The Climate and Cryosphere

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The term “cryosphere” collectively describes the portions of the Earth's surface where water is in a solid form and describes the elements of the earth system containing water in its frozen state and includes sea ice, lake and river ice, snow cover, solid precipitation, glaciers, ice caps, ice sheets, ice shelves and icebergs, permafrost, and seasonally frozen ground. The cryosphere is an integral part of the global climate system with important linkages and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. Key factors are the high albedo of snow and ice surfaces; the latent heat involved in phase changes of ice/water; and the insulating effect of snow cover on land and of floating ice on freshwater or seawater. The delays in annual energy and water cycles due to seasonal snow and ice cover, the water volume stored in ice sheets and glaciers, and the greenhouse gases locked up in permafrost are also major factors. Through these factors and associated feedback processes, the cryosphere plays a significant role in numerical, hydrological and climate models over a range of scales and it is essential to observe and model these accurately if we are to reduce uncertainties in our predictions and projections of weather, hydrological and climate change.

Elements of the cryosphere may be found at all latitudes and can be found in 95 countries (Fig. 1). It should not be considered as only a component that occurs in polar regions. The cryosphere not only plays a significant role in climate; it is a sensitive and informative indicator of its change. The residence time of water in each of the cryospheric sub-systems varies widely. Snow cover and freshwater ice are essentially seasonal, and most sea ice, except for that in the central Arctic, lasts only a few years if it is not seasonal. In terms of areal extent, Northern Hemisphere winter snow and ice extent comprise the largest area, amounting to an average 23% of total hemispheric surface area in January. However, a given water particle in glaciers, ice sheets, or ground ice may remain frozen for 10 to 100,000 years or longer, and deep ice in parts of East Antarctica may have an age of 1 million years. The majority of the world’s ice volume is in Antarctica, principally in the East Antarctic Ice Sheet. The concept of residence time (flux/storage) is important for the climate system. Water with short residence times participates in the fast-response regime of the climate system (atmosphere, upper-ocean layers, and land surface) that determines the amplitude and regional patterns of climate change. Long-residence-time components (e.g., ice sheets and the deep ocean) act to modulate and introduce delays into the transient response. However, the possibility of abrupt changes in the slow-response components of the climate system cannot be overlooked. The large areal extent and the important climatic roles of snow and ice, related to their unique physical properties, indicate that the ability to observe and model snow- and ice-cover extent, thickness, and radiative and thermal properties is of particular significance for climate research.

Changes in the extent and characteristics of global snow and ice cover will have broad impacts on the climate system, including the major modes of circulation (ENSO, the AO, NAO, AAO and others), temperature and precipitation anomalies, and on the occurrence of extreme events such as storms, floods and droughts. The research of the World Climate Research Program’s Climate and Cryosphere project (CliC) will contribute directly to understanding the processes involved in such climatic variability and change and to the assessment and monitoring of the associated environmental, economic and social impacts (Allison et al., 2001; CliC, 2005). Table 1 illustrates some of the major sectors that will be impacted by variability and change in components of the cryosphere. Improvements in our ability to detect and predict regional as well as global climate and environmental change patterns are likely to modify various socio-economic activities in many countries throughout the world. It is essential we think of these socio-economic impacts as they are real, and the cryosphere has become one of the most cited indicators and impacts of change in the media – shrinking Arctic sea ice cover, ice sheet loss, sea level rise, polar bears threatened, glaciers retreating, lack of snow threatening tourism economy, loss of snow and ice in alpine regions affecting water supply for domestic use, ice road disrupted, etc. It is essential to have the cryosphere adequately treated in the models and by the observation and monitoring systems.

