CliC
Climate and Cryosphere

WCRP World Climate Research Programme
WMO IOC ICSU

Cryosphere in a Changing Climate

16 - 18 October 2013, Tromsø, Norway

Workshop Report

The Research Council of Norway

Norsk Polarinstitutt

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Executive Summary

A workshop was convened to further develop the strategy to address the WCRP Cryosphere in a Changing Climate Grand Challenge. Keynote presentations were given on "WCRP Grand Challenges and the Cryosphere in a Changing Climate" (Greg Flato), "Polar Climate Predictability Initiative" (Marilyn Raphael), "Ice Sheets and Glaciers in a Changing Climate" (Andy Shepherd), "Sea Ice in a Changing Climate" (Dirk Notz), "Permafrost and Carbon in a Changing Climate" (Ted Schuur), and "Cryosphere Biases / Shortcomings in Earth System Models" (Gerhard Krinner). Interdisciplinary breakout groups were then tasked with brainstorming high priority issues for research on main cryospheric elements.

In the second half of the workshop, discipline-focused breakout groups (glaciology, snow, sea ice, and permafrost) further developed actionable items including motivation, specific questions, a timeframe, and suggested leaders and participants for the Grand Challenge to move forwards with. These topics include:

- Current state of the permafrost carbon reservoir and greenhouse gas balance of the circumpolar region
- Magnitude, timing and form of greenhouse gas release from permafrost carbon reservoir to the atmosphere in a warming world
- Current and future mass loss of global glaciers and ice caps
- Freshwater volume and availability from the cryosphere
- Ice sheet snowpack melt, storage, and runoff
- Impact of changing sea ice on high-latitude climate systems
- Internal variability of sea ice up to multi-decadal time scale
- Impact of snow changes on water resources
- The role of snow as an active component of the global climate system

These targeted activities will continue to be developed in a strategic plan.

This report serves as a summary of the different sessions from the workshop and to frame the outcomes and future action points. A separate and evolving Strategy Document is also being produced as a follow up to the original white paper. Sessions are presented in the order in which they occurred.

Meeting report compiled by Allen Pope, Jenny Baeseman, and Vladimir Ryabinin.

Introduction

Setting the course for addressing the WCRP Cryosphere in a Changing Climate Grand Challenge

The workshop goal was to further develop the strategy to address the WCRP Cryosphere in a Changing Climate Grand Challenge (http://www.climate-cryosphere.org/media-gallery/618-gc-cryo). Several keynote presentations on various science foci from the grand challenge white paper were given, followed by breakout groups to develop an action plan for each imperative. The workshop was held at the Fram Centre in Tromsø, Norway from the 16 - 18 October 2013. Funding was provided by the Research Council of Norway, the WCRP, and the CliC Project Office.

Cryosphere in a Changing Climate Grand Challenge Imperatives

Following the WCRP Open Science Conference in 2011, the WCRP Joint Science Committee decided to set forth a series of grand challenges to address highly specific and highly focused topics that are critical to improving our progress in understanding the climate system. One of these five challenges was the "Cryosphere in a Changing Climate". An initial draft white paper for the Cryosphere Grand Challenge was prepared in 2012, lead by V. Kattsov and contained the following imperatives:

- 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 changes in regional temperature, snow cover and frozen ground, the timing of the Arctic multiyear sea ice disappearance, the fate of mountain glaciers, etc.;
- More comprehensive, quality-controlled observational 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 models. In addition, further challenges are arising with respect to the effect of the carbon sequestered in the terrestrial and sub-sea permafrost, the role of ice sheet dynamics in sea level rise, etc.

Science Foci Addressed at this Workshop

The Cryosphere Grand Challenge White Paper also outlined a number of scientific foci to be addressed over the next 5-10 years as part of the grand challenge initiative. The foci addressed at this workshop are as follows:

- Predictions and Projections of Polar Climate
- Cryosphere Model Biases and Shortcoming
- Ice Sheet Models, dynamics and sea level rise
- Permafrost and Carbon for Earth System Models

Organizing committee

- Greg Flato, *Workshop and CliC SSG Chair, Environment Canada*
- Vladimir Kattsov, *Voeikov Main Geophysical Observatory, Russia*
- Marilyn Raphael, *University of California - Los Angeles, USA*
- Vladimir Ryabinin, *WCRP, Switzerland*
- Ghassem Asrar, *WCRP, Switzerland*
- Jenny Baeseman, *Climate and Cryosphere Project, Norway*

Keynote Presentations

WCRP Grand Challenges and the Cryosphere in a Changing Climate

Greg Flato

The WCRP identified six 'grand challenges' that would serve as cross-cutting, societally-relevant themes for research in the coming years. These grand challenges are intended to complement the ongoing work of the WCRP core projects and working groups, and build upon the capabilities that WCRP has established. These six grand challenges are:

1. Regional Climate Information
2. Sea-Level Rise and Regional Impacts
3. Cryosphere in a Changing Climate
4. Clouds, Circulation and Climate Sensitivity
5. Changes in Water Availability
6. Science Underpinning the Prediction and Attribution of Extreme Events

The 3rd of these is the subject of this workshop, and it was described in some detail, based on the white paper by Kattsov et al. (2012) http://www.climate-cryosphere.org/media-gallery/618-gc-cryo

The next step is to develop a concrete action plan, with specific activities that fill a particular knowledge gap or take advantage of some opportunity to coordinate, synthesize or extend work - ideally in a way that engages the broader research community and makes best use of the overall WCRP capabilities in climate research and climate change predictions and projections.

In this meeting, several invited overview talks were scheduled to set the stage for the subsequent discussion, largely via smaller breakout groups.

Polar Climate Predictability Initiative

Marilyn Raphael

Polar regions are important to the climate system not only because the climate is changing more rapidly in these regions than in the global mean, but because they may provide a source of predictability on seasonal and decadal time scales. Better understanding of the sources of polar climate predictability is one of the scientific foci identified by the Cryosphere in a Changing Climate Grand Challenge White paper. The Polar Climate Predictability Initiative (PCPI) will address this scientific focus. Its main goal is to advance our understanding of the sources of polar climate predictability over a range of timescales ranging from seasonal to multi-decadal. It will liaise closely with the WWRP Polar Prediction Project (PPP), which focuses on hourly to seasonal timescales, sharing a common coordination office.

The PCPI is led by Cecilia Bitz (University of Washington, USA) and Ted Shepherd (University of Reading, UK). It consists of six initiatives (three of which are joint with the PPP). In lieu of a steering committee each initiative is spearheaded by two champions to carry it forward. The six initiatives are to

1. Improve knowledge and understanding of past polar climate variations

2. Assess reanalyses in polar regions (joint with PPP)
3. Improve understanding of polar climate predictability on seasonal to decadal time scales (joint with PPP)
4. Assess performance of CMIP5 models in polar regions
5. Model error (joint with PPP)
6. Improve understanding of how jets and the non-zonal circulation couple to the rest of the system in the Southern Hemisphere.

The champions of each initiative have drafted plans to advance their goals. These plans are in various stages of action and include formation of subgroups of researchers interested in the initiative, workshops addressing the initiative, preparation of review documents to show the present state of knowledge and the science questions that need to be answered, and identifying concrete steps to answer the science questions. More information on the PCPI will soon be available on its website which will be hosted by CliC.

Ice Sheets and Glaciers in a Changing Climate

Andy Shepherd

Fluctuations in the mass of the Greenland and Antarctic ice sheets are of considerable importance to Society because of their direct impact on global sea levels. In recent decades, ice losses from Antarctica and Greenland, in addition to melting of small glaciers and ice caps, and thermal expansion of the oceans, has caused global sea levels to rise at an average rate of 3.1 millimeters per year. Forecasts indicate that rising sea levels will continue into the future at a rate that could pose a serious threat to lives and livelihoods across the globe, jeopardizing, for example, sanitation, agriculture and homes. Lessening the impacts of sea level rise through effective adaptation and mitigation measures relies upon accurate forecasts of its magnitude and rate; this, in turn, depends on our ability to accurately measure and understand each contributor to sea level rise.

