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| WEATHER CLIMATE WATER | **World Meteorological Organization**  **COMMISSION FOR OBSERVATION, INFRASTRUCTURE AND INFORMATION SYSTEMS**  **Second Session** 24 to 28 October 2022, Geneva | **INFCOM-2/Doc. 6.6** |
| Submitted by: Chair of SG-CRYO  26.IX.2022  **DRAFT 1** |

**AGENDA ITEM 6: TECHNICAL REGULATIONS AND OTHER TECHNICAL DECISIONS**

**AGENDA ITEM 6.6: Study Group on Cryosphere Cross-cutting Functions  
(SG-CRYO)**

# RECOMMENDATIONS OF THE STUDY GROUP: Closing the gap on the integration of CRYOSPHERE in the Earth system STRATEGY of WMO

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| **Summary** |
| **Document presented by:** Chair of the Study Group on Cryosphere Cross-cutting Functions – Global Cryosphere Watch (SG-CRYO)  **Strategic objective 2020–2023:** 2.1.6  **Financial and administrative implications:**   * Within the parameters of the Strategic and Operational Plans 2020–2023 * To be reflected in the Strategic and Operational Plans 2024–2027   **Key implementers:** INFCOM in collaboration with SERCOM, RB, EC-PHORS, RAs, and HCP  **Time frame:** 2023–2027 with a long-term outlook  **Action expected:**   * Approve the SG-CRYO Final Report and recommendations * Define and approve actions for INFCOM structures and recommendations to other WMO structures on closing the gap on the integration of cryosphere information in the Earth system strategy of WMO |

# GENERAL CONSIDERATIONS

### SG-Cryo Recommendations:

### Recommendations on closing the gap on the integration of cryosphere in the Earth system strategy of WMO

This draft Resolution presents the Commission for Observation, Infrastructure and Information Systems (INFCOM) decisions and actions resulting from the recommendations of the Final Report of the Study Group on Cryosphere Cross-cutting Functions – Global Cryosphere Watch (SG-CRYO) on closing the gap on the integration of cryosphere information in the Earth system strategy of WMO.

The recommendations were developed as actionable next steps for addressing key noted gaps, across the full value cycle, in support of WMO Members affected by the impacts of the accelerated and largely irreversible changes in snow and ice, at regional and global level, e.g. increased uncertainties in water resources, sea level rise, increased risk of cryosphere-related hazards, etc.

Outline of SG-Cryo Final Report

The Final Report of SG-CRYO to INFCOM is provided in the [annex](#_Annex_to_draft_3) to the present draft Resolution and it concludes the work of this Study Group.

The report includes an overview of the cryosphere cross-cutting functions relative to the WMO Strategic Priorities and the 14 recommendations made by SG-CRYO. These recommendations are addressed to INFCOM, with references for areas of collaboration with other WMO structures, covering:

1. Integration of cryosphere-related activities within the governance structure of WMO;
2. The role of the Global Cryosphere Watch Advisory Group (GCW-AG) as a coordination mechanism and its necessary engagements to sustainably meet the cryosphere information needs of WMO overarching priorities ([*WMO Strategic Plan 2020–2023*](https://library.wmo.int/index.php?lvl=notice_display&id=21525) (WMO-No. 1225);
3. An overall assessment of all components of the cryosphere that are relevant to the WMO service priorities, e.g. snow, sea-ice, glaciers, permafrost, ice sheets, freshwater ice, etc.

The results of the deliberations of SG-CRYO will publish a White Paper to complement the Final Report [annexed](#_Annex_to_draft_3) to this draft Resolution.

**Expected action**

The Commission to:

* Approve the SG-CRYO report and its recommendations
* Approve specific actions for its substructures
* Invite other WMO bodies and the WMO Members to collaborate with INFCOM structures in the implementation of these recommendations.

# DRAFT RESOLUTION

## Draft Resolution 6.6/1 (INFCOM-2)

## Closing the gap on the integration of CRYOSPHERE in the Earth system approach of WMO

THE COMMISSION FOR OBSERVATION, INFRASTRUCTURE AND INFORMATION SYSTEMS,

**Recalling**

1. [Resolution 48 (Cg-18)](https://library.wmo.int/doc_num.php?explnum_id=9827#page=162) – Key Directions of the Polar and High-Mountain Agenda for the next WMO financial period (2020–2023),
2. [Resolution 18 (EC-73)](https://library.wmo.int/doc_num.php?explnum_id=11008#page=338) – Transition and Pre-operational Plan of the Global Cryosphere Watch,
3. [Resolution 30 (EC-73)](https://library.wmo.int/doc_num.php?explnum_id=11008#page=495) – Executive Council Panel on Polar and High-Mountain Observations, Research and Services,
4. [Resolution 1 (INFCOM-1)](https://library.wmo.int/doc_num.php?explnum_id=11197#page=18) – Establishment of Standing Committees and study groups of the Commission for Observation, Infrastructure and Information Systems (Infrastructure Commission),
5. [Resolution 7 (INFCOM-1)](https://library.wmo.int/doc_num.php?explnum_id=11197#page=146) – Global Cryosphere Watch Advisory Group,

**Having examined** the Final Report to INFCOM of the Study Group on Cryosphere Cross-cutting Functions – Global Cryosphere Watch (SG-CRYO), as provided in the [annex](#_Annex_to_draft_3) to the present Resolution,

**Having considered** the recommendations of the eleventh Executive Panel on Polar and High-Mountain Observations, Research, and Services ([EC-PHORS-11](https://community.wmo.int/final-reports-ec-phors-sessions)),

**Mindful of** the findings of the [Sixth Assessment Report](https://www.ipcc.ch/assessment-report/ar6/) (AR6) of the International Panel on Climate Change (IPCC);

