CLIMATE AND CRYOSPHERE (CliC) PROJECT

SCIENCE AND CO-ORDINATION PLAN

VERSION 1

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The World Climate Programme launched by the World Meteorological Organization (WMO) includes four components:

- The World Climate Data and Monitoring Programme
- The World Climate Applications and Services Programme
- The World Climate Impact Assessment and Response Strategies Programme
- The World Climate Research Programme

The World Climate Research Programme is jointly sponsored by the WMO, the International Council for Science and the Intergovernmental Oceanographic Commission of Unesco.

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1 EXECUTIVE SUMMARY

The Climate and Cryosphere (CliC) Initial Science and Co-ordination Plan, outlines research and co-ordination initiatives required to fully integrate studies of the impact and response of the cryosphere, and the use of cryospheric indicators for climate change detection, within the World Climate Research Programme (WCRP). The report has been prepared by the CliC Task Group, which was established by the Joint Scientific Committee (JSC) for the WCRP in 1998, with input from many other climate scientists. It draws on the deliberations of an expert meeting on Cryospheric Processes and Climate in Cambridge, UK (February 1997) and meetings of the CliC Task Group in Utrecht, the Netherlands (July 1998) and in Grenoble, France (August 1999).

The term "cryosphere" collectively describes the portions of the Earth's surface where water is in a solid form and includes sea-, lake-, and river-ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (including permafrost)[1]. The cryosphere is an integral part of the global climate system with important linkages and feedback generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation. The cryosphere plays a significant role in global climate, in climate model response to global change, and as an indicator of change in the climate system.

However, the impact and response of the entire cryosphere in the global climate system, and the use of cryospheric indicators for climate change detection, have not been fully covered within WCRP. There are notable gaps in present studies of cryospheric elements and in the accurate and appropriate treatment of cryospheric processes in climate models.

In this report the cryosphere and its most important interactions are treated under the following headings:

- Interactions between the atmosphere, snow/ice and land.
- Interactions between land ice and sea level.
- Interactions between sea ice, oceans, and the atmosphere.
- Cryospheric interactions with the atmosphere and the ocean on a global scale.

The cryosphere is also considered as an indicator of climate variability and change.

Atmosphere-snow/ice-land interactions are concerned with the role of the terrestrial cryosphere[2] within the climate system and with 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 of the land/cryosphere system and their adequate parameterization within climate and hydrological models are still needed. Specific issues include the interactions and feedback of terrestrial snow and ice in the current climate and their variability; in land surface processes; and in the hydrological cycle. Improved knowledge is required of the amount, distribution, and variability of solid precipitation on a regional and global scale, and its response to a changing climate. 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? These issues require improved understanding of the processes and improved observational and modelling capabilities that describe the terrestrial cryosphere in 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

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[1] The discipline of glaciology encompasses the scientific study of snow, ice and glaciers.

[2] Terrestrial cryosphere is defined as snow, lake- and river-ice, glaciers and frozen ground/permafrost.

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 the current state of balance of ice sheets and ice caps is not well known, the sensitivity of the volume of ice stored in glaciers and ice sheets to climate change can and must be studied.

Over a considerable fraction of the high-latitude global ocean, 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. 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 of the sea ice responses to climate change are, 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.

Key issues on the global scale are understanding the direct interactions between the cryosphere and atmosphere, correctly 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 fresh-water 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 fresh-water 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.

Because of its response to regional and global variations in the climate system, the cryosphere is not only an integrator of climate processes, but also a strong indicator of change. Cryospheric change indicators are particularly valuable in regions where conventional observations are of short duration or completely lacking. Existing time series of the extent of sea ice, snow cover, and permafrost, and of glacier geometry and mass balance, should continue to be monitored for change. Records of past climatic variability at the multi-decadal and longer time-scales are available from historic and geomorphologic records of glacier fluctuations, borehole temperatures and ice cores. These data complement the existing instrumental records of temperature and precipitation and can improve both temporal and spatial coverage. The longer perspective can indicate how significant recent changes are in relation to natural variability.

The scientific strategy for a CliC project is similar in each of the areas of interaction: a combination of measurement, observation, monitoring and analysis, field process studies and modelling at a range of time and space scales. A CliC modelling strategy must address improved parameterization in models of the direct interactions between all components of the cryosphere, the atmosphere, and the ocean. It will need to do this at a variety of scales from the regional to global; and with a hierarchy of models ranging from those of individual processes to fully coupled climate models. It will also be essential to provide the improved data sets needed for validation of models and parameterization schemes.

A broad observational framework for CliC is provided by the World Meteorological Organization (WMO) meteorological and hydrological networks; the International Arctic Buoy Programme (IABP); elements of the Global Climate Observing System (GCOS), the Global Terrestrial Observing System (GTOS) and the Global Ocean Observing System (GOOS) relating to the cryosphere; and continuing WCRP projects for Antarctic buoys (International Programme for Antarctic Buoys (IPAB)) and for sea-ice thickness in the Arctic and in the Antarctic (Arctic Sea Ice Thickness Project (ASITP) and Antarctic Sea Ice Thickness Project (AnSITP)). Satellite remote sensing methods will be particularly important. They provide invaluable and often unique observational data for a range of climate and cryosphere studies, including: process-oriented studies; analyses of large-, regional-, and even global-scale spatio-temporal variability; monitoring and detection of climate change; and validation and/or assimilation data for numerical models. Numerous satellite-derived cryospheric data sets or products have already been developed, and more are under development or planned using data from present and near-future sensor systems. Several future techniques in remote sensing systems, data sets and methodologies for cryospheric studies may be realized within the coming decade. Potentially valuable new systems include the European Space Agency (ESA) CryoSat, a goal of which is to measure fluctuations in sea and land ice masses (thickness) at large space and time scales. Another is the (US) National Aeronautics and Space Administration's (NASA) planned Geoscience Laser Altimeter (GLAS), which will provide valuable data to map sea and land ice elevations, and which may directly address the problem of the mass balance of the large ice sheets. These will complement the current and future systems including Special Sensor Microwave Imager (SSM/I), Advanced Microwave Scanning Radiometer (AMSR) and Synthetic Aperture Radar (SAR), which provide valuable information on snow and ice resources.

The development of a plan for CliC data and their management will build directly on the experience of the Arctic Climate System Study (ACSYS) Data Management and Information Panel and the development of the Arctic Precipitation Data Archive as well as other WCRP projects. CliC data requirements will necessitate the continuation of many ACSYS data collection and archiving activities and their expansion to encompass Antarctic and other cryospheric data needs. Complementary national and international programmes will be particularly important.

The cryosphere is of interest to many diverse scientific organisations. CliC will develop an implementation plan that is complementary to other initiatives and draws on expertise of other organisations. There are a variety of gaps in ongoing programmes and a need for co-ordination between the proposed CliC and the other activities to achieve a global perspective of cryosphere research. In particular other WCRP and WMO programme components, International Geosphere-Biosphere Programme (IGBP), Scientific Committee on Antarctic Research (SCAR), Scientific Committee on Oceanic Research (SCOR) and International Arctic Science Committee (IASC) projects need to be considered. Many of the broader global issues in CliC are relevant to wider aspects of the Climate Variability and Predictability (CLIVAR) and the Global Energy and Water Cycle Experiment (GEWEX) projects, and it is critical that there are strong links between the projects and that science initiatives within CliC are co-ordinated with, and complementary to, those initiated or planned in CLIVAR and GEWEX.

The WCRP IPAB and An SITP are at present supervised by the ACSYS Scientific Steering Group. These projects will become part of CliC. Similarly, ACSYS/CliC is well represented in relevant WMO activities; for example, the Global Digital Sea-ice Data Bank (GDSIDB) within the joint WMO/IOC (International Oceanographic Commission) Technical Commission for Oceanography and Marine Meteorology (JCOMM), and the Solid Precipitation Measurement Intercomparison within the Commission for Instruments and Methods of Observation (CIMO). SCAR and SCOR have a number of important Antarctic programmes and projects, and there are several relevant scientific unions and commissions within the International Council for Science (ICSU), especially the International Permafrost Association (IPA) and the International Commission on Snow and Ice (ICSI). Options for establishing links with these programmes include joint participation on steering committees and science conferences; establishing links between project offices; co-sponsorship of projects with joint funding support; and full integration of international co-ordinated activities as sub-projects of WCRP/CliC. The particular mode(s) that CliC should adopt has not been determined, but options will be considered by the joint ACSYS/CliC SSG at its first meeting.

2 BACKGROUND

The main goal of the World Climate Research Programme (WCRP) is to understand and predict -- to the extent possible -- climate variability and change, including human influences. In a stepwise approach, it has first tried to understand seasonal to inter-annual climate variability by mounting projects like the *Tropical Ocean/Global Atmosphere (TOGA)* project. This project brought the breakthrough to physically based seasonal climate predictions, especially for areas affected by the El Niño phenomenon. Within the *Global Energy and Water Cycle Experiment (GEWEX)*, our understanding of cloud/radiation interaction and land-surface processes was greatly enhanced. These are becoming more and more important for both weather forecasting and climate variability predictions. Progress in understanding decadal timescale climate variability and climate change projections, however, also needs observations of global ocean structure and circulation and tested ocean models. Therefore, WCRP launched the *World Ocean Circulation Experiment (WOCE)*, which has now entered into an analysis, interpretation, modelling and synthesis phase. The importance of the positive snow/ice albedo feedback which amplifies high-latitude sensitivity to external forcing by the sun or an enhanced greenhouse effect, together with the opportunities for internationally co-ordinated Arctic research, stimulated the *Arctic Climate System Study (ACSYS).* This project is concentrating first on establishing data sets on the Arctic Ocean circulation and sea-ice cover, the Arctic atmosphere and land surface hydrology of the Arctic Basin, and on improved sea-ice models for climate research.

However, the impact and response of the entire cryosphere and the associated interactions and feedback of its components within the global climate system, and the use of the cryosphere as an indicator of climate change, have not been fully covered within WCRP. Fully coupled atmosphere/ocean/land models for decadal timescale simulations and projections of climate change scenarios, as envisaged in the WCRP *Climate Variability and Predictability Study (CLIVAR)* need this input. Therefore, at the JSC-XVII in Toulouse, France, March 1996 the Joint Scientific Committee (JSC) for WCRP charged ACSYS and CLIVAR with enhancing connections with other cryospheric activities outside WCRP, especially with SCAR-GLOCHANT, IASC-MAGICS and SCOR-iAnZone. In addition, in response to several external requests, the WCRP organized an expert meeting on Cryospheric Processes and Climate in Cambridge, UK, 3-5 February 1997 (WCRP, 1998b).

WCRP was also asked by experts representing climate-related activities in other international programmes, groups, and activities to initiate a broader cryospheric project without disrupting successful on-going studies (e.g., ACSYS). Therefore, at JSC-XVIII in March 1997 (Toronto, Canada) the JSC for WCRP invited the Conference on *WCRP: Achievements, Benefits and Challenges* (Geneva, August 1997) to consider the role of the cryosphere in climate, and to note the weaknesses and gaps in studies of cold climate processes. JSC-XVIII also instructed the 2nd ACSYS Science Conference on *Polar Processes and Global Climate* (Orcas Island, WA, USA, November 1997) to provide input and suggestions from the broader polar/cryosphere research community. The ACSYS Scientific Steering Group was also asked to prepare a comprehensive statement on the overall status of studies of cold climate processes for review by the JSC in March 1998.

The following were presented to JSC-XIX (Cape Town, South Africa, March 1998):

1) The WCRP 1997 Conference Statement calling for an enlarged WCRP activity with respect to cryosphere and climate.

2) The ACSYS Conference Statement voicing the desire of the broad scientific community for a comprehensive co-ordinated cryosphere and climate activity within WCRP.
3) The proposal from the 6th session of the ACSYS Scientific Steering Group (Seattle, WA, USA, November 1997).

A summary report on the first session of the CliC Task Group was published as *WCRP Informal Report No.4/1999 (WCRP, 1999a)*. The first draft of the *CliC Science and Co-ordination Plan* (SCP) developed by the Utrecht meeting was reviewed by the seventh session of the ACSYS Scientific Steering Group (Tokyo, Japan, November 1998). The revised draft was presented to JSC-XX (Kiel, Germany, March 1999) and the CliC Task Group was asked to continue its work to map out a full CliC science strategy and define other cryosphere-related scientific and observational programmes. At the JSC-XXI meeting in Tokyo, March 2000, the establishment of the CliC Project within the WCRP and the formation of a combined ACSYS/CliC SSG were approved. Co-ordination of CliC with other relevant projects/programmes is an ongoing part of the project and is essential for success.

The initial science and co-ordination plan for the WCRP Cryosphere and Climate (CliC) Project follows. The plan is seen as a "living document" that will continue to develop as our knowledge of processes and interactions of the cryosphere in the climate system increases. It will evolve as new data from satellite and *in situ* sources become available, and as our modelling of the hydrological and climate systems over a range of scales improves.

3 THE CRYOSPHERE AND CLIMATE: AN OVERVIEW

3.1 DEFINITION OF THE CRYOSPHERE AND ITS COMPONENTS

There have been several assessments of the role of the cryosphere in climate. The following draws on Barry (1985) and Goodison et al., (1998b, 1999) in particular.

The term "cryosphere" traces its origins to the Greek word *kryos* for frost or icy cold. It collectively describes the portions of the Earth's surface where water is in a solid form and includes sea-, lake-, and river-ice, snow cover, glaciers, ice caps and ice sheets, and frozen ground (including permafrost).

3.1.1 Snow Cover

Snow cover has the largest areal extent of any component of the cryosphere, with a mean annual areal extent of approximately 26 million km^2 (Table 1). Most of the Earth's snow-covered area is located in the Northern Hemisphere, and temporal variability is dominated by the seasonal cycle; Northern Hemisphere mean snow-cover extent ranges from 46.5 million km^2 in January to 3.8 million km^2 in August (Robinson et al., 1993).

3.1.2 Sea Ice

Sea ice, formed by freezing of seawater, covers much of the polar oceans. It exhibits considerable seasonal, regional, and inter-annual variability in both hemispheres. Seasonally, sea-ice extent in the Southern Hemisphere varies by a factor of 5, from a minimum of 3-4 million km^2 in February to a maximum of 17-20 million km^2 in September (Gloersen et al., 1993). The seasonal variation is much less in the Northern Hemisphere where the confined nature and high latitudes of the Arctic Ocean result in a much larger perennial ice cover, and the surrounding land limits the equator-ward extent of wintertime ice. Northern Hemisphere ice extent varies by only a factor of 2, from a minimum of 7-9 million km^2 in September to a maximum of 14-16 million km^2 in March (Gloersen et al., 1993). Table 1 shows the actual ice areas, excluding open water within the ice margins.

Table 1

Areal and Volumetric Extent of Major Components of the Cryosphere

Component	Area (10^6 km^2)	Ice Volume (10^6 km^3)	Sea Level Equivalent (m) a)
LAND SNOW COVER b)			
Northern Hemisphere Late January	46.5	0.002	
Late August	3.9		
Southern Hemisphere Late July	0.85		
Early May	0.07		
SEA ICE			
Northern Hemisphere Late March	14.0 c)	0.05	
Early September	6.0 c)	0.02	
Southern Hemisphere Late September	15.0 d)	0.02	
Late February	2.0 d)	0.002	
PERMAFROST (underlying the exposed land surface, excluding Antarctica and S. Hemisphere high mountains)			
Continuous e)	10.69	0.0097-0.0250	0.024-0.063
Discontinuous and Sporadic	12.10	0.0017-0.0115	0.004-0.028
CONTINENTAL ICE AND ICE SHELVES			
East Antarctica f)	10.1	22.7	56.8
West Antarctica and Antarctic Peninsula f)	2.3	3.0	7.5
Greenland g)	1.8	2.6	6.6
Small Ice Caps and Mountain Glaciers h)	0.68	0.18	0.5
Ice Shelves f)	1.5	0.66	—

a) Sea level equivalent does not equate directly with potential sea-level rise, as a correction is required for the volume of the Antarctic and Greenland ice sheets that are presently below sea level. 400,000 km^3 of ice is equivalent to 1 m of global sea level.

b) Snow cover includes that on land ice, but excludes snow-covered sea ice (Robinson et al., 1995).

c) Actual ice areas, excluding open water. Ice extent ranges between approximately 7.0 and 15.4 x 10^6 km^2 (Parkinson et al., 1999).

d) Actual ice area excluding open water (Gloersen et al., 1993). Ice extent ranges between approximately 3.8 and 18.8 x 10^6 km^2. Southern Hemisphere sea ice is mostly seasonal and generally much thinner than Arctic sea ice.

e) Data calculated using the Digital Circum-Arctic Map of Permafrost and Ground-Ice Conditions (Brown et al., 1998) and the GLOBE-1km Elevation Data Set (Zhang et al., 1999).

f) Ice sheet data include only grounded ice. Floating ice shelves, which do not affect sea level, are considered separately (Huybrechts et al., 2000; Drewry et al., 1982; Warrick et al., 1996).

g) Williams and Ferrigno (in press)

h) Meier and Bahr (1996).

3.1.3 Fresh-water Ice

Ice forms on rivers and lakes in response to seasonal cooling. The freeze-up/break-up processes respond to large-scale and local weather factors, producing considerable inter-annual variability in the dates of appearance and disappearance of the ice. Long series of lake-ice observations can serve as a climatic indicator; and freeze-up and break-up trends may provide a convenient integrated and seasonally specific index of climatic perturbations. The total area of ice-covered waters is not accurately known and hence this has not been included in Table 1.

3.1.4 Frozen Ground and Permafrost

Seasonally frozen ground, like snow, covers a large expanse of the globe. Its depth and distribution varies as a function of air temperature, snow depth and vegetation cover, ground moisture, and aspect. Hence it can exhibit high temporal and spatial variability. The area of seasonally frozen ground is not mapped annually.

Permafrost (perennially frozen ground) may occur where the Mean Annual Air Temperature (MAAT) is less than -1°C and is generally continuous where MAAT is less than -7°C. Although not accurately known, it is estimated that permafrost underlies about 24.5% of exposed Northern Hemisphere land areas (Table 1), with maximum areal extent between about 60º and 68ºN. Thickness exceeds 600 m along the Arctic coast of northeastern Siberia and Alaska, but permafrost thins and becomes horizontally discontinuous towards the margins. Only about 2 million km^2 consists of actual ground ice ("ice-rich"). The remainder (dry permafrost) is simply soil or rock at subfreezing temperatures.

3.1.5 Land Ice

Ice sheets are the greatest potential source of fresh water, holding approximately 77% of the global total. Fresh water in ice bodies corresponds to 71 m of world sea-level equivalent, with Antarctica accounting for 90% of this, Greenland almost 10%, and other ice bodies and glaciers less than 0.5% (Table 1).

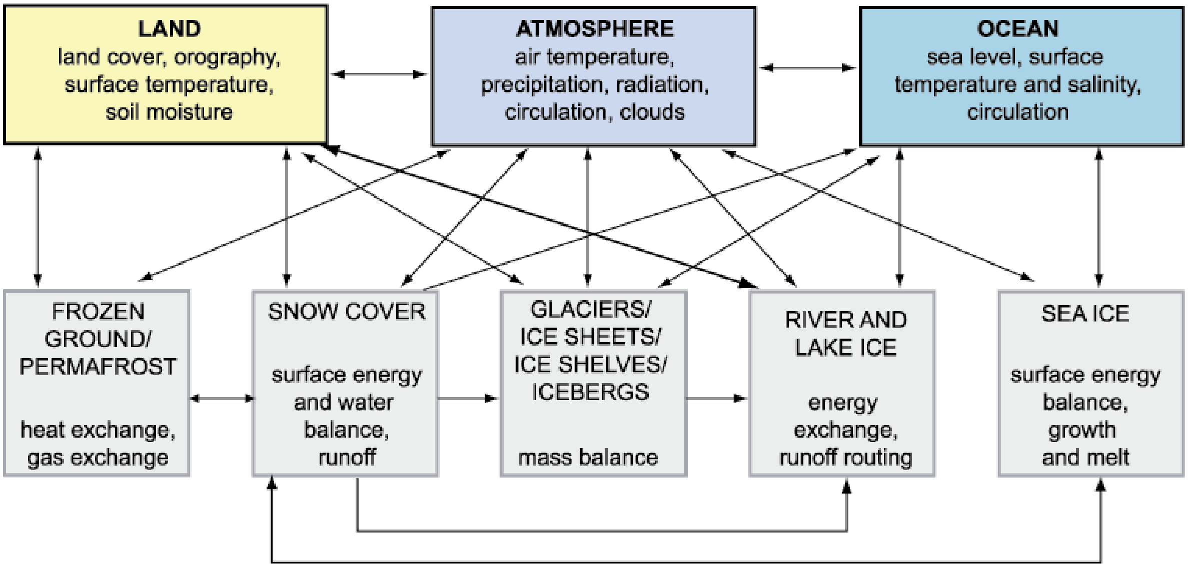
Much of the Antarctic ice sheet comprises a 3000-4000 m high ice plateau, while Greenland exceeds 3000 m in the centre. Both have significant effects on the atmospheric circulation and movement of cyclonic systems and on the global energy balance. Large areas of the West Antarctic ice sheet are grounded below sea level; these have an estimated ice volume of 1.9×10^6 km^3 (Warrick et al., 1996) that does not contribute to a potential sea level rise. Although most of the East Antarctic ice sheet rests on bedrock, in some areas the basal ice is at pressure melting point, and there are numerous sub-glacial lakes, including a large one about 3900 m below Vostok station. There are large floating ice shelves in the Ross and Weddell Sea embayments and smaller ones in other sectors, including the Antarctic Peninsula. Ice shelves and outlet glaciers calve continuously, releasing icebergs into the sea, which then drift while melting. Iceberg production from Greenland is estimated to be $235 \pm 33 \times 10^{12}$ kg yr^{-1}, whereas that from Antarctica amounts to $2072 \pm 304 \times 10^{12}$ kg yr^{-1} (Church et al., 2001).

