from climate warming affect the lives and livelihoods of Arctic communities. Polar amplification poses threats to many aspects of Arctic lifestyles (culture, identity, health, including mental health, safety), especially for indigenous peoples.

GOVERNING PRIORITIES

1. Science calls for a new international ambition in reducing greenhouse gas emissions and in removing carbon from the atmosphere to limit the expected overshoot of 1.5°C in time and to reach climate neutrality as soon as possible. This is an essential goal to avoid further

large declines of sea ice cover, and to reduce weather extremes globally.

2. International collaboration for the protection of polar oceans (as voiced in the Helsinki Declaration on Climate Change and the Antarctic (2023)) is essential to reach the goals of the COPs on climate and biodiversity.

3. To reduce the pressure on polar life due to intensifying and expanding human activities, marine and terrestrial protected areas are key actions and need a new international ambition supported by science. In their planning and maintenance collaboration and support for self-determination among indigenous communities is important.

4. Closing gaps in cryosphere literacy, information and forecasting is relevant for society. It needs support for better process understanding, modeling tools and frontier research, including implications for habitability, human security, unique ecosystems and biodiversity, equity, economy including eg. Insurability.

5. Socio-economic decision-making tools should include the cryosphere in estimates of the cost of carbon emissions and the planning of loss and damage funds.

6. Infrastructure to enhance resilience to climate change / sea ice loss, especially including self-determination of indigenous peoples.

SCIENTIFIC PRIORITIES

1. Support of long-term international sea-ice, ocean, biosphere and atmosphere programs in the Arctic and Antarctic by infrastructure (e.g. international sea ice buoy and Argo float programs, polar research vessel fleet, research aircrafts and stations) as well as by large international missions (e.g. Tara Polar Station, Antarctica InSync, International Polar Year), nested into and coordinated with international observing networks and initiatives.

2. Strongly reinforced cooperation among space agencies to consistently distribute Earth observation data for polar regions, develop new missions, new products and algorithms, and conduct dedicated field expeditions for ground truthing.

3. More research capacity, with new cutting-edge scientific expertises for exploring the sea ice biome.

4. Capacity building developed by, and co-developed with local communities, to serve both local and global science needs, and maximize "north by north" and "south by south" activities for more sustainable, year-round polar science

5. Transformation of polar infrastructure to better service information needs, and to allow for footprint reduction. Develop low-carbon footprint solutions for surveying polar sea-ice and related ecosystems, in addition to conventional research platforms

6. Accessible, context-specific sea-ice information products and tools, regional forecasts and projections to support decision-making

7. Digital twins of polar seas, including risk management modules (adequate and appropriate emergency responses and adaptation) and guiding observation strategies

8. Regional cooperation, multi-scale biodiversity & marine protection networks (monitoring and

governance), increasing science-based resources to reinforce resilient and sustainable development trajectories.

Permafrost and georisks

CONTEXT

About one fifth of the land surface of the Northern Hemisphere is underlain by permafrost. It extends beneath great portions of Alaska, Canada, Russia, and the Qinghai-Tibet Plateau, and is also found in northern Scandinavia, Antarctica, and high mountain regions around the world. The most densely populated and developed landscapes with permafrost are in the European Alps. Many permafrost regions contain valuable mineral and energy resources and a population urging their development. Most infrastructure design and construction in permafrost terrain is predicated on the ground remaining frozen.

The polar environments are experiencing climate changes two to four times greater than most of the world. The changes are apparent in temperature and are becoming evident in precipitation. The rates of climate change track or exceed the highest rates projected 20 years ago. Permafrost is essentially climate in the ground, so permafrost temperatures are rising throughout the polar and high mountain regions and near-surface permafrost is thawing.

In the last decade, the occurrence and risk of geo- and biohazards in thawing ground such as coastal erosion, landslides, oil spills, release of buried industrial wastes and natural contaminants such as mercury, ancient viruses, and emissions of methane and CO_2 from organic material now entombed in permafrost have all increased. Such regional carbon emissions have a magnitude with global implications. Thawing has accelerated following wildfires in the forests that cover about one half of our permafrost environments, and which are annually burning larger areas than ever before. Of direct importance to northern Indigenous peoples are physical threats to heritage sites and wildlife populations because the permafrost biome contains limited biodiversity, making ecosystems fragile when disturbed. For people in high mountain regions, the loss of water supply as permafrost thaws and surface water infiltrates into the ground is a serious concern.

Permafrost science and engineering is a challenging endeavor, in part due to the high cost of working in remote areas. In the past, people resident in the permafrost regions have played relatively minor roles in research. This must be better balanced in all phases of program development if policy and politics emanating from the North are to be fully informed by scientific progress. The peoples and private and public agencies of the permafrost realm face deterioration of built infrastructure and access to the land, emergent risks and unaccustomed rates of environmental change, and a need for mitigation and adaption tailored to a local context that promotes economic development.

PRIORITIES

1. We must recognize the inevitability of significant adjustments to permafrost environments and their ability to support infrastructure as it is currently designed. Efforts to advance adaptation of infrastructure design and construction techniques to thawing ground are urgently needed. Permafrost monitoring is essential to reduce the risk of damage to people and infrastructure, particularly in high mountain regions.

2. The timing and rate of projected CO_2 and methane emissions from thawing permafrost requires priority attention from the scientific community. We must improve dynamic modelling of emissions from permafrost under a range of potential future climate trajectories, critically including the role of the microbiological activity. Geopolitical solutions must be found to facilitate comprehensive scientific assessments of this existential issue for all permafrost regions.

3. Socio-economic aspects of anticipated losses and damages from, and adaptation to, a thawing cryosphere need greater emphasis in research, particularly the financial consequences of permafrost thaw for public agencies and private enterprises. Similarly, aspects of the environment that influence the health of people and the wildlife on which they depend need emphasis, particularly the distribution and density of species key to ecological and food security.

4. Greater involvement of Indigenous and other people of the cryosphere regions is essential in all aspects of research and deliberations regarding adaptation to and management of climate change impacts. Education and training for these residents must be enhanced to enable such engagement.

5. Emissions from wildfires and other disturbances, including coastal erosion, are now persistent and are compromising society's efforts to reach net zero carbon emissions. Enhanced thawing of permafrost from these disturbances accelerates permafrost carbon emissions over decades. We require dedicated research on methane and CO_2 emissions from burned and coastal areas, including those only accessible through remote sensing.

6. The expense of field research in remote areas and its essential role in validating theoretical progress and remote sensing observations must both be recognized. Some costs may be mitigated by greater involvement of agencies and institutions located in the permafrost regions.

7. Finally, international efforts to archive, manage, and make data regarding the changing permafrost state openly available must be supported on a permanent basis.