Measuring changes in the mass of ice sheets has been revolutionised by the advent of satellite geodetic techniques because they provide measurements at spatial scales and at a frequency that cannot be achieved with traditional methods. Since 1989, there have been more than 30 published estimates of ice sheet mass balance based variously on the three techniques of altimetry, gravimetry and the input-output method. However, the agreement between these results is poor, and the estimates and their respective uncertainties allow for a combined Greenland and Antarctic ice sheet mass imbalance of between -676 and + 69 Gt yr^{-1}. Such a large spread has limited our confidence in estimates of the ice sheet contribution to sea level.

In 2010, the Intergovernmental Panel on Climate Change (IPCC) highlighted the disagreement in ice sheet mass balance estimates as a primary emerging topic. They expressed concern that progress would not be made in the run up to the fifth assessment report and noted the potential value of inter-comparison projects for addressing the problem. The ice sheet mass balance inter-comparison exercise (IMBIE) was established in 2011 as a community effort to reconcile satellite measurements of ice sheet mass balance. IMBIE is a collaboration between scientists supported by the European Space Agency (ESA) and the National

Aeronautics and Space Administration (NASA), and contributes to assessment reports of the IPCC. In 2012, IMBIE reconciled measurements of ice sheet mass balance using satellite altimetry, gravimetry and the input-output method (Shepherd et al., 2012). Through a series of experiments that used common spatial definitions and time periods, and that investigated the impacts of various ancillary datasets used, it was shown that there is good agreement between estimates of Antarctic and Greenland mass balance determined from the three techniques. The project highlighted the complementary nature of the three approaches, showing that by combining techniques, the coverage and confidence in the results is improved by combining techniques.

The mass balance of the ice sheets changes over time. As an ongoing exercise, IMBIE seeks to provide continued assessments of ice sheet mass balance using all available satellite techniques at regular intervals in the future. This will ensure that an up-to-date and accurate record of Greenland and Antarctic Ice Sheet mass balance is maintained. It is anticipated that data from future satellite missions, for example CryoSat-2, and updates to existing methodologies and ancillary datasets, will lead to improved estimates of ice sheet mass balance. The aim is to open participation within this future assessment to the entire scientific community.

Sea Ice in a Changing Climate

Dirk Notz

This presentation summarized the quality of sea-ice simulations in modern Earth System Models. In particular, the point was made that differences between the observed and the modeled evolution of sea ice are to a great deal explicable by internal variability of the climate system and by uncertainties in the observational record. Internal variability must in particular be taken into account when analysing trends in sea-ice coverage. Because of the large internal variability, a number of CMIP5 models simulate in one of their ensemble members a sea-ice loss in the Arctic that is faster than what has been observed while another ensemble member of that same model shows an increase in sea-ice coverage over the past three decades. This exemplifies that the comparison of the single observed trend with a single model simulation does not often give much insight into the quality of a particular model. Another challenge for the evaluation of modeled trends is the fact that simulated 30-year long trends of sea-ice extent are very sensitive to their respective starting date, and can rapidly increase or decrease for a small shift in the time period considered.

Regarding the modeled mean sea-ice extent in the Arctic, differences between its simulation and individual satellite retrievals (dating back to 1979) can be as large as the differences between two different satellite retrievals, particularly in summer. This is primarily caused by the different methods used to compensate for melt ponds in individual satellite retrievals. Such melt ponds form on the ice surface during summer and are seen as open water/lower-concentration sea ice by the algorithms that are most commonly used for sea-ice retrievals from satellite passive microwave data. The different compensation for these melt ponds in the satellite algorithms leads to a very high percentage (i.e., overestimate) of high concentration summer sea-ice in some satellite products, while others have a rather low proportion of such high concentration sea-ice during summer. A similar split between a high or a low percentage of high-concentration sea-ice is seen for different CMIP5 models, but the uncertain robustness of the satellite retrievals makes it impossible to determine which group of the models shows the more realistic ice cover during summer.

Progress in Arctic sea-ice simulations will most likely primarily come from progress in the modeled atmospheric and oceanic forcing of the ice cover. For the most part, the key processes that govern the sea-ice evolution itself are represented in modern sea-ice models, and in a coupled setup the ice reacts very sensitively to changes in its forcing. Here, one of the main challenges to progress lies in the uncertainty of atmospheric reanalyses used to describe the past evolution of the Arctic atmosphere. Forcing a stand-alone ocean-sea-ice model with two different reanalysis products can easily cause a factor of-two difference in the simulated trends in sea-ice volume. Given these differences in the reanalysis products, it is difficult to robustly determine specific shortcomings in the modeled Arctic atmosphere in coupled Earth System Models (ESMs).

In summary, improved understanding that is evaluated against reliable observations is the key for progress in sea-ice simulations. The internal variability of the Arctic climate system will nevertheless always limit our capability to precisely simulate observed trends without data assimilation.

NOTE: This presentation was mainly focused on Arctic Sea Ice. In planning for the Cryosphere Grand Challenge, it is crucial to include Antarctic and lower-latitude sea ice changes and prediction as well.

Permafrost and Carbon in a Changing Climate

Ted Schuur

In the Arctic, temperatures are rising twice as fast as in the global mean, at 0.6°C per decade over the past thirty years. This is causing normally frozen ground to thaw and is exposing tremendous quantities of organic carbon to decomposition by soil microbes. This permafrost carbon is the remnants of plants and animals accumulated in perennially frozen soil over thousands of years. This pool has been estimated at 1700 Pg, which is twice as much carbon as currently contained in the atmosphere. Release of just a fraction of this frozen carbon pool as greenhouse gases into the atmosphere will likely increase the rate of future climate change.

New synthesis research conducted by the Permafrost Carbon Network (www.biology.ufl.edu/permafrostcarbon/, PCN) has enlarged the deep carbon inventory database by an order of magnitude, and continues to verify that tremendous quantities of carbon accumulated deep in permafrost soils is widespread. This network operates in synergy with the Global Terrestrial Network on Permafrost (GTN-P) that includes a ground temperature observatory (TSP; Thermal State of Permafrost) and active-layer monitoring program (CALM; Circumpolar Active Layer Monitoring).

The PCN is also working on a synthesis of laboratory incubations from these deep permafrost soils. Results show a significant fraction of this deep material can be mineralized by microbes and converted to carbon dioxide and methane on time-scales of years to decades, which could contribute to near-term climate warming. The exponential nature of microbial decomposition, carbon dioxide and methane release means that the initial decades will be the most important for greenhouse gas release, but because of momentum in the systems, emissions are likely in this century and beyond.

Upcoming model intercomparison results will help define the current state of model forecasts for permafrost carbon and to highlight important areas of model development. Initial model estimates point towards carbon gain in high latitude soils, but this doesn't match recent flux-based syntheses that indicate carbon losses over the past several decades. A model intercomparison is needed to help point the way for recommendations to improve our ability to describe important carbon-climate feedbacks from permafrost carbon.

Cryosphere Biases / Shortcomings in Earth System Models

Gerhard Krinner

ESMs need to accurately and realistically represent the fundamental processes governing the behaviour of the individual components of the climate system. Concerning the cryosphere, this means in principle that ESMs need to represent snow, frozen soil including permafrost, land ice, sea ice and glaciers. Due to their limited role in term of climate feedbacks, glaciers can arguably be neglected as active components of the climate system and therefore as parts of ESMs (depending on time scale of interest). This talk addressed the current state of the representation of cryospheric components in ESMs and assessed current shortcomings. It also addresses problems linked to the representation of the polar atmosphere.

Concerning **land ice**, significant challenges remain - in particular the representation of small-scale processes in marine-terminating glaciers, linked to the representation of grounding-line dynamics. Because of the required high resolution in land-ice models in these areas, there is an issue of spatial scale in coupling dedicated ice-sheet models to atmospheric and ocean models. It is also noteworthy that many **ocean models** don't "see" below ice shelves.

Atmospheric models have made progress in representing the polar atmosphere, but correctly representing the phase of polar clouds (in particular high liquid water fractions at cold temperatures) and very stable atmospheric boundary layers remains a clear challenge.

