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SCAR report

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Contents

WCRP/CliC
Global Prediction of the Cryosphere (GPC) Project

SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

at the

Scott Polar Research Institute, Cambridge, United Kingdom

SCAR Report

SCAR Report is an irregular series of publications, started in 1986 to complement SCAR Bulletin. Its purpose is to provide SCAR National Committees and other directly involved in the work of SCAR with the full texts of reports of SCAR Standing Scientific Groups and Group of Experts meetings, that had become too extensive to be published in the Bulletin, and with more comprehensive material from Antarctic Treaty meetings.

SCAR Bulletin

SCAR Bulletin, a quarterly publication of the Scientific Committee on Antarctic Research, carries reports of SCAR meetings, short summaries of SCAR Standing Scientific Groups, Action Groups and Groups of Experts meetings, notes, reviews, and articles, and material from Antarctic Treaty Consultative Meetings, considered to be of interest to a wide readership.

WCRP/CliC GLOBAL PREDICTION OF THE CRYOSPHERE (GPC) PROJECT

Workshop Report

8-9 October 2 007, British Antarctic Survey, Cambridge, UK

Attendees: John Turner (British Antarctic Survey), Tom Bracegirdle (British Antarctic Survey), Thierry Fichefet (Université Catholique de Louvain, Belgium), Adrian Jenkins (British Antarctic Survey), David Vaughan (British Antarctic Survey), Mattias de Woul (Stockholm University), Charles Harris (Cardiff University), Richard Hindmarsh (British Antarctic Survey), Tony Payne (University of Bristol), Jon Bamber (University of Bristol)

INTRODUCTION

Global Prediction of the Cryosphere (GPC) is one of the four themes of the CliC project and has the goal of improving the model projections of the global cryosphere over the 21st century. While each of the other three CliC themes has some elements of cryospheric prediction, GPC is closely linked to the climate modelling and meteorological communities, and has a strong focus on the atmospheric and oceanic forcings of the cryosphere.

This workshop was organised to bring together experts in various aspects of the global cryosphere with the goals of:

- reviewing our ability to predict the evolution of the cryosphere over the 21st century at the global scale;
- identifying gaps in our current understanding;
- proposing research activities in the framework of CliC.

The meeting consisted of short invited presentations on the different components of the cryosphere, followed by extensive discussion. John Turner described the functions of WCRP and its various projects and other activities, along with the goals of CliC.

SEA ICE

Thierry Fichefet began by assessing the ability of the current generation of atmosphere-ocean general circulation models (AOGCMs) to reproduce the sea ice changes observed during the last decades and by comparing the sea ice projections conducted with those models over the 21st century. The models have larger errors in summer than winter, and also have less skill in the Southern Hemisphere than in the Northern Hemisphere. This last characteristic is attributed to problems in simulating realistically the Southern Ocean. Furthermore, very few models are able to reproduce the sharp decline in arctic September sea ice extent observed during the last decades. There is also large variability between the models in simulating the late 20th century sea ice extent in both hemispheres, as well as the geographical distribution of the ice thickness.

Errors in the sea ice were attributed to biases in the wind forcing (perhaps the most important factor) and to the representation of atmospheric boundary layer processes, cloudiness and oceanic mixing processes in models. The sophistication of the sea ice models was often not a major factor. However, it was felt that sea ice models need better formulations for the snow cover on top of sea ice, the ice-ocean interactions and the sea ice rheology. Over the 21st century, a large loss of sea ice is projected for both hemispheres, with about half the IPCC AR4 models suggesting an ice-free Arctic Ocean during summertime by the end of the century. There is however a considerable uncertainty between models in predicting the sea ice concentration and thickness changes at the regional scale in both hemispheres.

Tom Bracegirdle considered the variability in representation of Antarctic sea ice across the AR4 models. Many of the 16 models examined had annual cycles of sea ice that were markedly different from that during the satellite era. Tom had weighted the projections of sea ice according to how skilful the models were in simulating late 20th century climate change. This had reduced the sd of the model spread in sea ice by 20%. In summary, most models struggle to reproduce the regional detail of sea ice. The largest correlation between model bias and projected change is at high latitudes. Weighting reduces the spread of projections of total annual average sea ice area and ice-sheet precipitation - evaporation by 20%.

