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Chair, Publications Board
World Meteorological Organization (WMO)
7 bis avenue de la Paix Tel.: +41 (0) 22 730 84 03
P.O. Box 2300 Email: publications@wmo.int
CH-1211 Geneva 2
Switzerland

Cover photo: Community members discussing flood EWS in Nepal (Practical Action)

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The Cryosphere – the Canary in the Coal Mine of the Climate System

By Rodica Nitu, Michael Sparrow and Stefan Uhlenbrook, WMO Secretariat, and Jeffrey Key (formerly National Oceanic and Atmospheric Administration (NOAA))

Coal mines once used canaries as early indicators of potential danger: their sensitivity to poisonous gases caused their early demise during gas leaks, sounding a danger alarm for miners. Today, "canary in the coal mine" is commonly used to express alert for environmental dangers: "The cryosphere, the white landscapes, is the canary in the coal mine of climate and biodiversity crises due to human pressures including greenhouse gas emissions," said Antje Boetius, Director of the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, at the conclusion of the One Planet – Polar Summit in Paris, November 2023. What are the signs and what do we urgently need to do not to miss them?

The changing Cryosphere

Earth's climate is changing. With the rising temperatures, the cryosphere is declining around much of the world. Due to modified ocean-sea-ice-atmosphere interactions, the sea-ice regime is changing. First-year ice is becoming prevalent in areas of the Arctic previously known for second or multi-year ice. In 2023, the sea ice around Antarctica was reported to have reached its lowest extent since satellite monitoring started in 1979. For the June-August 2024 period, the region south of 60°S was 2.1 °C above average (relative to 1979–2020).[1] An anomaly of 2.1 °C is the record highest value for that period since satellite data started to be widely assimilated over Antarctica (1979 onwards). Much of this seasonal anomaly occurred in the 0 ° to 60 °East region of Antarctica. This sector was exceptionally warm around the end of July and into early August according to Thomas Caton Harrison from the British Antarctic Survey.

Intergovernmental Panel on Climate Change (IPCC) reports have estimated the amount of carbon stored in permafrost at about twice the amount in the atmosphere today. Permafrost plays a key role in regulating the global climate system by acting as a carbon sink or source, which alters atmospheric greenhouse gas emissions. However, the IPCC reports present evidence that permafrost is undergoing rapid changes. This is creating challenges for planners, decision-makers and engineers as the structural stability and functional capacities of infrastructure are no longer secure as designed.

Rising temperatures in the atmosphere and ocean around Antarctica are melting the ice sheet. Evidence cited in IPCC reports suggests that if global temperature rise exceeds 2 °C in the long-term, both the Greenland and Antarctic ice sheets may reach tipping points[2] beyond which their melting would become unstoppable even with deep cuts in greenhouse gas emissions. In addition to sea-level rise, even a partial melting of ice sheets has large downstream impacts on, for example, ocean circulation and food as well as energy security, exacerbating climate change effects on human societies and the natural world. There are already signs that some large glaciers in Antarctica have entered a state of irreversible retreat and data from Greenland has shown an increase in surface melt and increases in iceberg calving over the last 30 years. The Global Tipping Points Report 2023 noted that "Large-scale tipping points exist for the Greenland and Antarctic ice sheets. Crossing these tipping points would lead to multimetre sea-level rise over hundreds to thousands of years."

Snow, glaciers, frozen ground, freshwater and sea ice extend well beyond polar and high mountain areas, being present in more than 100 countries and covering the entire continent of Antarctica[3]. On seasonal to decadal timescales, changes in snow cover, freshwater and sea ice, glaciers, ice sheets and permafrost impact water resources and

1 This value is based on the air temperature at 2-metre height from the early release (provisional) of the ERA5T climate reanalysis datasets produced by ECMWF.

2 Environmental stresses could become so severe that large parts of the natural world are unable to maintain their current state, leading to abrupt and/or irreversible changes. These moments are called Earth system "tipping points". Global Tipping Points – Summary Report 2023; T. M. Lenton, et al, University of Exeter, Exeter, UK.

3 Marshall, S.J. (2011). *The Cryosphere*. Primers in Climate Science, Princeton University Press.

Figure 1. The diminishing of the Tschierva Glacier beneath Piz Bernina, Switzerland - the highest peak of the Eastern Alps, between 1935 and 2024. This is the site of one of the biggest high-alpine landslide events in recent time (at Piz Scerscen, 16 April 2024). 8-9 million cubic metres of rock and ice have detached and run down into the valley, eroding the glacier. Luckily no damage happened.