The representation of **snow** in ESMs is in many respects too simplistic to allow for representing the range of effects of snow in the climate system. While the spatial extent of snow is more or less correctly represented in current ESMs, the physical properties of snow (e.g. thermal conductivity) and its evolution in time are often not correctly represented, leading to large biases in temperatures of the underlying soil. This leads to biases in simulated **permafrost** extent, for example, that are reinforced by overly-simplified soil physics in ESMs. Another permafrost-related issue is the absence of processes leading to large permafrost carbon reservoirs in most present-day ESMs, which in turn results in an unrealistic representation or complete absence of permafrost-carbon feedbacks.

Interdisciplinary Breakout Groups

In the first breakout session, participants were distributed randomly into four interdisciplinary groups. The task was given to all the groups to begin to target areas of scientific focus for consideration by the WCRP Grand Challenge. These areas were expected to be societally relevant, scientifically attractive, and with prospects for progress within several years. The workshop groups came up with a wide range of topics and ideas relevant for the Grand Challenge.

One of the breakout groups proposed high priority issues for research broken down with respect to main cryospheric elements. For example, the following topics were suggested for sea ice: evaluating seasonal and decadal predictions, model parameterizations, improving model physics and rheology, and research into the role of snow on sea ice. For ice sheets the suggested topics were: increased focus on coastal regions, continuation of research along the lines of the IMBIE project and an analysis of CMIP outcomes for ice sheets. According to that group, the focus of research on glaciers should be on their mass balance, volume, and runoff characteristics. For snow, the research could focus on development of models of various relevant processes, e.g. snow drift, thus contributing to the development of more comprehensive and all-embracing snow models. For permafrost the group proposed a review of strategy of studies for their further synthesis.

The approaches of three other “initial” groups to identifying high-priority topics were somewhat different and their input created a diverse set of more interdisciplinary proposals that was equally very helpful for Grand Challenge deliberations in the subsequent days of the meeting. Justifications and descriptions for some were more detailed than for others, and they are all preserved in this report for future reference.

The high-priority science topics initially proposed were as follows:

- Reconciliation of mountain glaciers’ contribution to sea level change including issues related to evaluation of mass balance of high-elevation glaciers based on remote sensing. Assessing and developing a capability to estimate and predict fresh-water runoff from glaciers.

    The positive example of the IMBIE project that showed the feasibility of usefully comparing data obtained from multiple sources and generated with the use of different techniques - in order to generate more substantive estimates of the ice sheet mass loss - was inspiring for the glaciological community. Meltwater run-off from glaciers is an important source of fresh water for hundreds of millions of people. Glaciers and their catchments are too small for their models to be forced by current generation of regional climate models, and science has to move forward to enable glacier model intercomparisons and improved forcing.

- Regional climate models' evaluation in the Arctic under the framework of CORDEX.

  The modern climate models of the polar regions still suffer from a range of pitfalls. WCRP and CliC have to continue efforts to further develop, intercompare, and validate them and address the existing problems specific to polar regions such as effective representation of stable boundary layer, etc. The WCRP CORDEX project provides a solid framework for such developments.]

- Creation and inter-comparison of useful datasets, identifying uncertainties and biases in them. Extending empirical datasets (e.g. on sea ice extent, permafrost, snow) back into the past including the Early Twentieth Century Warming period using proxies, regional data, etc. Research into internal variability of the polar climate and cryospheric elements, such as sea ice. Corresponding improvements in polar reanalyses.

  Within the sea ice community there is a big push to synergize the activities between satellite remote sensing and modeling to ensure the level 2 and 3 satellite products produce Sea Surface Temperature (SST), adequately informed from the level 1 resource, leading to the practical use of level 4 ocean and atmosphere data coming from the modelers. Often, the best resource to use from a data assimilation standpoint is not the ultimate level 2 project (in this case SST), but the underlying level 1 resource (satellite radiance in this case).

  Many observations involving the cryosphere would benefit from a similar approach. Ice concentration estimates suffer greatly from coarse thresholds and false accounts of positive/negative issues, overcoming these issues would enable greater synergy between the observations and models. The measurement of ice sheet mass balance entails greater need for synergy between the various retrieval methods used (i.e. observations) of mass or volume, and the ultimate contribution of that change in mass or volume to sea level change through the correct modeling process. In-situ measurements of snow, with a small representivity footprint, need to be compared to satellite retrievals of snow cover with a large representativity footprint – and these comparisons should ultimately be used in ESMs where such representativity will be of prime importance.

- Research focusing on sea-ice and snow cover feedbacks on atmosphere on global scale. The role of the linkages between different elements of cryosphere (e.g., sea ice – glaciers, sea ice - ice shelf). Small-scale – large-scale process interactions. Accounting for additional sub-grid processes and feedbacks important for realistic parameterizations. Benchmarking datasets for model evaluation.

Methodological considerations for implementation of the Grand Challenge proposed by one breakout group included an increased focus of research on feedbacks between different elements of the cryosphere and the rest of the climate system. The Grand Challenge activities could facilitate and exploit synergy between the work of observationalists and modellers and be implemented using new WCRP-supported approaches to sharing model and observation output such as Earth System Grid, OBS4MIPS, etc.

- Research on physical processes in permafrost (e.g., heat flux) that are important for reliable remote sensing of permafrost characteristics. Study of the role of sub-sea and terrestrial permafrost in the global carbon cycle and of the role of methane hydrates' role in the Arctic carbon cycle.

The potential of several climate feedbacks resulting in, or originating from, changes in permafrost was thought to be a high priority, and would cut across the gamut of CliC activity. The interaction between snow and permafrost was thought to be a big unknown, mostly resulting from the lack of a homogeneous data set for snow properties (see below). Feedbacks to sub-sea permafrost were also thought to be an open question. The subsequent loss of permafrost then has feedbacks into Arctic hydrology, glaciers and vegetation, as well as obvious local societal impact on infrastructure. The ultimate emission of CO_2 by permafrost loss further completes the feedback cycle, but much effort is required to improve the current generation of ESMs to adequately address all the physical processes involved in the creation and loss of permafrost so that the CO_2 feedback can be properly addressed.

Feedbacks in the permafrost would have direct connections to both the snow and the glacier components within CliC, as well connections to sea ice (e.g., lack of sea ice cover to sub-sea and terrestrial permafrost). Direct connections to the WCRP GEWEX group through the interactions between hydrology and snow cover, and the CLIVAR Global Synthesis and Observations Panel (GSOP) for subsurface ocean conditions would also be fostered.

- Progress of observing, understanding and modelling of snow and solid precipitation, including alpine precipitation, snow on sea ice, models of snow that include relevant processes such as firn compaction model, homogenization of snow datasets, etc.

Snow in the polar regions forms an integral part of predictability issues in the PCPI and PPP initiatives. The primary (mass) and secondary (thermodynamic) contributions of snow to ice sheet mass balance are of utmost importance. Snow on sea ice is a vastly understudied (both observations and modeling) component of the sea ice system, yet properties of the snow cover on ice are of critical importance to the thermodynamic evolution of the sea ice. A similar situation, with perhaps even greater consequences, exists for the snow cover over permafrost. There is remote sensing of snow, but this tells us little about the snow ice properties, or snow mass, plus there is a huge problem in the representativity of these *observations for modelling and process studies. Effort on a gridded data set of snow properties would be of great help and importance to the CliC community, as well as all of the other WCRP projects (GEWEX, CLIVAR, and even SPARC).   A comprehensive snow data properties data set would undoubtedly have direct societal impact through its use in wildlife, environmental, natural resource and commercial activities.*

- Evaluation and research into the closure of the surface energy and water balance in the polar regions that would take into account improved representation of clouds, black carbon, ice dynamics, etc.