All these results points to the need for a comprehensive comparison of AGCMs in polar regions driven by the best avalailable cryospheric data. It was also suggested to further assess the performance of ice-ocean models in polar regions through extensive model intercomparison exercises such as AOMIP for the Arctic and SOPHOCLES for the Antarctic. Finally, it was recommended to better constrain AOGCMs by using information from the past. For instance, a recent study carried out with a three-dimensional Earth system model of intermediate complexity and different sets of parameter values has revealed that there exists a strong link between the simulated minimum Arctic sea ice extents in the early Holocene and the middle of the 21st century. This relationship implies that our confidence in sea ice projections will be enhanced if the models are able to correctly simulate the early Holocene changes. But, of course, this calls for more numerous and more accurate sea ice proxy data.

THE ICE SHELVES

Adrian Jenkins discussed the importance of the ice shelves around the Antarctic continent and our current ability to model the oceanographic conditions under them. The ice shelves represent only 13% of the area of the continent, but receive about 80% of the discharge from the inland ice sheet. The rate of ice discharge is at least partially controlled by the thickness and extent of the ice shelves. In most cases the major forcing on ice shelf evolution is the basal melt/freeze rate, which is in turn determined by the oceanographic conditions on the continental shelf.

The Antarctic continental shelves fall into two categories: those dominated by near-freezing point waters formed in situ; and those dominated by Circumpolar Deep Water, which intrudes across the shelf edge. In the former regions, typified by the Ross and Weddell seas, melt rates beneath the large ice shelves average a few 10s of centimetres per year. In the latter, typified by the Amundsen and Bellingshausen seas, melt rates are one to two orders of magnitude higher and the ice shelves are much smaller as a result.

To understand how the ice shelves might respond to climate change we need to consider both the sensitivity of ice shelf melt to water temperature and the sensitivity of shelf water temperatures to climate forcing.

Observations suggest that the sensitivity of individual ice shelves to changes in water temperature varies over an order of magnitude. There are strong theoretical arguments for a non-linear relationship between ambient water temperature and melt rate that is dependent on the geometry of the ice shelf base. The non-linearity means that even for a fixed ice shelf geometry the sensitivity to temperature change is higher for higher initial water temperatures. All these factors complicate the problem of finding a simple parameterisation of ice shelf melting that could be used in climate models.

Shelf water temperatures (at the depths that matter to ice shelves) are linked only indirectly to atmospheric temperatures, and any changes are likely to be forced more by changes in ocean dynamics than by changes in ocean temperature. On the cold shelves the water temperature is fixed at the surface freezing point, and is unlikely to change without considerable alteration to the production rates of sea ice. Ironically a small reduction in sea ice growth could reduce the rate of sub-ice-shelf circulation while maintaining the same temperature. This would reduce the melt rates beneath the large ice shelves. However, further reduction in sea ice growth would presumably eventually lead to a transition (possibly rapid) to a warm shelf regime and with waters at least 2ºC warmer than at present. In this case the shelves would no longer act as sources of Antarctic Bottom Water, with consequent impacts on the deep ocean. The heat content of the warm shelf seas is intimately linked to the supply of Circumpolar Deep Water at the shelf edge, and this appears to be controlled at least in part by the wind forcing of the circulation north of the continental shelves. Changes in the large scale wind field, which drives upwelling of deep water around Antarctica, are thus a potential link between climate change and ice shelf evolution.

To make projections of the future mass balance of the ice shelves we need data to validate model physics, especially basal melt rates. Parameterisations that are currently in use are based on sea ice observations, and have been tested in one case only against sub-ice-shelf observation. We also need to know more about shelf water variability and understand the processes that drive it on seasonal and interannual timescales. At present observations are temporally and spatially sparse with a strong summertime bias. New technologies are likely to be the key to extending the observational database in regions that are perennially ice covered. We also need ocean/climate models that can resolve the key processes, especially the continental shelf edge frontal system, leads and polynyas, and the important physics of the ice-ocean boundary layer.