**Welcomes** the completion of the Year of Polar Prediction (YOPP) project and the outcomes of the International Symposium on Ice, Snow, and Water in a Warming World (Iceland, 2022);

**Takes note** of the cryosphere information required for effective weather, climate, water, and environmental services, as summarized by SG-CRYO in its Final Report;

**Accepts** the 14 recommendations made by SG-CRYO in its Final Report provided in the [annex](#_Annex_to_draft_3) to the present Resolution;

**Decides:**

1. To accelerate the integration of the cryosphere information across its activities to sustainably and equitably meet the needs of Members for addressing global and regional risks from the irreversible changes in the cryosphere and their downstream impacts, e.g. on water resources, sea level rise, disaster risks, etc.;
2. To amend the terms of reference of the Global Cryosphere Watch Advisory Group (GCW‑AG), to incorporate the SG-CRYO recommendations [((INFCOM-2)/Doc. 2.1)](https://meetings.wmo.int/INFCOM-2/English/Forms/AllItems.aspx?RootFolder=%2FINFCOM%2D2%2FEnglish%2F1%2E%20DRAFTS%20FOR%20DISCUSSION&FolderCTID=0x012000DFD47F9206CDD640A4FDFBAA2EB0EF6E&View=%7BDBBC48FA%2DBEE2%2D4A94%2D8905%2DFBE98B87E342%7D);

**Requests** its Standing Committees to incorporate in their work plan for the next intersessional period, prioritized actions responding to the SG-CRYO recommendations, in close collaboration with, and building on the expertise of GCW-AG;

**Requests GCW-AG:**

1. To collaborate with the INFCOM Standing Committees on the development of Technical Regulations and Guidance material implementing the SG-CRYO recommendations and operationalizing the GCW components in WMO Information System (WIS), WMO Integrated Global Observing System (WIGOS) and Global Data-processing and Forecasting System (GDPFS), by INFCOM-3;
2. To prepare in consultation with the SC-ON, terms of reference and a modus operandi for a task team on the coordination of space-based capabilities for advancing benefits of, and access to space-based cryosphere observations, by evolving those of the Polar Space Task Group, for approval by INFCOM President;
3. To report at INFCOM-3 on the progress made on addressing the SG-CRYO recommendations;

**Further requests** GCW-AG and SC-ESMP to report at INFCOM-3 on a road map for infrastructure supporting the fully coupled cryosphere in Earth system models, incorporating opportunities for transferring mature research results to operations, as are those from YOPP;

**Invites**

1. SERCOM, RB, and RAs to collaborate, as appropriate, under the guidance of INFCOM Management Group, on the implementation of the SG-CRYO recommendations;
2. EC-PHORS to consider the SG-CRYO Final Report in its strategies and advocacy;

**Urges** Members:

1. To continue fostering engagements of their National Meteorological and Hydrological Services (NMHSs) with partners, research institutions and academia to maximize the benefits of the integration of cryosphere through WIGOS, WIS, and GDPFS;
2. To support with resources the implementation of SG-CRYO recommendations, including through the GCW Trust Fund and/or seconded experts;

**Invites** partners to take part in implementation of SG-CRYO recommendations;

**Requests** the Secretary-General:

1. To provide the necessary assistance and Secretariat support to Members for the implementation of this Resolution, especially to developing and least developed countries, in respect to their requirements and within the available resources;
2. To assist in the mobilization of necessary resources and the engagement of experts to support the implementation of actions as outlined in this Resolution.

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[Annex:](#_Annex_to_draft_3) 1

## Annex to draft Resolution 6.6/1 (INFCOM-2)

## Study Group on Cryosphere Cross-cutting Functions – Global Cryosphere Watch (SG-Cryo)

# FINAL REPORT

**Closing the gap on the integration of CRYOSPHERE in the Earth system approach of WMO**

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### Summary

The Study Group on Cryosphere Cross-cutting Functions – Global Cryosphere Watch (SG-CRYO) was established by [Resolution 1 (INFCOM-1)](https://library.wmo.int/doc_num.php?explnum_id=11197#page=18) - Establishment of standing committees and study groups of the Commission for Observation, Infrastructure and Information Systems (Infrastructure Commission), with the following terms of reference:

1. Provide recommendations on the integration of Terms of Reference of the Global Cryosphere Watch (GCW) and the Executive Council Panel of Experts on Polar and High-Mountains Observations, Research, and Services (EC-PHORS), as approved by [Resolution 48 (Cg-18)](https://library.wmo.int/doc_num.php?explnum_id=9827#page=162), [Resolution 50 (Cg-18)](https://library.wmo.int/doc_num.php?explnum_id=9827#page=173) and [Resolution 6 (EC-71)](https://library.wmo.int/doc_num.php?explnum_id=10248#page=21), with the Terms of Reference and modus operandi of the Standing Committees of technical commissions and of the Research Board, to meet the requirements for cryosphere information of all WMO activities, as defined in the WMO Strategic and Operating Plans, and identify gaps;
2. Assess synergies with the Global Climate Observing System (GCOS), the World Climate Research Programme (WCRP), the International Union of Geodesy and Geophysics (IUGG), the Scientific Committee on Antarctic Research (SCAR) and other relevant programmes and partners, fostering greater reciprocity within the WMO community and with current and emerging partners in the field of cryosphere;
3. Recommend an optimal integration of these activities within the governance structure of WMO and a coordination mechanism to facilitate meeting the requirements for cryosphere information, including on further developments;

The outputs expected to be delivered by SG-CRYO were:

1. Report on cryosphere cross-cutting functions, across WMO activities;
2. Recommendations on an optimal integration of these activities within the governance structure of WMO, on a coordination mechanism of these activities, and on the necessary engagements to consistently meet the cryosphere information needs, by the next ordinary session of the Commission;
3. Recommendations on the mandate and functions of GCW as a coordination mechanism within the framework of WMO, addressing all components of the cryosphere that are relevant to the [WMO strategic priorities](https://library.wmo.int/doc_num.php?explnum_id=9939=page#11), e.g. snow, sea-ice, glaciers, permafrost, ice sheets, etc.