  Understanding of the surface energy balance is needed in polar regions for both land ice and sea ice regions. This would include a better understanding of such things as clouds, black carbon, and melt thresholds. A more thorough understanding of the energy balance would lead to improvements in models and a better understanding of variability in the climate system and ultimately improved predictability and improved prediction skill. Understanding the surface energy balance would entail crucial connections between snow and other cryospheric components: sea ice, permafrost and ice sheets and glaciers. It would also foster connections with the WCRP CLIVAR (through WGSIP and GSOP) and GEWEX groups.

- Scientific support to development of the Arctic Ocean Observing System that would enable ocean data synthesis for polar oceans, in connection with the Southern Ocean Observing System (SOOS).

  The role of the ocean is paramount to all components of CliC, but plays a definite role for sea ice. It can also play a crucial role in the melting of ice shelves and therefore ice sheets, as well as a role in the thawing of sub-sea permafrost. Further roles are played with all components through atmospheric teleconnections. However, unlike the rest of the world's oceans the Arctic and Southern Oceans are still very much under observed. Satellite SST measurements now cover all the world's oceans and major inland seas and lakes, but are not able to see through a sea ice cover, and so are non-existent under ice covered regions. Furthermore, the advance of the ARGO program has led to much better observational coverage of the ocean sub-surface, but here again, the experimental ARGO floats that are capable of operating in sea ice covered regions have been deployed only very sparingly in Arctic regions. The largest recent advance in the Arctic and Southern Ocean observing systems has been the development of sea mammal based instrumentation, but such measurements are mainly (through not exclusively) limited to ice-edge regions (depending on the mammal species). Technologies exist to better sample the Arctic Ocean (e.g. ice-tethered moorings, autonomous undersea vessels), but no coordinated international programs exist to push for increased and improved observations and monitoring capabilities, or to develop new ocean temperature etc. remote sensing opportunities appropriate for the Arctic. Whilst such an initiative falls under the core program of CLIVAR through GSOP, the outcomes are of vital importance to CliC and an avenue for interaction with other WCRP programs.

The Workshop agreed that further steps in the elaboration of the Grand Challenge would be based on in-depth reviewing of the above topics, trying to identify synergies between research on individual cryospheric elements, and focussing on topics where major improvement in understanding is most needed and synthesis can be achieved. At the same time, big items will need to be addressed using a phased approach by tackling “bite-size” pieces that have to be clearly identified.

Frostbytes & Poster Session

Early career attendees submitted Frostbytes – ‘Soundbytes of Cool Research.’ These short video recordings are designed to help researchers easily share their latest findings to a broad audience. All CliC Frostbyes are available at https://vimeo.com/channels/cryosphere

Allen Pope - Studying Ice and Snow with Landsat 8
http://www.climate-cryosphere.org/media-gallery/884-pope-frostbyte-2013

Alpio Costa - Antarctic Climate Change and Variability
http://www.climate-cryosphere.org/media-gallery/891-acosta-frostbyte-2013

Atsu Muto - Gravity Measurements
http://www.climate-cryosphere.org/media-gallery/892-muto-frostbyte-oct-2013

Nathalie Kehrwald - Playing with Fire
http://www.climate-cryosphere.org/media-gallery/890-kehrwald-frostbyte-2013

Shelley MacDonell - Finding Water in the Desert
http://www.climate-cryosphere.org/media-gallery/889-macdonell-frostbyte-2013

On the evening of the second day of the workshop, a poster session was held with 15 posters on a range of cryospheric research topics. Posters, along with other documents from the workshop, are archived at: http://www.climate-cryosphere.org/meetings/past-meetings/wcrp-cryo-gc-2013

Scientific Foci Breakout Groups

Further breakout sessions were divided into disciplinary groups: snow, glaciers/ice sheets, permafrost, and sea ice. Each disciplinary group went through an iterative process to motivate, identify, and produce an action plan for important scientific questions to be addressed by the Grand Challenge. These plans produced during the workshop are provided below. Further development and wider consultation will continue through a separate Strategy Document.

Note: This section includes potential collaborators who have not been consulted as of the publishing of this report, but were recommended as possibilities for carrying actions forward. They were just suggestions during the workshop. Other suggestions are welcome)

Permafrost

Proposal for permafrost-related actions as defined in the WCRP Cryosphere in a Changing Climate Grand Challenges document.

Prepared by Ted Schuur, Gerhard Krinner, Tetsuo Ohata

What is the current state of the permafrost carbon reservoir and greenhouse gas balance of the circumpolar region?

Goal: Developing **permafrost carbon observational network** that pairs with GTN-P and CALM to determine C balance and greenhouse gas emissions at the circumpolar scale. This network should include observational sites and remote sensing.

Justification: There is no circumpolar observatory of the permafrost carbon pool analogous to the borehole and active layer networks that monitor permafrost temperature and degradation. Directly monitoring changes in permafrost carbon stocks is not possible due to spatial heterogeneity, so observations of fluxes remain the most sensitive tool with which to detect changes in permafrost carbon storage. This is occurring at individual sites, but there is no coordinated effort to integrate observations at a range of sites and spatial scales or to make those observations available for model development and evaluation.

Actions: The following activities would be achieved by gathering people with appropriate expertise that can bring together current information from individual research site. This would occur in the format of small 15-40 person workshops held either as stand-alone or in combination with annual science meetings.

- Ensure continuation of Permafrost Carbon **synthesis** on permafrost C stocks, and decomposability (ongoing; present-5 years). [Schuur]
- Flux observation database (CO_2, CH_4) in permafrost ecosystems for model evaluation. Assemble benchmark site databases with necessary variables to run models at point locations. Develop observation databases in formats directly comparable to model output (2-3 years). (Modeler [RCN modeler], ecosystem flux person, remote sensing)
- Enhance observational network through development of supersites (internationalize NGEE Arctic; PAGE21, ABoVE, AON, CENPERM, warming experiments) (5-10 years). [Hugues Lantuit, Margareta Johansson]

What is the magnitude, timing and form of greenhouse gas release to the atmosphere in a warming world?

Goal: Essential permafrost processes included in a suite of Earth System Models for making credible projections of permafrost-climate feedbacks.

Justification: Current intercomparisons have demonstrated model inconsistencies in the representation of high latitude surface processes including permafrost distribution, permafrost carbon balance, and snow effects. These gaps undermine making credible projections of permafrost-related feedbacks in a warming climate.

Actions: The following activities would be achieved by gathering people with appropriate expertise that can bring together current information from individual research sites. This would occur in the format of small 15-40 person workshops held either as stand-alone or in combination with annual science meetings.

1. Synthesis paper on **conceptual approaches** that should be embraced by coupled permafrost-carbon models (1 year) [McGuire]
2. Model intercomparison project using **reformulated models** that have used site-scale, basin-scale, and remotely-sensed observations for evaluation (5 years). [RCN modeler]

These proposed activities are large in scope and full implementation will likely include a number of partner organizations and programs with intersecting interests within and beyond WCRP. For example, potential partner organizations:

- IARC - Located at University of Alaska Fairbanks; partner with DOE on NGEE Arctic. Contact: Larry Hinzman.
- GEWEX- Core project of energy and water cycles; link to permafrost through water cycle issue. WCRP activity. Contact: Eleanor Blyth (also part of PAGE21)
- IGBP - International Geosphere-Biosphere Program. Ecosystem and global change. Contact: iLEAPS Nathalie De Noblet (?)
- NEESPI- Northern Eurasian Earth Science Partnership Initiative. Contact: Pavel Groisman. Strong focus on land/ecosystem/climate in Siberia.
- AON - Arctic Observation Network. NSF funding program. Contact:?
- SEARCH - NSF funded Arctic ecosystem/earth system. Theme group on permafrost: Contact: Hajo Eicken (Schuur)
- GTN-P (TSP, CALM) - Global Terrestrial Network on Permafrost. Includes borehole network and circumpolar active layer network. Contact: Vladimir Romanovsky, Fritz Nelson
- IPA - International Permafrost Association
- Ameriflux- Network of flux towers including in permafrost zone. Contact: Oechel.
- NEON - Ecological observation with several sites in permafrost zone. Contact: Dave Tazik
- GRENE Arctic - Green network of excellence Arctic program. Contact: Sugimoto
- WGCM (MIP) - Link model intercomparison projects. Contact: Greg Flato (!)
- PEEX- Carbon and ecology in Siberia. Contact: ?
- DEFROST- Contact: Torben Christensen
- CENPERM- Greenland-focused permafrost carbon project. Contact: Bo Elberling
- Permafrost Carbon Network - synthesis project on permafrost carbon. Contact: Ted Schuur
- PAGE21 - European research initiative for permafrost carbon. Contact: Hans Hubberton

Glaciology

Proposal for glacier-related actions as defined in the WCRP Cryosphere in a Changing Climate Grand Challenges document.