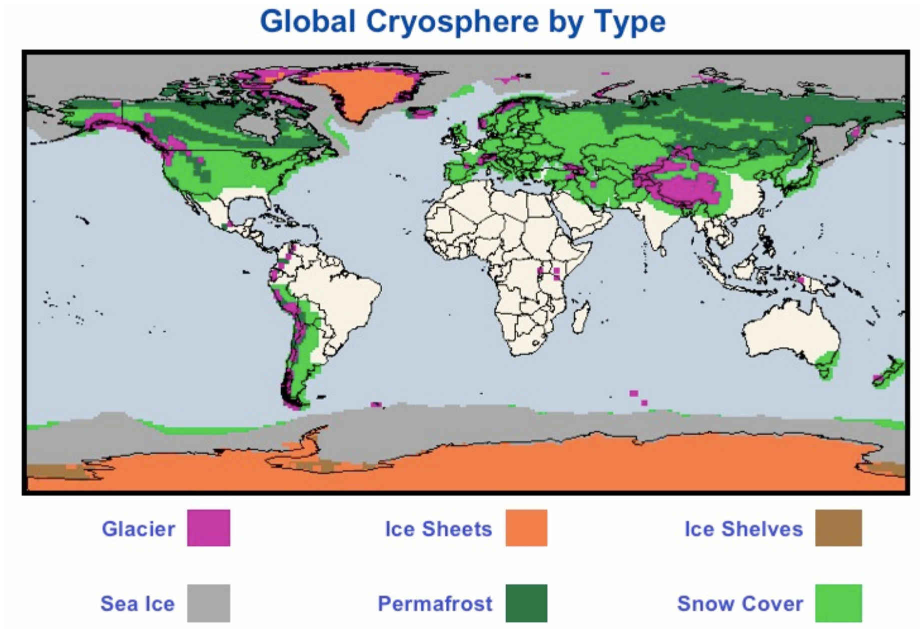

Figure 1 Global distribution of components of the cryosphere (from IGOS-cryosphere theme)

Table 1: Examples of Socio-Economic Sectors affected by Changes in the Cryosphere

A. Direct Effects	
Loss of coastal land and population displacement	Land ice melt contribution to sea level
Transportation:	
• Shipping	-Iceberg hazard; sea-ice extent, thickness
• Barge traffic	- Freshwater ice season
• Tundra roads	- Freshwater ice roads; frozen ground thaw
• Road/rail traffic	- Freeze events; snowfall
Water Resources:	
• Consumption	
• Irrigation	- Snow/glacier melt runoff
• Hydropower	- Snow/glacier melt runoff
• Agriculture	- Snow/Glacier melt contribution; Moisture recharge extremes
Hydrocarbon and mineral resource development:	Icebergs and sea ice; frozen ground duration and thickness
Wildlife population	Snow cover; frozen ground and sea ice
Recreation/safety	Snow cover; avalanches
B. Indirect Effects	
Enhanced greenhouse	Thaw of clathrates
Traditional lifestyles (Arctic, sub-arctic and high mountains)	Changes in sea ice and freshwater ice, snow cover, and frozen ground
Tourism/local economies	Loss of glaciers; shorter snow season
Insurance sector	Changes in risk factor

Gobal cryospheric research is growing as our recognition of its critical role for Earth System science improves. CliC (sponsored by the World Climate Research Program (WCRP) and Scientific Committee on Antarctic Research (SCAR)) is one of the leading organizations looking at the climate and cryosphere in the Earth System context. The principal goal of CliC is:

> *"To assess and quantify the impacts that climatic variability and change have on components of the cryosphere and its overall stability, and the consequences of these impacts for the climate system."*

To achieve this goal, CliC has the supporting objectives to enhance observation and monitoring of the cryosphere, improve understanding of the physical processes through which the cryosphere interacts within the climate system, improve the representation of cryospheric processes in models, and to use cryospheric changes to aid the detection of climate change. The Project is organised into four Project Areas.