In its work, SG-CRYO evaluated the cryosphere information needs for delivering on the WMO Strategic Priorities 2020–2030, taking into account the status and the outlook of international research on cryospheric sciences, the emerging information needs, and of the capabilities of Members.

The present report provides the summary of the cryosphere cross-cutting functions across WMO activities (Sections 3, 4, and [Appendix](#_Appendix_to_the) to the report) and 14 recommendations prepared by SG-CRYO for addressing the identified gaps in the WMO structure and activities (Section 5). In its work, SG-CRYO focused on all components of the cryosphere that are relevant to the WMO activities on weather, climate, water, and the environment, namely snow, sea-ice, lake and river-ice, glaciers, glacial ice sheets and shelves, icebergs, permafrost and seasonally frozen ground, as well as solid precipitation.

In preparing this report, SG-CRYO aimed at addressing the provisions of the seventy-third session of the WMO Executive Council, [Resolution 30 (EC-73)](https://library.wmo.int/doc_num.php?explnum_id=11008#page=496), that requested “*INFCOM, the Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM) and the Research Board to integrate in their respective work programmes the technical, operational, and research priorities and activities previously under the remit of EC-PHORS*”. [Resolution 30 (EC-73)](https://library.wmo.int/doc_num.php?explnum_id=11008#page=496) further requested that “*INFCOM, SERCOM and the Research Board to develop together a roadmap for science-to-services from the World Weather Research Programme (WWRP) Polar Prediction Project, leading to the integration of its outcomes via the Global Data-processing and Forecasting System (GDPFS) and for identifying new research priorities, including by contributing to the vision to be developed by the Science Advisory Panel*”.

Based on the recommendation of SG-CRYO, [Resolution 7 (INFCOM-1)](https://library.wmo.int/doc_num.php?explnum_id=11197#page=146) established the Global Cryosphere Watch Advisory Group (GCW-AG) under its remit, as a coordination mechanism. This report identifies additional areas of focus for GCW-AG, addressing emerging priorities, as for example the implementation of the WMO Unified Data Policy, with effective linkages across WMO structures and with relevant partners.

Overall, SG-CRYO concluded that the WMO goals of an Earth system approach to observations, modelling and prediction require additional actions on the integration and use of cryosphere information to close the gaps to a fully coupled cryosphere in the Earth system, as a mean to providing effective services responding to emerging needs.

Coordination through WMO, as an intergovernmental organization, is essential and most beneficial to Members, by extending the well-established practices for weather and climate to the integration of the cryosphere, reflective of its critical role in the Earth system.

The 14 recommendations outlined in [Section 5](#_Recommendations) provide a high-level roadmap for the optimal integration of cryosphere-related activities in the WMO structure, covering the foundation of observations and data, the representation of cryosphere processes in Earth system modelling and prediction, further understanding and research on cryosphere change and feedbacks in the climate system. The report includes a dedicated recommendation on the WMO role regarding Antarctic activities. Careful prioritization and collaboration across all structures of WMO, are needed.

This report will be followed by a White Paper to be published in a peer review journal and which will provide a comprehensive review of gaps and opportunities for WMO, as compiled by SG-CRYO.

### The Changing Cryosphere and the Evolving Information Needs

Snow, glaciers, frozen ground, freshwater and sea-ice extend well beyond polar and high-mountain areas, being present in more than 100 nations[[1]](#footnote-2), and influencing weather, hydrology, water availability, and climate, globally and regionally.

The recent reports published by the International Panel for Climate Change (IPCC), namely the Sixth Assessment Report (AR6 2021[[2]](#footnote-3), 2022[[3]](#footnote-4)) and the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC, 2019[[4]](#footnote-5)) that included chapters on high-mountains (Hock et al., 2019) and polar regions (Meredith et al., 2019), thoroughly documented the unprecedented changes in the global cryosphere and their impacts. Numerous other analyses of decadal-scale cryosphere trends are available in the scientific literature reflecting the global and regional perspectives.

Snow and ice are in decline across much of the planet, with significant feedbacks and impact on the world's weather, climate, and hydrologic systems. Sea level rise has accelerated globally in recent decades, largely due to increasing ice loss from the Greenland and Antarctic ice sheets and glaciers around the world (IPCC SROCC, SMP, A3).

Often, impacts of changes in the cryosphere are felt well beyond the countries where they occur, in downstream countries and by coastal communities and small islands, being transmitted from polar and headwaters to vast human populations and the oceans, via hydrological systems and the cascading impacts of snow and ice changes on weather and climate.

Changes in the cryosphere are largely irreversible under global warming and several parallel tracks are necessary to support decisions and action on mitigation and adaptation of people and societies to these changes. Concurrently, advances in understanding and representing cryospheric processes in the Earth system, are needed to augment the capacity of Members to meet their needs. The emerging requirements and priorities in the provision of services and the reduction of existing information gaps, in particular for mountain and polar communities, have to be in sync with the need for equity of information, forecasts and mitigation advice for all.

### Cryosphere Information for Services to Society

This section provides an overview of key cryospheric service functions (So et al., 2019[[5]](#footnote-6)) that are relevant to WMO priorities.

The magnitude and sustainability of monitoring changes in the cryosphere and the gaps in knowledge about their impacts and about their service function, are not fully compatible with the socio-economic needs of affected regions and their importance for society. In the value cycle, critical observing and data-analysis and the distribution of these results, are still missing or are under-developed and addressing them has remained a priority.