3.2 THE ROLE OF THE CRYOSPHERE IN CLIMATE

The cryosphere is an integral part of the global climate system with important links and feedbacks generated through its influence on surface energy and moisture fluxes, clouds, precipitation, hydrology, and atmospheric and oceanic circulation (*Figure 3.1*). Major 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 fresh water 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 global climate and in climate model response to global change.

The residence time of water in each of the cryospheric sub-systems varies widely. Snow cover and fresh-water ice are essentially seasonal, and most sea ice, except for that in the central Arctic, lasts only a few years at most. A given water molecule in glaciers, ice sheets, or ground ice, however, may remain frozen for 10 to 100,000 years or longer, and deep ice in parts of East Antarctica may have an age approaching 1 million years. 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 majority of the world's ice volume is in Antarctica (Table 1), principally in the East Antarctic Ice Sheet. In terms of areal extent, however, Northern Hemisphere winter snow and ice extent comprise the largest area, amounting to an average 23% of total hemispheric surface area in January. 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.

Crysophere-Climate Interactions



Lists in upper boxes indicate important state variables.
Lists in lower boxes indicate important processes involved in interactions.
Arrows indicate **direct** interactions.

Figure 3.1 Schematic of cryosphere-climate interactions. After G. Flato (AES, Climate Research Branch).

The processes operating in the coupled cryosphere-climate system involve three time scales - intraseasonal-interannual, decadal-centennial, and millenial or longer. The longest time scale is addressed through the IGBP PAGES programme, although abrupt climate shifts evidenced in ice core and ocean sediment records (Heinrich events, involving extensive deposition of ice-rafted detritus in the North Atlantic) are also highly relevant to CliC. The other two time scales are commensurate with WCRP interests, as manifest in ACSYS, GEWEX and CLIVAR. In the space domain, cryospheric processes and phenomena need to be investigated over a wide range of scales from metres to thousands of kilometres.

3.3 ECONOMIC AND SOCIAL IMPACT OF CHANGES IN THE CRYOSPHERE

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. CliC research 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.

Table 2 illustrates some of the major sectors that may be impacted by variability and change in components of the cryosphere. Socio-economic impacts may be direct or indirect and they have both beneficial and detrimental consequences. Improvements in our ability to detect and predict regional climate and environmental change patterns are likely to modify various socio-economic activities in many countries throughout the world.

Table 2

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

SOCIO-ECONOMIC COMPONENT	CRYOSPHERE FACTOR
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	• Fresh-water ice season
• Tundra roads	• Fresh-water ice roads; frozen ground thaw
• Road/rail traffic	• Freeze events; snowfall
Water Resources:	
• Consumption	
• Irrigation	• Snow/glacier melt runoff
• Hydropower	
• Agriculture	• 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 fresh-water ice, snow cover, and frozen ground
Tourism/local economies:	• Loss of glaciers; shorter snow season
Insurance sector:	• Changes in risk factor

The rate of sea level rise is a major concern for heavily populated coastal areas of the world and is even more critical for a number of small island nations. Improved assessment of the contribution to sea level change of land ice melt and calving, as well as study of the effects on ocean warming resulting from deep water formation processes will be major components of CliC research.

The transportation sector will be substantially affected by changes in snow cover, fresh-water and sea-ice extent and thickness. Persistent reductions in Arctic or Antarctic sea-ice cover would allow marine operations through normally ice covered regions, such as the Northwest Passage, a benefit to marine transportation, but a potential risk for marine ecosystems. Snowfall frequency and magnitude directly affect road and rail traffic, and aircraft operations, with fewer and smaller events being considered an economic benefit. River and lake-ice provide winter roads for access to remote areas. Improved information and understanding of their spatial and temporal characteristics is required. Fresh-water ice can have a significant influence on aquatic and riparian ecosystems, geochemical processes, and sediment transport (Ferrick and Prowse, 2000). Long-term trends and regional variations in extreme snow events and sea-ice conditions need to be better understood. Such changes would also negatively impact native transportation and life style and adversely affect wildlife on land and sea, such as polar bear populations. Such issues form part of the IASC-BASIS and BESIS projects.

Changes in the amount and timing of snow-melt runoff from mountain snow packs and glaciers will have significant impacts on water resources in many dry climates such as the western United States, north-west China, central Asia and Andean countries. This will also impact hydropower operations in the Alps, Scandinavia, Canada and New Zealand, for example. Changes in the amount and distribution of continental snow cover will directly impact the timing of spring runoff and the characteristics of the annual runoff hydrograph, affecting the nature and occurrence of floods and droughts, irrigation needs for agriculture, community water supply, wetland recharge, and moisture supply for spring planting. In addition to the socio-economic impact, there will be direct effects on the functioning of the ecosystems in these regions.

Building design already accounts for the challenges of building in areas of seasonally frozen ground, resulting in higher building costs. Permafrost regions add another dimension as thawing of permafrost has important direct effects on structures in arctic and sub-arctic areas, including buildings, pipelines, roads and railways. Increased risk of such impacts may lead to changes in engineering design codes, building inspections, etc. Improved observation and prediction of sea-ice variability should lead to increased operational ability to exploit potential hydrocarbon resources in the arctic shelf seas. There may also be feedback on greenhouse warming through the release of methane from clathrates as frozen ground thaws.

There is evidence that inter-annual variability and trends in atmospheric circulation patterns and ocean temperatures influence the North Atlantic and its fisheries. Regional climate change would certainly affect the northern marine environment, impacting fisheries and marine mammals.

Other economic sectors such as recreation and tourism are significantly affected by short term and long term changes in snow and ice conditions (e.g., skiing, snowmobiling, ice fishing) and the scenic contribution of glaciers. The insurance industry is also greatly affected by changing risks associated with a wide range of cryospheric phenomena.

It is inappropriate to develop an exhaustive list of such potential impacts here. Nevertheless, CliC will contribute to assessments of the socio-economic and environmental impacts of changes in the cryosphere by providing scientific input to national and international policy making relating to global change issues.

4 GOALS AND KEY SCIENTIFIC QUESTIONS FOR CliC

Four overarching goals that address major concerns for the WCRP can be identified. These are:

1. Improve understanding of the physical processes and feedbacks through which the cryosphere interacts within the climate system.

2. Improve the representation of cryospheric processes in models to reduce uncertainties in simulations of climate and predictions of climate change.
3. Assess and quantify the impacts of past and future climatic variability and change on components of the cryosphere and their consequences, particularly for global energy and water budgets, frozen ground conditions, sea level change, and the maintenance of polar sea-ice covers.
4. Enhance the observation and monitoring of the cryosphere in support of process studies, model evaluation, and change detection.

Specific questions that help define the primary tasks of CliC are:

(i) How stable is the global cryosphere?
  - How well do we understand and model the key processes involved in each cryospheric component of the climate system?
  - How do we best determine the rates of change in the cryospheric components?

(ii) What is the contribution of glaciers, ice caps and ice sheets to changes in global sea level on decadal-to-century time scales?
  - How can we reduce the current uncertainties in these estimates?

(iii) What changes in frozen ground regimes can be anticipated on decadal-to-century time scales that would have major socio-economic consequences, either directly or through feedback on the climate system?

(iv) What will be the annual magnitudes, rates of change, and patterns of seasonal redistribution in water supplies from snow- and ice-fed rivers under climate changes?

(v) What will be the nature of changes in sea-ice mass balance in both polar regions in response to climate change?

(vi) What is the likelihood of abrupt climate changes resulting from regime changes in ice shelf - ocean and sea ice - ocean interactions that impact the ocean thermohaline circulation?

(vii) How do we monitor cryospheric components as indicators of change in the climate system?

In this report we begin by discussing the links between the different cryospheric elements and other components of the physical climate system. For convenience, we treat the cryosphere and the most important interactions under the following headings:

- Interactions between the atmosphere, snow and land.
- Interactions between land ice and sea level.
- Interactions between sea ice, oceans, and the atmosphere.

Then the role of the cryosphere in the global climate system is considered through its interactions with the atmosphere and the ocean on a global scale. A number of key questions and issues are discussed under each of these categories, followed by appropriate strategies to address them.

As part of the overall implementation of the CliC science plan, a comprehensive strategy will need to be developed to address the science questions and associated issues identified above. Many of the strategies will in fact be common or could best be co-ordinated with those of the other components of CliC. The Task Group identified and documented some of the key needs related to observation, process studies and modelling at a range of scales at the Cambridge meeting of cryospheric experts (WCRP, 1998b) and at the Utrecht team meeting (WCRP, 1999a).

5 INTERACTIONS BETWEEN THE ATMOSPHERE, SNOW AND LAND

5.1 INTRODUCTION AND KEY SCIENTIFIC QUESTIONS

Atmosphere-snow-land interactions are concerned with the role of the terrestrial cryosphere (snow, lake and river ice, glaciers and frozen ground/permafrost) within the climate system. The terrestrial components play an important role in the energy and water cycles, on a range of time scales (daily to seasonal, inter-annual, decadal and century), through their influence on surface energy and water exchange processes. These processes include radiative balance (e.g., snow and ice albedo feedback), modulation of the heat and moisture fluxes to land and ocean, the role of ice and snow as a storage component in the water cycle, and the influence on runoff (particularly in regions of frozen ground and permafrost). The greenhouse gases stored in the permafrost also influence the carbon cycle.

An accurate representation of the terrestrial cryosphere, the associated interactions and feedback within the climate system over a wide range of time and space scales, is critical to achieve credible prediction of the future state of the cryosphere and the associated variability and change.

Scientific issues to be addressed include:

- Interactions and feedbacks of terrestrial snow and ice in land surface processes and the hydrological cycle.
- Distribution, and variability of precipitation, especially solid precipitation, on a regional and global scale, and its response in a changing climate.
- Effect of climate induced changes in seasonal snow cover, frozen ground/permafrost, and floating ice on land surface processes and the timing and amount of stream-flow.

Current fully coupled global-climate models do not incorporate many of the important cryospheric processes of terrestrial areas, or they display important limitations in their ability to simulate key characteristics of cold region climates (temperature, precipitation, blowing snow, sublimation, snow melt and runoff). Climate models consistently simulate enhanced climate warming at higher latitudes over continental areas. Given the high sensitivity of much of the cryosphere to temperature and precipitation changes, it is important to assess, and ultimately ensure, that model parameterizations of important cryospheric processes affecting the energy and water cycle are properly incorporated and validated in global and regional climate and hydrological models. Improved simulation of the exchanges of fresh water between the atmosphere, hydrosphere and cryosphere, their validation through field process experiments, and an understanding of the role of such exchanges in climate variability and change require further co-ordinated study (e.g., with GEWEX and CLIVAR) on regional to global scales. Also needed is an improved ability to monitor and understand variability and change in important components of the cryosphere on land and fresh-water surfaces. A number of questions, issues and gaps must be considered to best address the potential influences, feedbacks, and ultimately the consequences, of these cryospheric processes and their associated impacts on natural ecosystems, or on socio-economic development.

5.1.1 Climate System Interactions with the Terrestrial Cryosphere

- What are the interactions and feedbacks between the terrestrial cryosphere, atmosphere and land surface and current climate, its variability and change?

Snow and permafrost/frozen ground have the largest areal extent of the cryospheric components (Table 1); glaciers and lake and river ice are individually small in extent, but collectively they play a role in the regional and even the global climate system. They play important roles in the global and regional energy, water and carbon cycles through:

- their influence on surface exchange processes, including snow-vegetation-albedo feedback,
- the insulating effect of snow on land and ice,
- the storage of precipitation as snow and ice and the subsequent release as melt-water runoff,
- their influence on runoff, both its amount and timing, particularly in regions of frozen ground and permafrost, and
- the release of greenhouse gases stored in permafrost.

Accurate representations of the seasonal cycle of the cryosphere on land and of the associated cryosphere-climate interactions are critical. As for other cryospheric components, observation and measurement, process studies, monitoring and modelling of the terrestrial cryosphere are all essential in furthering this knowledge and understanding.

Snow cover has a number of important physical properties, which exert an influence on climate, notably, its high albedo, low heat conductivity, large latent heat of fusion, and low surface roughness. *Figure 5.1* shows the large area of influence that snow cover has on the Northern Hemisphere atmosphere and land systems. The combination of high albedo (as high as 0.8 - 0.9 for dry snow) and low thermal conductivity promote low surface temperatures and low-level temperature inversions. The low thermal conductivity of snow allows it to insulate the surface

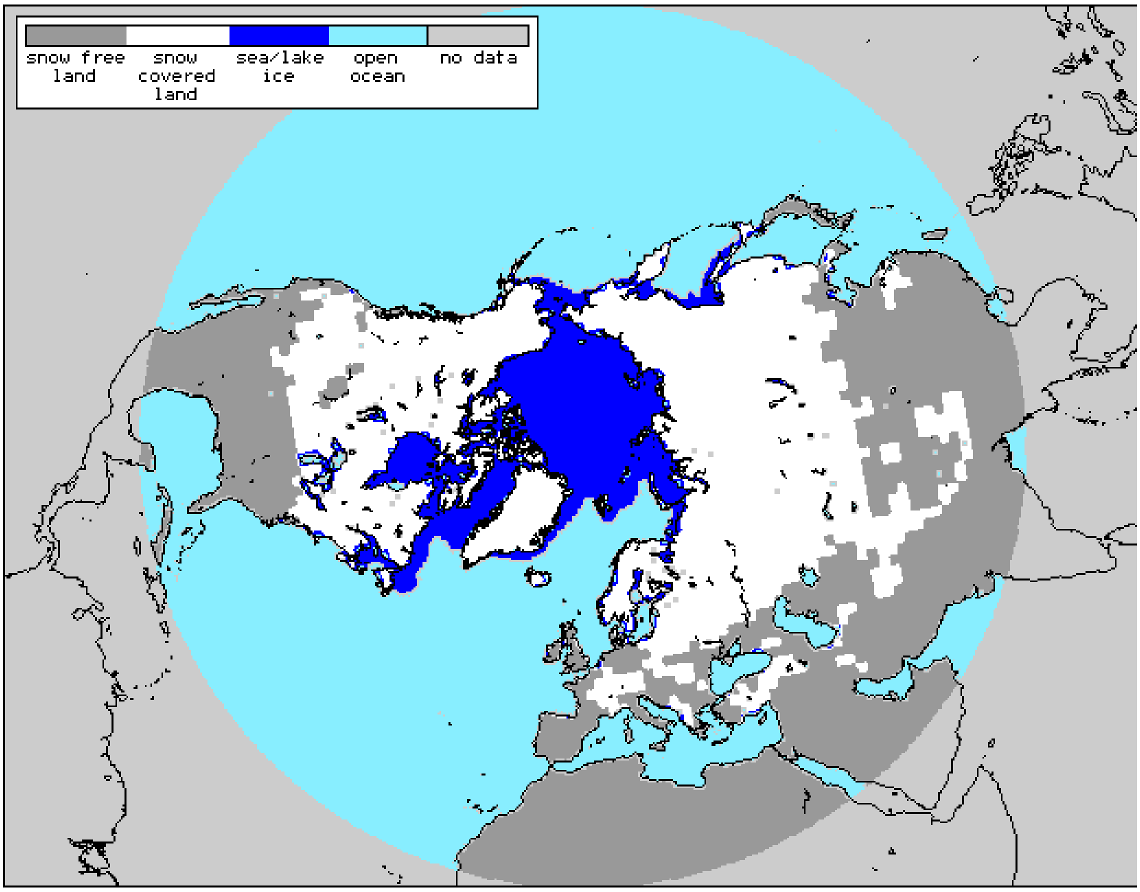


Figure 5.1: Northern Hemisphere snow and ice extent for January 23-29, 1984. (Source: Northern Hemisphere Weekly Snow Cover and Sea Ice Extent from the EOSDIS/NSIDC Distributed Active Archive Center (NSIDC DAAC, University of Colorado at Boulder))

from large energy losses in winter, having major implications for the energy and moisture fluxes in the near surface layers. This insulating effect on not only sea ice, but also lake ice has an effect on ice thickness. The development of seasonally frozen ground, its extent and depth from autumn through winter to spring is very closely related to the snow cover on the surface. There is a need to improve our ability to simulate the important geophysical properties and processes (e.g., snow density, ice thickness distribution) controlling energy exchanges in the cryosphere with the over- and under-lying surfaces. Due to the surface temperature limit of 0^{o}C, convective heating of the troposphere above the snow is either low or absent. The interactions and links between snow cover and atmospheric circulation, including variability and change in both, must be better determined. The close relationship between hemispheric air temperature and snow cover extent is also important to monitoring and detecting climate change on both regional and hemispheric scales (Brown, 1997). The ice surfaces that form seasonally on rivers and lakes are individually too small to exert other than localised climatic effects. However, the freeze-up/break-up processes respond to large-scale and local weather, and melt and associated runoff processes. The freeze- up/break-up time series may provide integrated as well as seasonally specific information on regional climatic variations.

Another key question concerns the radiative balance and associated feedback over cryospheric surfaces. Absorbed short-wave radiation is three times lower than for most non-snow-covered surfaces due to high albedo. But snow cover has less of an effect on modifying surface albedo over forested areas, especially coniferous forests, where the area-averaged albedo may be as low as 0.2 during the snow season (Robinson and Kukla, 1985). Field process studies, such as BOREAS have confirmed these low values, but this result will depend on whether there is snow captured in the canopy or not. Currently, most models are unable to simulate snow on the canopy. The spatial variability in snow cover and the heterogeneity of the land surface (cover type and openness or density) result in a potentially very variable surface albedo. Some NWP models are known to assign excessively high albedo values to boreal forest regions during snow cover, leading to cold-biased temperature forecasts over these areas. Similarly, the albedo of a melting snow or ice surface will be significantly lower than 0.8. More accurate parameterization of the albedo of snow covered surfaces under a variety of land covers and for changes in condition (e.g., wet/dry) is required (Barry, 1996). There is a need also for improved understanding of how the ice/snow-cloud feedback works (Shine et al., 1984) and characterisation of differences between coastal (where most measurements are made in high latitudes) and inland areas, as well as vegetated and non-vegetated surfaces.

5.1.2 Key Land Cryospheric Processes and their Role in the Hydrological Cycle

- What is the role of land cryospheric processes in the spatial and temporal variability of the hydrological cycle of cold climate regions, and how can they be parameterized?

Cold climate/cold season processes in mountainous and mid- and high-latitude zones strongly influence hydrologic processes over a range of river basin scales, in addition to the land-atmosphere interactions at continental or larger scales noted above. Precipitation, sublimation, snow-accumulation, melt and runoff, glacier runoff, freeze/thaw processes and freeze-up/break-up of ice cover all play a role in the hydrological cycle in cold climate regions. The seasonal changes and inter-annual variability in cryospheric processes in temperate and mountain regions, as well as at higher latitudes, must be accurately characterised over a range of time and space scales. This is because many of the same components become even more significant to the climate system as the space and/or time scale is refined (reduced/decreased). There is a need to develop and validate land surface parameterizations of cold climate and cryospheric processes for inclusion in coupled land-atmosphere-ocean climate models to improve simulations and predictions of the fresh-water balance components (e.g., precipitation, snow cover/water equivalent, evaporation/sublimation soil moisture, and run-off).

The proper scaling (scale down climate parameters; scale up cryospheric processes) and verification of the scaling procedure are essential in the development of land surface process models and their link to hydrological models and incorporation into climate models. There is a need to extend and expand the ACSYS hydrological objectives in both time and space to other regions where land cryosphere processes are an important part of the regional hydrological cycle, at the same time complementing related GEWEX initiatives, such as the Continental Scale Experiments (CSE). Issues include the magnitude and variability of snow sublimation, high spatial variability associated with snow redistribution, the representation of lakes and wetlands and their influence on seasonal runoff. Water exchange in frozen ground and permafrost zones during both summer and winter, seasonal redistribution of stream-flow associated with river ice processes, and the role of freezing/melting in modulating river runoff are also included.