Source: Leo Hösli, Matthias Huss (VAW-GL, ETH Zürich, Switzerland) and swisstopo.

ecosystems, including near-coastal and marine ecology. The accelerated changes are felt by people, society, and economies around the globe.

Impacts far and wide

In many places snowfall has been replaced by rain, and the amount and seasonality of runoff have changed. These have local to regional impacts on water resources and on the frequency, magnitude and location of related natural hazards, especially landslides and floods. Human settlements and livelihoods in high mountain areas and the Arctic are exposed to new risks.

On 16 August 2024, a devastating flood struck Thame, a village in the Khumbu region of Nepal. Nepalese scientists confirmed that it was caused by a Glacial Lake Outburst Flood (GLOF) from the Thyanbo Glacial Lake. Thame Village, a prominent village located inside the World Heritage Sagarmatha National Park site, is home to renowned mountaineers. While there was no loss of life, the floods destroyed a large area around the village (Figure 2). It is not an isolated event. According to Professor Rijan Kayastha, Kathmandu University, Nepal, over the last 30 years more than 20 GLOFs have occurred in the Hindu Kush-Himalayan region alone. The risk is great. There are over 25 000 glacial lakes in the Hindu Kush Himalaya region, 47 of them potentially dangerous within the Koshi, Gandaki and Karnali river basins of India, Nepal and the Tibet Autonomous Region of China. The Pakistan Meteorological Department's 2013 inventory of glacier lakes in Northern Pakistan, conducted as part of an internationally funded project through United Nations Development Programme (UNDP), identified 3 044 glacier lakes, of which 36 were assessed as potentially dangerous. Since then, several GLOF events have occurred on the Shishper Glacier Dammed Lake (2019, 2020, 2021 and 2022), causing repeated and significant damage to housing, highways, bridges, agriculture lands, and other infrastructure.

The increasing ice loss from the Greenland and Antarctic ice sheets and from glaciers around the world contribute to about a half of the sea-level rise observed globally in recent decades (IPCC SROCC, SMP, A3). Coastal environments and small islands are already impacted by the combination of sea-level rise, other climate-related ocean changes and diverse adverse effects from human activities. Even tropical coastal regions feel the effect of melting ice sheets and glaciers through their contribution to sea-level rise.

Dr Garvin Cummings, the Permanent Representative of Guyana to the WMO, recently highlighted that his country, like all coastal states and SIDS, is "not isolated nor insulated from the impacts of melting of ice sheets and glaciers. We may be far away from poles and glaciers but the potential consequences from the escalating threat of sea-level rise are dire and imminent. Sea-level rise is leading to more powerful storm surges, saltwater intrusion and a loss of coastal fertile land. Understanding these

Figure 2. Thame village in the Khumbu region of Nepal following a devastating GLOF

changes is at least as important for countries like Guyana as it is for countries in close proximity to the poles and glaciers."

People with highest exposure and vulnerability to cryosphere hazards are often the ones living in countries that have the least adaptive capacity. The changing of the cryosphere in the changing global climate is exposing vulnerable populations to new hazards, including more frequent GLOFs, landslides and slope detachment/rockfall caused by degrading permafrost, retreating glaciers, and extreme weather events. Improved monitoring – with the backbone of in situ observations – and modelling are paramount to providing policy and decision-makers with the information and climate services they need for mitigation and adaptation to cryospheric changes and their downstream cascading impacts.

Collaboration – The key to understanding the changing cryosphere

Projections of changes in the cryosphere, with a high degree of confidence under different climate scenarios, are needed to augment the capacity of the global community to better prepare, manage and adapt to the many emerging risks and to guide policy and decision-making. Improvements in projections require advances in understanding and representing cryospheric processes via an Earth system approach, supported by systematic observations and engagements across disciplines and organizations.

Collaborative engagements across multiple scientific domains, involving research and operational organizations, are essential. Four International Polar Years (IPY) have demonstrated this by propelling science forward through cooperation. The 5th IPY, being planned for 2032/2033, provides WMO with the opportunity to play a leadership role in supporting the international community to address specific scientific and long-term adaptation questions, and to leave a legacy of improved monitoring and modelling capacities to better inform the global community.