- The terrestrial cryosphere and hydrometeorology of cold regions
- Glaciers, ice caps and ice sheets, and their relation to sea level
- The marine cryosphere and its interactions with high latitude oceans and atmosphere
- Links between the cryosphere and global climate

The role of **the terrestrial cryosphere** within the climate system requires improved understanding of the processes and of observational and predictive capabilities applicable over a range of time and space scales. Better understanding of the interactions and feedback's of the land/cryosphere system and their adequate parameterization within climate and hydrological models are still needed. Issues that are being investigated, but still need assessment and improvement include:

- Interactions and feedback of terrestrial snow and ice in the current climate and their variability;
- Representation of snow cover and snow cover climate feedbacks in climate models
- Comparison of observed and simulated 20th C snow cover extent – do models replicate current observed change?
- Do IPCC GCMs provide a reasonable representation of the 20thC snow cover climatology, especially snow water equivalent (SWE), of the northern hemisphere including realistic interannual variability and snow cover temperature sensitivity
- Parameterization of the type of precipitation in land surface schemes, rather than precipitation being diagnosed as rain or snow using a simple threshold air temperature of 0°C
- Using field process studies (e.g. SnowMIP) to compare observed and modelled snow properties (e.g. SWE, depth, density)
- For SWE, how do land surface models compare to each other and to satellite estimates on a global scale?
- Can models adequately represent snow properties for different terrain and land covers over a range of space and time – we need field process studies; ground, airborne, satellite evaluation campaigns; linkage with regional climate, hydrological and NWP models
- Can river and lake ice thickness, extent, freeze-up/break-up and associated trends be adequately observed and also replicated by our models?

- Seasonally frozen ground and permafrost modulate water and energy fluxes and the exchange of carbon, between the land and the atmosphere - how do changes of the seasonal thaw depth alter the land-atmosphere interaction, and what will be the response and feedback of permafrost to changes in the climate system?
- The hydrological cycle of the polar regions is one of the biggest unknowns, but is also one of the most crucial triggers in the global climate system
- The need for high latitude “super sites” or environmental observatories like for WCRP’s CEOP network or the Arctic Observing Network (AON) for process studies, to provide baseline data for satellite product evaluation and validation and model comparison
- Improved knowledge is required of the amount, distribution, and variability of precipitation, especially solid precipitation, in cold climate regions on a regional and global scale, and its response to a changing climate.
- Need for ongoing assessment of regional precipitation biases in reanalyses (ECMWF, NCEP) and satellite/ground observed and derived precipitation products (GPCP combined product, GPCC synoptic products)

These issues require improved understanding of the processes and improved observational and modelling capabilities that describe the terrestrial cryosphere within the entire coupled atmosphere-land-ice-ocean climate system.

The primary issue regarding the role of the cryosphere on sea level is the **past, present and future contribution of land ice to sea level change**. We need to know how much of the sea level rise over the last 100 years can be explained by changes in land ice volume. In order to understand past sea level change and predict future change, it is essential to measure and explain the current state of balance of glaciers, ice caps and ice sheets, and especially to resolve the large present uncertainties in the mass budgets of the Greenland and Antarctic ice sheets. In spite of the fact that there are uncertainties in the current state of balance of ice sheets and ice caps, the sensitivity of the volume of ice stored in glaciers and ice sheets to climate change can and must be studied. The CliC project aims:

- to improve direct estimates of the mass balances of the Antarctic and Greenland ice sheets and their contribution to sea level changes;
- to develop enhanced capability to estimate past and predict future ice sheet change;
- to implement a system for monitoring, assessing and predicting glaciers and ice caps globally to determine their contribution to mean sea level changes.

Contributions to sea level rise from glaciers and ice sheets are being compiled, and one compilation courtesy of K. Steffen (CliC Lead for this topic) is given below:

Ice-Covered Region	Sea Level Input (mm/yr)	
Canadian Ice Caps[1]		+0.065 (1995-2000)
Patagonian Ice Fields[2]	+0.042 (1968/75 - 2000)	+0.105 (1995-2000)
Alaskan Glaciers[3]	+0.14 (mid 50s - mid 90s)	+0.27 (1995-2000)
Greenland[4]	+0.13 (1993/4 -1998/9)	+0.20 (1997-2003)
Pine Island[5,6]	+0.01 (1992-1999)	+0.24 (2002-2003)
Antarctica[7]		0.00 (1993–2003)

References.1: Abdalati et al., JGR, 2004; 2: Rignot et al., Science, 302, 2003; 3: Ahrendt et al., Science, 2002; 4:Krabill et al., Science, 289, 2000 & GRL, 2005; 5: Shepherd et al., GRL, 29, 2002; 6: Thomas et al., Science, 306, 2004; 7: Rignot et al., GRL, 31,2004.

