CRYOSPHERE IN A CHANGING CLIMATE: A GRAND CHALLENGE OF CLIMATE SCIENCE[1]

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1. WCRP JSC; 2. WGCM; 3. WGSIP; 4. JPS for WCRP; 5. GEWEX

The prospect of an ice-free Arctic Ocean; the fate of mountain glaciers providing fresh water to hundreds of millions of people worldwide; the strength of positive feedbacks between the warming climate and natural emissions of greenhouse gases from the thawing permafrost (both terrestrial and sub-sea); the role of ice-sheet dynamics in amplification of Greenland's contribution to the global sea-level rise. These issues are getting increasing attention in the international scientific research community and relate directly to societal needs for information about climate change and its impacts. These and other processes, in which components of the cryosphere play a central role, remain an important source of uncertainty in projections of future climate change, and so improved understanding of the cryosphere in a changing climate (CCC) clearly is a "Grand Challenge"[2].

1. Scientific context

"The cryosphere collectively describes elements of the Earth System containing water in its frozen state and includes solid precipitation, snow cover, sea ice, lake and river ice, glaciers, ice caps, ice sheets, permafrost, and seasonally frozen ground. The presence of frozen water in the atmosphere, on land, and on the ocean surface affects energy, moisture, gas and particle fluxes; clouds; precipitation; hydrological conditions; and, atmospheric and oceanic circulation. Elements of the cryosphere also contain important records of past climate, providing benchmarks for interpreting modern climate change." (WMO Info note No.59).

The cryosphere plays a key role in the global water cycle, in sea-level rise, in climate sensitivity, and presumably in climate predictability and teleconnections. The cryosphere also affects water availability, weather, energy and agriculture. Accurate observation of precipitation, including the difficult to measure solid component, is essential to

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[1] The original title of this paper "Cryosphere response to climate change (including ice sheets, water resources, permafrost and carbon)" has been changed because it presented the cryosphere as an object of impacts rather than an interactive component of the climate system.

[2] The following criteria were suggested by CLIVAR for a Grand Challenge:

- A Grand Challenge is both ***highly specific and highly focused*** identifying a specific barrier preventing progress in a critical area of climate science.
- This focus enables the development of ***targeted research efforts*** with the likelihood of significant progress over 5-10 years, even if its ultimate success is uncertain.
- It should thus enable the implementation of effective and ***measurable performance metrics.***
- By being transformative, a Grand Challenge should bring the ***best minds*** to the table (voluntarily), ***building and strengthening communities of innovators that are collaborative***, perhaps also extending beyond "in-house expertise".
- It can ***capture the public's imagination***: teams of world-leading scientists working to solve pressing challenges can offer compelling storylines to capture the interest of media and the public.

The Cryosphere is a multi-facetted component of the climate system and so does not lend itself to a 'single-issue' approach. We present here a set of Grand Challenges targeted at components of the cryosphere and the different time scales of the corresponding processes. However, each of these "sub-Grand Challenges" meets the above criteria, and so we suggest pursuing a grouping of related and societally relevant themes.

quantitative understanding the global water cycle. Snow- and glacier-melt are critical sources of water for agricultural, domestic and industrial water supply, and hydropower production, and contribute to flood and drought hazard conditions. Lake-, river- and sea-ice directly affect high latitude transportation and ecosystems, including regional and global transportation routes, regional economic development, and the well-being of people both within and outside high latitude regions. Other short and long term hazards directly related to the cryosphere include avalanches, glacier lake outburst floods, subsidence due to thawing permafrost, snowstorms, blizzards, icing, and coastal erosion.

Various feedbacks involving the cryosphere are an important contributor to climate system responses to external forcings. Among them, the ice albedo feedback is probably best understood and quantified. The IPCC Working Group 1 Fourth Assessment Report (IPCC AR4, 2007) highlighted CCC as a major source of uncertainty in global climate projections, particularly for future changes of the sea level.

One significant knowledge gap relates to the impact of thawing permafrost on the global carbon cycle. The magnitude of the positive feedback between a warming climate and the emission of greenhouse gases from natural sources, particularly from thawing permafrost, is only starting to be systematically studied. Some experts believe the resultant effect of this feedback may be catastrophic, while others are skeptical about its significance. The picture is complicated by limited information on the quantity and form of carbon sequestered in permafrost, by inadequate knowledge of arctic biogeochemistry, and by insufficient understanding of the interactions between the terrestrial cryosphere, hydrology and vegetation in northern high latitudes in a warming climate.

Complex and in many cases poorly understood processes, specific to the cryosphere, contribute significantly to the challenge that high latitudes pose from the viewpoint of physically-based climate modelling and prediction. The resulting uncertainty contributes directly to the spread amongst results of state-of-the-art global climate models and to the spread amongst seasonal to decadal climate predictions and longer-term projections in both northern and southern high-latitude regions. For example, following the IPCC AR4, it was noted that the global climate models whose results were summarized in the report as ensemble apparently under-represented the observed Arctic sea-ice decline during the latter part of the 20th century, and therefore might underestimate the future decline.