The WMO unified Earth system approach for monitoring and prediction is the best mechanism for addressing critical information gaps for mountain and polar regions and for informing those affected by changes in the cryosphere. This includes assessments of climate trends and projections (for example, for climate services), reporting extreme events, producing early warnings for mountain regions, and supporting drought or flood forecasting (for agriculture, and early warnings).

Observations – The challenges

Advances in climate science, climate services and early warning systems require (1) systematic, sustainable observing networks with timely, effective data exchange and access, and (2) modelling systems across Earth system components. Much work is still needed to achieve both, especially for the cryosphere and the surrounding environments. In most countries, the responsibility for observations on the cryosphere continues to be distributed along multiple institutions, ministries and stakeholders, as the monitoring of cryospheric regions has developed relatively recently, mostly as scientifically driven bottom-up initiatives. This fragmentation has limited the ability to fully understand and document the current observing system gaps.

A survey conducted by WMO on the Andean countries in 2020, following-up on the conclusions of the 2019 High Mountain Summit, highlighted the complexity of coordinating engagements in the cryosphere domain, especially in mountain environments. In Colombia and Peru, the National Meteorological and Hydrological Services (NMHSs) share responsibility for observing snow and glaciers with other organizations, while in Argentina, Plurinational State of Bolivia and Chile these observations are under the remit of other national or regional institutions. This is representative of the situation in many other countries around the world.

Even though there have been significant improvements in recent years, globally, many mountain regions have remained insufficiently monitored due to high costs, difficult access, extreme operating conditions, insufficient local technical and operational capacity, and the absence of, or weak, institutional mandates (IPCC SROCC, 2019). Even meteorological stations are sparse at high elevations. This provides an altitudinal bias in precipitation and other observations. Where existing, the resolution of monitoring networks in high-mountains and polar regions is usually insufficient to adequately resolve complex terrain and related hydroclimatic processes.

The Third Pole Regional Climate Centre is a network aimed at developing climate services for the vast high mountain region around the Tibetan