The fresh-water balance of the polar oceans is a key factor affecting global ocean circulation. Inputs from sea-ice melt, fresh-water river runoff (commonly from snowmelt), and net precipitation (P-E) produce a stabilising fresh-water layer at the surface. Accurate determination of the amount, distribution and space and time variability of precipitation and runoff is essential for not only the Arctic (Lewis et al., 2000), but for other cold climate regions, including Antarctica. The determination of fresh-water runoff into the Arctic Basin was a key component of the ACSYS hydrological programme. Net snow accumulation (snow water equivalent) is an extremely important storage component of water, often storing precipitation for more than 6 months per year. The subsequent seasonal melt cycle commonly determines the timing and magnitude of peak fresh-water runoff, and, when combined with river ice jams, can also result in overbank flooding of riparian systems, further affecting the timing and magnitude of the pulse. Understanding the contribution of snowmelt runoff from gauged and ungauged rivers and its response to climate variability and change needs to be known. Available hydrological and oceanographic data allow order-of-magnitude estimations of the annual inflows and outflows of fresh water in the Arctic region. The accuracy is insufficient, however, to quantify even relatively large inter-annual differences, let alone long-term climatic trends (WCRP, 1999b). Better modelling and observation are needed.

In mountain regions, glaciers can have an important regional effect on the climate and hydrological cycle in addition to snowpack contributions. The seasonal snow pack is a major contributor to both floods and droughts in many regions and a major water source for drinking, irrigation, hydropower and recreation for many highly populated areas. In glacier dominated basins, snow melt runoff is important, but instead of a brief peak in the spring runoff, glacier melt augments the summer flow and tends to dampen inter-annual and inter-seasonal variations in flow (Mountain Agenda, 1998). In those regions where stream flow is affected by the presence of glaciers, and where water is in high demand for human use and consumption, there is a practical need to assess the contribution of glacier wastage to stream flow (both in total quantity and in regime). It has been demonstrated that although total water quantity from glacier wastage is relatively small, the timing of release of those waters is critical. It is in years of generally low flow that glacier wastage contributes most and it is in late summer (when evaporation rates are high and when demand for water is also high) that glaciers make their biggest contributions to stream flow. There is a need for continued research into glacier contributions to water availability in regions where demand is projected to continue to rise, but where glaciers cannot continue indefinitely to waste away. Such studies are being conducted in Qilian Shan, China for the Hei He basin, for example.

5.1.3 Precipitation in Cold Regions

- What is the distribution and spatio-temporal variability of precipitation (especially snowfall) in cold regions?

Knowledge of the amount, distribution, and type of precipitation and its temporal and spatial variability on a wide range of scales, is essential for the study of cold climate and related hydrological processes. Unfortunately, the spatial and temporal distributions of precipitation in high-latitude and alpine regions is generally poorly known due to the lack of data, particularly *in situ* data. Year-to-year fluctuations and lower frequency variations in precipitation over land areas control, to a large extent, the inter-annual variability of stream flow in regions where snowfall and snow cover have a significant effect on the basin hydrology. Orographic effects in alpine regions produce high spatial variability in type and amount of precipitation. There is a need to better understand precipitation mechanisms in these regions and their predictability. Factors contributing to uncertainties in precipitation estimates over land areas include the sparseness of the precipitation network, the uneven distribution of measurement sites biased toward coastal and low-elevation (valley) areas, and the difficulty of measuring snow precipitation in windy environments. These factors are also applicable to Antarctica and over the central Arctic Ocean. In the polar regions, even the seasonal cycle of precipitation is poorly defined, because long records at fixed observing stations simply do not exist.

The accurate measurement of solid precipitation is critical for all regions where snowfall occurs, including the oceans and ice sheets. There is a need for a capability to measure precipitation in all its forms. The WMO/CIMO Solid Precipitation Measurement Intercomparison (Goodison et al., 1998a) provides a good foundation for adjusting *in situ* measurements for systematic errors. CliC will extend ACSYS (WCRP, 1997), GEWEX and national efforts to derive accurate estimates of precipitation in all regions where solid precipitation occurs. The development of standardised solid precipitation measurements and correction procedures for the Arctic, Antarctic and other regions where solid precipitation occurs is a matter of paramount importance. The verification of simulations of the hydrological cycle in these regions is at present impossible due to the absence of reliable observations of high-latitude solid precipitation. An observational basis to determine long-term trends in the amount, type and timing of precipitation, and the associated relation to runoff, is essential for assessing impacts of a changing climate in cold climate regions. The role of new technologies should continue to be assessed.

In *Figure 5.2* the mean winter snow water equivalent as produced by the Canadian Centre for Climate Modelling and Analysis Global Coupled Model (Flato et al., 2000) is compared with the observed snow edge determined from the USAF global climatology (Foster and Davy, 1988). It shows there are discrepancies in reproducing global snow extent, but it also points out the need for global and regional snow water equivalent products that can be used for model evaluation, model development and as a reliable input for hydrological analyses. The quality of snow climatologies is still inadequate, especially in central Asia. This information is essential to determine the variability and change in snow water equivalent with a change in climate and to establish the links to hydrological and land surface processes, including the influence on changes in permafrost. Determination of global snow mass will allow further investigation of the interactions with atmospheric circulation. Only with an improved knowledge of precipitation and snow water equivalent in cold climate regions can we address these issues. The status of remote sensing techniques to determine snow water equivalent, particularly at regional scales, is discussed in Section 10.

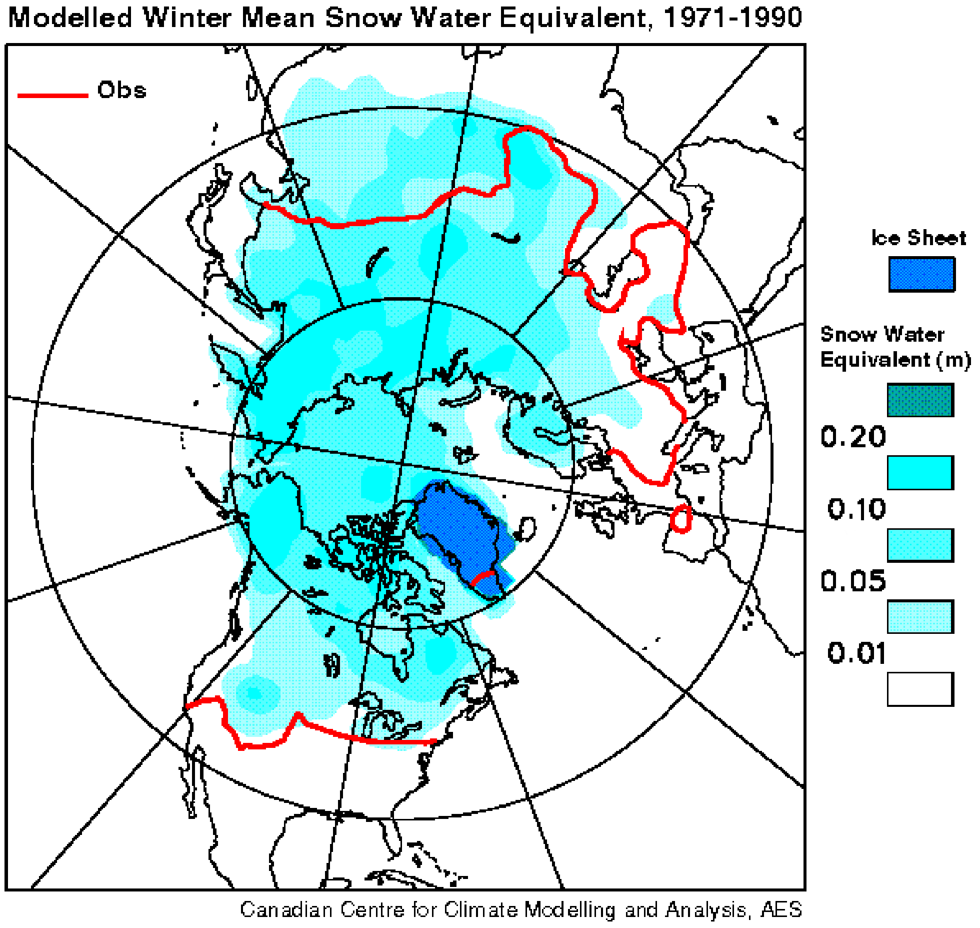


Figure 5.2: Mean December/January/February snow water equivalent (m) produced by the CCCMA global coupled model, compared with the snow extent derived from the USAF global climatology (Foster and Davey, 1988) (red line). *Courtesy of G. Flato, CCCMA.*

5.1.4 Frozen Ground/Permafrost and Surface and Atmospheric Exchanges

- What is the role of seasonally frozen ground in water and energy fluxes between the land and the atmosphere and how do cryospheric processes control the exchange of carbon between the land and the atmosphere?

Frozen ground and permafrost do have direct feedback on the climate system. Permafrost is a condition in which the subsurface earth has remained at or below 0°C for two consecutive years or longer; it currently underlies 24% of the northern continental areas (Table 1). *Figure 5.3* shows the circumpolar distribution of continuous and discontinuous permafrost in the Northern Hemisphere, and also shows the proposed distribution of boreholes for monitoring permafrost as part of the GTOS/GCOS observing network. As noted for other cryospheric observing networks (GCOS, 1997), the distribution is sparse. In the presence of permafrost, mass exchange between land and atmosphere in the cold period of the year is negligibly small. In summer it is limited to the water and gas fluxes between the atmosphere and the relatively shallow near-surface layer of seasonal thaw, the active layer. The deeper the active layer, the larger is its storage capacity and the amount of matter potentially available for exchange with the atmosphere. Extent and thickness are affected by ground moisture content, vegetation-cover, winter snow depth and aspect. Seasonally frozen ground extends well beyond the permafrost limit and somewhat follows snow cover extent; depth of frozen ground exhibits wide spatial and temporal variability seasonally and inter-annually, and is affected by the factors noted above. Frozen ground has a direct influence on the seasonal energy and water cycle of the climate system, and hence on the availability of water for transpiration, timing of leaf-out in the spring, and the uptake of carbon.

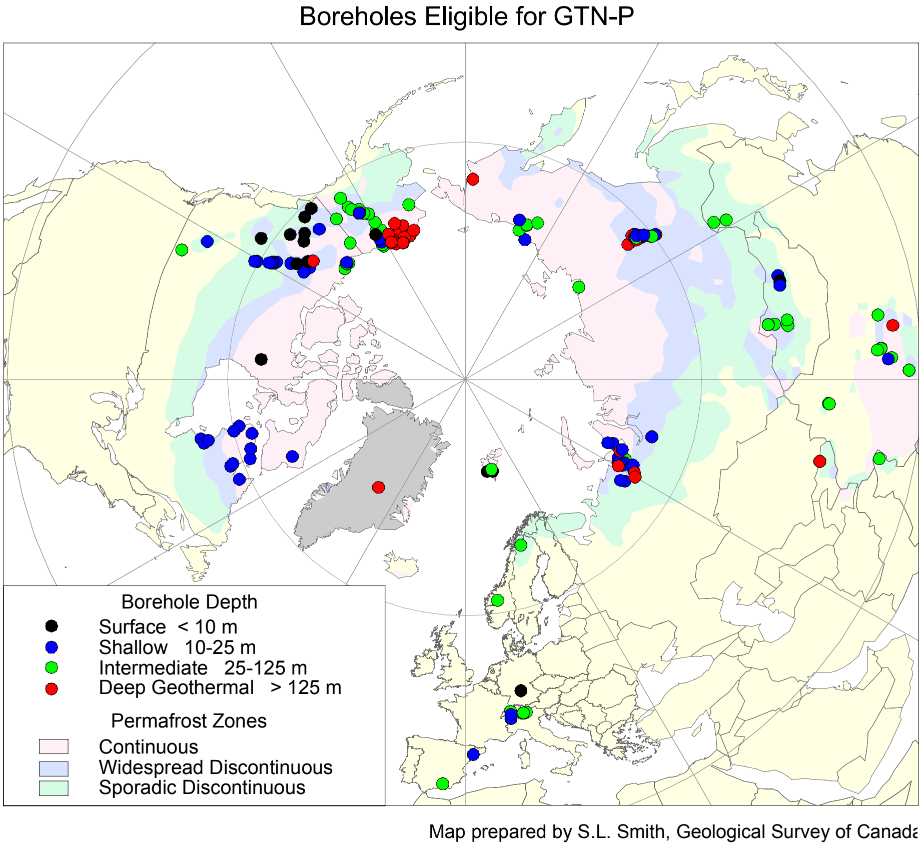


Figure 5.3: Distribution of Northern Hemisphere permafrost zones (Brown et al., 1997) and the proposed distribution of borehole sites for the Global Terrestrial Network for Permafrost. *Courtesy of M. Burgess, Geological Survey of Canada.*

With warming and thawing, permafrost will have an effect on the surface heat and moisture balances, runoff, and chemical fluxes to the atmosphere and hydrosphere (CO_2 and methane), with the potential for releasing large quantities of these greenhouse gases. There is a need for improved understanding of the link between permafrost/frozen ground changes and the carbon cycle (greenhouse gases) taking into account changes in other components of the climate system.

Anthropogenic warming is expected to produce a noticeable effect on the active layer. Because the depth of seasonal thaw depends solely on the weather conditions of the specific year, the response of the active layer to changing climate is immediate, unlike permafrost distribution, which has a delayed reaction. There is an increasing belief that substantial changes in the active layer thickness may take place in the next few decades (Anisimov et al., 1997). However, it is still not certain what the net effect of climate change on the active layer thickness will be. Although higher air temperature generally results in deeper seasonal thaw, the annual temperature cycle plays an important role. Under certain circumstances the differential increase of the winter and summer temperatures may produce the opposite effect. For example, at Barrow, Alaska the active layer decreased slightly in the last 30 years, although annual air temperature became higher. A key factor is changing snow cover. In north-western Canada, for example, snow depth has shown a marked decrease over the last 30 years, reducing the thickness of the insulating layer provided by the snow and allowing additional cooling of the ground temperatures in winter, that may not be compensated by the summer warming. Another important regulator is vegetation. Warmer climate conditions may result in the increase of the upper organic layer of soil, in which case the overall net effect would be a shallower active layer.

Given the difficulties of *in situ* precipitation measurement and the subsequent derivation of reliable precipitation climatologies for cold climate regions (particularly high latitudes and high altitudes), alternative approaches are also being used. Satellite methods for estimating rainfall have been developed and are in use in lower latitude regions. Satellite methods for estimating snowfall are currently lacking. Instead, snow water equivalent is being used as an alternative to estimate net winter precipitation (precipitation less ablation and sublimation). In the polar regions, products of model re-analysis, such as that carried out by the ECMWF, provide another approach to determining snow water equivalent. Snow water equivalent, or snow mass, is a critical input for hydrological models and for evaluation of climatological models.

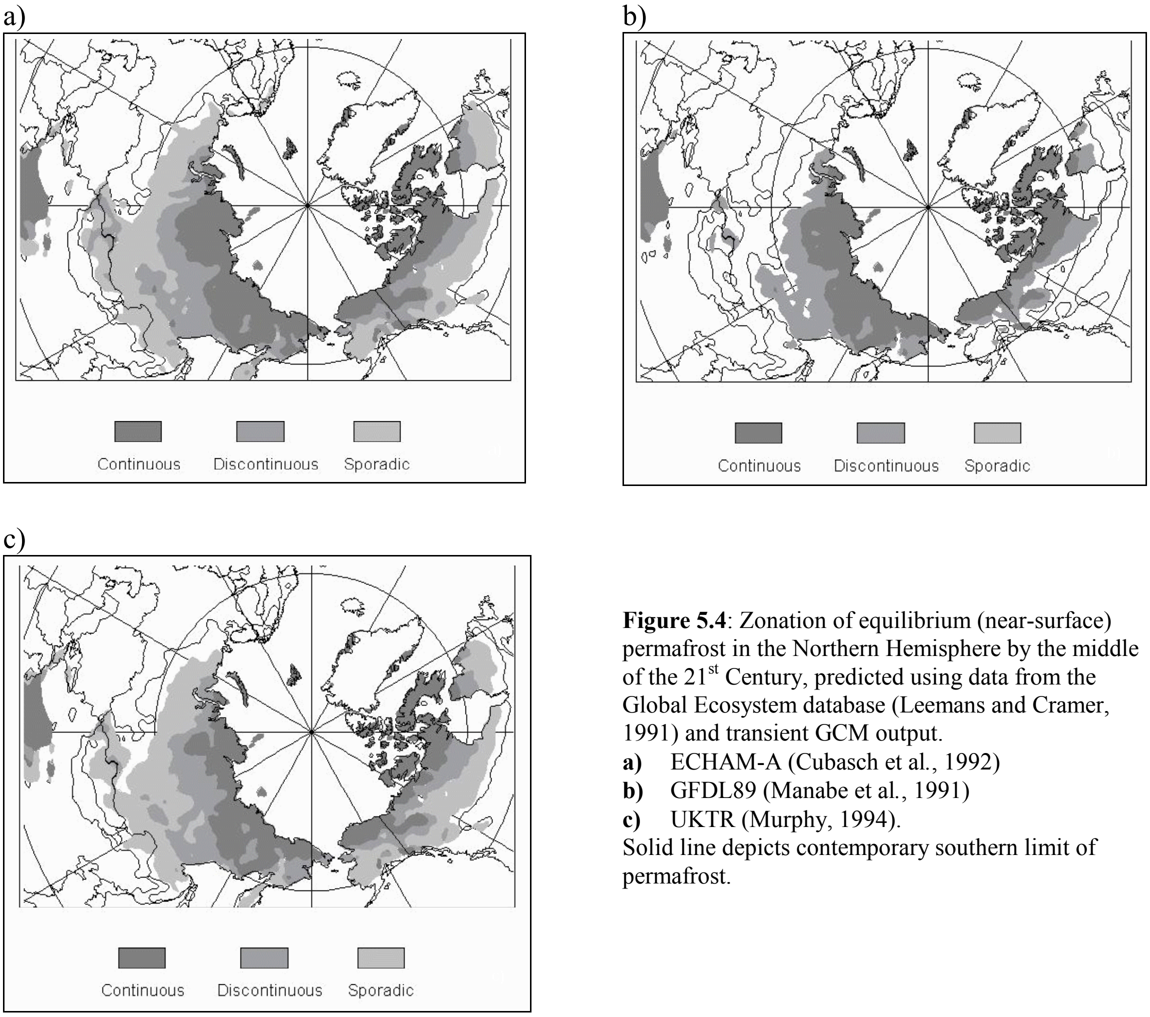


Figure 5.4: Zonation of equilibrium (near-surface) permafrost in the Northern Hemisphere by the middle of the 21st Century, predicted using data from the Global Ecosystem database (Leemans and Cramer, 1991) and transient GCM output.
a) ECHAM-A (Cubasch et al., 1992)
b) GFDL89 (Manabe et al., 1991)
c) UKTR (Murphy, 1994).
Solid line depicts contemporary southern limit of permafrost.

- What will be the response of permafrost to changes in the climate system?

Permafrost interactions with the surface above and the atmosphere generally occur over a longer time period. Permafrost contributes valuable information on palaeoclimates, being a source of information on changing near-surface temperatures over past centuries. Anisimov and Nelson (1997) show that transient climate models suggest major changes in the distribution of permafrost in the Northern Hemisphere, with a general poleward retreat, but the model simulations can differ appreciably (*Figure 5.4*). The stability of permafrost in the future is a key question as thawing disrupts man's engineered works. Warm and cold states are principally different in their response to the climate signal; cold permafrost will potentially have a fast reaction in a changed temperature regime while warm permafrost may have a delayed response due to phase changes during its thawing. Identification of zones of permafrost based on stability could be done using heat flux as a criterion.

The marginal zones will be more immediately subject to any melting caused by a warming trend. However, because of the latent heat, thawing of the few metres of ice-rich permafrost may take several decades. Although most of the presently existing permafrost formed during previous colder conditions and is therefore relic, it may form under present-day polar climates where glaciers retreat or land emergence exposes unfrozen ground. Washburn (1973) concluded that most continuous permafrost is in balance with the present climate at its upper surface, but changes at the base depend on the present climate and geothermal heat flow. In contrast, most discontinuous permafrost is probably unstable or in such delicate equilibrium that the slightest climatic or surface change will have drastic effects (Harris, 1986; Anisimov and Nelson, 1997). There is empirical evidence that such changes of permafrost took place in the past; and, as suggested by the results of numerical modelling, may be expected to occur in the future (Anisimov and Nelson, 1996).

5.2 SCIENCE STRATEGY FOR ATMOSPHERE-SNOW-LAND INTERACTIONS

Essential to improving our understanding of the role of the terrestrial cryosphere in the climate system is the effective combination of measurement, observation, monitoring and analysis, process field studies and modelling of land-cryosphere-atmosphere processes at a range of time and space scales.