Prepared by: Alfredo Costa, Allen Pope, Atsu Muto, Jack Kohler, Jorge Arigony, Kenichi Matsuoka, Nathalie Kehrwald, Sebastian Mernild, Shelley MacDonell, and Shichang Kang

Current and future melt of global glaciers and ice caps

Rapid decrease of small ice masses in the 20th Century has contributed more to global sea level rise than the Antarctic and Greenland ice sheets. Glaciers and ice caps will continue to be important contributors in the future. There are multiple estimates and projections of current and future global glacier and ice cap melt and runoff. Despite being globally important, these studies are currently not all in agreement and must be reconciled. In addition, global glacier volume is still an important unknown.

NOTE: This ties directly to the Role of Snow in the Earth and Climate Systems activities.

Specific Questions

- What is glacier and ice cap contribution to sea level rise?
- How can we reconcile various regional mass balance studies?
- How can we reconcile a range of in situ, remote sensing, modeling, and scaling techniques for mass balance measurement and projection?
- What is global glacier volume?

Action Item: Global glacier mass balance intercomparison workshop/project

Timeframe: 2 workshops in the space of one year. 1st workshop frames problem and assigns tasks. 2nd workshop to consolidate results. Consult IMBIE timeline.

Potential Collaborators: WGMS, IACS, GCW, TPE, GLIMS, WCRP-related sea level grand challenge

Potential Participants: Arendt, **Arigony**, Bahr, Bolch, Braithwaite, Cogley, Fujita, Gardner, Giesen, Hock, **Kang**, Kaser, **Kohler**, Leclercq, Mackintosh, Marzeion, **Mernild**, Mölg, Oerlemans, **Pope**, Radić, Yao, Zemp, E. Berthier (LEGOS); A. Kääb (U Oslo); Y. Arnaud (IRD)

Freshwater volume and availability from the cryosphere

Twenty-five percent of the world's population depends on rivers, which are fed by glaciers. Further cryospheric contributions affect even more people globally. Communities that rely upon these freshwater sources, in particular in arid environments, are especially vulnerable to disruption of their water supply. The amount of water locked away in the cryosphere remains a great unknown.

Specific Questions
What is the volume and availability of fresh water from cryospheric sources (including snow, glaciers, permafrost ice, and rock glaciers)?

1) How do we measure/estimate individual freshwater resources?
2) How do we make it global?
3) How do we make this hydrologically meaningful?
   i.e. availability, models

Action Items

- One workshop for each sub-question (may not be completely independent from each other).
- Smaller, more specific component meetings (e.g. at AGU) in between.
- This activity has clear links to the snow activities also discussed at this workshop. When moving forward connections need to be established early on.

Timeframe: Major workshops should be spaced 2 years apart.

Potential Collaborators: WCRP/GEWEX water availability grand challenge, IAHS, IACS, WGMS, IPA, 'Current and future melt of global glaciers and ice caps' group

Potential participants: Cohen, Fountain, Gogineni, Hinzman, Huss, Immerzeel, **Kehrwald**, **MacDonell, Matsuoka,** McPhee, Miles, Pelliciotti, Prouse, Rignot, Vorosmarty, Yang; B. Hingray (LTHE), T. Lebel (LTHE) {looking for further inclusion}.

Ice sheet snowpack melt, storage & runoff

Extensive surface melt has been recently documented over the Greenland Ice Sheet, previously unprecedented in the observational record. Meltwater can be trapped within the firn layer, and so the magnitude and delay of runoff remains unknown. Large inputs of meltwater could initiate changes in ice flow, there is an unknown upper limit on ice sheet snow pack storage capacity, and coupling these processes is key to understanding Greenland's contribution to sea level rise which may happen in a timescale much shorter than previously thought. Runoff from the Greenland Ice Sheet will also have important consequences for the Atlantic Meridional Overturning Circulation (AMOC) and the Arctic sea ice cover, which will in turn feed back to accumulation. Similar processes are becoming increasingly important on the Antarctic Peninsula and other warming regions of West, and potentially East, Antarctica.

Specific Questions
What are the magnitude and timing of delays in ice sheet runoff related to water storage in the snowpack and firn? (i.e. non-immediate contributions to sea level rise)
   Where are these processes important?
   What are the changes in firn/ice thermal structure?
   What is the changing role of albedo including that caused by Local Area Coverage (LAC)?
   …and how do these processes connect with/affect ice dynamics?
How do snow models need to be further developed to capture these processes (e.g. 3D water transport)?

Action Items
- Workshop aimed bringing the ice sheet-snow pack modeling and observing communities together.
- Instigation of ice sheet-snow model development network.
- Coordinated session proposals at major conferences.
- Include ice sheet snow cover in ESM-SnowMIP or broader high-latitude surface process model intercomparison (see "Role of Snow in the Earth and Climate Systems")

Timeframe: Begin within a year.

Potential Collaborators: Greenland observation networks, Antarctic observation networks, IACS, IGS, IASC, SCAR, SOOS, WCRP-related sea level grand challenge

Potential Participants: Arnold, Box, **Costa**, Forster, Hanna, Harper, Howat, Humphrey, Luthi, **Mernild,** Mottram, **Muto**, Pettit, Pfeffer, Willis, and representatives from major modeling communities. E. Brun (Meteo France), C. Genthon (LGGE), M van den Broeke (IMAU), W.J. van den Berg (IMAU), Cullather (Maryland)

Sea Ice

Impact of changing sea ice on high-latitude climate systems

Sea ice plays a crucial, but generally poorly understood role in the functioning and evolution of the Earth's climate system. Sea ice in high latitudes is currently behaving in very different ways: the ice is retreating in the Arctic, while there is regionally-contrasting change in the Antarctic. The changes in the Arctic represent one of the most obvious indicators of climatic change. As of yet, there is substantial uncertainty related to how this evolution of sea ice affects regional climate systems. This question is of importance from a climate perspective because of possibly relevant feedbacks to other components of the high-latitude climate system (ice-shelf evolution -> sea-level rise, snow distribution, polar amplification) and thus has direct societal importance.

Specific questions
How do changes in sea ice affect...
- Snow distribution on land and ice?
- Sub-sea and terrestrial permafrost?
- Ice-shelf dynamics?
- Extreme weather events?
- (Local) atmosphere dynamics?
- (Local) ocean dynamics?

Connections to other projects/programs
One focus of this research topic is interaction with other components of the cryosphere, which means that it can ideally be addressed through the interdisciplinary nature of CliC. Input and collaboration with other projects is crucial, including PCPI initiative 5 (model biases, feedbacks), initiative 4 (evaluation of

CMIP5 model simulations), other Grand Challenges such as the one on extreme events and regional climate change, ASPeCt, CLIVAR, WMO's GCW, and MOSAiC.