Components of the cryosphere are represented in state-of-the-art climate models at very different levels of sophistication. Improving these components and the representation of processes/feedbacks connecting the cryosphere to the rest of the climate system will be important in decreasing the above uncertainties in global and regional earth system models and their predictions.

2. Imperatives

An overarching mandate of the WCRP is to improve our understanding of the climate system and our ability to make quantitative predictions and projections of future climate. To fulfill this mandate, over the next 5-7 years, the WCRP should actively promote targeted research activities aimed at ***substantially improving*** our understanding of cryospheric processes and feedbacks and our ability to make quantitative initialized predictions and long term projections of cryospheric quantities and their interactions with the global climate system. The expected results should include:

- Increased confidence in climate models and their predictions/projections of cryosphere changes including those on regional scale;
- Improved information regarding future changes in the cryosphere, with a specific focus on information relevant for impact assessment and adaptation decision-making, such as the timing of the Arctic multiyear sea ice disappearance, the fate of mountain glaciers, etc.;

- More comprehensive, quality-controlled observational, observationally-based, and proxy datasets of cryospheric variables suitable for a range of research and model evaluation activities;
- Better quantitative understanding of processes involved in cryosphere/climate interactions and better representation of these processes in global and regional climate predictions from months to decades ahead, as well as longer-term projections, particularly with respect to the effect of the carbon sequestered in the terrestrial and sub-sea permafrost on the atmospheric, the role of ice sheet dynamics in sea level rise, etc.

There are a number of ways, in which the WCRP can contribute to the above objectives, including:

- Providing fora for improved communication between those involved in cryospheric observations and process studies and those involved in development and application of global and regional climate models and predictions. This might involve a pan-WCRP group or a sub-activity of an existing panel (such as WGCM or WGSIP). This could be a topic for the WCRP Modelling Advisory Council to consider.
- Promoting and facilitating targeted analysis of the CMIP5 and CORDEX results, and seasonal hindcasts in the CHFP database, focusing on the cryosphere and polar regions. There is already a community of scientists working in this area, but often partitioned into various disciplines (sea ice, permafrost, snow, ice sheets), and there are undoubtedly benefits to be had in promoting more cross-disciplinary work. For example, many model shortcomings in representing aspects of the cryosphere stem from errors not in the cryosphere components themselves, but rather from the coupled atmosphere or ocean. Probing these errors from various perspectives may accelerate overall model improvement.[3]
- Promoting detection and attribution studies of the cryosphere change (i.e. quantification of the interplay of its forced and unforced aspects) and evaluation of the ability of the state-of-the art climate models to reproduce the observed or reconstructed cryosphere behaviour as a part of the broader Earth system, with as full as possible accounting of cryosphere-climate processes, interactions and feedbacks.
- Promoting more coordinated evaluation and perhaps consolidation of cryospheric data sets (e.g. those derived from satellite remote sensing) so as to better inform and guide those using such data in research and model evaluation activities. A closely related activity is the development of more robust and revealing metrics to quantitatively evaluate model performance using these data sets.
- Developing relevant international mechanisms. Promising opportunities on the observational side are connected to a number of international initiatives such as WMO's Global Cryosphere Watch (GCW). GCW is the outcome of the Integrated Global Observing Strategy Theme on Cryosphere, which was lead by CliC and the Scientific Committee on Antarctic Research. It will be the primary international mechanism for supporting all key cryospheric in-situ and remote sensing observations, from research and operations. The continuing cooperation of WCRP and GCW must be insured.

[3] The Modelling Advisory Council should help to connect different modeling communities (CLIC, WGCM, GCSS, WGOMD, WGSIP, PMIP, CFMIP) around CCC, and facilitate initiatives that would be both useful and practical (specific workshops, particular outputs in future model intercomparisons, etc).

- Enhancing connections between various sub-disciplines and region-specific research programs and coordinating bodies. For example facilitating better connections between the physical climate research activities more traditionally associated with WCRP and the biological, ecosystem and pollution related research more closely associated with the Arctic Council and its Arctic Monitoring and Assessment Program. Regional WCRP activities, such as Asia-CliC, can provide valuable input to these activities.
- Enhancing connections with the palaeo community. There are a number of key issues associated with the CCC that can be (or are already) addressed by this community.

Within WCRP, there is also a need to enhance communication an collaboration between projects, particularly for CCC, which connects intimately to the atmosphere, ocean and land surface, and to the global water, energy and carbon cycles. There is also a need to make better connections with those involved in the delivery of climate services, some of which directly involve the cryosphere (e.g. prediction of sea-ice conditions in support of Arctic shipping; prediction of glacial meltwater availability to support drinking water and agricultural irrigation, etc.). CliC should serve as the focal point for such efforts and there is a need to take this on as a high-profile activity in collaboration with WGSIP and WGCM.

An opportunity for WCRP to achieve its goals in the polar regions and with respect to the cryosphere is the emerging long-term polar initiative intended to solidify the useful legacy of the International Polar Year 2007-2008 and provide coordinated input of polar observations, research and services to addressing important regional and global issues[4].