Cryosphere information is integral to all services coordinated through WMO, from global to regional and local levels and is critical for meeting the goal of better serving the societal needs, as defined under Long-Term Goal 1 of the WMO Strategic Plan. The [appendix](#_Appendix_to_the) to this report provides a mapping of cryosphere information required to provide services coordinated through the Services Commission of WMO.

3.1 Cryosphere regulating functions and services

The cryosphere has a strong regulating function on weather, climate, and water resources, across all timescales. For example:

Changes in sea-ice have the potential to influence mid-latitude weather. The high albedo of sea-ice keeps its surface cooler than its surroundings. Snow on sea-ice has an even higher albedo, insulating the sea-ice and delaying ice-melt in the summer.

Snowmelt and ice-melt over land help regulate hydrological runoff and are critical to regulating water availability and ecosystem services, downstream.

Ice sheet meltwater runoff has implications for physical oceanography (e.g. ocean mixing, stratification and currents, etc.) and is a key contributor to the global sea level rise.

On seasonal to decadal timescales, changes in snow cover, freshwater and sea-ice, glaciers, ice sheets, and permafrost impact water resources and ecosystems, including near-coastal and marine ecology.

The cryosphere is an integral component of the ecology and geomorphology of mountain and polar regions, shaping the landscape and providing essential ecosystem services such as habitat to snow-dependent terrestrial species and maintaining cooler river and lake water temperatures in glacier or snow dominated watersheds, e.g. fish habitats.

The northern hemisphere cryosphere, especially the permafrost, plays a key regulating role in the global climate system by acting as a carbon sink or source, which alters atmospheric greenhouse gas emissions. IPCC (SROCC, 2019) estimated the amount of carbon stored in permafrost at about twice the amount in the atmosphere, today.

3.2 Cryosphere provisioning and cultural functions and services

Cryosphere information is essential for services for many economic sectors.

Glaciers and snow are natural reservoirs of water for hydroelectric production and operations, agricultural and industrial water supply, and for drinking water to billions. Mountains are often called natural “water towers” because they are vital headwaters to many rivers that originate from snow and ice, and other freshwater sources that replenish aquifers.

Mountain snow cover and glaciers are key to mountain tourism and the ski industry, while meltwater from rain, snow and the timing of frozen ground cycles affect agriculture, grazing practices, and the livelihood of indigenous peoples. Snow and ice have critical cultural and spiritual value for mountain and northern communities.

3.3 Cryosphere functions and services related to transportation and infrastructure

Information on the state of snow and ice is key to operational and seasonal planning for polar shipping routes and for winter transportation networks on land, rivers, lakes, often the lifeline of many communities.

Marine traffic across a range of commercial activities (e.g. fishing, resource exploitation, tourism, shipping) in the Arctic and the Southern Ocean rely on the forecast skill, e.g. weather and ice warnings, to inform navigation and maritime emergency services such as search and rescue operations or for oil spill clean-ups.

The energy sector depends on the understanding of fall and spring temperatures for the building of ice roads to protect the tundra and for using frozen rivers as access routes to extractions sites. The timing of sea-ice freeze-up impacts the transport of liquid natural gas (LNG), as well as tourism in the high latitudes.

On multi-annual to decadal timescales, knowledge of how snow, permafrost and ice conditions (on land and at sea) are changing is critical to inform infrastructure design standards, decisions on planning, insurance and reinsurance predictions, and on investments. This is the case of buildings, housing, railroads and roads that are strongly affected by subsidence and coastal erosion (polar and high-mountain regions), as well as of investments in major marine infrastructure such as icebreaker capabilities, deep-sea port capacity, and off-shore structures (e.g. drill rigs).

3.4 Cryosphere changes and related hazards

As noted by IPCC (SROCC, 2019), changes in glaciers, snow, ice, and permafrost have altered the frequency, timing, magnitude, and location of most related natural hazards, leading to exposure of human settlements and livelihoods to increased risks, with prevalence in high-mountain areas and the Arctic. Most common cryosphere hazards are related to increases and shifts in rain on snow and spring snowmelt flooding, glacier lake outburst floods (GLOFs), landslides and slope detachment/rockfall from degrading permafrost and retreating glaciers, snow and ice avalanches, unreliable and unstable ice and snow conditions, and the changing presence of icebergs, etc. People with highest exposure and vulnerability to cryosphere hazards are often those living in developing countries, the ones that have the least adaptive capacity.

Near real-time cryosphere information is essential to support the development of adequate early warning systems, monitor and report on extreme events, and conduct the necessary risk assessments. For example, due to modified ocean-sea-ice-atmosphere interactions the sea-ice regime is changing, and first-year ice is becoming prevalent in areas of the Arctic previously known for second or multi-year ice. This is a challenge for the current observing techniques used operationally to map and report sea-ice conditions. And calls for advanced monitoring techniques to enable the tracking of sea-ice conditions at regional and synoptic scales.

Adequate risk assessments require reliable and long-term climate records on the cryosphere to understand and characterize the level of risk and to support adaptation strategies, including on infrastructure design standards and parameters that reflect anticipated future changes.

3.5 Stakeholders

In many countries, the responsibilities for hydrometeorological observations and services for mountain and polar regions, are shared across multiple agencies, ministries and stakeholders.

Most of the existing hydrometeorological services are designed for lowlands and for mid to low latitudes where human population is concentrated and have insufficient spatial Resolution to adequately represent complex terrain and related hydroclimatic processes in mountain areas and high latitudes. This results in an insufficient representation of the cryosphere in operational applications, with diminished reliability of forecasts and predictions. In most countries the majority of cryosphere monitoring has remained driven through the research communities, in spite of expectations for continuous, long-term programmes.

Where existing, the Resolution of monitoring networks in high-mountains and polar regions is insufficient to adequately resolve complex terrain and related hydroclimatic processes.

Engagement and active collaboration, in particular between research and operational entities, are necessary steps to overcome the current cryosphere information gap.