Time frame: variable

Action items

- Open workshop on the **atmospheric response** to sea ice changes (including observations and modelling work on response in **snow fall**, mid-latitude weather patterns, extreme events, etc) (Annette Rinke, Vladimir Semenov, Marilyn Raphael; Possible attendees: Jim Overland, Jen Francis, Ivan Orsolini, Clara Deser, Klaus Dethloff, Meiji Honda, Judah Cohen, Jiping Liu, James Screen, Ian Simmonds, Thorsten Mauritsen, Jun Inoue, Steve Hudson, Katie Leonard, Graham Simpkins, Ryan Fogt, Odd Helge Ottera, etc; maybe in 2014)
- Use IGS session **sea-ice -- ice-shelf** interaction as a platform to define the current state of knowledge. Maybe review article? (Hobart, March 2014, Rob Massom, Ted Scambos; possible attendees of future workshop in 2015: Alex Fraser, Sharon Stammerjohn, FRISP community, WAIS community, Dave Holland, Mike Dinniman, Phil Reid, Dirk Notz, Einar Olason, Peter Jensen, Vernon Squire, Sohey Nihashi, Tim Williams, Pat Langhorne, R. Bintanja, Petra Heil, Mike Pook, David Vaughan, Luke Copeland, Jason Amundsen, Axel Timmermann, Hartmut Hellmer, Michael Schodlok, Eric Rignot, Lars Henrik Smedsrud, Inga Smith, Hamish Pritchard, Paul Dodd, Laurie Padman, etc)
- Analysis of CMIP5 archive, ocean state estimates, FAMOS (former AOMIP) simulations, and other dedicated modelling studies on changes in oceanic temperature to drive changes in **sub-sea permafrost,** links to permafrost community regarding impact of boundary conditions on permafrost thaw (Dirk Notz, Ted Schuur, Victor Brovkin, Wieslaw Maslowski, FAMOS community, GSOP community, Martin Heimann, Paul Overduin, Sergey Denisov, Aksenov, Igor Polyakov, Andrey Proshutinsky, Vladimir Romanovski, Dmitry Nicolsky, Hans-Wolfgang Huberten, Mikhail Grogoriev, Ilana Wainer..., maybe session in connection with FAMOS workshop 2014)
- Analyse model output of seasonal and decadal prediction initiatives on the impact of sea ice on predictability of high-latitude processes (Drew Peterson, Steffen Tietsche, Holger Pohlmann, APPOSITE community, Marika Holland, Dörte Handorf, Cecilia Bitz, June Inoue, Torben König, Hugues Goosse, Eugeny Volodin, Jim Renwick, etc, maybe session in connection with APPOSITE/SPECS workshop)
- Analyse available observational data sets for possible links between sea ice and the behaviour of the high-latitude climate system (e.g., interaction between sea ice and ice-shelves, correlation between sea-ice and snow-fall patterns,...) (Gunnar Spreen, workshop participants of item 1, Eric Rignot, Paul Holland, Jay Zwally, Andy Shepherd, Geir Moholt, Ron Kwok, Lars Kaleschke, Leif Toudal Pedersen, Allen Pope, Joey Comiso, Orsolini, Walt Meier, snow remote sensing, Thorsten Markus, Helmut Rott, Stefan Hendricks, ... maybe informal meeting at IGS in Hobart)

Internal variability of sea ice up to multi-decadal time scale

Many components of the cryosphere experience substantial variability on multi-decadal time scales that is driven by internal feedbacks within the Earth's climate system. The mechanisms for this variability are poorly understood. Developing/ improving such understanding is crucial for the assessing both the relative importance of anthropogenic climate change and for assessing limits of the predictability of the future evolution of the Earth's cryosphere. In particular, the evolution of sea ice in the Southern Ocean might be driven to a large degree by internal variability and the amount by which internal variability, contributed to the rapid decline of Arctic sea ice in recent years is not clear, either.

Specific questions

- What role do teleconnections play in internal variability of sea-ice?
- How important is variable oceanic and atmospheric forcing?
- What governs the memory of internal variability?
- What's the internal variability on regional scales?
- How significant are observed changes?
- How does internal variability limit predictability?
- How reliable are long-term sea-ice time series? How can we improve them and create gridded Arctic- and Antarctic-wide sea-ice data sets covering the entire 20th Century?

Connections to other projects/programs

Despite being targeted at sea ice, this research topic will provide insights into other components of the cryosphere. As such, it is again ideally suited for placement within CliC. The research theme has direct links to PCPI, PPP, CLIVAR, SPARC, and the wealth of initiatives that look at general predictability on seasonal and decadal time scales.

Time frame: 5 years

Action items

- Possible workshop on historical and proxy sea-ice data, aimed at compiling all available data sources, datasets, re-assessing methods to extend and improve sea-ice data in sparsely-sampled regions and periods etc. (Vladimir Semenov, Dmitry Divine (?), Mark Curran, Nerelie Abram, ASPeCt community, HadISST people, John Walsh, Alekseev, Shapiro, Igor Polyakov, Ola Johannessen, et al.; workshop possibly together with PCPI in early summer 2014)
- Analysis of CMIP5 archive, decadal prediction simulations, and reanalysis simulations to gain insights into modelled internal variability (magnitude, drivers) (Dirk Notz, Will Hobbs, Cecilia Bitz, Marika Holland, Massonnet, Clara Deser, David Schneider, Reto Knutti, Alex Hall, Vladimir Kattsov, Greg Flato, John Turner, Irina Mahlstein, Jen Kay, Hugues Goosse, etc, dedicated workshop in 2014/15)
- Examine agreement and biases between observed and modelled internal variability in order to reduce uncertainty and identify underlying processes (tbd.)

Role of Snow in the Earth and Climate Systems

Snow is an essential component of the Earth System. As both a permanent and an intermittent component of the cryosphere, it interacts with the atmosphere and the surfaces it covers (land, ice, sea ice) and it is one of the principal sources of feedbacks within the climate system. The most well-known positive feedback stems from the albedo contrast between snow-covered and snow-free surfaces. This can be modulated by aerosol deposition on snow, which decreases snow albedo and thus leads to a local warming and melt, which further decreases albedo. Other important effects of snow cover are linked to its physical properties. Depending on local conditions and meteorology, snow can be an extremely efficient isolator that thermally separates the underlying surface from the atmosphere above, for example, to critically determine the conditions for persistence or decay of permafrost. Undergoing quick changes, snow is also a prominent and powerful indicator of climate change. Relative changes in seasonal snow can be as large as or even stronger than changes in seasonal sea-ice extent. Last but not least, snow is a critical determinant of water resources in many regions of the Earth.

In spite of this importance, there are still fundamental knowledge gaps concerning the physical properties of snow and their evolution in time in both seasonal and permanent snow packs, past, present and future trends in snow mass and distribution, and the effects of snow in the Earth System. These are linked to fundamental deficiencies in representation of snow physics in models, insufficient in-situ measurement coverage in many sparsely populated areas, on ice sheets and sea-ice, in alpine regions, issues with remote sensing of snow cover (in particular concerning thickness, snow-water equivalent (SWE), small-scale snow cover variability, etc.) and overly-simplified representation of snow-related processes in ESMs.

A large-scale integrated study of snow in the climate system would therefore be timely. This is something that has not been tackled before within a large international framework such as under CliC. There is a clear need to better tie together observational data, remote sensing, and modelling using novel approaches available through WCRP. Field experiments, dataset generation and compilation, model development, and process studies need to be done together at a societally relevant range of time and spatial scales, and could be complemented by a multi-scale observing and modelling experiment.

Within the Cryosphere Grand Challenge, the following targeted actions arising from identified scientific knowledge gaps could prepare and initiate this *Snow in the Earth System* study.

NOTE: This ties directly to the Ice sheet snowpack melt, storage & runoff activity above

How can we improve our current knowledge and understanding of the temporal dynamics and physical properties of snow as a component of the coupled climate system?

Goal: Produce better global-scale datasets of snow cover, SWE, and snow thermal properties by drawing together local and remote sensing observations.

Justification: Snow extent, water equivalent and physical properties are highly variable in space and time, and knowledge of this variability is of paramount importance to better understand the role snow plays in the global climate system.

Actions:

- Workshop/white paper designed to develop new strategies to integrate the wide variety of snow-related ground-based observations, airborne and space-based remote sensing measurements, and modelling tools to produce accurate, high-resolution snow-distribution and snow-property datasets. (2 years)
- Workshop/panel to identify snow-related observation supersites with a representative variety of regimes: ice sheets (Dome C?), alpine type (Col de Porte?), Siberia, sea ice (MOSAIC platform), permafrost-related (Barrow?); develop common long-term observation strategies and protocols. These supersites are designed to host comprehensive observations of physical and chemical effects of snow in order to improve scientific process understanding and for the development and evaluation of a new generation of dedicated models and snow models in ESMs. This can start from a small number of sites. (1 year)
- Design novel ways to foster citizen support for distributed snow observations. (?)