THE ANTARCTIC PENINSULA

David Vaughan discussed recent glaciological change across the Antarctic Peninsula and the state of projections. The peninsula has seen remarkable change in recent decades and warmed much more than the rest of the continent. The warming has been largest during winter (summer) on the western (eastern) side. The temperature increase is evident via the retreat of glaciers at many locations across the region, for example at

Rothera station the glacier opposite the station has been retreating at a rate of 1 m/year.

There is a reasonable amount of in-situ meteorological data for some coastal parts of the region, but large areas where we only have annual mean temperature as derived from 10 m snow temperatures. Therefore, relationships have been developed between positive degree days (PDD), which is important in melt, and annual mean temperature. Using these relationships, PDD at locations across the peninsula have been predicted for 2050.

In summary on melt, long-term meteorological station data show increased duration of melt season across the Antarctic Peninsula over the past 50 years. Parameterization of the number of PDDs as a function of mean annual temperature allows mapping of change. Increasing surface ablation has been estimated and shown to be likely to have doubled between 1950 and 2000, and given continued summer warming could double or treble by 2050.

Across the peninsula most glaciers are retreating. Some are not, although the reasons for this are not known. Many glaciers are also accelerating.

Many ice shelves around the peninsula are disintegrating with around 14,000 km^2 of ice having been lost. The loss of the Larsen B Ice Shelf in early 2002 received a great deal of publicity.

There is some uncertainty in the contribution of ice loss from the peninsula to sea level rise, but estimates are:

Runoff up to 0.06 mm/year
Shelf collapse 0.07 mm/year
Flow imbalance at least 0.06 mm/year
Total around 0.19 mm/year
For comparison Alaska is 0.14 mm/year.

It is likely that with continued warming, runoff will perhaps treble within 50 years.

To improve projections we need better estimates of summer season temperature increases.

GLOBAL GLACIERS

Mattias de Woul dealt with glacier changes during the 20th Century and future projections. Glaciers are retreating in all parts of the world, but only about 300 out of approximately 200,000 glaciers across the Earth have been sampled via mass balance. Mass balance budget measurements is the most common technique for estimates of ice mass changes. In addition, volume changes are calculated using techniques such as altimetry and temporal changes in gravity.

To estimate global glacier change during the 21st century IPCC 2007 determined global mass balance sensitivity based on observed mass balance in combination with area-volume scaling, using different initial area and volume estimates. They excluded glaciers and ice caps on Greenland and Antarctica.

Uncertainties in predicting past and future glacier and ice cap volume change using modelling are:

- Lack of mass balance observations
- Downscaling of RCM and GCM data
- Changes in climate at the glacier surface
- Mass balance model
- Extrapolation of local/regional data to global scale
- Global glacier area and volume
- Change (past and future) in glacier area and volume
- Changing dynamic discharge (e.g. calving)
- Internal accumulation
- Basal melting
- Meltwater not flowing directly into the oceans

Regarding climate input data (mainly temperature and precipitation data), there are problems related to downscaling gridded data to local glacier, difficulties in downscaling energy balance components, a need for data with a horizontal resolution ~0.5 x 0.5° or higher, and problems with strong vertical gradients in mountain regions.

Potential improvements could be made by:

- Further analyses (past and future) using global simplified models that include precipitation changes and ice dynamics (volume and area changes)
- Improve volume and area inventory (with a defined reference period)
- Complete GLIMS (Global Land Ice Measurements from Space) project
- Enhance methods on repeated laser altimetry, radar mapping, remote sensing
- Mass balance observations in previously unmeasured regions
- Improved understanding of internal accumulation (field studies and models)
- Improved understanding of calving (field studies and models)

SNOW COVER

John Turner gave a presentation that had been prepared by Terry Prowse. There has been a marked decline in Northern Hemisphere snow cover over recent years, with the greatest loss during the spring and summer. The AR4 quoted a decline of 1.3% per decade in mean monthly snow cover. Where snow cover or snowpack has decreased, temperature often dominated and where snow increased, precipitation almost always dominated.

The ACIA produced projections for 21st century snow cover using output from five models from the IPCC Third Assessment. They estimated that relative to the 1981-2000 reference period, by 2050 the Arctic is expected to receive about 8% more precipitation, increasing to 17% and 24% by the end of the century with the B2 and A2 emission scenarios respectively. There is expected to be a general decreasing trend in snow depth because of increase in air temperature along with an increase in snow depth in the extreme north due to substantial increase in total precipitation. There is expected to be a strong negative correlation between snow depth and air temperature in most areas with a seasonal snow cover. Very high latitude and altitude areas may experience an increase in snow accumulation in the future.