### Enhance Earth System Predictions Through the Integration of Cryosphere Information at all Scales

For its 2030 strategic priorities, WMO has taken a unified Earth system approach to monitoring and prediction for improved decision– and policy– making.

Earth system analysis and modelling includes the coupled evolution of the atmosphere, ocean, land-surface, cryosphere, ecosystems, the hydrological cycle, and biogeochemical cycles across the full spectrum of timescales. Coupled analysis and prediction requires consistency in the observing and modelling systems across Earth system components, including the cryosphere, with 1) sustainable observing networks and 2) reliable data exchanges and mechanisms for timely access to observations and their data.

Earth system and cryosphere processes operate across a continuum of timescales (Fig. 1), which are represented naturally within seamless global prediction systems.

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 (or benefit from) detailed initialization of the current state of seasonal snow and ice cover.

Diagram

Description automatically generated

**Figure 1 The continuum of timescales for modelling of cryosphere processes   
in the Earth system**

To improve the capabilities of Earth system models in polar and high-mountain regions, and on the integration of cryospheric information, it is necessary to increase our understanding and model representation of the complex interactions between ocean, land, sea-ice, and atmosphere that dictate environmental conditions. Depending on the model Resolution, many of these processes and interactions are predominately sub-grid-scale, and must be represented through simplified physics (i.e. parameterized). However, many sub-grid-scale processes are not well represented in the current prediction models, notable being the suboptimal representation of the inhomogeneous mountain terrain (Rotach et al., 2022[[6]](#footnote-7)). These shortcomings become even more important with the move to fully coupled models.

Land-surface hydrology is an integral part of Earth system modelling. For many applications, there are benefits to coupling of hydrological models within Earth system models to capture feedbacks to the atmosphere (e.g. 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. This often requires an additional step to downscale and adapt such outputs to the native Resolution of process-based hydrological and cryosphere models, often of tens to hundreds of metres. This line of modelling enables the generation of ensembles of hydrological predictions (i.e. 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.

### Recommendations

As NWP underpins most hydrometeorological, climate, and environmental services and climate reanalyses, the SG-CRYO recommendations focus on improvements to the capabilities of NWP that are currently insufficient for integrating information on the cryosphere, as a prerequisite to effective information services, at regional to global levels. Improved infrastructures (e.g. observations, access to quality data, computing and code refactoring, etc.) to enable the assimilation of cryosphere data and increasing model accuracy and reliability are needed for forecast improvements for short-term and tactical events, as well as longer term projections and climate reanalyses.

Given that polar and high-mountain regions are home to many indigenous populations and rural communities, SG-CRYO acknowledges the priority of working with these groups to co-develop information systems that would effectively communicate the impact of the changing climate to their livelihoods (changing ice conditions and more hazardous travel on frozen lakes and rivers, glacier changes, etc.).

Recommendation 1

**GCW-AG – with a focused mandate to support he WMO strategy**

SG-CRYO recommends that INFCOM update the terms of reference of GCW-AG to incorporate the recommendations of this report. GCW-AG plays a critical role in INFCOM and, broadly, in WMO, by ensuring mutually beneficial engagements of the diverse expertise from partner communities.

In preparing its recommendations, SG-CRYO took into account the significant progress made by GCW on the integration of cryosphere observations and data in WMO Integrated Global Observing System (WIGOS) and WMO Information System (WIS), on bridging between WMO and the cryosphere communities, and the support to developing specific services, as demonstrated through the Arctic Regional Climate Centre network (ArcRCC-Network) and the Third Pole Regional Climate Centre – network (TPRCC-Network).

The GCW-AG membership need to enable access to the critical level of expertise and reflect the information needs on each of the cryosphere components. Sustained working-level engagements with the relevant structures of SERCOM, the WWRP and the World Weather Climate Programme (WCRP) of the Research Board, are recommended. Additional beneficial engagements are those with WMO partners, as established through the Executive Council Panel on Polar and High-Mountains Observations, Research, and Services (EC-PHORS), e.g. IUGG, SCAR, Mountain Research Initiative, Third Pole Environments, Sustaining Arctic Observing Networks, etc.

Recommendation 2

**Cryosphere – an integral component of the WMO activities**

SG-CRYO recommends that the Standing Committees of INFCOM include in their work plans actions to systematically integrate the cryosphere in the WIGOS, WIS and the GDPFS, and that GCW-AG provides the sustained expert engagement and support to achieve these goals.

Recommendation 3

**Infrastructure roadmap to a fully integrated cryosphere in Earth system models**

Noting the goal of Earth system monitoring, modelling and prediction at the core of the WMO strategy, SG-CRYO recommends that INFCOM taskGCW-AG and SC-ESMP to coordinate the development of a roadmap for infrastructure to support the fully coupled cryosphere in Earth system models (atmosphere-cryosphere-terrestrial-ocean), as a prerequisite to effective information services, at regional to global levels, as noted in sections 3 and 4 of this report.

Consultations with relevant WMO structures and partners are needed, to efficiently build on current and relevant initiatives, identify pilot projects, and reflecting user needs. A report on progress should be tabled at the next ordinary session of the Commission.