Some of the key issues include the need to:

- develop regional and global cryospheric data sets for model parameterization, including identification of additional data sets, as required; augment current measurement programmes, in co-operation with GCOS/GTOS, to provide systematic measurements of key variables (e.g., active layer monitoring on a circumpolar scale);
- develop for cold climate regions, especially polar regions, appropriate and consistent data sets characterising the water budgets, including precipitation;
- use, and further develop, remote sensing techniques to derive key elements of the climate systems of mid- and high-latitude and mountainous regions where data networks are sparse;
- validate atmosphere-cryosphere-land interactions from *in situ* and remotely-sensed data;
- improve monitoring and modelling of the seasonal storage of fresh water by the cryosphere, its variability and change, and its role in cold climate hydrology;
- study the energy and water budgets as derived from climatological observations, field process experiments and assimilated data fields, and determine the degree to which these are properly represented within land surface process models, and ultimately regional and global climate models;

- assess the sensitivity of NWP models to cryospheric parameters and the potential for improving the models to account for atmosphere-cryosphere-land interactions at a range of time and space scales; validate model output;
- conduct hydrological process studies involving the terrestrial cryosphere over critical regions not currently well understood, building on previous focused experiments such as BOREAS and NOPEX; and,
- develop procedures to scale up process studies to regional and global climate models, and to scale down global and regional climate models, to develop models on both global and regional scales capable of better reproducing the essential features of the sub-grid-scale land-atmosphere interactions.

CliC terrestrial studies will build on, co-operate with, and co-ordinate with other initiatives within WMO and WCRP, other international scientific bodies such as IGBP, IPA, and ICSU/IAHS/ICSI, national initiatives, such as CRYSYS and PARCA, and national space agencies. Building on the accomplishments of the ACSYS hydrological programme is especially important. Partnerships and co-ordination with efforts initiated within WCRP, particularly GEWEX, will be essential. Co-ordination with GCOS/GTOS initiatives on cryospheric networks will benefit both communities. CliC will have a prime responsibility for integrating regional and global initiatives related to the terrestrial cryosphere into the global climate effort.

There is a clear, continuing need for high quality, consistent data sets of all available standard hydrometeorological measurements from global and national networks to support the CliC science goals. A comprehensive observing system for cryospheric variables, particularly related to the energy and water cycle, is essential to support process studies, monitoring, model development and validation. Conventional networks are often short in duration, the coverage is sparse in high-latitude regions, and data are not always easily accessible. Data rescue may be required. CliC will define the needs for terrestrial cryospheric data to meet its scientific programme as part of, and in addition to, the GCOS/IOS terrestrial observing programme.

Co-operating in the design and implementation of the Global Terrestrial Networks will benefit both CliC and GCOS/GTOS climate initiatives. For example, the GTNet-G, with the World Glacier Monitoring Service, proposes a global network of glacier sites that would allow global and regional analyses of glacier changes, with different levels of measurement at various sites. Proposed studies range from detailed annual mass balance studies, to long term changes in glacier length at selected sites in the major mountain ranges, to glacier inventories repeated at time intervals of a few decades by using satellite remote sensing. This would provide an essential core network, which could then be enhanced to meet CliC initiatives.

Similarly, the GTNet-P would enhance and provide a core network of active layer/permafrost measurements (*Figure 5.3*). Data from this network will make an important contribution to the requirements of CliC modelling and process studies for surface and borehole profile temperatures in the active layer, precipitation, soil moisture and runoff. Co-operation with organisations such as the International Permafrost Association (IPA), which has encouraged the establishment of a circum-Antarctic permafrost monitoring programme to complement ongoing Northern Hemisphere activities, would enhance permafrost and periglacial studies in both polar regions. The IPA co-ordinates the collection of annual active layer depth and permafrost temperatures under the aegis of GCOS/GTOS and publishes the data online.

CliC also has a need for other global and regional data that are not as readily accessible, or even available with the shift to automation. These include lake and river freeze-up/break-up data for hydrological process studies and climate model development and validation, as well as precipitation data from national networks not regularly exchanged via the Global Telecommunications System. GEWEX studies in the Continental Scale Experiments (CSE) have similar challenges and close co-operation with GEWEX will be required. ACSYS and GEWEX have co-operated in the past, for example in meeting some of their respective data needs through the Global Runoff Data Centre (GRDC) and Global Precipitation Climatology Centre (GPCC). CliC would continue these co-operative initiatives. For example, CliC needs to develop and implement improved precipitation methodologies, conduct further comparisons to interpret precipitation observations, and develop gridded fields for its modelling initiatives. There is also a need to develop specialized runoff data sets for rivers affected by cryospheric processes. CliC plans to work co-operatively with GEWEX/GHP and the GPCC and GRDC, respectively, and WMO Departments and Commissions to accomplish these tasks.

The terrestrial cryosphere component of CliC will require the development and use of satellite derived variables to meet the needs of a wide range of climate and cryosphere studies, including process-oriented studies, spatial-temporal variability, monitoring and detection of climate change and for assimilation and/or validation of numerical models. Section 10 provides a comprehensive discussion of remote sensing in CliC, including the terrestrial variables. There must be an accelerated use of remote sensing data and information in monitoring and modelling of the state of the cryosphere and cryospheric processes. The need to assess whether different components of the cryosphere are responding in a similar manner in a region is essential. For example, the prospects for daily monitoring of global snow cover and the determination of snow water equivalent (SWE) for use in hydrological forecasting and regional model validation are quickly improving with the development and validation of new snow products, such as those from passive microwave data.

Figure 5.5 shows the distribution of SWE in western Canada derived from passive microwave satellite data. This information is delivered to users in near real-time. The points on the map show the available conventional snow depth data (few were reporting), and illustrate the added information that satellite derived information can provide on spatial variability over regions. The challenge is to develop algorithms to derive SWE for other landscape regions, including the mountain regions, to permit global or at least large region analyses and the assessment of variability and change based on satellite derived information. This may be accomplished through the development of new techniques involving data fusion, data assimilation and data merging. This is but one example. CliC must engage the remote-sensing specialists to continue development of new cryospheric products that will allow the science to advance steadily. CliC, along with other WCRP projects, will make its needs known to the national remote sensing agencies, to encourage continuation of existing operational sensors, development of improved sensors and the development and launch of new sensors to address issues of importance in understanding climate and cryosphere interactions and feedbacks.

Another key issue is to improve our understanding of the terrestrial climate-cryosphere processes, and especially those cryospheric processes affecting local, regional and global energy and water budgets. Several different spatial and temporal scales are currently used in land-atmosphere interaction models, which range from several hundreds to tens of kilometres (GCMs to nested regional climate models). Recent improvements in the availability of fine resolution climatic, soil, and cryospheric data, and advances in process modelling, allow us to develop our understanding of the links between various geographical scales. These in turn will enable us to tackle the development of both global and regional scale models capable of better reproducing the essential characteristics of the sub-grid scale features that occur in nature. Scaling is a high priority task. The study of cold climate processes, their interaction and the associated feedback between the atmosphere and the land (including fresh-water bodies) requires investigation on a range of temporal and spatial scales and involving land surface process models, regional and global climate models and linkages to hydrological models. Gaps in models and associated data requirements were identified at the Cambridge meeting of cryospheric experts (WCRP, 1998b). The CliC strategy for land areas must address these gaps.

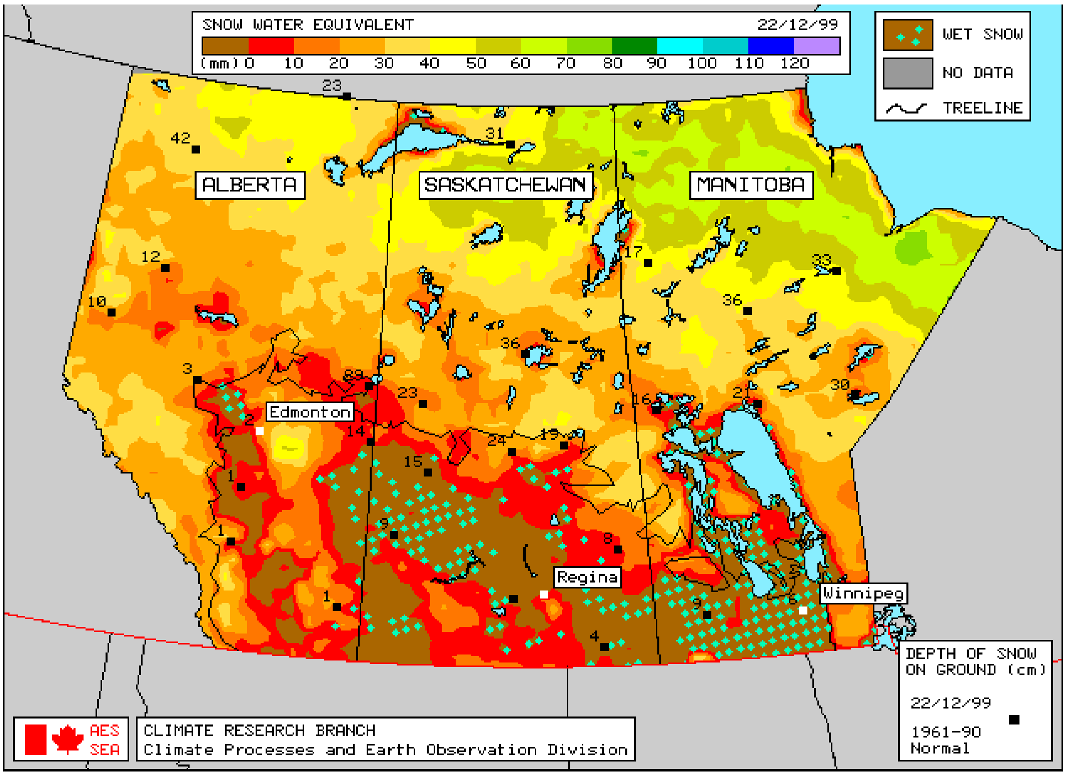


Figure 5.5: Near real-time product of snow water equivalent derived from SSM/I satellite data for western Canada, December 22, 1999. Available snow depth normals are shown for the synoptic stations in the region. *Courtesy of Anne Walker, Climate Research Branch, Meteorological Service of Canada.*

Many recent studies have been concerned with the effects that changes in the global climate may have on surface and subsurface conditions in the cold regions, i.e., on snow cover, its depth and water equivalent, fresh-water ice, ground temperature, soil moisture, active layer thickness and permafrost. However, current knowledge about atmosphere - snow - land interactions is not adequate to evaluate these effects quantitatively, particularly on hemispheric and global scales.

Assessment of cryospheric components in LSP models used today that can be coupled to RCMs and GCMs is required. This requires specific model comparisons of the different cryospheric components (e.g., as in the Sea-ice Model Intercomparison Project (SIMIP)). An evaluation of the sensitivity of these models to processes/boundary conditions that are known to strongly affect components of the cryosphere is necessary. Existing models of land - atmosphere interaction differ substantially in complexity and computational details. The most advanced models are capable of producing realistic patterns of the annual and inter-annual cycles of the surface temperature, soil moisture, depths of thaw and frost. Application of such models for hemispheric and global calculations is, however, difficult because many of the input parameters are rarely available on small geographical scales and the models are computationally expensive. Simple models that use only few parameters, typically air temperature and precipitation and/or snow depth, to evaluate the mean annual ground temperature and depths of thaw/frost represent another extreme. These models are widely used in the studies of climate-cryosphere interactions, but they need to be empirically adjusted for each region against control data, and their accuracy is critically dependent on the availability of such data. An important task will be to develop the intermediate-class, physically based models with the appropriate level of complexity of the land-atmosphere system for use in coupled applications for a range of scales.

ACSYS and GEWEX are currently co-operating in a hydrological model comparison under the auspices of PILPS to assess LSP-hydrologic coupled models in basins where cryospheric processes are important. CliC will ensure this initiative continues. CliC is also expected to co-operate with others (e.g., IAHS/ICSI) in implementing a snow model comparison that will test models for different regions in order to improve parameterization of snow processes in land surface models. This comparison, which is a natural extension of earlier WMO initiatives on the comparison of snowmelt models, will require specialized observations from both operational and field process experiment sites. The need for high quality measurements to evaluate/validate the models cannot be overstated.

The need for co-ordinated field experiments, such as conducted by GEWEX through BOREAS/ISCLSCP or the CSEs, to improve our understanding of land-cryosphere-atmosphere processes, is recognised. This is also an area where close co-operation with GEWEX is both logical and essential. The GEWEX Co-ordinated Enhanced Observing Period (CEOP), a limited scale hydroclimatic experiment planned for 2001-2002, offers an opportunity for CliC to contribute to an experiment that has similar scientific issues to those noted above. The CEOP, as expressed in the current science plan, is summarised as follows: *"Given the state of the global circulation and its ocean and cryosphere for a particular two-year period, what are the water and energy cycles over various land areas for this period, how are they functioning, can we model these adequately for our needs, and what are the implications for predictability?"* CliC will participate in forthcoming discussions of CEOP and its implementation and identify areas where it can contribute to the initiatives related to climate and cryosphere. CliC might assist in the initiation of the experiment in the cold climate regions. CliC and GEWEX have complementary interests in the study of land-atmosphere processes, and close co-operation will be essential. ACSYS and GEWEX co-operated in defining areas of responsibility with respect to their hydrological programmes. CliC and GEWEX will have to discuss their mutual interests and collectively define areas of responsibility related to programme needs. CEOP offers an excellent opportunity to bring the resources of both WCRP projects together to address issues of mutual concern.

6 INTERACTIONS BETWEEN LAND ICE AND SEA LEVEL

6.1 KEY SCIENTIFIC QUESTIONS

The primary issue regarding the role of the cryosphere in sea level is:

- What is the past, present and future contribution of land ice to sea-level change?

To address this question, it will also be important to ask where the major uncertainties are and what mechanisms control the mass balance of the major components of the system. The issue of interactions between atmosphere, land ice and sea level is a major concern for the IPCC. 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. For smaller glaciers all regions must be suitably represented in order to refine existing estimates of mass balance.

Of all the terms that enter the sea-level change equation, the largest uncertainty pertains to the Antarctic and Greenland ice sheets. In spite of the fact that the current state of balance of ice sheets and ice caps is not well known, the sensitivity to climate change can and must be studied to provide our best estimate of the future contribution of land-ice to sea-level change.

6.1.1 Observed Sea-Level Change over the Last 100 Years

- How much of the sea-level rise over the last 100 years can be explained by changes in land-ice volume?

Global mean sea level has risen 10–25 cm over the last 100 years (Warrick et al., 1996). This rise has not been explained in a satisfactory way. It is generally accepted that a significant contribution came from thermal expansion of ocean water. Estimates of this are in the 2–7 cm range. The remainder should come from changes in groundwater storage, lakes, irrigation and land ice. Order-of-magnitude estimates show that land-ice is likely to be the most significant contributor.

Many valley glaciers in the world have retreated significantly during the last 100 years. This applies to glaciers in the Alps, Scandinavia, Svalbard, the Canadian Rockies, central Asia, the Himalayas, New Zealand, the Caucasus and the tropics (South America, Central Africa, and Irian Jaya). Also, many outlets of the Patagonian ice fields and ice caps on Iceland have retreated. Although this list is long, it does not include a number of subpolar glaciers and ice caps that in fact store roughly half of the ice outside Greenland and Antarctica (Canadian Arctic, Alaska, Novaya Zemlya, and Severnaya Zemlya). Very little is known about changes to these ice caps during the last century.

Estimates of the contribution of ice caps and glaciers to sea-level rise are in the 2–5 cm range for the last 100 years (e.g., Meier, 1984; Zuo and Oerlemans, 1997), which is similar to the range estimated for ocean thermal expansion (de Wolde et al., 1995). Dyurgerov and Meier (1997) made a detailed study of all glacier mass balance observations with emphasis on the 1961–1990 period and suggest a 1 cm contribution to sea-level rise in this period. All these estimates should be considered with caution. Intensified studies of subpolar ice caps and the ice fields of Alaska and Patagonia are needed to arrive at more reliable estimates.

Valley glaciers respond rapidly to climatic fluctuations with typical response times of 10 to 50 years (Oerlemans, 1996). However, the response of individual glaciers may be asynchronous to the same climatic forcing because of differences in glacier length, elevation, slope, and speed of motion. Oerlemans (1996) provided evidence of coherent global retreat in glaciers, which could be explained by a linear warming trend of 0.66°C per 100 years.

The contribution of the Greenland and Antarctic ice sheets to 20th century sea-level change has not been determined, and even their overall state-of-balance is uncertain at present.

6.1.2 Present State of Balance of Polar Ice Sheets

- To what extent are the Greenland and Antarctic ice sheets in balance with the present climate?

The mass budgets of the Greenland and Antarctic ice sheets are still poorly known. With present data a 20% imbalance at the Antarctic grounding line, corresponding to about 10 cm of sea-level change per century, cannot be detected with confidence. Better estimates of ice sheet mass budget require improved data on surface balance and the discharge of grounded ice, combined with remote sensing and modelling studies. Consideration of the balance of floating ice shelves, which may indirectly affect ice sheet discharge, requires additional data on iceberg calving and basal melt.

There is a large disparity in the time-scale of the processes affecting the surface mass balance and the dynamic response of large ice sheets. Changes to the surface mass balance determine sea level change at the decadal to century time-scale. For Antarctica, where surface temperatures are generally well below the melting point, this short term impact results from changes in precipitation, whereas for Greenland melt and run-off may dominate. The dynamic response of the large ice sheets takes thousands of years and the ice sheets are probably still adjusting to changes since the Last Glacial Maximum. Ice sheets are not single dynamic entities, but comprise different drainage systems with different regimens and different responses of both surface mass balance and dynamics to changes in forcing.

For Greenland, the NASA Program for Arctic Regional Climate Assessment (PARCA) has used airborne laser-altimetry surveys along precise repeat tracks across all major ice drainage basins to directly measure changes in ice-surface elevation. The laser-altimeter survey of the northern part of the ice sheet over the 5-year period 1988/9–1993/4 shows a pattern of significant change, predominantly thinning, near the coast, but very little elevation change over most of the interior ice sheet. For the Antarctic, Wingham et al. (1998a) used satellite radar altimetry to estimate that there had been no significant change (±5 mm) to the elevation of the East Antarctic ice sheet (north of 82°S and excluding the coastal slopes), but that there had been a thinning in West Antarctica of (53 ± 9) mm per year.

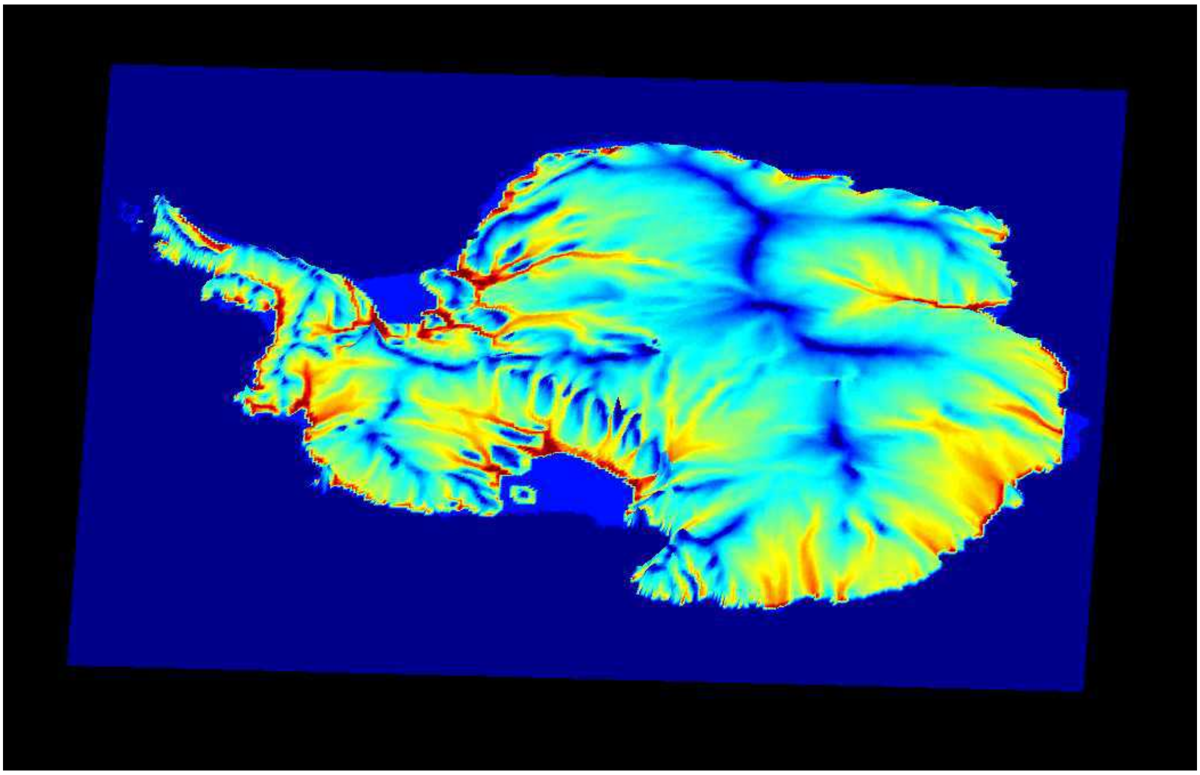


Figure 6.1: Distribution of the mass flux (log scale) required for the Antarctic ice sheet to maintain balance. High mass fluxes are "warm" colours. Balance fluxes are calculated using a 20-km digital elevation model of the ice sheet surface and a distribution of snow accumulation. After Budd and Warner (1996). [*Courtesy of Roland Warner, Australian Antarctic Division]*

Although these and other recent field- and remote-sensing studies have not provided a definitive answer to the mass budget of the large ice sheets, they have considerably narrowed our uncertainty and provided a solid basis for future work. In the Antarctic, improvements have been made to our knowledge of the distribution of the surface mass balance. This has come from new *in situ* observations for individual basins (e.g., Higham et al., 1997) and from improved data compilations using interpolation based on satellite passive microwave brightness temperatures (Giovinetto and Zwally, 1995). GCM results (Vaughan et al., 1999); and estimations from atmospheric moisture convergence in meteorological model analyses (Budd et al., 1995; Bromwich et al., 1998) also improved our knowledge of the distribution of the surface mass balance. New digital elevation models from satellite altimetry and synthetic aperture radar permit detailed calculations of the ice mass flux necessary to maintain a steady state ice sheet for different surface mass balance distributions (*Figure 6.1*) (Budd and Warner, 1996; Huybrechts et al., 2000). These can be compared with field mass flux measurements (Fricker et al., 2000).