Since 1993 global sea level has risen 37 mm., 60% from expansion as ocean temperatures rise, and 40% from melting glaciers (Steve Nerem/K.Steffen). Although glaciers comprise 0.5% of the total ice volume on the Earth, they contribute 70% of the sea level rise attributed to ice melt. The need to know the extent and volume of our ice masses is obvious. Fortunately there are new data streams and observing systems becoming available which will contribute directly to this question (see Key et al., 2006).

In addition, there is a need to know what is happening on our major ice sheets – Greenland and Antarctica. Surface melt extent is one measure that sheds light on our changing climate and the impact on the cryosphere. Konrad Steffen (University of Colorado) provides the graph and image below (Fig 2 and 3). The impacts are evident. As well there is a need to monitor the edges of the ice sheets, as that is where “the action is”. Airborne laser altimetry data has been used to document the thinning of Greenland, particularly at the outlet glaciers. One notable change is what happened in Jakobshavn, where the glacier accelerated as the calving front retreated, as identified from Landsat and RADARSAT data. The 1997-2003 negative balance was up 33% over mid/late 1990s rate to 80 km3/yr (0.20 mm/yr sea level rise). Antarctica is experiencing similar signs of major change along the edges. A major portion of West Antarctic ice sheet exhibits expected signs of collapsing. Satellites have shown thinning increasing towards the coast (satellite and aircraft altimetry), flow acceleration (InSAR), retreat of the grounding line (Landsat and InSAR), and calving of large icebergs (MODIS). Change can be rapid and dramatic. Satellite systems, completed by airborne and ground surveys where feasible, are essential to monitoring our large, remote ice sheets and shelves.

Modelling of the glaciers and ice sheets/shelves still require considerable work. At the regional scale and in hydrological models, the water stored in glaciers is usually ignored. Regional and global climate models may have a static mask of ice areas. There may be coupling of ice sheet models to GCMs, but considerable work is needed to fully couple the models.

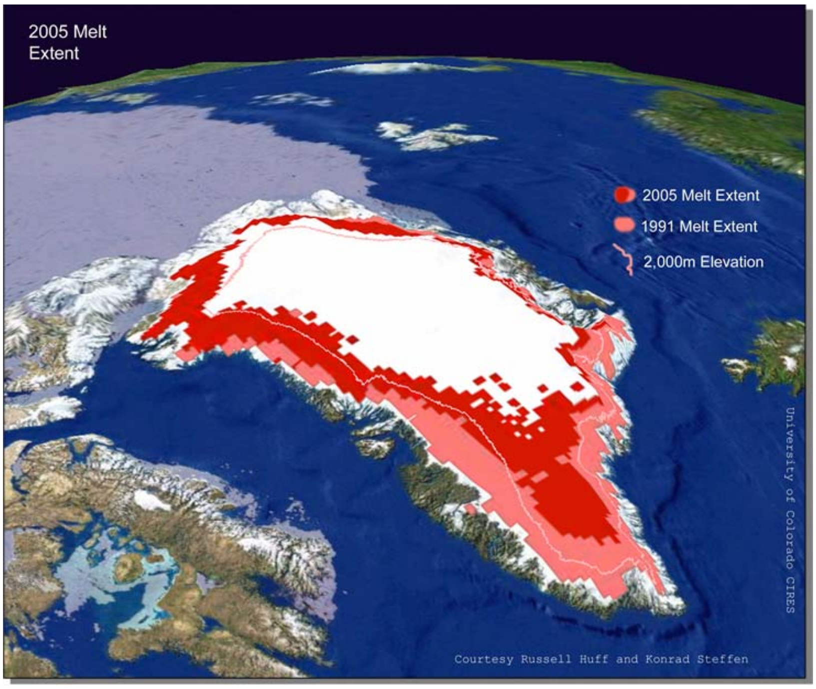

Figure 2 Greenland melt extent compared to 1991.