Can we improve our understanding of the role of snow as an active component of the global climate system?

Goal: Make progress on the representation of snow in ESMs, and conduct systematic model studies and data analysis for a better understanding of the role of snow in the global climate system.

Justification: The effect of snow in the climate system is generally recognised as an important one, but the amplitude of snow-related feedbacks, the effect of snow on other components of the cryosphere, and its effect on climate predictability (seasonal or longer-term) are not well quantified.

Actions:

- Develop an Earth System Model – Snow Model Intercomparison Project (ESM-SnowMIP) designed to quantify the state of the art of the representation of snow in ESM and RCMs and identify ways to move forward (building on the experience of SnowMIP and extending it specifically to ESM and RCM land surface modules). Intercomparison involving dedicated detailed snow models to gauge requisite complexity and necessary processes to be represented in ESMs, and an assessment of snow-related processes and feedbacks in CMIP5/6. This action could, and actually should, be part of a broader-scope *high-latitude surface processes model intercomparison* addressing permafrost physics and biogeochemistry, snow (on sea ice, on land ice and on land), vegetation dynamics, and their interactions in ESMs and RCMs. (5 years, could be an important part of a future *Snow in the Earth System* study)
- Workshop on the role of snow in climate predictability and snow-related climate feedbacks. Design dedicated model experiments (extensions of CMIP5/6, PCPI).

How will future changes in snow cover affect freshwater availability for human societies?

Justification: Snow cover could undergo profound changes in extent and water equivalent in the future; these changes are likely to impact on the freshwater resources of many human communities.

Actions:
Assessment of the impact of snow changes on water resources based on an analysis of CMIP5/6 archives, downscaling and use of snow models. This activity clearly links to other activities discussed in the glacier group at this workshop. When moving forward links should be established from the beginning.

Potential participants (for the whole snow theme):
Eric Brun, Alex Hall, Richard Essery, Nick Rutter, Pavel Groisman, Chris Derksen, Glen Liston, Olga Zolina, Yulia Zaika, Shelley MacDonell, Samuel Morin, Gerhard Krinner, Matthew Sturm, and more...

Partners:
GCW (addresses snow from viewpoint of observations and monitoring), GlobSnow and CryoClim, PPP, PCPI, modelling groups, SnowMIPx participants (which characteristics of snow should be used for which parts of a model?), SPICE (WMO Solid Precipitation Instrument Intercomparison Experiment), IASOA (International Arctic Systems for Observing the Atmosphere), IASC Scientific Standing Committee on Cryosphere, IACS (International Association of Cryospheric Sciences), ASPeCt, and more to be identified.

Workshop Conclusion

The workshop ended with a summary discussion on the way forward with recommendations for follow up conference calls, meetings of opportunity, and a request for increased project administration from the CliC Office, preferably in the form of a science officer to help coordinate activities.

The workshop organizers thanked the participants and noted more information on follow up activities and a draft action plan for executing the activities of the Grand Challenge will be distributed by Greg Flato in the coming weeks.

Appendix 1: Agenda

All presentations will be in the Ny-Ålesund room (2011), 2nd Floor, Fram Centre, unless otherwise noted

Wednesday, 16 October 2013

Time	Agenda Item
08:30 - 09:00	**Registration**
09:00 - 09:20	**Welcoming Remarks** *- Sebastian Gerland, Norwegian Polar Institute* *- Greg Flato, CliC Chair, Environment Canada*
09:20 - 09:45	**WCRP Grand Challenges and the Cryosphere in a Changing Climate** *- Greg Flato, CliC Chair, Environment Canada*
09:45 – 10:00	**Polar Climate Predictability Initiative** *- Marilyn Raphael, UCLA*
10:00 - 10:30	**Discussion**
10:30 - 11:00	**Coffee Break**
11:00 - 11:30	**Ice Sheets and Glaciers in a Changing Climate** *- Andrew Shepherd, University of Leeds, UK*
11:30 - 12:00	**Sea Ice in a Changing Climate** *- Dirk Notz, Max Planck Institute for Meteorology, Germany*
12:00 - 12:30	**Permafrost and Carbon in a Changing Climate** *- Ted Schuur, University of Florida, USA*
12:30 - 13:30	**Group Photo followed by Lunch**
13:30 - 14:00	**Cryosphere Biases/Shortcomings in Earth System Models** *- Gerhard Krinner, Laboratoire de Glaciologie et Géophysique de l'Environnement, France*
14:00 - 14:10	**Introduction to Science Foci Breakout Groups** *- Greg Flato, CliC Chair, Environment Canada*
14:10 - 15:20	**Science Foci & Priorities Breakout Groups** *Red group: Ny-Ålesund (2nd floor, 2011)* *Orange group: Tre Kroner (5th floor, 5010-5012)* *Purple group: Barentsburg (2nd Floor, 2012)* *Blue group: Sarkofagen (5th floor, 5093)* *Green group: Pyramiden (2nd floor, 2013)*
15:20 – 15:50	**Coffee Break**
15:50 – 17:00	**Breakout Group Reports and Discussion**
19:00 -	**Workshop Dinner**

Appendix 1: Agenda

WCRP World Climate Research Programme

Cryosphere in a Changing Climate

16 - 18 October 2013, Tromsø, Norway

All presentations will be in the Ny-Ålesund room (2011), 2nd Floor, Fram Centre, unless otherwise noted

Thursday, 17 October 2013

Time	Agenda Item
09:00 - 09:20	**Now What - Where Do We Go From Here?** Direction to breakout groups on ways to achieve actions *- Greg Flato, CliC Chair, Environment Canada*
09:20 – 11:00	**Approaches to Progress Breakout Groups** *Red group: Ny-Ålesund (2nd floor, 2011)* *Orange group: Tre Kroner (5th floor, 5010-5012)* *Purple group: Barentsburg (2nd Floor, 2012)* *Blue group: Sarkofagen (5th floor, 5093)* *Green group: Pyramiden (2nd floor, 2013)*
11:00 – 11:30	**Coffee Break**
11:30 – 12:30	**Breakout Group Reports and Discussion** *- Greg Flato, CliC Chair, Environment Canada*
12:30 - 13:30	**Lunch**
13:30 – 13:40	**Let's Do This – Developing Concrete Action Plans** Direction to breakout groups on ways to achieve actions *- Greg Flato, CliC Chair, Environment Canada*
13:40 - 15:30	**Concrete Action Plan Breakout Groups** *Red group: Ny-Ålesund (2nd floor, 2011)* *Orange group: Tre Kroner (5th floor, 5010-5012)* *Purple group: Barentsburg (2nd Floor, 2012)* *Blue group: Sarkofagen (5th floor, 5093)* *Green group: Pyramiden (2nd floor, 2013)*
15:30 - 16:00	**Coffee Break**
16:00 - 17:30	**Report Back and Discussion**
17:30 – 19:00	**Poster Session with Appetizers**

Friday, 18 October 2013

Time	Agenda Item
09:00 - 10:30	**Where Do We Go From Here Discussion** *- Greg Flato, CliC Chair, Environment Canada*
10:30 - 11:00	**Coffee Break**
11:00 - 12:00	**Summary of Plan and Strategy: A Way Forward and Discussion** *- Greg Flato, CliC Chair, Environment Canada*
12:00 - 13:00	**Farewell Lunch**
13:00 - 16:00	**Organizers and Report Writers Meeting**