In terms of runoff, there has been earlier snowmelt peaks and centres of runoff mass evident in some regions, e.g., western cordilleran of North America. There is projected further advancement, although volume estimates are uncertain due to uncertainties in precipitation changes and snow accumulation.

Many climate and hydrologic models rely on simplistic degree-day approaches as opposed to more complex full energy balance (e.g., partitioning precipitation, rate of melt, etc.). However, a concern for future predictions is that degree-day to energy balance relationships may not hold under changing climate (e.g., due to changes in cloud and radiation regimes). For prognosis, energy and temperature-index models may have to coexist for some time, at least until more confidence is realized in downscaled energy budget components.

LAKE ICE

We have records of lake ice for 39 sites extending back to 1946. Freeze up and break up dates have changed by 5.9 days over 100 years. There are no regional trends.

Many empirical relationships have been established between freeze-up and break-up dates and:

- Various monthly air temperatures, or
- Timing of isotherms, which shows broad-scale spatial coherence
- Empirical relationships may not apply to future climatic conditions because of changes in the composition of the major heat fluxes on which the temperature relationships are founded

In the future we expect mixed response. Increasing snowfall in some regions will give a delay in break-up (BU) (due to white ice, longer lasting, higher albedo), while less snowfall will result in earlier BU (due to lower spring albedo…BUT…less insulation could give enhanced ice growth). FU (freeze-up)/BU timing respond more strongly to warming than cooling due to albedo-radiation feedbacks.

Modelling needs are:

- Refinement of models of lake-ice growth and ablation for use in forecasting future conditions
- Models need to consider detailed heat storage components, including open-water heat budgets which influence FU timing and ice growth
- Atmospheric coupling for feedbacks still outstanding for large-lake environments

RIVER ICE

There is a 100 year plus record of river ice, with freeze-up delayed by 5.7 days/100 years and breakup having a long-term advance of 6.3d/100yr ~ 1.2°C/100yr. On the regional scale over the last 50 years there have been inter-regional contrasts (e.g., W-E in North America & Siberia). This mirrors warming trends.

River Break-up timing is linked statistically with:

- date of spring 0ºC isotherm
- winter accumulated freezing degree days
- water & freeze-up levels/ice thickness
- atmospheric teleconnections
- upstream snowmelt runoff and downstream ice-cover resistance

In terms of future projections, spring breakup timing is expected to advance by 15-35 days by 2100. There will also be changes in breakup severity with changes in "northward flowing" rivers due to different rates of warming in downstream (higher latitude) "resistance zones" versus upstream (lower latitude) "driving zones".

Key improvements are needed to predictive modelling in terms of:

- Thickness: Changes in freshwater ice thickness (and composition) are a consequence not just of the energy balance but also of changes in snow accumulation, which must be factored into future modelling
- Extreme Events (spring floods and winter low flows): Required integration of terrestrial snow/snowmelt models coupled with full-season ice thermodynamic / mechanics/ hydraulic model

A major overarching need was seen as increased collaboration between terrestrial snow/ice and the atmospheric modelling communities.

PERMAFROST

Permafrost was dealt with by Charles Harris who described its importance, the observational network and the modelling techniques used to understand changes in permafrost and how it might evolve in the future.

There are several IPY projects focusing on permafrost, including Thermal State of Permafrost (TSP). This is the International Permafrost Association's (IPA) main contribution to IPY, which will be the development of a spatially distributed set of observations on past and present status of permafrost temperatures and active layer thicknesses.

To better understand and predict permafrost change we need regional high resolution downscaling from global climate models. Data at a horizontal resolution of 10 km was thought to be desirable. But forcing is strongly modulated by snow cover and we need better snow distribution modelling.

Greater understanding is needed of active layer processes – especially phase changes. We need physically based energy balance models to better constrain thermal offset. Spatial complexity in ground surface response is best approached through remotely sensed data and field sampling within a GIS framework. We also need integration of high resolution climate modelling with substrate characterisation/modelling.