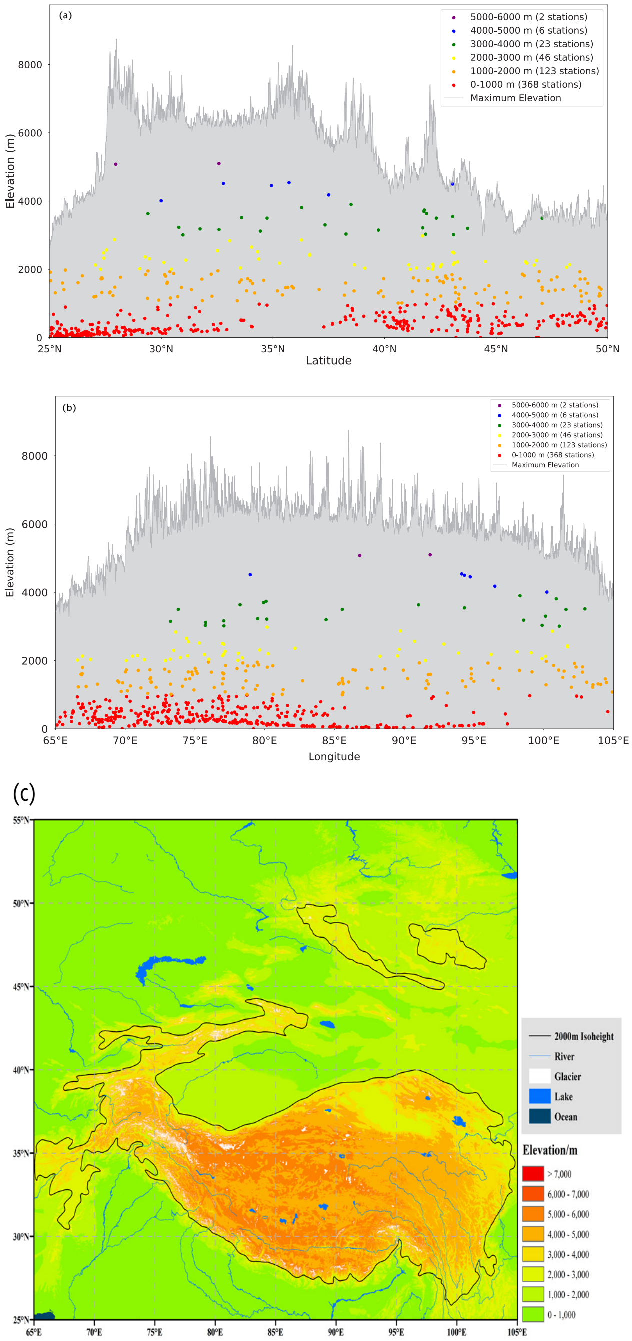

Figure 3. Meteorological stations registered in the WMO Observing Systems Capability Analysis and Review Tool – OSCAR/Surface in the geographical area covered by the Third Pole Regional Climate Centre Network. (a) stations by elevation in the East-West transect of the region 65 °E to 100 °E (elevations from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM); (b) stations by elevation in the North-South transect of the region 25 °N to 50 °N (elevations from SRTM DEM); (c) the geographical area covered by the Third Pole Regional Climate Centre Network (rccra2.org)

Source: Ran Shang (WMO), Pengling Wang (China Meteorological Administration)

Plateau. Figure 3 illustrates that most operational meteorological observations[1] are predominantly located at elevations below 1000 m. The limited number of systematic observations, including of air temperature and precipitation, at higher elevations makes it difficult to generate reliable forecasts and predictive products and to monitor extreme events over the vast extent of these mountain regions, which are known to provide water resources for ecosystems and the livelihoods of well over 1.5 billion people.

Globally, observations of snow, glaciers, permafrost and critical tropical highland ecosystems have remained sparse, being operated primarily within time-bound research projects. There are limited engagements with operational entities and these data are seldom used in the production of climate services.

Progress has been made on addressing polar and space-based high mountain cryosphere observing needs by combining optical and radar imaging, altimetry and gravimetry, and Digital Elevation Models (DEM). However, for numerical weather prediction and climate reanalysis there remains the challenge of availability and sustainability of relevant operational satellites. Additionally, to fully harness the wealth of satellites, there remain challenges in accessing, processing and interpreting results from large datasets (S Gascoin, et al., 2023).

WMO has undertaken a consolidated approach to documenting requirements for monitoring of the high mountain cryosphere, which is critical to inform the strategic goals of space agencies. The existing observations are not fulfilling the spatiotemporal resolution required by users – for example, for snow extent, melt, surging glaciers, GLOFs or avalanche monitoring – and the combination of satellite and in situ data and models is fundamental to bridge existing sampling issues.

There is still a lack of operational satellite products for accurately measuring solid precipitation, snow depth or the water equivalent of snow cover (SWE), which are needed to respond to hydrological expectations concerning snow water monitoring in high mountain regions. SWE is a crucial parameter for warning on snowmelt conditions and proper

1 Registered in the WMO database for Surface Observing System Capability Analysis and Review Tools (OSCAR/Surface), which provides data in real-time for Global Numerical Weather Prediction

runoff modelling. These are of high importance for water resource management, hydropower energy production, other sectors.

Engagement and active collaboration, especially between research and operational entities, are necessary steps to overcome the current cryosphere information gaps, and to improve the monitoring and assessment of risks due to climate change and melting ice. Installing and sustaining automatic weather stations at high altitudes – over 4 000 m – that transmit data in real time via the WMO Information System (WIS2) is essential for improved monitor and prediction of hazards for effective early warnings systems for GLOFs and other risks further downstream. This is one of the recommendations discussed by the Nepalese experts in the aftermath of the Thyanbo Glacier Lake disaster.

Challenges – Enhancing Earth system Predictions

Cryosphere information needs differ by application, depending on their timescales. For instance, numerical weather prediction (NWP) efforts can generally neglect changes in the polar ice sheets or permafrost over timescales of hours to days. On the other end of the spectrum, climate projections for the end of the century do not require detailed initialization of the current state of seasonal snow and ice cover.

Reliable and long-term climate records on and about the cryosphere are essential for understanding changes, representing processes in models (for example, ice sheet-ocean-atmosphere interaction), projecting future scenarios, and for risk assessments. Near real-time information is essential for monitoring the cryosphere and detecting extreme events for adequate early warning systems.

An increased understanding and model representation of the complex interactions between ocean, land, water, sea ice and atmosphere at scales representative of processes – the inhomogeneous mountain terrain (Rotach et al., 2022[2]) – is required to improve capabilities of Earth system models in polar and high mountain regions.