In recent years, numerical ice sheet models have been used to simulate the evolution of the Greenland and Antarctic ice sheets through the last glacial cycle (e.g., Huybrechts, 1990; Huybrechts and de Wolde, 1999). In these calculations climate records from the deep ice cores (Vostok, GISP/GRIP) and schematic sea-level histories were used as forcing functions. For the present, although error bars are large, the results suggest a considerable imbalance for Antarctica, which is still losing mass in response to the glacial-interglacial transition, and a very small imbalance for Greenland.

6.1.3 Internal Variability in Ice Sheet - Ice Shelf Systems

- Do we understand the internal dynamics of the ice sheet/stream/shelf system well enough to be sure they cannot contribute to rapid sea-level change?

The mass export from the vast Antarctic and Greenland ice sheets is dominated by the flux within fast-flowing wet-based outlet glaciers and ice streams. In Antarctica, much of the out-flowing ice passes through floating ice shelves. Up to 40% of the Antarctic coastline is composed of ice shelves, either large shelves (such as the Filchner-Ronne, Ross and Amery) in coastal embayments, or fringing shelves on the periphery of the ice sheet (e.g., West, Shackleton and Larsen). Most of the ice discharged from the Antarctic continent comes from the front of ice shelves - the source of the typical tabular icebergs of Antarctica. Some tabular bergs can be massive; e.g., the 180 km-long B9 iceberg discharged from the Ross Ice Shelf in 1987, and the even longer B15 iceberg discharged off a more westerly section of the same ice shelf in 2000. But these large calvings are natural and episodic, occurring only every few decades.

The contribution of the ice sheets to sea level depends not only on accumulation and ablation, but also strongly on the dynamic behaviour of the ice streams and ice shelves. There is evidence that marine ice sheets are subject to considerable internal variability associated with changes in the behaviour of ice streams. Field studies on the dynamics of ice streams in West Antarctica (e.g., Retzlaff and Bentley, 1993) suggest that ice streams have active and stagnant phases that are not directly related to climate change (although climate change can influence the processes involved). This has severe implications for understanding and projecting sea-level rise on the centennial to millennial time scale. No doubt the West Antarctic ice sheet, with its major ice streams, had started a strong retreat when the last glacial ended. This retreat may still be continuing. Further observations and modelling are needed to assess the role of internal variability in this large-scale development.

Since ice shelves are floating on an ocean at the freezing point, even a small change in ocean temperature (induced perhaps by changes in ocean currents) can significantly affect the basal melt rate and thin the shelves much more quickly than an increase in air temperature. Any disintegration of ice shelves will not itself affect global sea level (the ice is already floating), but past studies suggest that their removal may lead to increased drainage of grounded ice which is "buttressed" by the shelves, and an eventual sea-level rise from this source. However, more recent work indicates that the dynamic constraints at other ice stream boundaries, such as the shear zones at the sides (Echelmeyer et al., 1994), are also important, and the role of ice shelves in restraining inland ice is now considered less important. Ice shelves may, however, play a role for *some* ice streams and glaciers in the Antarctic.

In the past, it was considered that marine ice sheets (resting on bedrock below sea level) were potentially unstable, and that rapid disintegration of the West Antarctic ice sheet was a distinct possibility. Now, a collapse leading to a rapid rise in sea level (10 mm per year or greater) is *not* considered a strong possibility within the next century or two (Bentley, 1998). However, the potential effects are so great that it is essential to refine our understanding of the ice-sheet/ice-stream/ice-shelf system. Although coupling of ice sheet, ice stream and ice shelf dynamics is generally treated simplistically in large scale models, some model studies suggest that large increases in basal melt could remove ice shelves within a few hundred years and float the West Antarctic ice sheet within about 1500 years (Warner and Budd, 1998). Some records of past sea level suggest that major reductions in ice sheet volume compared to the present may have occurred in previous interglacials only slightly warmer than to-day, and such evidence must be further assessed.

6.2 SCIENCE STRATEGY FOR INTERACTIONS BETWEEN LAND ICE AND SEA LEVEL

6.2.1 Glaciers and Ice Caps

The IPCC Second Assessment Report (Warrick et al., 1996) lists four major initiatives that are needed to obtain better estimates of the contribution of glaciers to sea-level rise:

- The development of models that link meteorology to glacier mass balance and dynamic response.

- Extension of the models to the glaciers that are expected to have the largest influence on sea level (valley and piedmont glaciers of Alaska, Patagonian ice caps, and monsoon-fed Asian glaciers).
- Quantification of the re-freezing of melt-water inside glaciers.
- Better understanding of iceberg calving and its interaction with ice dynamics.

Because of a paucity of data, it is impossible to establish a direct statistical relation between global climate parameters and ice volume/sea level. The only way forward is a process-oriented approach, in which the relation between glacier mass balance and climatic conditions is carefully modelled. This builds on the vast experience with coupled climate models currently available, complemented by field experiments that focus on the processes that determine mass and energy exchange between the atmosphere and the glacier surface. To extrapolate the results of field measurements in space and time, the use of satellite data is crucial. Daily estimates of polar surface albedo are being provided by the AVHRR Polar Pathfinder project in the U.S.A. (Barry, 1997). Stroeve et al., (1998) demonstrate the use of AVHRR-derived surface albedo over Greenland. Further, Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) passive microwave data can be used for determining snow type and other signals of climatological significance (Steffen et al., 1993).

Existing data for land ice over the last century (prepared mainly under the auspices of the World Glacier Monitoring Service (WGMS)) should be compiled and synthesised to provide improved estimates of the contribution of glacier and ice cap retreat during the last 100 years. Data on future change of these systems will be available from the international consortium for Global Land Ice Measurements from Space (GLIMS) and the Global Terrestrial Network for Glaciers (GTNet-G), proposed as a joint venture between GTOS and WGMS. (GLIMS and GTNet-G are discussed further in Section 9.3.1.) One level of observations envisioned for selected GTNet-G sites within major climatic zones would provide process-oriented glacier mass balance studies, at an annual reporting period.

The programme Mass Balance of Arctic Glaciers and Ice Sheets in Relation to the Climate and Sea Level Changes (MAGICS) – an initiative of the IASC Working Group on Arctic Glaciology – provides an umbrella for studies of Arctic land ice. The objectives of the MAGICS study are:

- to predict the change in ice volume in the Arctic that may occur in the next decades to several centuries as a result of possible climate change for different climate scenarios;
- to give input to the estimate of the future rate of sea-level change;
- to measure and predict fresh-water input to the sea from melting of glacier ice;
- to provide data needed by global climate models; and,
- to reconstruct Holocene climatic variations in the Arctic.

Detailed information on MAGICS is given in Appendix B7 to "Proceedings of a meeting of experts on Cryosphere and Climate" (WCRP, 1998b).

6.2.2 Ice Sheets

The largest unknown in future changes to sea level is due to uncertainty in the response of the large ice sheets, particularly Antarctica. We require better knowledge of the present mass balance of Antarctica and Greenland and information on how the ice sheets have responded to past changes, in order to test and improve the models used to predict future response. The emphasis should be on a two-pronged approach of obtaining critical new data and modelling in a co-ordinated programme. A number of exciting, new remote sensing tools are becoming available for ice sheet studies, but *in situ* observations will also be required to validate these. Similarly, further field process studies are needed to improve both ice-sheet models and the high-latitude performance of atmospheric models.

The IPCC Second Assessment Report (Warrick et al., 1996) made the following recommendations to reduce the uncertainty pertaining to the ice sheets of Greenland and Antarctica:

- Continue and extend field observations of the components of ice sheet mass balance (snow accumulation, iceberg and melt-water discharge).
- Detect and understand changes in ice dynamics, including ice streams and iceberg calving.
- Document changes of snow accumulation in the past (historical data, ice cores) and better define the processes involved that may lead to changes in the future.
- Detail the relations between the ice-shelves and the mass balance of the ice sheets.
- Implement improved satellite altimetry (laser altimetry) to monitor surface elevation.

A number of existing programmes are addressing these issues, and CliC will need to co-ordinate with these initiatives and to build on their accomplishments. Improved estimates of the modern state of mass balance will be progressively determined from internationally planned fieldwork, advances in satellite altimetry measurements of ice sheet surface changes, and ice-sheet modelling. Potential changes in precipitation are a major issue for ice-sheet mass balance. Hence, process and modelling studies are needed to further understanding of precipitation and evaporation/sublimation over Antarctica and Greenland, and of the dynamics and sources of precipitation and evaporation over ice sheets and land surfaces. But these must be supported by significant new data, for example, on polar precipitation and its spatial and temporal variability.

The Program for Arctic Regional Climate Assessment (PARCA) is a USA NASA project whose prime goal is to measure and understand the mass balance of the Greenland ice sheet, with a view to assessing its present and possible future impact on sea level. PARCA, which was formalized in 1995, combined a number of separate investigations that began in 1991 into one co-ordinated programme to assess whether airborne laser altimetry could be applied to measure ice-sheet thickness changes. Collaboration with Danish scientists has been established. The main components of the programme now are:

- airborne laser-altimetry surveys along precise repeat tracks across all major ice drainage basins to measure changes in ice-surface elevation;
- ice thickness measurements along the same flight lines;
- shallow ice cores at many locations to infer snow-accumulation rates and their inter-annual variability, recent climate history, and atmospheric chemistry;
- estimating snow-accumulation rates by climate-model analysis of column water vapour obtained from radiosondes, satellite atmospheric sounding observations, and European Centre for Medium-Range Weather Forecasts (ECMWF) model data;
- surface-based measurements of ice motion at 30 km intervals approximately along the 2000 m contour completely around the ice sheet, in order to calculate total ice discharge for comparison with total snow accumulation and, thus, to infer the mass balance of most of the ice sheet;
- local measurements of ice-thickness changes in shallow drill holes;
- investigations of individual glaciers and ice streams responsible for much of the outflow from the ice sheet;
- monitoring of surface characteristics of the ice sheet using satellite radar altimetry, Synthetic Aperture Radar (SAR), passive-microwave, scatterometer, and visible and infrared data;
- investigations of surface energy balance and factors affecting snow accumulation and surface ablation; and
- continuous monitoring of crustal motion using Global Positioning System (GPS) receivers at coastal sites.

The estimates of elevation change over the five-year period 1993/4 – 1998/9 from airborne laser-altimetry will be extended by NASA's Geoscience Laser Altimeter System (GLAS) to be launched on ICESAT in 2001. The PARCA measurements will also provide baseline data sets for comparison with GLAS data to yield a total time series of elevation change from 1993/4 through the GLAS lifetime. Together with the earlier coverage by satellite radar altimeters, these data sets will yield a time series of elevation change over southern Greenland covering almost 30 years. The laser data have also been used (in a collaborative project with European scientists) to produce an improved DEM for the ice sheet.

For the Antarctic, we need data that will allow us to determine if the ice sheet is growing or shrinking and how any mass imbalance is distributed spatially. Large-scale field surveys of the Antarctic accumulation distribution and ice outflux provide data for initialising and validating ice sheet models, and for narrowing the limits of our uncertainty of the ice sheet mass budget, but are alone unlikely to provide the accuracy to resolve the state of balance. Various national and international programmes in Antarctica contribute to the requirements. Examples are the US West Antarctic Ice Sheet Initiative (WAIS), which addresses the mass balance and stability of the West Antarctic Ice Sheet, the SCAR WG Glaciology FRISP (Filchner-Ronne Ice Shelf Programme), and projects in Dronning Maud Land, the Pine Island Glacier and the Lambert Glacier - Amery Ice Shelf system. However, despite national and multinational research activity on the mass balance of Antarctica, there remains a gap in synthesising the results of the field glaciology, remote sensing and modelling communities.

A component of the SCAR global change programme, Ice Sheet Mass Balance (ISMASS), was established as a focus for studies of the Antarctic ice-sheet mass balance and its contribution to global sea level. This project is largely dormant at present and CliC will need to help promote this work. A priority for the immediate future is a forum to assess the certainties and uncertainties in determining mass balance by field, remote sensing and modelling techniques, and to evaluate methods of combining the three approaches.

For the polar ice sheets, information on snow accumulation distribution and variability can be obtained from shallow ice cores. For Greenland, this is one of the objectives of PARCA; and for Antarctica, of ITASE (International TransAntarctic Scientific Expedition). The latter aims to establish how the recent atmospheric environment (climate and atmospheric composition) is represented in the upper layers of the Antarctic ice sheet, with primary emphasis placed on the last 200 years of the record. This time period was chosen because observational records for the Antarctic are sparse in time and space and because it covers the onset of major anthropogenic impact on the atmosphere. Products from ITASE will include continental-scale environmental maps, transfer functions between components of the atmosphere and snow/ice, validation of atmospheric models and interpolation between sampling sites by satellite remote sensing. Of particular interest regarding sea level, ITASE will derive a history of snow accumulation across the Antarctic continent.

A new 5-km resolution compilation of the Antarctic under-ice topography has been prepared by the BEDMAP consortium using all accessible data, but there are still significant areas where there are no data on bedrock elevation. Further airborne ice thickness soundings are required to compile a complete bedrock data set for modelling. This should be at a resolution of at least 10 km (preferably at 5 km), to resolve the location and structure of major ice streams.

6.2.3 Remote Sensing

Remote sensing from space will be a powerful tool for making further mass balance estimates for Antarctica and Greenland. Conventional radar altimetry can, in principle, be used to detect changes in surface elevation which, under certain assumptions, can be related to ice volume. However, it has become clear that the accuracy is not adequate to reduce mass budget errors below 10% of the turnover, which is not good enough. More promising is the future use of laser altimetry from space. A laser altimeter mission with NASA-ICESat is planned to start in 2001, and another instrument is also proposed for ESA-CryoSat. The accuracy of laser altimetry is not only higher than radar altimetry, but it also provides data from regions of steep and varying topography. Space-borne laser altimetry has the potential to directly determine elevation change, but converting changes in ice-sheet elevation to changes in ice volume requires knowledge of isostatic movement of the crust and possible systematic effects in the density structure of the upper layers (affecting surface elevation but not mass). Basic research is needed here. The ICESat laser altimeter will also provide new data on seasonal and interannual elevation changes (caused by variations in ice accumulation and melting) which can be used for validation of GCM modelling of net precipitation (P-E) and energy-balance modelling of melting.

Tracking surface features is a powerful tool to derive surface ice velocities. Much more detail on ice velocities can be obtained by Synthetic Aperture Radar (SAR) interferometry than from conventional techniques, but there are other severe limitations for mass budget studies. Nevertheless, it should be possible to estimate from satellite images the loss of ice through calving glaciers from the Greenland ice sheet, for instance.

Passive microwave satellite data can be used to map and monitor surface melting in Greenland and Antarctica. The method of melt determination used is the cross-polarized gradient ratio (XPGR) method (Abdalati and Steffen, 1997) with some adjustments in the melt-threshold made for the newest F-13 SSM/I instrument. Passive microwave data are available since 1978 from Scanning Multi-channel Microwave Radiometer (SMMR) and Special Sensing Microwave Imager (SSM/I) sensors.

6.2.4 Modelling

Improved coupling of ice sheet, ice stream and ice shelf dynamics in models is required to enhance understanding of the stability of the ice sheet/stream/shelf system and to predict future change. Interactions between ice streams and their beds must be incorporated into models. There is an ongoing requirement for international co-ordination of ice sheet models; similar to the activity organized within EISMINT (European Ice Sheet Modelling Initiative). The EISMINT comparison tested and compared existing numerical ice-sheet, ice-shelf, and glacier models run by several groups world wide, in order to narrow down uncertainties and to enable participating groups to upgrade their models. Five comparison topics were addressed: the Greenland ice sheet, the Antarctic ice sheet, ice-shelf models, basal sliding, and grounding-line treatments.

To estimate future changes in sea level, observational studies must be combined with GCM and ice sheet modelling projects. General Circulation Models offer possibilities to study the mass balance of the large ice sheets and their sensitivity to climate change. A two-pronged approach is required involving:

- simulation of ice-sheet mass balance with GCMs, using nested models; and
- mass balance models for glaciers and ice caps, including downscaling techniques to feed such models with GCM data.

Significant new data are required to support these studies.

Model studies simulating the evolution of the Greenland and Antarctic ice sheets over a full glacial cycle (e.g., Huybrechts, 1990) are another promising approach. Ice-sheet models can be used to aggregate data of a very different nature. For instance, the range of possible de-glaciation histories can be narrowed down, by temperature records from deep bore holes, mass accumulation histories from ice cores, and data on rates of isostatic uplift from geomorphological studies, as well as from accurate GPS measurements. Combined with further development of ice-sheet models, significant progress can be achieved.

7 INTERACTIONS BETWEEN SEA ICE, OCEANS, AND THE ATMOSPHERE

7.1 INTRODUCTION AND KEY SCIENTIFIC QUESTIONS

Over about 10% of the surface area of the global ocean, sea ice forms a boundary between the two much larger geophysical fluids – the atmosphere and the ocean – and considerably influences their interaction. The Antarctic sea-ice cover is almost totally seasonal, whereas the central Arctic Ocean retains an extensive permanent pack ice cover throughout the year. The details and consequences of the role of sea ice in moderating exchanges between the atmosphere and ocean are still poorly known.

Sea ice has a dramatic effect on the physical characteristics of the ocean surface. It modifies the surface radiation balance due to its high albedo, and it influences the exchange of momentum, heat, and matter between atmosphere and ocean. It also results in much lower surface air temperatures over the ice-covered areas in winter than are maintained by the ocean immediately underneath. Freezing of sea ice expels brine which deepens the surface mixed layer and can, through convection, influence the formation of deep and bottom water in both hemispheres. Melting, in contrast, produces relatively fresh water that stratifies the oceanic surface layers (i.e., the mixed layer retreats to shallower depths). In contrast to low latitudes, the mixed layer evolution in polar regions is dominated by surface fluxes of salt or fresh water (positive or negative freezing rates). Through these effects, sea ice plays a key role in the global heat balance and the global thermohaline circulation. A retreat of sea ice associated with climate warming can therefore have global consequences and contributes, through various feedback processes, to enhanced climate change, particularly at high latitudes.

To facilitate a credible prediction concerning the state of the polar pack ice over the next few decades, both theoretical and observational knowledge of the processes of interaction among the ice, the ocean, and the atmosphere must continue to be improved. In particular, we must reach a position where predictions of change in the ice regime over short time scales (seasons, years, and decades) can be comprehensively tested against observations. At present this is not possible, though substantial progress is being made in this area of work under ACSYS.

The specific scientific questions to be addressed are as follows:

- What is the observed mean state and natural variability of sea ice?
- What are the roles of physical processes in determining the mean state and variability of sea ice and its interactions with the atmosphere and ocean?
- How well do models represent sea ice and its interactions with the atmosphere and ocean?
- How can we improve the representation of atmosphere – sea ice – ocean interactions in climate models?
- Can we predict a change in sea ice in response to natural variability or anthropogenic forcing?

These questions, and the manner in which they will be addressed, are expanded upon in the following sections.

7.1.1 Mean State and Variability

Knowledge of climatological sea-ice conditions in both hemispheres forms the basis for understanding the role of sea ice in the climate system, modelling its behaviour, and predicting and detecting changes that have occurred or will occur. There are currently only a few systematic, spatially distributed data sets available of the seasonal and regional variability of the sea-ice extent and overlying snow-thickness distribution for the Northern Hemisphere, and almost none from the Southern Hemisphere. The result is that the climatological mean state, and variability about this state, are poorly known at present. However, such data, together with those on ice concentration and thickness (derivable from remote sensing and field observations), are essential to evaluate the performance of climate models. Similarly, climatic compilations of the main features of ice drift and, where available, the percentage total ice formed by different processes (basal freezing, frazil formation, snow flooding) provide a means of evaluating higher resolution models and process parameterizations.