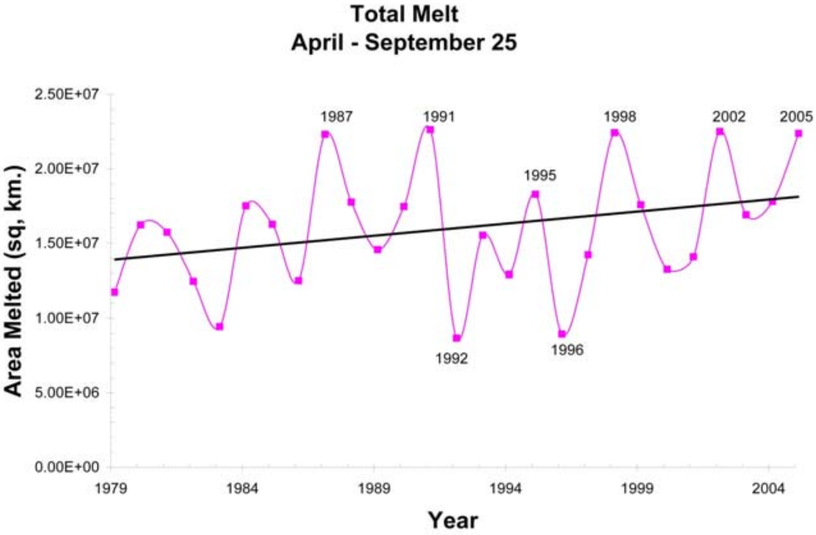

Figure 3 Area where surface melt occurred on Greenland, 1979-2005, derived from passive microwave satellite data.

Over a considerable fraction of the high latitude global ocean surface sea ice forms a boundary between the atmosphere and the ocean, and considerably influences their interaction. The details and consequences of the role of sea ice in the global climate system are still poorly known. Sea Ice, its present state, its response to change, and its feedbacks in the climate system need to be known. For example, what are the present mean states, natural variability and recent trends in sea-ice characteristics in both hemispheres, and what are the physical processes that determine these? Improved knowledge is needed of the broad-scale time-varying distributions of the physical characteristics of sea ice, particularly ice thickness and the overlying snow-cover thickness in both hemispheres, and the dominant processes of ice formation, modification, decay and transport which influence and determine ice thickness, composition and distribution. We do not know how accurate present model predictions are of the sea ice responses to climate change, since the representation of much of the physics is incomplete in many models, and it will be necessary to improve coupled models considerably to provide this predictive capability. How will sea ice respond in future to a changing climate; for example will the summer Arctic Ocean be ice-free in 50 years? How will a changing sea-ice cover affect climate through its interactions with the atmosphere and the ocean? There is also the specific interaction of the ocean with ice shelves and icebergs. How do processes of ice-ocean interaction, including basal melt and marine ice accretion, affect the mass balance and stability of ice shelves? What is the distribution and variability of freshwater input to the oceans from ice shelves, icebergs and ice-sheet runoff, and what role does this have on ocean circulation (for example maintenance of global thermohaline circulation)?

The shrinking Arctic ice cover has drawn continuous attention over the last 5 years as new minimum extent was recorded almost annually. Fig 4 and 5 document this change (courtesy, M.Serreze, NSIDC). The area of Arctic sea ice has been decreasing about 10% per decade since 1980. In addition the ice has been thinning proportionately faster then area. Observational verification of thickness change is a critical need to estimate when the Arctic Ocean may be “ice-free” during the summer. Current models predict the decreasing trend to accelerate in the future. The Antarctic does not experience permanent ice cover as does the Arctic. However, thickness change is as a pressing issue and the importance of a changing and variable snow depth on ice thickness and change is arguably more important in the Antarctic. There remains much to be done using our observations and models to understand and have improved estimates of change in the future in both hemispheres.