Geohazards (slope instability, thaw settlement) arising from permafrost warming can be addressed through application of new high resolution remote sensing to detect early signs of change or movement of the ground surface.

Coupled Thermal-Hydraulic-Mechanical (THM) numerical models are currently being developed to predict slope movements in thawing soils – assess geotechnical risks.

It was also agreed that for better prediction of change in permafrost we need:

- Knowledge of extreme events
- In certain arctic maritime settings, good sea ice predictions at the local scale
- High resolution temperature predictions
- Good snow cover forecasts
- Blowing snow included in GCMs

THE ICE SHEETS

Much of the second day of the workshop was concerned with the Antarctic and Greenland ice sheets, with three talks from Richard Hindmarsh, Tony Payne and Jon Bamber.

Richard Hindmarsh discussed modelling the Antarctic ice sheet and indicated that at the moment, there is no ice-sheet model that predicts both the retreat of the Antarctic ice-sheet since the end of the ice-age **and** correctly represents current variability. He discussed the major advance in grounding line dynamics that had been made through the work of Schoof (2006-7).

He described BASISM - a thermo-mechanically coupled shallow ice approximation ice-sheet model. This has applications to:

- Theoretical studies of ice sheet dynamics
- Pliocene Antarctica (Dan Hill)
- Maastrichtian Antarctica (Stephen Hunter)
- Equatorial High Obliquity Martian glaciation (Ed Kite)

The new grounding-line theory is being incorporated.
The next generation of ice sheet models will:

- Incorporate grounding line boundary layer
- Thermoviscous instabilities modulated by membrane stresses
- Will be able to answer deficiencies in current generation ice sheet models.

Conclusions:

- Grounding line - big advance made
- Able to evaluate the significance of the rapid change observed.
- A lot will happen in the next 2-3 years, including the first forecasts.
- Validated models of g.l. retreat.
- Forecasts of AIS and GIS

Tony Payne started by examining the 2001 IPCC predictions for the Antarctic ice sheet, which were based on stand-alone ice sheet model forced by regional temperature anomalies from scenarios. They had increased precipitation in the interior and the only mechanism of mass loss was surface melt, which required warming of ~8 °C. This led to coastal thinning and grounding-line retreat.

He considered the loss of the ice shelves on the eastern side of the Antarctic Peninsula. The breakup of the Larsen B shelf is now fairly well understood through meltwater fracture. In the future we may see loss of ice shelves at more southerly locations, e.g. the Amundsen Sea.

In the Amundsen Sea sector the ice streams and ice shelves are both thinning, suggesting a connection. Missing physics in ice sheet models is:

- the interaction between ocean circulation in coastal waters and floating ice shelves
- the coupling between this floating ice and the main grounded ice mass
- the controls on ice stream flow, in particular the need to incorporate longitudinal stresses and realistic basal hydrology
- role of fracture and shear margins in the ice shelves

Jon Bamber discussed the Greenland ice sheet. He identified three types of uncertainty in producing predictions for the ice sheet. These three types of uncertainty are generic to predicting any component of the cryosphere in a changing climate if the first is taken to be the uncertainty in the cryospheric model component:

- ice sheet response (surface mass balance & ice dynamics)
- climate response to GHG forcing
- GHG forcing scenario

Predictions had been made out to 3000 years in the future but with a large envelope of uncertainty resulting from the three influences outlined above, when only 3% of the ice volume remained (Ridley et al 2005).

He thought that the big questions regarding the ice sheet were:

- What was the past variability in dynamics? (aka: is what we see now unusual?)
- Are recent dynamic changes due to ocean or atmosphere?

- How far can the PDD approach be used to extrapolate beyond present climate?
- => how well can we really model surface mass balance?
- => envelope of uncertainty in forcing (precipitation, temperature, basal conditions)

The need was stressed for a high resolution ice sheet model to resolve all the outlet glaciers – perhaps 2 or 3 km resolution. Although this would not be needed for the interior, where 10-20 km would suffice. Finite element methods may be of value here.

GENERAL POINTS THAT EMERGED FROM THE DISCUSSIONS AND RECOMMENDATIONS.