Land-surface hydrology is an integral part of Earth system modelling. Many applications would benefit from the integration of hydrological models with Earth system models to capture feedback to the atmosphere, for example, soil moisture; open water vs. ice conditions for fluxes of energy, momentum and moisture; the thermal state and albedo of snow and ice surfaces. For other applications, hydrological models run effectively in a "stand-alone" mode, forced by the outputs of weather and climate models, downscaled to the required resolution. This line of modelling enables the generation of ensembles of hydrological predictions (that is, spanning the uncertainties of parameter settings and model forcings) to provide probabilistic information for key applications such as flood forecasts or seasonal water resource scenarios.

Addressing the challenges

There are several domains where WMO is best positioned to advocate and support enhancing capacity to respond to the increasing demand for information in polar and high mountain regions, specifically on the cryosphere.

A priority continues to be the establishment of automatic weather stations for continuously monitoring meteorological and environmental conditions in proximity to glaciers, permafrost and on ice sheets. Real-time access to these observations – in particular air temperature, precipitation and snow – are essential to support monitoring and predicting snow and ice retreat and their associated risks. These are key to establishing early warning systems for these regions. The framework of an expanded WMO coordinated Global Basic Observing Network, with appropriate technical solutions for real-time transmission via satellite, and funding through Systematic Observations Financing Facility (SOFF) are the only way to address current gaps in the framework of the Early Warnings for All initiative launched by the United Nations Secretary-General.

Furthermore, the development of hydrometeorological alerts specific to mountain and polar regions, and modelling and forecast programmes designed for their specific conditions, would benefit from routine access to high spatial resolution satellite images of high mountain areas, including covering the equatorial glaciers.

2 Rotach, M. W., et al (2022). A Collaborative Effort to Better Understand, Measure, and Model Atmospheric Exchange Processes over Mountains, *Bulletin of the American Meteorological Society*, 103(5), E1282-E1295. Retrieved 5 September 2022, from https://journals.ametsoc.org/view/journals/bams/103/5/BAMS-D-21–0232.1.xml.

The Early Warnings for All strategy should evolve a focus in the climate domain for risks related to the cryosphere, with a time horizon from short term to decade-century scales. These should include the link between the melting of the cryosphere under different climate scenarios, its contribution to sea-level rise and the impacts on coastal areas, low-lying countries and small islands, and the thawing of permafrost and the release of carbon in the atmosphere.

Investment in people remains paramount. Training of technicians and specialists in mountain meteorology, hydrology and cryospheric observations and data management, engaging experts from research and operational organizations in the Member States and Territories directly affected by changes in the cryosphere would build the sustainable solutions to address future challenges.

Over the last decade, WMO, through the Global Cryosphere Watch, has taken concrete steps to building collaborative engagements at regional and global scales with existing programmes and research networks in the cryosphere domain, by building on its proven experience in the meteorological domain. This has fostered an increased understanding of existing observing and data capabilities and collaborative efforts towards addressing systematic observing gaps. An example of these contributions is the publication of the Volume II, Measurement of Cryospheric Variables in the *Guide to Instruments and Methods of Observations* (WMO-No. 8), in collaboration with the International Association of Cryospheric Sciences, the Global Terrestrial Network for Permafrost, the Global Climate Observing System (GCOS), and other scientific networks. A continuation of these engagements is critical for WMO to remain effective in the cryosphere domain in initiatives such as the Mountain Research Initiative, the Third Pole Environment (TPE), the Sustaining Arctic Observing Networks (SAON) and others.

The advocacy and contribution to the strategic actions supported by WMO has been coordinated through the Panel of the Executive Council on Polar and High Mountain Observations, Research and Services (PHORS). PHORS spearheaded the development of WMO Cryosphere High-Level Ambitions endorsed by the 78th session of the WMO Executive Council in June 2024. These are principles for engagement and advocacy in support of the actions on the cryosphere endorsed by the 19th World Meteorological Congress in 2023.

Reference

IPCC, Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), Summary for Policymakers (SMP), A3.

S. Gascoin, 2023: A call for an accurate presentation

WMO Cryosphere High-Level Ambitions

Addressing the gaps and challenges identified in this article and fostering global actions for cooperation across different scales and planning horizons rely increasingly on the ability to communicate to responsible policy makers and implementers, and to increase public awareness.