Continuing effort to develop climatologies of Arctic and Antarctic sea ice is required, based on available historical observations and new observing initiatives. Initial progress at assembling relevant data sets has been made by ACSYS and other initiatives, including ASPeCt (Allison et al., 1998), GDSIDB and the joint American-Russian Environmental Working Group. Synthesizing and analyzing the available observations, and making use of advances in data assimilation techniques currently being applied in re-analysis of atmospheric and other climate data will make further progress. Improvements to *in situ* measurement techniques and satellite remote sensing will be vital in the longer term to build on the time series presently available for use in documenting sea-ice variability at a range of time scales and for detecting change.

7.1.2 Role of Physical Processes

On the geophysical scale, sea ice is a thin, broken layer on the polar oceans whose thickness, concentration and other properties are modified by a variety of dynamic and thermodynamic processes (motion, deformation, freezing and melting) coupled directly to the atmospheric and oceanic boundary layers. The net effect of all these interacting processes determines the state of the ice cover, its variability, its role in moderating exchanges between the ocean and atmosphere, and its response to and impact on climate change. Many of the important processes are, at present, only poorly understood and hence a source of uncertainty in climate models and their projections.

The most direct interaction between the atmosphere and sea ice involves the surface energy balance. In summer, this is dominated by short-wave radiation and variations in surface albedo. Of particular importance is the dependence of albedo on surface conditions (temperature, snow amount and distribution, evolution of melt ponds, etc.) which vary rapidly in time and over spatial scales far too small to be explicitly resolved in models. Sensible and latent heat exchanges present additional modelling challenges owing to the predominance of very stable stratified boundary layers. These surface energy and moisture exchange processes afford an opportunity to capitalize and expand on studies underway in GEWEX, and will benefit greatly from the recent SHEBA field experiment in the western Arctic and its ongoing modelling and analysis phase.

Processes involving ice growth and melt have direct implications for the mass balance of sea ice and reveal one of the more fundamental differences between Arctic and Antarctic sea ice. A key early finding about the composition of Antarctic sea ice (Gow et al., 1982) is the high percentage of frazil ice (typically about 50% of the ice structure compared to 10% in the Arctic). Frazil growth occurs where the open ocean wave field interacts with the growing ice cover, quickly expanding the ice edge by lateral accumulation. By contrast, in the Arctic, most ice growth occurs via bottom accumulation, offsetting vertical heat conduction through the ice. Also in the Antarctic, submergence and flooding of the snow cover, followed by re-freezing, is an important contribution to ice thickness (a negligible process in the Arctic), which leads to a higher than usual surface salinity. Changes in precipitation over the Antarctic sea-ice zone may have a significant impact on the ice characteristics and mass balance. Improved understanding of these processes is required to represent sea-ice growth and decay accurately in climate models, and to capture differences between the Arctic and the Antarctic not currently reflected in such models.

Dynamic processes involving ice motion and deformation contribute directly to energy and moisture exchanges by creating open water regions within the ice (thereby enhancing local ice growth in winter and melt in summer), and by transporting ice from regions of net growth to regions of net melt. Ice transport plays an important role, in both hemispheres, in redistributing fresh water and thereby influencing ocean water mass properties, deep-water production rates, and circulation. Representation of ice motion in climate models was a topic of particular emphasis in ACSYS (especially the Sea-ice Model Intercomparison Project (SIMIP)), and this knowledge base must be built upon since many current global climate models still ignore ice motion or represent it very crudely.

The more localized deformation processes of rafting and ridge building are also important in the development and distribution of sea ice in both hemispheres. Episodic periods of divergence and ice formation in new open water, followed by convergence and thickening by rafting and ridging, are related to the passage of synoptic weather systems. Explicit representation of these processes is becoming more common in stand-alone sea-ice models, but many uncertainties remain. In particular the processes of ridge formation and subsequent thermodynamic evolution are only poorly understood at present, despite the fact that ridged ice has been estimated to account for roughly half of the Arctic ice volume and up to 45% of east Antarctic sea ice (Worby et al., 1998). Related effects of momentum dissipation by ridge formation, and the anisotropy of ice strength (arising when leads form with a predominant direction), are likewise poorly understood.

The influence of the ocean on sea ice is mainly through the oceanic heat advection and the entrainment of heat at the base of the mixed layer, which then enters the ice cover. This heat flux has large spatial gradients, with large values in early and mid-winter at the sea-ice margin and in divergent drift areas, mainly near coastlines, where new ice is formed and strong convection occurs. Relatively small values have been measured under the central part of the Arctic Ocean ice pack. Experiments conducted with coupled sea ice - ocean models illustrate the importance of ocean currents and oceanic heat flux on the simulated sea-ice cover, especially in the Greenland and Barents Seas.

Coastal polynyas are a common feature of the perimeter of the Antarctic continent and northern Siberia. The generally larger deep-water polynyas, such as the Weddell Polynya, are thought to remain ice-free because of the welling up of sensible heat from below the pycnocline. The coastal polynyas on the continental shelf in contrast are believed to have a significant "latent heat" component. That is, heat loss from the ocean surface is balanced by the latent heat of new ice formation. The polynya is partially maintained by wind or tidal current removal of the new ice and, in some cases, by the addition of sensible heat from upwelling. The coastal polynyas are regions of intense heat loss from the ocean to the atmosphere, and of rapid and copious ice growth: they may be significant as "ice factories" for the total sea-ice zone. Brine rejected during ice growth is concentrated in the polynya areas and can cause localised water mass modification as well as significantly increasing the salinity of Antarctic continental shelf water.

Ice edges, or the zones where the ice cover interacts with the open ocean, have high seasonal and regional variability around Antarctica and in the Arctic marginal seas. Ice edges essentially can be divided into three phases: a growth phase of ice advance, a decay phase where the ice edge retreats, and an intermediate or "equilibrium phase" with small advance and retreat oscillations. The regional variability in the ice edge can be characterised by the period of time that the ice edge exists in these various phases. For example, the Weddell Sea undergoes a short advance period, a prolonged equilibrium phase, and a rapid decay phase due to the high transport. In other regions, the ice edge regime is primarily thermodynamically or air temperature controlled, so that the equilibrium phase is very short at the maximum ice edge extent, and the ice advance and retreat are both relatively lengthy and nearly equal in time. The result of these differences in regime can affect the amount, and the position and timing of fresh-water flux at the ice edge, and thus impact strongly on the biological regime.

7.1.3 Representation in Models

As indicated in the previous section, many of the important processes involving sea ice and its interaction with the ocean and atmosphere remain poorly understood and so the accuracy of parameterizations used in models remains unclear. Nevertheless, the representation of sea-ice processes in models, particularly global climate models, lags well behind the current level of understanding. As an example, of the 20 coupled climate models whose results were contributed to the WGCM Coupled Model Intercomparison Project (CMIP), only seven include any representation of sea-ice motion; and of those, only four compute ice motion by solving a momentum equation. (The remaining three assume that only ocean surface currents advect ice.) The importance of sea-ice related feedback in enhancing projected climate change at high latitudes (e.g., *Figure 7.1*) demands that more attention be paid to the representation of sea ice in such models.

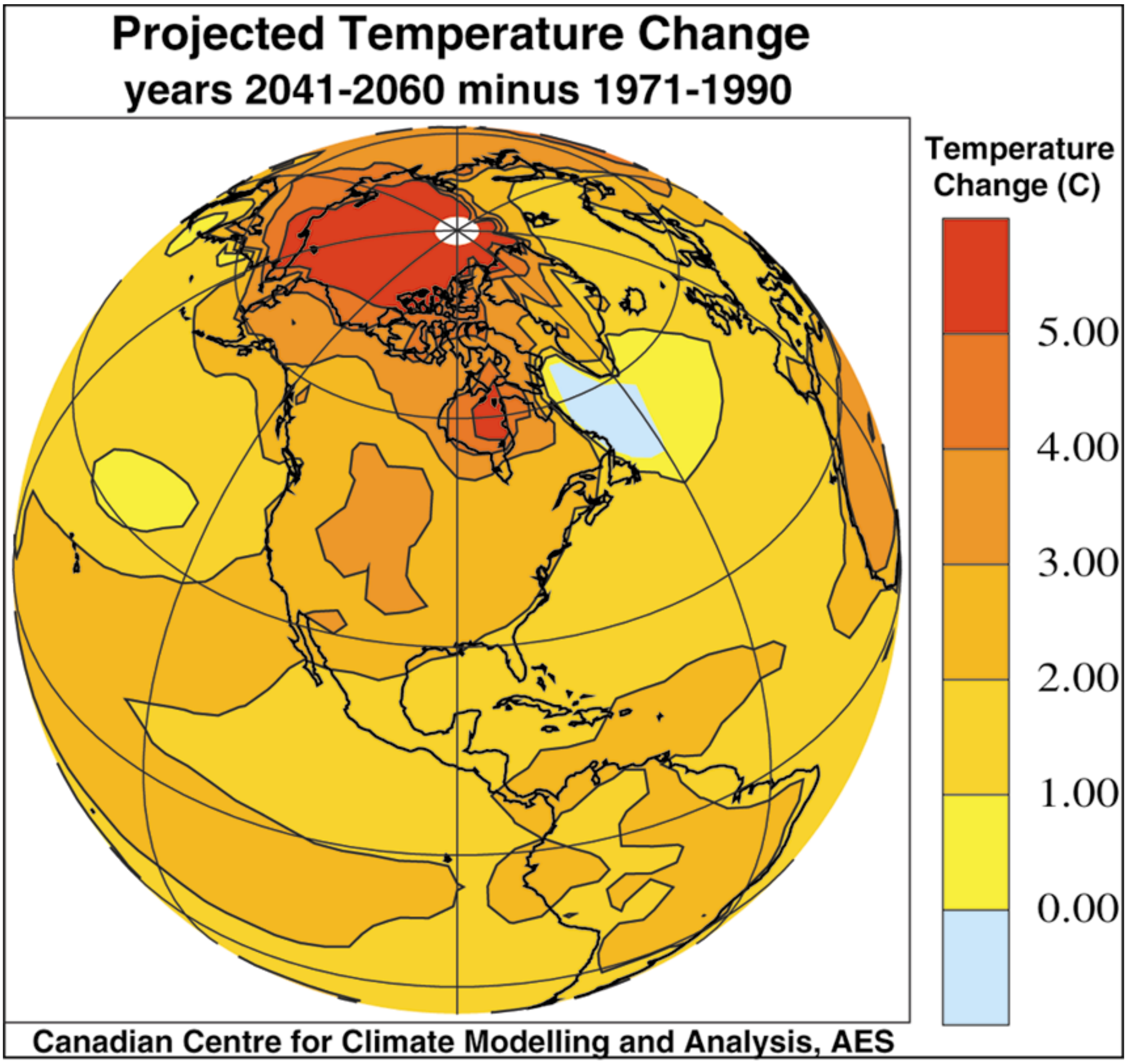


Figure 7.1: **Figure 7.1:** Warming by the middle of the next century as projected by the Canadian Centre for Climate Modelling and Analysis global coupled model (Boer et al., 1999).

Assessment of sea-ice model performance has so far been hampered by a lack of suitable observational data. In recent years, work done in ACSYS and other national and international projects has improved access to historical data collected by various means, and provided new and expanded data sets for use in such assessment. This is an ongoing process that requires continued support and encouragement. Initial attempts to evaluate the performance of sea-ice models, and the sea-ice component of coupled models have been made using existing data, but more comprehensive analyses are needed both to evaluate the modelled sea ice and its interactions, and to assess the modelled response to perturbations. Simulations of both the mean state and interannual-to-decadal variability of sea ice and its interactions with the atmosphere and upper ocean must be thoroughly compared with a range of data in order to identify the model deficiencies. Sensitivity experiments can then be used to determine which physical parameterizations contribute most to the errors. Such simulations should be carried out with a hierarchy of models to assess the impact of increasing complex interactions with other components of the climate system.

7.1.4 Improving Models

The sea-ice modelling investigations carried out so far have shown that a realistic simulation of sea ice can only be accomplished if both ice thermodynamic and dynamic processes are adequately taken into account. Among the thermodynamic processes that must be included in a sea-ice model, the following must be emphasized:

(1) the strong dependence of the snow and ice albedo on surface conditions (Barry, 1996);

(2) the thermal inertia of the snow-ice system and, in particular, the buffering effect associated with volume changes of the internal brine pockets;

(3) the distribution of snow and ice in different thickness categories within a given area, which greatly affects the ice growth and melt rates;

(4) the blowing snow process and the transformation of snow into ice due to flooding of the snow; and,

(5) the lead-related processes, such as lateral ice melting, and frazil ice growth at the lead surface).

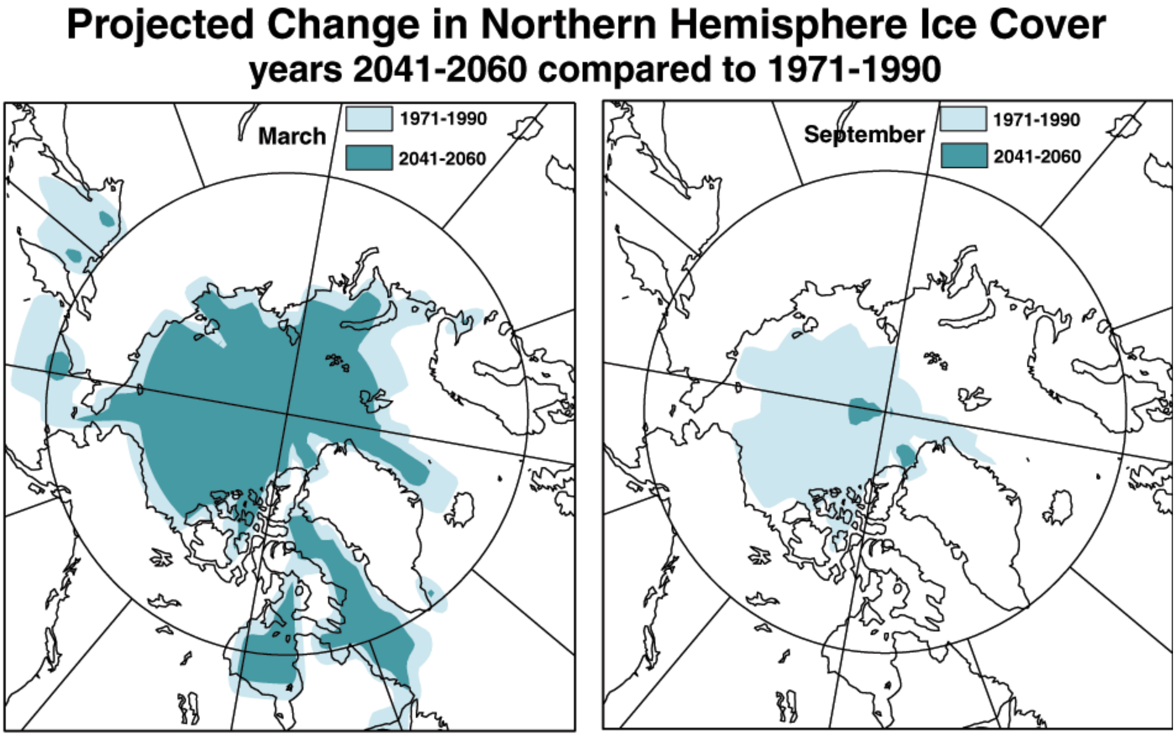
Regarding the dynamic processes, it has been shown that the sea-ice transport is notably sensitive to the choice of ice rheology. In this respect, there is a need for further research into improving the mathematical treatment of internal ice forces. Finally, there is increasing awareness among the sea-ice modelling community about the role played by the dynamic processes in the continuous modification of the state of the ice cover, especially via the opening and closing of leads and the formation of ice ridges. The development (or improvement) of parameterizations of these processes for use in climate models is one of the major challenges to be addressed in the immediate future.

The other crucial part of the sea-ice treatment in climate models is the proper determination of the fluxes between the atmosphere, sea ice and ocean components. In order to ensure this, it appears to be necessary to resolve more physical processes within the transition zones from one component to the other, i.e., to account for boundary layer processes including subgrid-scale features due to surface heterogeneities. There is also a need to continue to improve parameterization of the cloud-radiation interactions and interactions between the planetary boundary layer and clouds over the polar oceans.

7.1.5 Predicting Change

The response of the sea-ice cover of the polar oceans to a changing climate is of key concern. This is particularly important given the possibility that a transition to an ice-free state would have major feedback in the climate system, and might be irreversible. There is increasing evidence that changes to the Northern Hemisphere sea ice are already occurring, increasing the urgency of a good predictive capability. Using data from submarine cruises, Rothrock et al., (1999) detected a decrease of as much as 1.3 m in the mean draft of late summer sea-ice thickness in the deep water portion of the Arctic Ocean between 1958-76 and the 1990s. There is preliminary evidence that the ice has continued to thin through the 1990s. From satellite passive microwave data, Johannessen et al., (1999) show a 14% decrease in the area of wintertime multi-year ice in the Arctic from 1978 to 1998. Since there is a strong correlation between the extent of multi-year ice and the average ice thickness, this also suggests a decrease in the ice thickness. Several different studies have shown that Arctic sea-ice extent has decreased by about 3% over the last 25 years; the period for which satellite passive microwave data are available (e.g., Cavalieri et al., 1997). Using these and surface data, Vinnikov et al., (1999) derive a record of Northern Hemisphere sea-ice extent this century. Transient simulations using two different GCMs (forced by observed greenhouse gas and aerosol concentrations) show that there is less than 0.1% probability that the decrease in sea-ice extent between 1958 and 1993 is due to natural variability. Both models predict continuing sea-ice decrease.

Figure 7.2 provides an example of the change in sea-ice cover projected by the Canadian global climate model (CGCM2) when forced with a typical greenhouse gas and aerosol scenario. Of particular note is the near disappearance of summer ice cover in the Arctic. *Figure 7.3* shows the result of a similar study for the Southern Hemisphere using the CSIRO9/R21 coupled model forced by the IS92a greenhouse gas scenario. Although no significant trends have been yet observed in Antarctic sea-ice extent, this model simulation shows an accelerating decrease in Southern Hemisphere ice in the 21st century. Even in the absence of changes as extreme as these, changes in the ice concentration, extent, seasonality, and thickness all influence the manner in which the air and ice interact. Both theoretical and observational knowledge of the processes through which the ice, the ocean and the atmosphere interact must be improved in order to provide more confident predictions. In order to improve confidence, it will be necessary to test simulations of historical change on time scales from seasons to decades against observations. But present data sets, especially of ice thickness, are not adequate for the Arctic, and even less so for the Antarctic. There is also a need for better data on sea-surface-temperature in the seasonal sea-ice zone and in the transient marginal ice zone in particular.



Canadian Centre for Climate Modelling and Analysis, AES

Figure 7.2: Arctic sea-ice extent change in March and September at the middle of the 21st century as projected by the Canadian Centre for Climate Modelling and Analysis global coupled model (CGCM2).

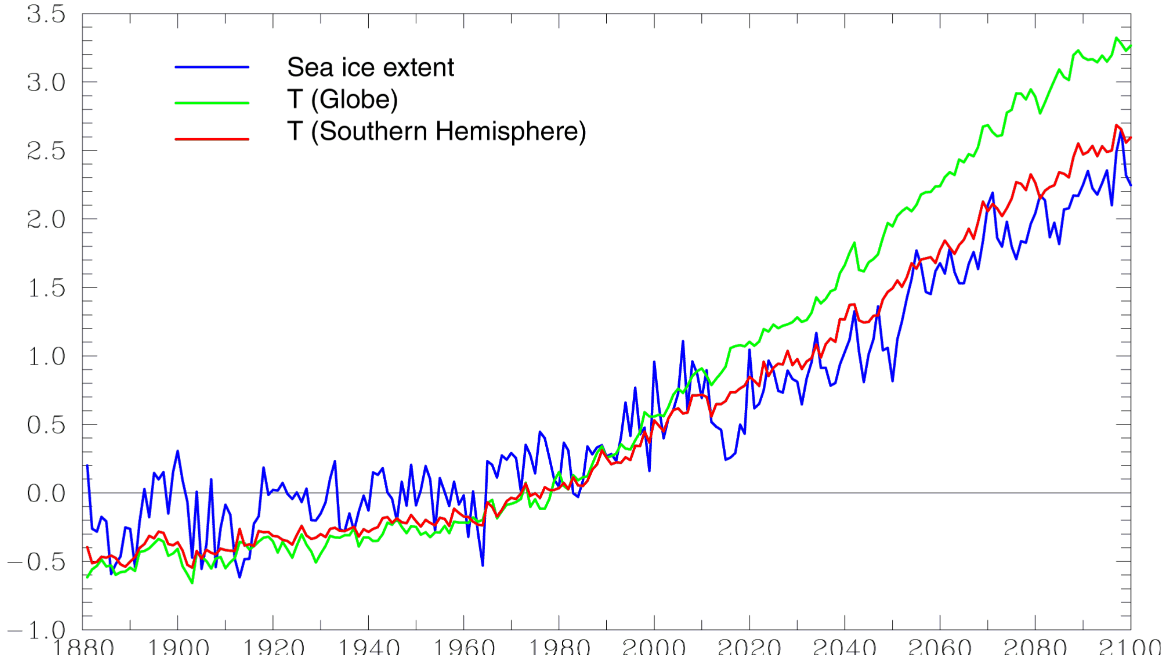


Figure 7.3: CSIRO9 coupled model simulations of the annual-mean Antarctic sea-ice extent and surface temperature for the globe and Southern Hemisphere, 1881 to 2100. Values are expressed as differences relative to the 30-year average between 1961 and 1990. Values of the vertical axis coincide for both global and Southern Hemisphere temperatures (˚C) and sea-ice extent (deg. Latitude; greater latitude indicating a reduction in sea-ice extent). Mean Antarctic sea-ice extent for 1961-1990 is 62.69ºS. After Wu et al., 2000.