- For prediction of many aspects of the cryosphere, we need higher resolution atmospheric forcing data with which to drive cryospheric models.
- The reanalysis data were thought to be too coarse for many applications.
- Getting the ocean right in coupled models is essential, since this affects projections of many aspects of the cryosphere, such as sea ice.
- Although there have been many model intercomparison projects, further such initiatives are needed. For example, a comparison of ice-ocean models to determine why the sea ice projections are so variable. One option would be to use the same ice-ocean model driven by different forcing fields.
- Iceberg calving is handled badly by current models, yet is very important in the freshwater balance of the Southern Ocean. Further investigation of the calving laws is needed.
- An intercomparison of permafrost models would be valuable.
- In models, we need better coupling between the ice sheet, the ice shelves, the sea ice and the ocean

There was extensive discussion on how CliC could contribute to producing improved predictions of the cryosphere. A common theme in many of the talks was a need for high resolution atmospheric and oceanic fields with which to drive cryospheric models. The best solution would be to have a high resolution, coupled atmosphere-ice-ocean model, but to get the resolution required would be extremely expensive. Thierry Fichefet suggested the following as a possible means of obtaining such data, and also gaining insight into the role of different types of forcing on the cryosphere:

1. Force various high resolution, regional (Arctic and Antarctic) **atmosphere-only models** with SSTs, sea ice and snow data, plus reanalysis fields. Such models would be run over the last couple of decades and would generate the boundary conditions for the cryospheric models. A resolution of 10-20 km would be needed.
2. The output from those regional models would then be used to assess the performance of the atmospheric component of AOGCMs in polar regions, which are typically run at much coarser resolution. This would require to launch a comprehensive comparison of AGCMs in polar regions driven by the best avalaible cryospheric data.
3. The output from both the regional and global models would finally be used to drive

intercomparisons of:

a. ice sheet models,
b. permafrost models,
c. snow models,
d. ice-ocean models.

Several groups are developing regional Arctic and/or Antarctic climate models, and it was suggested that interested parties could meet at EGU in April 2008 to explore the possibility of such an exercise. If it was decided to move forward with the project, a workshop could possibly be held later in 2008.

CONCLUSIONS

There are clearly many challenges in producing reliable projections of how the cryosphere will evolve over the 21st century and beyond. For elements such as sea ice, snow cover and permafrost it is currently possible to produce estimates using models, but there are large or very large discrepancies between models. This is particularly the case with sea ice, especially in the Southern Hemisphere where the ocean forcing is very important. For the ice shelves and the ice sheets, it is currently very difficult to use models to estimate their change in the future.

More data on recent changes in the cryosphere are needed for validation of models and to understand the pattern of change and the processes involved.

Many processes important in cryospheric change are not understood or included in models. For examples, few models are able to reproduce the recent loss of sea ice in the Arctic.

Failure to correctly simulate many recent changes in the cryosphere has often been found to be a result of poor atmospheric or oceanic forcing. We therefore recommend the production of high resolution forcing fields using regional climate models.

ACKNOWLEDGEMENT

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AGENDA

Monday 8 October

Brief introduction to CliC and the Global Prediction of the Cryosphere (GPC) Project – John Turner (BAS)

Sea ice – Tom Bracegirdle (BAS) and Thierry Fichefet (Université Catholique de Louvain, Belgium). Followed by discussion.

Ice shelves – Adrian Jenkins (BAS).

Ice loss on the Antarctic Peninsula – David Vaughan (BAS)

Monday PM

14:00 Discussion of cryospheric changes on the Antarctic Peninsula

15:15 Glaciers – presentation by Mattias de Woul (Stockholm University) Followed by discussion

Snow cover and lake and river ice – Terry Prowse (University of Victoria, Canada) – Given by John Turner. Followed by discussion.

17:30 End of session.

Tuesday 9 October

9:30 Permafrost – Charles Harris (Cardiff University). Followed by discussion.

The Antarctic Ice Sheet – presentations by Richard Hindmarsh (BAS) and Tony Payne (Univ of Bristol).

Lunch

14:00 The Greenland Ice Sheet – Jon Bamber (Univ of Bristol). Followed by discussion

15:00 Coffee

Discussion on the evolution of the Greenland and Antarctic ice sheets.

General discussion, agreement on conclusions and further work needed. Outline of report.

17:30 End of meeting