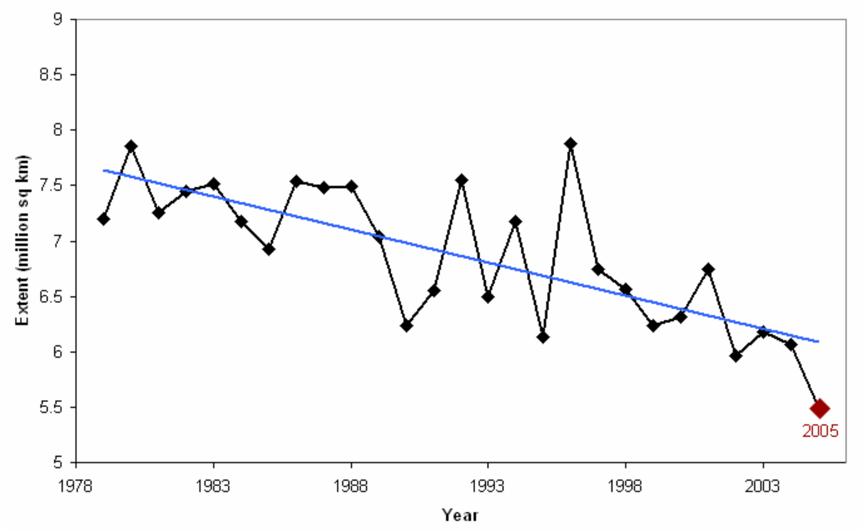

Figure 4 Annual minimum sea ice extent (late September) for the Arctic Ocean

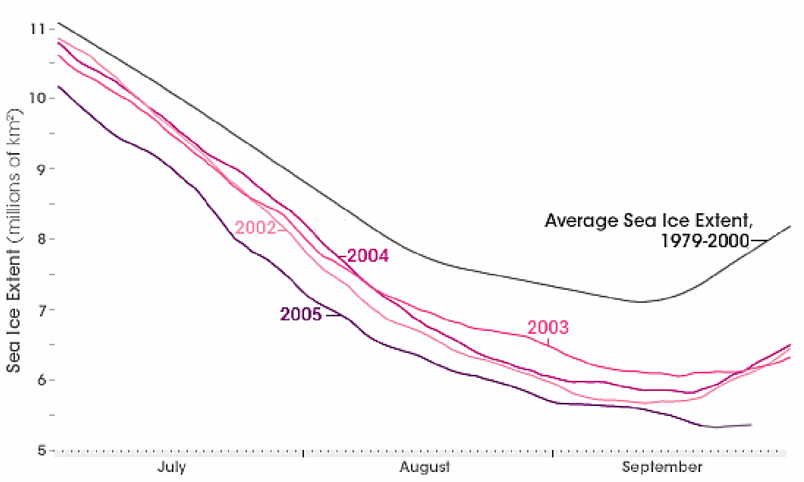

Figure 5 Arctic ocean sea ice extent, July-Sep 2002-2005 compared to 1979-2000

Key issues on the **global scale** are understanding the direct interactions between the cryosphere and atmosphere, correctl y parameterizing the processes involved in models, and providing improved data sets to support these activities. In particular, improved interactive modelling of the atmosphere-cryosphere surface energy budget and surface hydrology, including freshwater runoff, is required. Better formulations and data sets on surface albedo and its dependence on surface type, vegetative cover, underlying surface albedo, and surface temperature are also required, particularly in regions of ice and snow melt. Other important global issues are the impact of cryospheric anomalies on the atmosphere; and the sensitivity to variability and change of atmospheric moisture transport, which controls snow accumulation and thus the mass balance of ice sheets. Another important aspect of the cryosphere for global change concerns the ice-albedo feedback. A key question, given the impact this has on the high sensitivity of the polar regions to climate change, is how the atmosphere responds to and helps determine systematic changes in the ice and snow cover, and how these will influence the response to global warming. The cryosphere also has the potential for influencing the global ocean through changes in sea level; modulation of the thermohaline circulation, which affects meridional heat and freshwater transport; and impacts on efficiency of carbon uptake and exchange. The key-underlying interactive processes and feedback between large-scale ocean circulation and the cryosphere must be better understood. To achieve these advances will require a sustained global climate observing system capable of resolving the cryospheric-global climate linkages; models – GCMs, regional Models, models of intermediate complexity; and, re-analysis fields – atmosphere, ocean, cryosphere.

The cryosphere is not only an integrator of processes within the climate system, but also an indicator of change in that system. Cryospheric signatures of climate change are strong because of the nature of the melt process. Some indicators which are especially useful include:

- sea-ice extent, concentration, and thickness distribution
- change in date of beginning or end of continuous snow cover; change in number of days of continuous snow cover;
- change in date of onset of spring melt; change in frequency of the number of melt events during the winter season;
- change in snow water equivalent at peak accumulation for selected locations; change in date of peak accumulation
- change in spatial distribution of snow cover over a region and the earth
- freeze-up and break-up dates of lake ice