7.2 SCIENCE STRATEGY FOR RESEARCH ON INTERACTIONS BETWEEN SEA ICE, OCEANS, AND THE ATMOSPHERE

Fundamental to achieving a better understanding of the role of sea ice in the global climate system is improved knowledge of the distribution of ice, its characteristics, its variability, and the processes which determine its growth, melt, and movement, and its interaction with the atmosphere and ocean.

This will require a combination of field observations, remote sensing, and numerical modelling of the coupled atmosphere-ice-ocean system. CliC sea-ice research will build on and co-ordinate with efforts initiated in the Arctic Ocean within ACSYS, and in the Antarctic under SCAR (e.g., ASPeCt) and SCOR (e.g., iAnZone). CliC will have a prime responsibility for integrating regional development in cryospheric research into the global climate effort.

A major objective will be to derive a climatological archive which documents the present and recent past distribution of the basic physical properties of pack ice in both the Arctic and Antarctic. Techniques contributing to this will include:

- a quantitative and qualitative improvement in the use of existing observational techniques such as upward-looking sonar and submarine acoustic profiling, ship-based measurements, and passive and active remote sensing;
- development and use of innovative ice thickness-measuring techniques, including acoustic and inductive electro-magnetic methods, radar and optical altimetry, and active remote sensing;

- the development and application of integrated techniques whereby directly measured data and data from satellite sensors are assimilated into sea-ice models to give an overall synoptic picture of the ice, and to derive optimized parameterizations in models; and,
- assembly and interpretation of historical and proxy sea-ice data sets.

A second objective will be to improve understanding of the processes of interaction between polar pack ice and other elements of the global climate system. This will include investigation of processes of ice formation, ice mass budget, water mass modification, the maintenance of polynyas, ice margins and coastal fronts, and air-sea interaction. A rigorous test of how well we understand the physics involved in these processes will be our ability to simulate correctly both Arctic and Antarctic sea ice, with their very different geography and forcing conditions, with globally-applicable process models.

Finally, it will be necessary to improve and validate parameterization of sea-ice processes in coupled atmosphere-ice-ocean models. This will include addressing the problem of processes and inhomogeneities that are sub-grid scale even in regional models, and of linking local to regional scale models and regional scale to global models.

8 CRYOSPHERE-CLIMATE INTERACTIONS ON A GLOBAL SCALE

8.1 CRYOSPHERE–ATMOSPHERE INTERACTIONS ON A GLOBAL SCALE

8.1.1 Representation of Cryospheric Processes in Climate Models

Cryosphere-atmosphere interactions have their origins, in the first instance, in the connections between the snow and ice-covered surface, the atmospheric boundary layer, and the atmospheric cloud and radiation fields. In this respect, a continuing key issues are:

- to understand and parameterize in models the direct interactions between the cryosphere and atmosphere; and,
- to provide the improved data sets necessary for this understanding.

This is essential if models are to represent the processes involved correctly. Considerable progress has been made in this area, but a number of uncertainties remain. In particular, there is a need to improve interactive modelling of the atmosphere and the elements of the cryosphere in respect of the surface energy budget and the surface hydrology, including fresh-water runoff. Improved formulations of 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 (the ablation zone). Improved data sets are also required. Continued efforts are needed to understand and represent the stable atmospheric boundary layer, which is often present over cold ice and snow-covered surfaces in winter. This includes improving our understanding and representation of the boundary layer over sloping terrain. A continuing issue is the treatment of clouds and radiation in cold regions, including the effects of so-called diamond dust. On the surface, the impact of the difference between riming and precipitation on surface albedo may need to be considered. Many of these issues are already being addressed under GEWEX and ACSYS, but some (e.g., surface albedo in ice sheet ablation zones; aspects of the stable boundary layer over sloping terrain) are not. As well as providing general support for such activities, CliC will also need to stimulate appropriate initiatives in these areas.

8.1.2 Cryospheric Impact on Broad-scale Atmospheric Circulation

The cryosphere also has a broader-scale influence on the temperature and humidity structure of the atmosphere and its circulation, affecting the mean state and variability of the atmosphere as well as longer time-scale climate change. An important aspect of this is to understand the impact of cryospheric anomalies on the atmosphere. A number of both observational and modelling studies of the influence of snow and ice anomalies on the atmospheric circulation have been undertaken in the past. However, full quantification of the scale and relevance of cryospheric anomalies for the atmospheric circulation and their impact on its variability remains to be determined. Key questions in this respect are related to:

- How, depending on the components of the cryosphere involved, does the storage of (negative) latent heat and water in snow and ice cover modulate the climate on different time scales?
- What are the interactions between anomalies in the extent of the cryosphere and the major components of climate variability? In particular, how does the snow/ice cover interact with the North Atlantic Oscillation/Arctic Oscillation and with the corresponding Southern Hemisphere annular mode (Thompson and Wallace, 1999) and the Antarctic Circumpolar Wave, and how do these influence the cryosphere in turn?

The presence of the Greenland and Antarctic ice sheets is well known to have a major influence on the character of the atmospheric flow. For example, the Antarctic ice sheet has a demonstrated influence on the Southern Hemisphere jet stream; the Greenland ice sheet on the pathways for transport of heat and moisture and cyclone tracks over the North Atlantic and into the Arctic. In addition, spring snow cover on the Tibetan Plateau is a factor in determining the timing and intensity of the Asian summer monsoon. Past studies have helped to elucidate these influences, but questions still remain. On longer time scales, the following topic is of particular and continuing interest:

- What is the response of the atmosphere to large-scale changes in snow and ice distribution on time scales of 10^3 - 10^6 years?

The topic is being addressed both through modelling experiments incorporating past ice sheet and other changed boundary conditions and through palaeoclimatic data studies.

8.1.3 Atmospheric Influences on Large-scale Cryospheric Change

The atmospheric circulation, of course, determines the pathways for moisture transport that controls the mass balance of the ice sheets themselves. While we have a good idea of the mean atmospheric moisture transports, the impact of climate variability on them is less well known. Determination of the pathways of moisture transport, its magnitude and variability, is limited by the available observations. For example, the periphery of the Antarctic continent is poorly served by radiosonde observations and we must therefore increasingly turn to the use of models to help resolve the transports and their variability. The issue particularly important to determine is:

- What is the atmospheric contribution, both in terms of its mean and variability, to the mass balance of the ice sheets; and how will this change with the effects of global climate change?

The atmosphere may be implicated in observed changes in the cryosphere. The warming of the Antarctic Peninsula and the break up of a number of ice shelves in the region in recent years, in particular the Wordie and Larsen A Ice Shelves, are well known. The mechanisms by which this takes place are not known. A particular question, therefore is:

- What role has the atmosphere played, if any, in determining the recent observed changes to the cryosphere in the Antarctic Peninsula region?

8.1.4 Atmosphere – Cryosphere Feedback

Finally, an important aspect of the cryosphere for global change is the well-known effect of ice-albedo feedback. In its simplest terms, the mechanism for this is that reduced ice or snow extent at the surface leads to increased surface heating from additional absorption of solar radiation arising from reduced surface albedo. This in turn further reduces ice/snow cover leading to amplification of the effect. However, the process is eventually limited by changes in other parts of the system, in particular in the atmospheric cloud and radiation fields and the atmospheric circulation. These processes need to be accurately represented in models if the magnitude of global change and its impacts on the cryosphere are to be better established. Given the well known impact which ice albedo feedback is known to have on the high sensitivity of the polar regions in the transition seasons to climate changes induced by increased greenhouse gas concentrations, a continuing question is:

- How does the atmosphere and, in particular, its fields of cloud and radiation respond to and help to determine systematic changes in the ice and snow cover (Groisman et al., 1994), and how will this influence the response to global climate change?

The key here is the provision of accurate, and scientifically justified, parameterizations of cryospheric processes and their interactions with the atmosphere. Appropriate data sets are needed to both derive and verify model parameterizations and to provide the appropriate boundary conditions needed as input to the models themselves.

8.2 SCIENCE STRATEGY FOR GLOBAL SCALE CRYOSPHERE-ATMOSPHERE INTERACTIONS

Many of the issues raised in Section 8.1 (Cryosphere-Atmosphere Interactions on the Global Scale) are relevant to wider aspects of CLIVAR and GEWEX and it is anticipated that strong links will be required between these components of WCRP and CliC in investigation of these issues. Key tools for exploring these issues will be atmospheric and coupled atmosphere-land surface-ocean general circulation models (GCMs) as well as ocean and sea-ice models driven by atmospheric surface forcing either from atmospheric GCMs themselves or, for example, from re-analyses. As noted, a key issue is continued improvement of the parameterizations in models of the interactions between cryosphere and atmosphere. A particular role for atmospheric models is in their use for sensitivity experiments, for example to help determine the impact of snow and ice cover changes on the atmospheric circulation. A limited number of such experiments have been carried out in the past, but more are urgently required. For example, to help determine whether the snow/ice cover provides information that is useful for the predictability of the atmosphere on seasonal to inter-annual time scales (relevant to CLIVAR GOALS and GEWEX). Other types of sensitivity experiments will also form part of the strategy for CliC (e.g., to help clarify the role of the large ice masses on the atmospheric circulation by modification of model boundary conditions such as land surface topography, albedo, etc.). Such experiments are relevant to the determination of how atmospheric circulation might change in response to changes in ice cover on palaeoclimatic time scales. In this context, the use of atmospheric models to help establish the geographical extent of climate anomalies seen in ice core records, and whether they are likely to be of truly global or only regional significance, may prove a valuable approach. True time-dependent palaeoclimate experiments are now becoming possible with coupled atmosphere-ocean models incorporating land ice dynamics. Such work is being addressed as part of IGBP PAGES.

At the same time, CliC will encourage the analysis of atmospheric data sets to identify observational evidence of cryosphere-global atmosphere interactions, and their impact on climate variability (relevant to CLIVAR DecCen). It is anticipated that atmospheric re-analyses will provide valuable data sets for such work. Changes in storm tracks and modes of circulation related to snow and ice anomalies (Clarke and Serreze, 1999) provide an example of such work. Palaeoclimate reconstruction for the recent past, where feasible, will provide a longer time scale perspective. The role of the cryosphere in atmospheric/climate variability will also be explored with use of coupled models that will contribute to understanding of the role and response of the cryosphere to greenhouse gas-induced climate change (with links to CLIVAR ACC).

Existing activities within the ACSYS Arctic Atmosphere Programme include the development of Arctic atmosphere historical data sets, and the development of data sets of atmospheric forcing on sea ice and the ocean (for integration of ice-ocean models and verification of coupled climate models). The work of the ACSYS Panel on Polar Products from Re-analysis supports this activity.

Aspects of the work of the ACSYS NEG and of the WCRP Working Group on Coupled Models are also relevant.

8.3 CRYOSPHERE-OCEAN INTERACTIONS ON A GLOBAL SCALE: KEY QUESTIONS

Polar Region processes involving both sea-ice and shelf/basin exchanges affect and are affected by the Global Ocean Conveyor Belt and its loops. Therefore, the polar regions, through their cryospheric components, are fully interactive elements of the global conveyor.

8.3.1 Cryospheric Impact on Thermohaline Circulation

The oceanic heat transport has an obvious and well-known impact on climate. Most of this heat transport is a consequence of the warm-to-cold water conversion associated with the thermohaline circulation (THC), which originates in the polar and sub-polar sea areas of both hemispheres. If the THC is altered, presumably the oceanic meridional heat transport is also altered, and with it, the nature of the global heat balance.

The roles of sea ice, glacial ice and the polar hydrological cycle are crucial in affecting the surface buoyancy flux that controls the vertical overturning that regulates the THC. In the Northern Hemisphere, principal effects are associated with the hydrological cycle (riverine fresh-water input, sea-ice transport through restricted passageways), whereas in the Southern Hemisphere sea-ice formation and transport, and glacial melt from the ice shelves are the principal processes. The specific role of iceberg meltwater in both hemispheres is currently not well known, though it is thought not to be a major contributor to the fresh-water budget in the Arctic. However, extreme calving events, as have occurred during the past few years in Antarctica, might have the potential to affect the water column stability in areas of deep and bottom water formation.

There are a number of questions related to the time scales over which the THC influences climate. For example, the THC has been implicated in abrupt climate change as well as long-term climate change (through changes in heat, fresh water and storage of atmospherically active gas). However, it is still not clear if short term changes in the THC itself drive significant changes in climate or if they are a consequence of the climate change. Thus, to evaluate any such influences properly, we must improve our general understanding of the THC and its sensitivity to processes in polar regions. This includes improving our understanding of how the surface forcing is changing and how such changes may alter the dominant atmospheric patterns corresponding to some aspects of the THC (such as the state of the North Atlantic Oscillation (NAO) and of the Antarctic Circumpolar Wave (ACW)). In addition, the THC is at the heart of model-generated internal modes of decadal and longer variability. These are the only known modes of long-term internal climate variability, and consequently there is great interest in determining their fundamental mechanisms and sensitivities.

Finally, the intermediate water components of the THC, such as the Labrador Sea Water, Antarctic Intermediate Water and Subantarctic Mode Waters all spread away from the poles to extra-polar gyres where they set the characteristics of these gyre's pycnocline. Consequently, they determine the volume of the surface water and its ability to mix with deeper waters and, as such, they strongly influence the SST for any given surface flux (which plays a predominant role in the atmospheric temperature). Therefore, changes in these intermediate waters can lead to changes in subtropical SST on longer time scales and broader space scales than those that instigated the change in the intermediate waters.

The following questions have to be answered:

- What are the atmosphere-ice-ocean processes that influence the THC variations? For example, what is the effect of the sea-ice distribution and ice-albedo feedback on the stability and heat content of the pycnocline?

- What is the sensitivity of the THC to changes in fresh water, heat and momentum fluxes; to changes in perennial ice fields in response to variations in river input and ice transport from the Arctic; and to changes in deep water formation within the Arctic Ocean itself (Anderson et al., 1999)?
- What is the sensitivity of specific deep-water formation processes; such as, slope convection or open-ocean convection, and accompanying changes in sea-ice distribution, as well as impact of changes in coastal polynyas (especially in the Antarctic)?
- What is the sensitivity of the global THC to changes in the Arctic Ocean circulation that provides the fresh-water transport from the Pacific to the Atlantic Ocean?
- Under which conditions can sudden transitions of the THC and sea-ice distribution to another state occur (e.g., from ice cover to polynya conditions; truncation of NADW; etc.)?
- What is the relationship between the large scale extra-polar patterns (such as NAO, PNA, etc.) and polar patterns related to cryosphere characteristics that influence the THC? What are the various driving mechanisms, controls and feedbacks?
- What is the influence of cryospheric changes in the subduction of cool and fresh polar/subpolar waters, which may themselves influence and otherwise control the subtropical oceanic stratification and thermohaline characteristics (e.g., by altering the thermohaline properties at the base of the surface layer)? What are the sensitivities?

In the Southern Hemisphere it is thought that these processes are intimately related to the nature of the sea-ice distribution and to surface divergence at the northern rim of the polar gyres. Thus this involves addressing a number of more specific issues related to the nature of the sea ice and surface ocean feedback, as well as general atmosphere-ice-ocean interactions.

8.3.2 Impact of the Thermohaline Circulation on the Cryosphere

The global THC provides the source water masses in both hemispheres for the poleward heat and salt transports that are required to maintain the stratification in polar and subpolar seas. Changes in the ocean stratification influence the sea-ice cover (e.g., the large Weddell polynya of the seventies might have been formed by increased inflow of warm and salty Circumpolar Deep Water).

- What are the atmosphere-ice-ocean (AIO) processes by which the THC influences changes in sea-ice distribution? For example, what is the effect of stability and heat content of the pycnocline on sea-ice distribution?

8.3.3 Cryospheric Impact on the Large-Scale Meridional Gradient

In addition to the fairly direct influence the cryosphere may have on the THC and sea level, it can also influence the large-scale climatic circulation not only by changing the nature of the pycnocline (or ocean stratification), but also by altering the meridional pole-to-equator thermal gradient. The Arctic Ocean is the main pathway for the return flow to the North Atlantic of the fresh water from the North Pacific, via Bering Strait, and that delivered to the Arctic by river runoff. Any change in surface energy balance in the polar regions can lead to changes in the energetics involved in the large-scale meridional heat transport, of which the ocean contributes approximately 50%. Such changes may change both the oceanic and atmospheric circulation, driving commensurate changes in the global energy balance and nature of the climate itself. The mechanisms involved in this are not fully understood. Neither are the various feedbacks that can be expected to accommodate any such change in this heat transport. Here the question is more global and involves fundamental mechanisms and global circulation dynamics and thermodynamics:

- What role does the cryosphere play in the mechanisms, processes, feedbacks and sensitivities controlling the large-scale ocean and atmospheric circulation as a function of the global meridional thermal gradient?

8.3.4 Efficiency of Carbon Uptake and Exchange

The ocean plays a major role in the global carbon cycle, and the sequestration of atmospheric carbon by the ocean is critical to the overall radiative balance of the Earth. Presently, the ocean takes up a large fraction of the carbon dioxide introduced to the atmosphere each year by anthropogenic processes. This uptake is a reflection of three primary processes:

1) the solubility pump whereby the colder the ocean gets, the more CO_2 it can sequester in near surface waters;
2) the biological pump, whereby the oceanic planktonic biota takes up CO_2 and then releases it upon death, decaying and sinking into the deep water; and,
3) deep water formation and entrainment, whereby CO_2 in surface and intermediate waters is transported directly to deeper layers.

Carbon budgets for the Arctic Ocean indicate that it does not at present represent a major sink region (Anderson et al., 1998a, 1998b). Model results suggest that a primary factor in the response of the ocean to carbon uptake under conditions of global warming may be a reduction in the effectiveness of the solubility pump. This presents a positive feedback, since the increased warming will lead to a reduction of the ocean uptake and thus a more rapid global warming. Model results also indicate that in high southern latitudes, the effectiveness of the solubility pump is not reduced so much by warming of the surface water. Instead, the increase of fresh water in the sub-Antarctic polar regions may reduce the production of intermediate water, and thus reduce the transport of newly absorbed CO_2 from the surface into the deeper layers. That is, the ocean cannot transport the CO_2 away fast enough to maximise uptake. While this particular inference is the result of a less-than-perfect model, it does point to the hydrological cycle (precipitation and evaporation, as well as sea-ice formation and melt) in the polar regions as being of fundamental importance in this process. This warrants additional study, as does the overall susceptibility of the ocean to uptake of CO_2 in the circumpolar region where it is presently highly efficient. The central issue is:

- What are the processes and sensitivities controlling the exchange of CO_2 between the ocean and atmosphere in polar regions and its subsequent sequestering in all layers from the surface to the deep water, including the role of sea ice and the larger scale mechanisms and feedbacks controlling these processes?

8.4 SCIENCE STRATEGY FOR GLOBAL-SCALE CRYOSPHERE-OCEAN INTERACTIONS

There are a number of gaps that currently exist, and which need to be addressed in order to advance our understanding of climatically-relevant interactions between the cryosphere and global ocean. Many of these issues are presently being addressed, or have been targeted for study, by projects within WCRP (e.g., CLIVAR, ACSYS, GEWEX); IGBP (e.g., PAGES), SCAR (e.g., ASPeCt, GLOCHANT), and SCOR (e.g., iAnZone), among others. Some of these activities are outlined in Chapter 4 of the WCRP report of the first CliC Task Group Meeting (WCRP, 1999a). The relation to CLIVAR needs special consideration, because detailed knowledge of water mass distribution and circulation in polar oceans is required to fulfil the goals of both CLIVAR and CliC, implying a natural overlap of the two. Consequently, appropriate studies are suggested in both projects. CliC will emphasize the effect of the ocean on the cryosphere whereas CLIVAR will emphasize the relation between the polar and the global oceans. However, as both are subject to interactions, they cannot be understood separately. Communication at the level of the scientific steering groups is required to ensure that no gaps occur.