1. **The urgency:** Everyone on the planet is prepared for, and resilient to, the impacts from changes in the cryosphere – The changing cryosphere affects the global community, whether through the sea-level rise, water and food scarcity, geotechnical risks, leading to threats to economies, livelihoods, energy sources, trade, and geopolitical stability

2. **Global collaboration:** The global community works collaboratively to limit and reduce cryosphere loss and its impacts – The cryosphere transcends international borders and geopolitics and only coordinated action can enable changes towards limiting cryospheric loss and its catastrophic impacts

3. **Accessible data and knowledge:** Data as well as scientific and indigenous knowledge are accessible and provide a sound basis for policies and decisions relating to the cryosphere – Improved observation coverage, good data management, integration of indigenous knowledge and improved global data sharing are needed to enable analysis and prediction services that support decisions

4. **Action:** The importance of the cryosphere and the consequences of its changes are known, universally understood and inspire action – Global, urgent and effective actions need to be mobilized through increased understanding and cooperation to address the root causes of climate change and of the cryosphere loss.

The observance of the International Year of Glaciers' Preservation, supported by WMO, is an example of global engagements to increase awareness at multiple levels about complex changes that affect everyone on the planet.

International Year of Glaciers' Preservation (IYGP 2025)

In December 2022, the United Nations General Assembly adopted resolution A/RES/77/158 to declare 2025 as the International Year of Glaciers' Preservation (IYGP 2025), accompanied by the proclamation that 21 March of each year will be the "World Day for Glaciers", starting in 2025. WMO and the United Nations Educational, Scientific and Cultural Organization (UNESCO) were invited to facilitate the implementation of the International Year and observance of the World Day. This initiative, through coordinated momentum to address the urgency of the matter, is aimed at raising awareness, pursuing policy advocacy, and facilitating actionable and sustainable measures for preservation of glaciers.

The coordination mechanism of IYGP 2025 is composed of four Task Forces (TF):

- TF-1: Global Campaign for International Year of Glaciers' Preservation 2025 (Lead: FAO Mountain Partnership Secretariat)
- TF-2: International Conference on Glaciers' Preservation, Regional Workshops and Capacity Building (Lead: ICIMOD-International Center for Integrated Mountain Development)
- TF-3: Research and Monitoring Initiatives (Lead: University of Chile in Santiago)
- TF-4: Policy Advocacy, Partnerships and Resource Mobilization (Lead: ICCI- International Cryosphere Climate Initiative)

WMO encourages its Members to actively engage in the initiatives related to the IYGP 2025. Examples of foreseen/ongoing activities range from communication and awareness raising (TF-1 and TF-3) to capacity development and IYGP 2025 launch (TF-2) as well as policy advice, networking, lobbying and advocacy (TF-4) in addition to research and monitoring (TF-3).

The International Polar Year 2032/2033

The planning for a 5th International Polar Year (IPY) for 2032/2033 is taking shape under the early leadership of International Arctic Science Committee (IASC) and Science Committee on Antarctic Research (SCAR) and with the support of WMO. The 5th IPY will foster vital cooperation among countries, disciplines, programmes, and knowledge systems to produce urgently needed actionable information to support evidence-based challenges. It will build directly on the legacy of the 4th IPY (2007/2008), which drew together evidence from thousands of polar scientists and others emphasizing that what happens at the poles has global impacts. It also generated an impetus in polar science communication, education, and public engagement.

The collaborative global efforts will allow researchers and knowledge holders to capitalize on the outcomes of previous IPYs by expanding integrated and coordinated observations of accelerating changes, and long-term monitoring to enhance the understand of current conditions and inform predictions of future states. It will build on the methodological, technological and epistemological advancements of the 4th IPY, including major shifts toward working across knowledge systems.

- It will provide a comprehensive assessment of the operation and evolution of polar ecosystems enabling a more holistic understanding of the Earth's interconnected systems and climate change trajectory, as well as supporting practical global and local adaptation solutions
- An important goal of the 5th IPY is to achieve a step change in transdisciplinary polar research through meaningful integration of natural sciences, social sciences, humanities research, and Indigenous knowledge systems.

For further details see: https://iasc.info/cooperations/international-polar-year-2032-33.

World Meteorological Organization

7 bis, avenue de la Paix - Case postale 2300 - CH-1211 Geneva 2 - Switzerland
Tel.: +41 (0) 22 730 81 11 - Fax: +41 (0) 22 730 81 81
Email: wmo@wmo.int - Website: wmo.int

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