SG-CRYO prepared a non-exhaustive list of key areas for consideration in this process, including:

* Dynamical and statistical downscaling for modelling of cryospheric, hydrologic, and oceanographic processes, as relevant to local and regional stakeholders.
* Closing the gaps between NWP and seasonal prediction, in support of the generation of operational hydrological and climate products for polar and high-mountain regions, e.g. support to the implementation of TPRCC-Network.
* Data assimilation and model prediction capabilities for extreme cryospheric events and risk assessment of cryosphere hazards (e.g. ice jams, landslides, avalanches, GLOFs, icebergs, etc.).
* Coupling NWP and hydrological modelling with advanced downscaling methods (air temperature, radiation, precipitation amount and phase, etc.), and provision of high-Resolution atmospheric forcing to stand-alone hydrological and glaciological models.
* Operationalization of existing glacio-hydrological models, i.e. for daily to seasonal meltwater runoff predictions.
* Cryosphere data access, quality control, and curated datasets for data assimilation and model validation.
* Advancing the understanding of the associated uncertainties (also inconsistency and representativeness) in cryosphere observations and data, and foster their operational use, including to constrain models.
* Exploitation of cryosphere satellite observations in Earth system models, including increased capacity to assimilate satellite cryosphere products.
* Advancing the understanding of biases and uncertainties (including inconsistency and representativeness) in cryosphere observations and data, and foster their operational use, including to constrain models, e.g. quantifying uncertainties in solid precipitation for basin water budget analysis and hydrological models.
* Evaluate standards for high-Resolution (sub-km) cryospheric observations for initializing, verifying, and downscaling weather and Earth system models; promote research and observational campaigns to generate such datasets.

Recommendation 4

**Enhance the availability of cryosphere observations in WIGOS**

SG-CRYO recommends that GCW-AG continue to support Members in understanding and addressing their observing gaps for all components of the cryosphere and related observations (e.g. over polar and high-mountains), as related to their needs, by contributing to the development of relevant Technical Regulations and Guides, e.g. standardization of observations. The collaboration of GCW-AG with the Standing Committee on Earth Observing Systems and Monitoring Networks (SC-ON) and the Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT), is key to the expected results.

SG-CRYO emphasizes the need for documented cryosphere observing requirements for the Application Areas of the WMO Rolling Review of Requirements (RRR), critical to overcoming the significant fragmentation, today. The analysis needs to provide a critical review of observing system capabilities (in situ and remote sensing), to draw attention to the most important gaps in existing cryosphere observing system capabilities, and to identify opportunities to improving the understanding of uncertainties of cryosphere observations (in situ and remotely-sensed), including through continuing to promote intercomparisons.

A priority action is recommended on synthesizing the observing requirements for Global NWP and climate reanalysis, for consideration for the Global Basic Observing Network (GBON).

Recommendation 5

**Cryosphere data in the WMO Unified Data Policy**

SG-CRYO recommends that GCW-AG collaborate with SC-ON to routinely review and update [Annex 1 of Resolution 1 (Cg-Ext(2021))](https://library.wmo.int/doc_num.php?explnum_id=11113#page=15) on the WMO Unified Data Policy, to specify the minimum set of core cryosphere data that Members shall exchange on a free and unrestricted basis, as well as any recommended data that they consider that it should be specified, and draft changes to the appropriate technical regulations for consideration by INFCOM.

Recommendation 6

**Cryosphere data: standardization and increased access through WIS**

SC-CRYO recommends that INFCOM, task GCW-AG to work with the relevant INFCOM Standing Committees and partners to address gaps in the standardization of cryosphere observations and data and to promote and facilitate cryosphere and polar data sharing though the application of interoperability standards at that are compliant with the FAIR (Findable, Accessible, Interoperable, Reusable) guiding principles, and in the framework of WIS. In this respect, SG-CRYO identified three key priorities:

1. Development and submission of updates, when necessary, to the WMO Technical Regulations, on measurement and data reporting standards and best practices for all cryosphere components, and promulgate uptake as part of GCW implementation;
2. Facilitate the integration of relevant cryospheric and third-party data in WIS, with a focus on the exchange of data in real-time;
3. Promote access and long-term archival of cryosphere data, e.g. dedicated Data Centres.

Recommendation: 7

**Integrate cryosphere specific functions in** [**GDPFS**](https://public.wmo.int/en/programmes/global-data-processing-and-forecasting-system)**,**

SG-CRYO recommends that GCW-AG and SC-ESMP facilitate the integration of cryosphere specific functions in the GDPFS framework, reflecting the information needs of polar and high-mountain regions, by leveraging the experience of ArcRCC-Network and TPRCC-Network, and the recommendations from the 2019 High-Mountain Summit, which remain highly relevant. Consideration should be given to multi-domain and multi-scale information needs of polar and high-mountain regions, e.g. stronger link climate-hydrology, etc.

Recommendation 8

**Systematic approach to cryosphere-related hazards in the existing Disaster Risk Reduction (DRR) framework of WMO.**

SG-CRYO recommends that a scoping exercise be undertaken to enable the integration of cryosphere-related hazards in the existing WMO DRR framework, as a collaborative effort of INFCOM and SERCOM. This approach needs to support the priority of WMO for Early Warning Systems for all.

SG-CRYO recommends that INFCOM task GCW-AG to facilitate the engagement of relevant partners with proven practice in this domain, as are the International Association of Cryospheric Sciences, the International Permafrost Association, Third Pole Environment program, etc.

The scoping exercise should identify components for consideration under the WMO activities, e.g. hazard definitions and cataloguing, the observing requirements and data access, monitoring of extreme events, early warning practices, additional research, etc.

Recommendation 9

**Cryosphere in the Global Climate Observing System (GCOS)**

SG-CRYO recommends that INFCOM task GCW-AG to convene a dialogue with the Steering Committee of GCOS on the evolution of cryosphere monitoring in the GCOS framework by leveraging the evolution of approaches to Essential Climate Variables (ECVs), e.g. sea-ice ECV, Lavergne et al. 2022[[7]](#footnote-8).