3. Focused science topics

In the next few years there are several specific topics that are 'ripe' for enhanced attention, are tractable, and would yield tangible and visible progress with rather modest investment in terms of organization and coordination:

- ***A coordinated focus on seasonal, interannual and longer-term predictions and projections of polar climate and the role of cryosphere in climate predictability.*** Activity in this area has already been initiated jointly by SPARC and CliC, and that momentum should be further built upon in collaboration with WGSIP. Development of assimilation of cryospheric observations, such as sea ice and snow, in prediction models should be actively supported by WCRP. Attention should be paid not only to improving our capabilities in making quantitative predictions/projections, but also in translating these results into information that is directly useable by northern residents, decision-makers and other stakeholders as part of the WCRP's overall contribution to the Global Framework for Climate

[4] The WMO workshop on the International Polar Decade Initiative (April 2011, Sankt Petersburg, Russia) proposed a Consultative Process on the development of a Concept for a new long-term polar international cooperative initiative, in which representatives of several agencies interested in polar activities, including WMO, would participate. This initiative, provisionally entitled Polar Regions Of the Globe: REsearch and Services for Sustainability (PROGRESS), is being developed to secure the legacy of most useful and promising IPY developments. It is expected to result in addressing essential regional issues that are of great significance both in polar regions and globally. The initiative will be very thoroughly planned to achieve high return on investment. The planning process will take into account the feedback received by the Steering Group at the IPY2012 Conference "From Knowledge to Action" (Montreal, Canada, 22-27 April 2012) and will include consultations with a number of agencies and programmes involved in polar activities. The WMO EC-PORS is representing WMO in this consultative process. The WMO-related initiatives, such as the Global Integrated Polar Prediction System (GIPPS), Global Cryosphere Watch (GCW), the World Weather Research Programme Polar Prediction Project, and the WCRP Polar Climate Predictability are likely contributions of WMO and WCRP to the emerging initiative.

Services (GFCS) and the Global Integrated Polar Prediction System (GIPPS). Many activities, in the Arctic in particular, are very sensitive to the state of the cryosphere (transportation of supplies on seasonal ice roads, shipping of natural resources, hunting and fishing, etc.) and although the population density is low, the people living and working in the north are often very vulnerable to environmental change. This will be a contribution to the WCRP Grand Challenge of providing useful climate information on regional scale.

- ***A more focused analysis of model intercomparison results aimed specifically at understanding and attributing model biases and shortcomings related to cryosphere .*** CliC and the WGCM might pursue this as a joint initiative which would serve to build better linkages between the cryosphere observation and process study community and the global and regional modelling community. This connection has not been effectively made in the past, but there is considerable scope for improving various aspects of model performance[5]. There is a need to connect different MIPs and draw lessons from them regarding the cryosphere.[6]
- ***A focused effort on improving the representation of permafrost and high-latitude land surface, including wetlands, in climate models, with specific emphasis on their role in the global carbon cycle.*** CliC initiated some activity in this area, together with the International Permafrost Association and the Global Carbon Project, but there is certainly scope to expand on this and to make more explicit connections with the Earth System modelling community and the terrestrial ecosystem and hydrological research communities. Again, this requires activities that cross-disciplinary and project boundaries, but is a topic currently seen as a large source of uncertainty in future projections of climate change and the associated carbon-cycle feedbacks.
- ***A focused effort on developing ice sheet models, with specific emphasis on the role of ice sheet dynamics on the rate of the sea-level rise.*** CliC has such activity among its priorities, but there is a need in enhancing the ice sheet modelling activity as a part of the Earth system modelling and establishing connections between this community and WGCM. CliC should play a key role in this bridging[7].

There are of course many other topics that could be tackled, such as improving the projections of future glacier mass balance, but in many of these cases there is already an active community at work, and progress is being made. We have focused here on a limited set of topics that are perhaps not being as actively addressed as they might, would build on existing WCRP structures and capabilities, could be initiated rapidly, and would provide short-term visible results. From this rather modest beginning, one could develop a more vigorous cryospheric research community within the WCRP 'family' and expand it further as opportunities and resources present themselves.

[5] One of the recurring issues for evaluating high-latitude model performance is that we don't have a firm handle on fluxes between different components of the climate system in high latitude (e.g. air-sea, land-atmosphere, ocean-ice). These fluxes are not being measured in situ in any concerted way, and existing flux products differ enormously. The IPCC AR4 indicates this is a real issue for Arctic climate assessment. New satellite products and new reanalyses might help, but a concerted product assessment effort may be required. The WCRP could take a leadership role in this activity by supporting data intercomparison as well as model intercomparison.

[6] As far as WGCM is concerned, PMIP but also CFMIP are key targets. Within CFMIP, the need was recognized to develop efforts on the evaluation and intercomparison of model clouds over the cryosphere, and on the assessment and understanding of polar cloud feedbacks in climate change and their connection with cryospheric changes.

[7] Here again, the connection with palaeo community is important.