Appendix 2: Participant List

WCRP World Climate Research Programme

WMO IOC ICSU

Cryosphere in a Changing Climate

16 - 18 October 2013, Tromsø, Norway

CliC

Name	Institution / Affiliation	Email
Arigony, Jorge	Universidade Federal do Rio Grande, Brazil	jorgearigony@furg.br
Baeseman, Jenny	Climate and Cryosphere, Norway	jbaeseman@gmail.com
Costa, Alfredo J *	Instituto Antartico Argentino - Direccion Nacional del Antartico, Argentina	alpiocosta@gmail.com
Flato, Gregory	Environment Canada, Canada	greg.flato@ec.gc.ca
Gerland, Sebastian	Norwegian Polar Institute, Norway	Sebastian.Gerland@npolar.no
Isaksen, Heidi	Climate and Cryosphere, Norway	heidi@climate-cryosphere.org
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Kehrwald, Natalie	University of Venice, Italy	kehrwald@unive.it
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Liston, Glen	Colorado State University, USA	glen.liston@colostate.edu
MacDonell, Shelley *	Centro de Estudios Avanzados en Zonas Aridas, Chile	shelley.macdonell@ceaza.cl
Massom, Rob	Australian Antarctic Division and Antarctic Climate and Ecosystems Cooperative Research Centre, Australia	rob.massom@aad.gov.au
Matsuoka, Kenichi	Norwegian Polar Institute, Norway	matsuoka@npolar.no
Mernild, Sebastian	Center for Scientific Studies/Centro de Estudios Cientificos, Chile	smernild@gmail.com
Muto, Atsuhiro *	The Pennsylvania State University, USA	aum34@psu.edu
Notz, Dirk	Max Planck Institute for Meteorology, Germany	dirk.notz@zmaw.de
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Pavlov, Alexey	Norwegian Polar Institute, Norway	pavlov.alexey.k@gmail.com
Peterson, K Andrew	Met Office Hadley Centre, UK	drew.peterson@metoffice.gov.uk
Pope, Allen *	National Snow & Ice Data Center, University of Colorado, USA	allen.pope@post.harvard.edu
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Rinke, Annette	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany	Annette.Rinke@awi.de
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Zaika, Yulia	Lomonosov Moscow State University, Russia	yzaika@inbox.ru
Zolina, Olga	Université Joseph Fourier, France	olga.zolina@lgge.obs.ujf-grenoble.fr

* *Denotes participants who have FrostBytes, 30-60 second 'soundsbytes of cool research'*

Appendix 3: Online Participant List and Social Media

Online participation in plenaries and breakout sessions was possible through the GoToMeeting platform. Participants provided their name, and sometimes affiliation. Attendees largely attended the first day of the workshop, but some were present for later discussions. The workshop was recorded and videos will be archived for future viewing and consultation.

Alexander Beitsch - Center for Marine and Atmospheric Sciences, Hamburg, Germany
Clara Turetta - IDPA-CNR Venice, Italy
Ingrid Onarheim - University of Bergen, Norway
Henning Åkesson - University of Bergen, Norway
Jason Box - National Geological Survey of Denmark and Greenland, Copenhagen, Denmark
Jennifer Riley - CLIVAR, Plymouth, UK
Kerim Nisancioglu - University of Bergen, Norway
Mareike Burba - World Meteorological Organization, Geneva, Switzerland
Mari Jensen - University of Bergen, Norway
Mauri Pelto - North Cascade Glacier Climate Project, MA, United States
Michel Rixen - World Climate Research Programme, Geneva, Switzerland
Petteri Uotila - CSIRO Marine & Atmospheric Research, Australia
Roberta Boscolo - World Climate Research Programme, Geneva, Switzerland
Sara Mynott - European Geosciences Union, Munich, Germany
Siobhan O'Farrell - CSIRO Marine & Atmospheric Research, Australia
Tony Payne - University of Bristol, UK
Xiangshen Tian-Kunze - Center for Marine and Atmospheric Sciences, Hamburg, Germany
Yongmei Gong - Uppsala University, Sweden

In addition, the workshop also used the Twitter hashtag #CryClim13. CliC maintains a presence on Twitter through @CliC_Cryosphere. Participants engaged through include Allen Pope (@PopePolar), Angelika Renner (@ahhrenner), Anna Maria Trofaier (@WhinnyHowe), Cat Downy (@catwny), Josh King (@geomatics), Greenland Surface Mass Balance Program (@greenlandicesmb), Mauri Pelto (@realglacier), Mona Nasser (@monalisa1n), O Bothe (@geschictenpost), Ruth Mottram (@ruth_mottram), Sara Mynott (@SaraMynott), and Steve Bloom (@stevebloom55). Tweets using the workshop hashtag have been archived with Storify here: http://storify.com/popepolar/wcrp-cryosphere-in-a-changing-climate-workshop

Appendix 4: Acronym List

ABoVE	Arctic Boreal Vulnerability Experiment
AGU	American Geophysical Union
AMOC	Atlantic Meridional Overturning Circulation
AOMIP	Arctic Ocean Model Intercomparison Project
AON	Arctic Observation Network
APPOSITE	Arctic Predictability and Prediction on Seasonal To inter-annual Timescales
ASPeCT	Antarctic Sea Ice Processes and Climate
CALM	Circumpolar Active Layer Monitoring
CENPERM	Center for Permafrost – University of Copenhagen
CLIVAR	Variability and Predictability of the Ocean-Atmosphere System
CMIP	Coupled Model Intercomparison Project
CORDEX	Coordinated Regional Climate Downscaling Experiment
CryoClim	Initiative to develop new operational services for long-term systematic climate monitoring of the cryosphere
DEFROST	Part of the Top-level Research Initiative, aiming to strengthen research and innovation regarding climate change issues in the Nordic Region.
ESMs	Earth System Models
ESA	European Space Agency
FAMOS	Forum for Arctic Ocean Modeling and Observational Synthesis
FRISP	Forum for Research into Ice Shelf Processes
GCW	Global Cryosphere Watch
GEWEX	Global Energy and Water Exchanges Project
GLIMS	Global Land Ice Measurements from Space
GlobSnow	Aims to produce global long term records of snow parameters

	intended for climate research purposes on hemispherical scale
GRENE Arctic	Green Network of Excellence Arctic Program
GSOP	Global Synthesis and Observations Panel
GTN-P	Global Terrestrial Network on Permafrost
HadISST	Hadley Centre Sea Ice and Sea Surface Temperature Data Set
IACS	International Association of Cryospheric Sciences
IAHS	International Association of Hydrological Science
IARC	International Arctic Research Center
IASC	International Arctic Science Committee
IASOA	International Arctic Systems for Observing the Atmosphere
IGBP	International Geosphere-Biosphere Program
IGS	International Glaciological Society
iLEAPS	Integrated Land Ecosystem – Atmosphere Processes Study
IMBIE	Ice Sheet Mass Balance Inter-Comparison Exercise
IPA	International Permafrost Association
IPCC	Intergovernmental Panel on Climate Change
LAC	Local Area Coverage
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
NASA	National Aeronautics and Space Administration
NEESPI	Northern Eurasian Earth Science Partnership Initiative
NEON	National Ecological Observatory Network
NGEE Arctic	Next-Generation Ecosystem Experiments
OBS4MIPS	A pilot activity to make observational products more accessible for climate model intercomparisons
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PCN	Permafrost Carbon Network
PCPI	Polar Climate Predictability Initiative
PEEX	Pan-Eurasian Experiment
PPP	Polar Prediction Project
RCM	Regional Climate Model
SCAR	Scientific Committee on Antarctic Research
SEARCH	Study of Environmental Change in the Arctic
SnowMIP	Snow Model Intercomparison Projects
SOOS	Southern Ocean Observing System
SPARC	Stratospheric Processes and their Role in Climate
SPECS	Seasonal-to-decadal climate Prediction for the improvement of European Climate Services
SPICE	Solid Precipitation Instrument Intercomparison Experiment
SST	Sea Surface Temperature
SWE	Snow-Water Equivalent
TPE	Third Pole Environment
TSP	Thermal State of Permafrost
UAF	University of Alaska Fairbanks
WAIS	West Antarctic Ice Sheet
WCRP	World Climate Research Project
WGCM (MIP)	Working Group on Coupled Modelling (Model Intercomparison Project)
WGMS	World Glacier Monitoring Service
WGSIP	Working Group on Seasonal to Interannual Prediction
WMO’s GCW	World Meteorological Organization’s Global Cryosphere Watch