SG-CRYO recognizes the need to address the evolving climate monitoring needs of Members at different scales through a revised ECV structure as coordinated by GCOS, to effectively support the monitoring of climate change and its consequences in mountains and polar regions. In preparing this recommendation, SG-CRYO took note of the work undertaken on defining Shared Arctic Variables, as proposed by the Sustaining Arctic Observing Networks (SAON) Roadmap to Arctic Observing and Data Systems ([ROADS](https://www.arcticobserving.org/news/378-guidelines-for-contributing-to-saon-s-roadmap-for-arctic-observing-and-data-systems-roads)) process, and the consideration of Mountain ECVs[[8]](#footnote-9). The Group acknowledged the potential linkages to operational climate services. A harmonized system that acknowledges the necessary complexity while remaining parsimonious, would be valuable to the global community.

Recommendation 10

**Roadmap for Research to Services for Polar and High-Mountain Regions**

SG-CRYO urges INFCOM to work with the Research Board and use the opportunity of the completion of the Year of Polar Prediction (YOPP) project to develop a roadmap for translating mature research results into sustainable services. The Group noted the need for advocacy for resources necessary for transferring the knowledge developed into sustained capabilities and to incorporate lessons learned, e.g. user engagements in the design phase.

SG-CRYO is of the opinion that the significant investments made by Members for organizing large-scale research projects, as in YOPP, must lead to sustained improvements for the WMO community, e.g. the optimization of observing and data systems in data sparse regions, improved models, etc.

More broadly, SG-CRYO acknowledged the relevance of other internationally coordinated research projects and observing campaigns, to advancing the understanding and the representation of physical processes of the cryosphere in the Earth system. The Group noted the opportunity of the Multi-Scale Transport and Exchange Processes in the Atmosphere over Mountains–Program and Experiment (TEAMx), the Second Tibetan Plateau Expedition (STEP2), the Regional Hydroclimate Panels of the Global Energy and Water Exchanges (GEWEX) of the World Climate Research Programme (WCRP), as well as those organized under the auspices of Climate and Cryosphere project – CliC, also of WCRP.

Recommendation 11

**Further research on key questions on the cryosphere and its impacts, from local to global scales**

SG-CRYO recommends that further research is undertaken under the coordination of the Research Board and with active engagements of the Technical Commissions to enhance the capacity of Members to address emerging information needs.

Based on its evaluation, SG-CRYO identified benefits in addressing:

1. Better understanding and representing in numerical models, those polar and high-mountain specific processes implicated in the rapid and profound climate-driven changes that affect all regions of the globe, and
2. Advancing modelling capabilities to meet increasing demands for regional-to-local weather, climate and hydrological products and services via synthesis of historical and new observations, improvements to model fidelity, analyses, and operational outputs.

The non-exhaustive list of areas of consideration for future research, include:

* Higher spatial and temporal Resolution of models: convection-permitting Resolution for climate projection, and NWP forecast at scales aligned with specific needs
* Examination of the trade-off between higher Resolution and ensemble approaches that can give probabilistic information
* Standardization in post-processing such that output of models needs to lend itself to post-processing at relevant scales
* Advancement of ice sheet/ocean/Earth system modelling and prediction
* Quantification of evolving uncertainties, that account for the inconsistency and representativeness in the cryosphere observations, at regional and local scale, as a prerequisite for the operationalization of mature models
* Examination of model /Artificial Intelligence/Machine Learning-guided observations

Recommendation 12

**Access to cryosphere space-based products: engagement with space agencies**

Space-based observations of the cryosphere are essential, not least since costs, difficult access, extreme operating conditions, and limited representativeness are significant barriers to expanding and sustaining in situ cryosphere observing systems. WMO is best positioned to lobby for new satellite missions that would ensure continuity of critical data streams with the publication of well-documented observing requirements and by fostering the development of operational satellite products for the cryosphere, for use by operational models and applications.

In this respect, SG-CRYO recommends that INFCOM ensure the continuity of sustained engagements with the space agencies that operate cryosphere observing missions, by building on the success of the Polar Space Task Group (PSTG) under the remit of EC-PHORS, and as part of the implementation of Resolution 30 (EC-73). Benefits will be realized through the convening role of WMO, by mobilizing the unique and complementary capabilities of each of the respective participating agencies, whether research and development or operationally oriented.

SG-CRYO is of the opinion that GCW-AG in collaboration with SC-ON and with a regular loop back to EC-PHORS provide the right balance of expertise and engagement, externally and with the core WMO activities, to deliver benefits to Members. The expected coordination should focus on facilitating the acquisition and distribution of cryosphere, polar, and high-mountain satellite datasets, with the goal of contributing to the development of specific derived products in support of cryospheric scientific research and advancing the use for operational applications.

A complementary role for WMO is that of fostering satellite cryosphere product intercomparisons, including the access to and assurance of complementary in situ observations, with the goal of enhancing derivation of variable uncertainties to support their use for assimilation, validation and verification. SG-CRYO recognized the success of GCW in fostering such intercomparisons (snow cover, sea-ice thickness) and recommends that GCW continue these activities, in the future.

Recommendation 13

**Cryosphere as a regional and global climate change indicator**

SG-CRYO recommends that INFCOM task GCW-AG to foster the definition of representative indicators of change in the cryosphere in support of hydroclimate services at different scales, in collaboration with relevant structures of SERCOM and of Regional Associations, as contributions to WMO publications (e.g. State of the Climate – Global and Regional) and for communication with users, e.g. Climate Forums, etc. These may include, for example, projected changes in water resources, risk assessments, seasonal assessments and trackers of changes in snow and ice, extremes events (all components), etc.

Recommendation 14

**Role of WMO on Antarctica**

WMO Antarctic activities have always been a priority for WMO, the Second Wold Meteorological Congress (1963) establishing the first Antarctica Standing Committee under the remit of the Executive Council. Between 2007 and 2019 this function was undertaken by EC-PHORS. Following the WMO governance reform, [Resolution 30 (EC-73)](https://library.wmo.int/doc_num.php?explnum_id=11008#page=495) re-established the role of EC-PHORS on the coordination of Antarctica activities, with a focus on the strategic engagements and advocacy.