- thickening of the active layer and changes in the distribution of permafrost are important indicators of warming in the Arctic.
- mass balance and extent of glaciers, ice sheet, ice shelves, ice caps

There are now major initiatives being undertaken where the cryosphere and its role in the climate system will be a major part of the Earth System investigations being planned. The International Conference on Arctic Research Planning: Research Planning in the Context of Understanding the Arctic System in a Changing World identified two key research areas that relate to the cryosphere and climate - Terrestrial Cryospheric and Hydrologic Processes and Systems, and Modelling and Predicting Arctic Weather and Climate. These new initiatives identified needs to advance our understanding over the next decade, and follow-on activities are now looking at implementation of these suggestions. Modelling of the Arctic climate system in the context of the global Earth system will be a very important aspect of understanding climate-cryosphere interactions. These will contribute to the International Polar Year 2007-2008, the most important collaborative effort in polar earth system studies to be undertaken over the next few years. An IPY Framework was established and collaborative teams have been formed over the last two years. The cryosphere is an obvious component of this “snapshot” of the polar regions. Up to date information can be found at http://www.ipy.org/. The legacy of IPY needs a strong modelling contribution from hydrological, RCM, GCM and NWP centres, including ECMWF.

Modelling, observation and process studies are needed to advance our understanding of the cryosphere and climate. The cryosphere is a global issue and needs to be treated in the global context. There is much to be done, but opportunities to contribute await us all.

Selected References:

Useful documents on climate and cryosphere recommended for additional reference are:

Allison Ian, Roger G. Barry and Barry E. Goodison (ed.), 2001: Climate and Cryosphere (CliC) Project: Science and Co-Ordination Plan, V.1. WMO/TD No. 1053, WCRP-114, January 2001. (http://wcrp.wmo.int/pdf/WCRP_114.pdf).

CliC, 2005: World Climate Research Programme and Scientific Committee on Antarctic Research Climate and Cryosphere (CliC) Project Implementation Strategy Document. WCRP Informal Report No. 126, WMO/TD-No. 1301 (http://clic.npolar.no/introduction/wcrp_inf_2005_126.pdf).

Key, J. (co-ordinator) et.al. November 2006: A Cryosphere Theme for the IGOS Partnership. Report of the Cryosphere Theme Team, Version 1.0r1. (http://stratus.ssec.wisc.edu/cryos/)

Many relevant and related cryosphere documents may be accessed from the site http://stratus.ssec.wisc.edu/cryos/documents.html. The presentation drew on these documents and recent results and contributions from CliC Science Steering Group members and other cryospheric scientists. This presentation would not have been possible without these contributions.