Consultations between EC-PHORS and INFCOM were coordinated through SG-CRYO, and the reports of meetings EC-PHORS-10 and EC-PHORS-11 document the agreement that the technical aspects related to observations, data exchange, and improvements to observing methods and instruments in the extreme conditions of Antarctica be aligned with the mandate of INFCOM SCs, and reflected in their work plans. EC-PHORS established its Antarctica Advisory Group, to provide a focused coordination of its engagement and advocacy role.

As a conclusion of the SG-CRYO review of the engagements on Antarctica activities, it is recommended that a strong link between GCW-AG and the Antarctica activities is maintained, to link to the small scientific community active in that region.

### Appendix to the SG-CRYO Final Report: mapping of cryosphere in the WMO Services

The mapping below provides an indication of the information on the cryosphere that is necessary to generate the respective services, as aligned with the service areas coordinated through WMO.

**Climate Services (SC-CLI)**

* + 1. Long-term water resource forecasts: snow, glaciers, solid precipitation;
    2. Sea level rise and related coastal services: glaciers, ice sheets, sea-ice, permafrost;
    3. Freshwater routing and fluxes to the oceans: snow, glaciers, ice sheets, permafrost;
    4. Permafrost carbon feedbacks: permafrost, snow (impacts on the active layer depth);
    5. Landscape evolution and link to infrastructure standards and design considerations: snow, permafrost, glaciers, ice sheets;
    6. Climate-cryosphere: albedo, latent energy, feedbacks (sea-ice, snow, ice sheets);
    7. Ocean freshwater budget and circulation: snow/snowfall, sea-ice, ice sheets;
    8. Changes to the precipitation cycle, e.g. increased freshwater runoff from rainfall;
    9. Regional changes in open water days/year: ocean/sea-ice, river-ice, lake-ice;
    10. Climate change projections and carbon fluxes associated with changing permafrost and sea-ice conditions (snow cover, sea-ice, permafrost).

**Hydrological Services (SC-HYD)**

* + 1. Operational hydrological modelling: snow, glaciers, permafrost, frozen ground;
    2. Flood modelling: operational forecasts, seasonal risk assessments: snow accumulation, lake and river-ice, frozen ground;
    3. Seasonal water resource forecasts for agriculture, drought management: snow, glaciers;
    4. Hydroelectric operations and municipal water management: snow, glaciers;
    5. Long-term (e.g. decadal) water resource projections: snow, glaciers, permafrost.

**Disaster Risk Reduction and Public Weather Services (Hazards, Warnings)**

* + 1. (Early) warning systems to address changing cryospheric hazard risks:
* Heavy snowfall, freezing rain
* Avalanches (snow, mountain weather)
* Glacier collapse, Glacial lake outburst floods; ice- and rockfall (glaciers, mountain permafrost and seasonally frozen ground)
* Coastal erosion (permafrost, sea-ice, land fast ice, solid precipitation)
* Changing lake-, river-, sea-ice thickness and phenology (freshwater and sea-ice)
  + 1. Infrastructure resilience to flooding, permafrost thaw, icing, heavy snow/blizzards/polar lows: snow, rain on snow, permafrost;
    2. Food security/ecosystem risk reduction;
    3. Subsistence activities that are heavily impacted by a changing cryosphere;
    4. Support to emergency prevention, preparedness and response, e.g. Search and Rescue in polar and high-mountains, support to oil spill response, or impacts from an increase in vessel traffic, etc.

**Marine Meteorological and Oceanographic Services (SC-MMO)**

* + 1. Routine ice information to support mariners and communities;
    2. Sea-ice prediction systems, from operational to seasonal timescales: sea-ice;
    3. Iceberg tracking: ice sheets, ice shelves, ice-ocean interactions;
    4. Freshwater budgets: snowfall/snow, permafrost for hydrological/runoff models;
    5. Mixing and currents: sea-ice, ice shelves, ice sheet runoff;
    6. Long-term planning for shipping routes, infrastructure: sea-ice, icebergs.

**Services for Agriculture (SC-AGR)**

* + 1. Operational hydrological forecasts to guide water usage: snow;
    2. Seasonal water resource forecasts for irrigation and crop management: snow, glaciers.

**Integrated Energy Services (SG-ENE)** - weather and climate services delivery for energy

* + 1. Management of operation of hydropower plants and reservoirs: snow, glaciers;
    2. Water availability for thermal energy plants, industrial needs: snow, glaciers;

**Ecological Services**

* + 1. Water quality, quantity linked to aquatic ecology: snow, glaciers;
    2. Ice-dependent and snow-dependent ecosystems, from algae to lemmings to polar bears: sea-ice, snow, glaciers, ice sheets.

**Economic Services**

* + 1. Mountain tourism and recreation: snow, glaciers;
    2. Polar tourism: snow, glaciers, ice sheets, icebergs, lake-ice, sea-ice, permafrost;
    3. Seasonal transportation, commerce, mobility via ice roads: lake, river, and sea-ice, freeze and spring break-up;
    4. Commercial shipping and fishing that depend on ice conditions: river, lake, and sea-ice;
    5. Subsistence activities (hunting, fishing) of indigenous, northern, and mountain communities: snow, river, lake, glaciers, permafrost, sea-ice;

**Health Considerations**

* + 1. Water quality, availability: snow, glaciers, permafrost;
    2. Aquatic ecosystem health and implications for food security: snow, freshwater ice;
    3. Legacy contaminants (e.g. PCBs) and viruses: glaciers, permafrost.

**Geopolitical and Policy Considerations**

* + 1. International partnerships and science diplomacy (e.g. cryosphere research and monitoring under the Antarctic Treaty, Arctic Council working groups, the International Science Council, etc.);
    2. Cross-border water security in mountain regions: snow, glaciers;
    3. Global impact of the Mean Sea level rise.

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