In addition to these general issues, a number of particular needs regarding models, data, and process study requirements have been identified as central to this component.

Many of the issues outlined previously are explicitly tied to details of the cryosphere, which are functions of local scale AIO processes. For example, the growth/decay and transport of sea ice dominates the fresh-water budget in many polar locations and thus the ability of the ocean to convect and form deep water. Thus, the cryospheric characteristics require treatment of the smallest scale processes (often sub-grid-scale) in order to properly simulate their influence. A number of such processes have been identified that require considerable attention in order to improve their representation in models. These include vertical convection, boundary layer processes (AIO interactions in detail, including ice-cloud, ice-albedo and ice-ocean feedbacks, exchanges and interactions), sea-ice dynamics and thermodynamics (including improved prognostic representation of leads and thickness distribution), and ice-ocean shelf interactions. The entire treatment of the hydrological cycle in polar regions is inadequate, as is the treatment of air-snow-land interactions that influence runoff into the oceans.

Presently, climate models often drive the thermohaline circulation by open-ocean convection, which does occur, but is not the dominant process. There must be considerable improvement in the treatment of THC source mechanisms and processes, and subsequent circulation characteristics, such as plume and flow rates, characteristics, paths and entrainment (these dictate, among other things, how the THC waters will influence the subtropical pycnocline, and how they will influence the meridional circulation).

These problems require a hierarchy of models, from detailed process models, through regional- to global-scale models.

There is a dearth of oceanographic observations in polar regions where the cryosphere has its biggest impact on the ocean circulation. In particular, there is a need for increased time-series of data so that patterns of response and the nature of the AIO interaction under a variety of conditions can begin to be established. Especially important are surface salinity measurements in high-latitude regions (since salinity dominates the density and other upper ocean characteristics that influence THC, sea-ice distribution and water properties). Also important are observations of co-varying fields of sea-ice forcing parameters (air temperature, salinity and wind speed), so that the relationships between easily observed system components can be diagnosed, models initiated and forced correctly, and physical relationships understood. Finally, there is also a need for tracer observations to allow us to accurately determine the rates, paths, mixing and residence times of the different water masses and ice sources involved in the ocean-ice processes.

Satellite observations of sea-ice distribution, supplemented by thickness observations (providing mass balance estimates for fresh-water and energy budget estimates) are essential. These must be supported by upper ocean and lower atmosphere profile measurements so that the surface conditions and ice characteristics can be interpreted in terms of the total upper ocean and lower atmosphere budgets.

Existing data archives of these critical cryosphere variables must be preserved and extended with the new observations.

9 CRYOSPHERIC INDICATORS OF CLIMATE CHANGE

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. The temperature of a melting surface cannot exceed the melting point. Higher air temperature leads to an increase of the downward fluxes of heat and long-wave radiation. In contrast to a "normal" surface, a melting surface cannot compensate for this by emitting more long-wave radiation, so all the surplus energy is used for melting. This is why sea ice, snow cover and glaciers are very sensitive to temperature variations. *Snow Watch '92* (Barry et al., 1993) was held specifically to review strategies for detection of changes in global snow and lake ice cover as climate system indicators.

The cryosphere is common to regions where records from conventional observations are often short or completely lacking (remote sparse data networks); hence conventional *in situ* measurements, specialised field studies and more recent remote-sensing data are all essential in studying the cryosphere. Care must be taken to understand the measurements to ensure their compatibility. It is of great importance to continue existing time series of the extent of sea ice, snow cover, and permafrost; and of glacier geometry and mass balance. The cryosphere as an indicator of climate change is one aspect within the science plan of the CRYSYS (Cryospheric System to Monitor Global Change in Canada) investigation within NASA's Earth System Enterprise (ESE).

9.1 MONITORING CRYOSPHERIC INDICATORS OF CURRENT CHANGE

9.1.1 Sea Ice

Sea ice is responsible for numerous feedbacks to the global climate system (e.g., albedo, surface energy transfers, deep water formation, transport of latent heat and fresh water) and the monitoring of key properties of sea ice (extent, concentration, thickness distribution) is important for climate change detection and model validation studies. Sea-ice extent, concentration, and thickness distribution are controlled by a complex interaction of oceanic and atmospheric dynamics and thermodynamics. The sensitivity of sea ice to climatic change is therefore complex, and according to Fitzharris (1996), difficult to determine. Empirical data and GCM experiments suggest that sea-ice extent should shrink in response to a CO_2-induced climate warming. Remote sensing and *in situ* data are essential if sea ice is to be used effectively in the detection of change in the climate system.

Empirical data from satellites suggests that sea-ice extent in the Northern Hemisphere is declining (Bjørgo et al., 1997; Cavalieri et al., 1997; Parkinson et al., 1999) at 3% per decade with large inter-annual variability since the late 1970s. This observed change in Northern Hemisphere sea-ice extent has been linked using GCM studies to anthropogenically induced climate change (Vinnikov et al., 1999). Southern Hemisphere data show large regional differences, with a small significant increase for 1978-1996, mostly from increases at the end of the time series (Gloersen et al., 1999). Coupled GCM experiments give differing predictions of changes in sea-ice extent for future climate scenarios; many show reductions in sea-ice extent in the Northern Hemisphere, while Southern Hemisphere sea ice shrinks in some, but may actually expand in others. The best indicator of climate change is ice volume. The results of 40-year sea-ice model simulations for the Arctic conducted by the ACSYS-NEG indicate that the largest response and variability should be apparent in ice volume and surface deformation, but systematic monitoring of these conditions has barely begun. Ice volume determination requires knowledge of the measured ice-thickness distribution, as well as ice extent data. Analysis of the limited submarine sonar data suggests a significant decrease in sea-ice thickness in the central Arctic Ocean over the last few decades (Rothrock et al., 1999). This is supported by satellite evidence of a decrease in the fraction of thick multi-year ice in the Arctic (Johannessen et al., 1999). Shipboard or other direct measurements of ice thickness, as well as records from moored upward looking sonars, are also becoming more widely available. However, data limitations, especially for the Antarctic, will reduce the confidence level of change identification in current and future analyses, unless new data sources and techniques can be developed.

Another present difficulty is the highly regional nature of the trends and variability in both hemispheres. Walsh (1993) showed that warming in the central Arctic corresponded with reductions in sea ice, but the overall decrease was mitigated regionally by increases in other areas such as the Labrador and Kara Seas. Similarly in the Southern Hemisphere, a secular decrease in the Bellingshausen-Amundsen Sea region (Jacobs and Comiso, 1993) is balanced, with increases in ice extent in the Weddell and Ross Seas giving overall no change or a slight increase in circumpolar ice extent.

9.1.2 Snow Cover

Regular satellite-derived observations of Northern Hemisphere snow extent have been made since the late-1960s (Robinson et al., 1993). Robinson et al., (1991) used these data to document a close inverse relationship between hemispheric snow extent and surface air temperature. Groisman (1994) analysed these data further to demonstrate that snow exerted the strongest positive feedback on the Earth radiative balance during the spring period. These findings suggest that spring snow extent should be a sensitive indicator of hemispheric temperature changes. Recent efforts to expand the Northern Hemisphere satellite snow extent record with *in situ* data (Brown, 1997) provided evidence of a significant decrease in spring snow extent over Eurasia since 1915.

Areal extent, however, is only one characteristic of snow cover. Goodison and Walker (1993) presented other potentially important indicators of changes in snow conditions that should reflect changes in climate. These include:

- 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; and,
- change in spatial distribution of snow cover over a region.

These parameters can be determined from a growing number of both *in situ* and remotely sensed snow data sets to obtain insights into regional and continental-scale variations in snow cover, particularly over North America and Eurasia. A time series of monthly Northern Hemisphere snow cover has been prepared for the combined SMMR and SSM/I data sets for 1978-present (Armstrong and Brodzik, 1999). Seasonal biases in these estimates have been identified, with the passive microwave derived products significantly underestimating snow extent during the October-December period. This again highlights the need for multiple data sources to provide the suite of snow cover indicators outlined above. Several algorithms have also been developed to estimate snow depth and snow water equivalent (SWE) on a regional basis. Evaluation of these new products is in progress; however, there is currently no global product of SWE. In addition to monthly data, information about daily variability is important for modelling and impact studies. Daily maps of Northern Hemisphere snow extent replaced the previous NOAA weekly product in 1999.

9.1.3 Lake Ice Freeze-Up and Break-Up

Numerous empirical studies have clearly established a close correlation between freeze-up and break-up dates of lake ice and air temperatures during the early winter and spring. Long series of lake-ice observations can serve as a proxy climate record, and the monitoring of freeze-up and break-up trends may provide a convenient integrated and seasonally specific index of climatic perturbations. Skinner (1993) reported strong regionally statistical relationships between composite lake ice conditions and mean air temperatures for Canadian regions, with lake ice as a useful indicator of climate change in the spring and fall transition period. Such information on freeze-up/break-up can be used to infer information about temperature variations and trends in data-sparse areas of the world such as the Canadian Arctic and Siberia.

The new generation high resolution visible and microwave satellites will permit the routine monitoring of ice formation and decay of both small shallow and larger deep fresh-water lakes (e.g., Barry and Maslanik, 1993; Walker and Davey, 1993; Duguay and Lafleur, 1997). Small lakes are well suited for cryospheric monitoring because the effects of heat storage and circulation are reduced; larger lakes provide an integrated response to regional change involving several related elements (e.g., temperature, precipitation, runoff). There is a clear need to combine *in situ* and satellite data to generate longer time series for change assessment, although this will require some care as the two sources of data have quite different spatial scales (point versus area).

9.1.4 Permafrost/Active Layer Thickness

Thickening of the active layer and changes in the distribution of permafrost are important indicators of warming in the Arctic. The difference between them is that the first is an immediate indicator of climatic warming, while the retreat of permafrost requires substantial time after new climatic conditions have been established. Circumpolar active layer monitoring has been started under the CALM International project and currently data are available for 1991 -1997 from 69 sites in North America, Eurasia and Greenland (*Frozen Ground*, No. 21, 1997). Three types of active layer observations have been performed:

1. Probing of grids ranging in size from 10 to 1000 m (up to 121 points): performed at 45 sites;
2. probing at a single point or transects: at 20 sites; and
3. temperature measurements and interpolation of thaw depth: at 50 sites.

The collected CALM data (available via http://www.geography.uc.edu/~kenhinke/CALM), together with the climatic data (air temperature, precipitation), are available on the International Permafrost Association (http://www.geodata.soton.ac.uk/ipa) and ITEX web sites. These provide an excellent resource for the study of the short-term reaction of permafrost to climate fluctuations. The IPA is organising a Global Terrestrial Network for Permafrost (GTNet-P) monitoring of active layer thickness and permafrost thermal state as a contribution to GCOS. Efforts are underway to expand the CALM network to the Southern Hemisphere. To study the reaction of permafrost, longer time-series of observations are necessary to evaluate tendencies in active layer changes and horizontal retreat of the permafrost boundary. Indications that such retreat has already begun were found in the Russian part of the Arctic, where parts of the southern boundary of permafrost were reported to be shifting northward in the last several decades (Pavlov, 1997). Considering active layer data and distribution of permafrost as cryospheric indicators of anthropogenic warming, it is important to distinguish between the impacts caused by climate change and other factors, such as changes of land use, technological impacts and effects of changing vegetation. There is a potential for multiple feedbacks that in some cases can make questionable even the sign of the response of permafrost and active layer thickness to climatic warming. An example is given by Walker et al., (1998), who compared the active layer thickness in moist non-acidic tundra (deep thaw) and acidic tundra (shallow thaw). Climate warming creates prerequisites for the increasing plant density and evolutionary transitions from non-acidic to acidic tundra. Such changes, despite increasing air temperature, could mitigate the impact of changing climate on the active layer thickness, or even lead to modest decreases.

9.2 CRYOSPHERIC RECORDS OF HISTORICAL CHANGE

9.2.1 Mass Balance and Extent of Glaciers

Mass balance has been measured on 40-50 glaciers for up to six decades. These measurements are very useful as they directly reflect climatic conditions, whereas glacier extent responds to changes over a longer time period. There is, however, a problem of global coverage. Mass balance measurements tend to be clustered (Alps, Norway, Iceland, Svalbard, North America) and there is a need for a more strategic approach to these measurements. The current mass balance programme should be reinforced and expanded to obtain a better global coverage.

Records of glacier length exist for the Alps, Scandinavia, Iceland, Svalbard, Canadian Rockies, tropics (Africa, South America, Irian Jaya), New Zealand and Central Asia. Some are 50 - 100 years long, and a few in Europe are up to 400 years. Recent moraines are found almost everywhere in the world. Historical records of glacier fluctuations have demonstrated that glaciers are sensitive to climatic change. Many small equatorial glaciers in east Africa, Irian Jaya and South America are rapidly disappearing due to a recent rise in snow line (Kaser, 1999; Diaz and Graham, 1996).

The current global searchable inventory at NSIDC (http://www-nsidc.colorado.edu/NSIDC/Catalog/ENTRIES/GO1130.html) contains about 40 percent of the world total of approximately 160,000 glaciers, a number estimated from statistical extrapolations (Meier and Bahr, 1996). Existing inventories generally give the glacier name, location, area, length, orientation, and topographic classification (Haeberli et al., 1998). Temporal data showing trends or fluctuations exist for only 1,533 glaciers world wide, and only 736 of these have been measured in the 1990s for frontal position and change of length. Detailed monitoring of hydrologic mass balance and precise tracking of glacier margins exists for only about 50 glaciers world wide.

Extensive meteorological experiments carried out in recent years have made it possible to model the relation between climate and glacier mass balance with greater accuracy. Such mass balance models have been coupled to ice-flow models. The resulting glacier model enables a calculation of the full dynamic response of glaciers to climatic change. In some recent studies it has been demonstrated that with such a glacier model, a mass balance history (i.e., a climatic signal) can be reconstructed from the record of glacier length. So the vast amount of data on glacier fluctuations in historic times can now be explored by modern modelling techniques. Typically, 50 glaciers could be used for inverse modelling. However, this modelling technique still needs to be validated for high-latitude cold and polythermal glaciers.

9.2.2 Mass Balance and Extent of Ice Caps, Ice Sheets and Ice Shelves

Ice sheets generally respond to climate forcing on long time scales spanning glacial/interglacial periods (10^4-10^5 year), and thus we cannot easily relate changes to recent climate variations. It is timely to use satellite data in combination with calibrated mass-balance models to obtain mass balance for a well chosen set of ice caps and for selected basins of the large ice sheets. Data from optical sensors and radar should be combined. A pilot study for central West Greenland has shown that a yearly balance can be estimated quite well from the evolution of the albedo pattern from NOAA-AVHRR images (Stroeve et al., 1998). Mass balance could thus be reconstructed back to the late 1960s- early 1970s. Radar altimetry measurements have already been used to estimate elevation changes for interior Antarctica from 1992 to 1996 (Wingham et al., 1998a).

Through various satellite techniques it is possible to monitor the extent of ablation zones (Abdlati and Steffen, 1995) and blue ice areas. More generally, wet melting surfaces have a characteristic spectral signature, which makes it easy to identify melt digitally from a number of satellites. A global melting signal can be defined that can be monitored from space relatively easy.

Some ice shelves may have fast response to climate variations. Ice shelves along the Antarctic Peninsula are at relatively high northerly latitude, and probably at the climatic limit at which ice shelves can exist. There has been significant atmospheric warming in the Antarctic Peninsula region since 1978. A number of ice shelves in the region, particularly the more northerly ones, have retreated dramatically in the past fifty years. In January 1995, 4200 sq. km of the northern Larsen Ice Shelf broke away: the two northernmost sections of the ice shelf fractured and disintegrated almost completely within a few days. This break-up, following the longer steady retreat, suggests that after an ice shelf retreats beyond a critical limit, it may collapse rapidly (Doake et al., 1998). The retreat of the Peninsula ice shelves is probably a result of climatic warming, either regional or global, but continued monitoring of the ice shelves is essential. However, it is unlikely that the break up could spread to the larger ice shelves further south, as they are well within the climatic limit for survival.

9.2.3 Borehole Temperatures

A number of studies have been made on borehole temperatures from ice sheets, ice caps, permafrost, and in bedrock. These have demonstrated the great potential for deriving temperature records for the last several centuries. Borehole temperatures are relatively easy to obtain. The surface temperature record can be obtained by means of inverse modelling. It should be realized, however, that diffusion is effective in smoothing out temperature changes on a relatively short time scale, so rapid changes (decade) cannot be detected. There are many ice caps and permafrost sites that can be exploited, and many of these are in regions where instrumental records are scarce or absent. Over 180 borehole sites in the Northern Hemisphere, that can provide thermal data to be included in the GTNet-P, have been identified *(Figure 5.3*).

9.2.4 Shallow Ice Cores

Ice cores covering the last few centuries can give information on temperature, snow accumulation rates and other parameters (for example, there is potential to estimate sea-ice extent from ice core chemical records). Polar ice cores especially deliver a wealth of information, although the climatic interpretation on shorter time scales is not always straightforward. Shallow cores are collected in many existing projects including ITASE in Antarctica and ICAPP in the Arctic. In recent years, several cores have been drilled on low-latitude ice caps (e.g., Peru, China). These have demonstrated the usefulness of such cores for reconstructing past climatic change. However, in the inner tropics, a rapid rise in snow line has led to surface melting and the obliteration of the important Quelccaya Ice Cap record (Thompson et al., 1993). New ice cores are, however, being collected at higher elevations in the tropical Andes. By looking at suitable combinations of the chemical and physical records from these cores, there is a great potential for pinning down quasi-cyclic climatic events during the last 10,000 years or more (e.g., ENSO, NAO, position of ITCZ). When analysed carefully, shallow ice cores from sub-polar ice caps may reveal a precipitation history.

9.3 PROXY RECORDS FROM THE DISTANT PAST

Data from glacier extent, borehole temperatures and ice cores complement the existing instrumental records of temperature and precipitation. Information can be extended back in time, and spatial coverage can be greatly improved. The longer perspective can indicate how significant recent changes are in relation to natural variability.

9.3.1 Deep Ice Cores and Ice Ages

Geomorphological evidence of past glacier and ice sheet extent complement the historical glacier records. Information can be extended in some cases more than 150,000 years, and spatial coverage is nearly global in contrast to the modern glaciological data. The longer perspective can indicate how significant recent changes are in relation to natural variability.

Deep ice core records of a suite of atmospheric and chemical variables can extend climate histories through past millennia and back into previous climatic cycles. Its geographical location, ice thickness and climatology combine to make Antarctica the storehouse of the longest and most representative proxy data for the composition and temperature of ancient atmospheres. Such records are the domains of programmes like IGBP PAGES and GLOCHANT PICE but they can be extensively exploited by CliC. Deep ice core recovery from Antarctica is ongoing under projects such as EPICA and WAIS. Along with other records of the distant past (marine and continental sediments, coral terraces, geological data), deep ice cores have evidenced major interrelated fluctuations of climate and the cryosphere on the time scales of glacial-interglacial cycles. Consistent and accurate information on climate change on polar ice sheets (temperature, accumulation, etc.), global and regional climate change forcing (green-house gases, dust, cloud condensation nuclei, etc.), and potential changes in ice sheet surface elevation are available from ice cores. This information quantifies climate sensitivity in ice-covered regions and provides benchmarks against which theories and models of polar climate, mass balance and sea-level changes, past and future, can be tested.

Ice cores have also presented the first clear evidence of very rapid (transitions in decades) climate changes in the past, in particular the Dansgaard-Oeschger events. Combined with other palaeoclimate records, ice core records show that the cryosphere has played a major role in such changes, especially through the interplay between ice sheets, fresh-water input to the oceans, changes in ocean circulation, and climate. Common markers in Greenland and Antarctica allow bipolar studies of the north-south phasing of change, giving further clues about the operation of the cryosphere-climate system.

9.4 SCIENCE STRATEGY FOR CRYOSPHERIC INDICATORS AND MONITORING

The science community has devoted considerable attention to the definition of appropriate cryospheric indicators. This has been done through the Snow Watch and other workshops (Barry et al., 1993; Crane, 1993; Barry et al., 1995), WCRP Working Groups (WCRP, 1998c), planning for the Earth Observing System (Goodison at al., 1999), and through the GCOS/GTOS Terrestrial Observation Panel for Climate (TOPC) (GCOS, 1997). The TOPC identifies observations required to understand the impacts of climate change on the cryosphere, and those required for GCM modelling and validation. Typically, the latter need to be available consistently for the globe, while the former need only be regional to be of value. Global Terrestrial Networks are being implemented for the GCOS Initial Observing System (IOS) for two cryospheric elements. These are the GTNet-G for glaciers and the GTNet-P for permafrost. The GTNet-P is a recent initiative of the International Permafrost Association, while GTNet-G will formalize the extensive prior work of the World Glacier Monitoring Service in Zürich.

It is envisioned that GTNet-G will establish a network of sites representing all major mountain ranges of the world to give information regarding significant climate changes and that can be used to detect regional differences that may occur in global warming. The global network of glacier sites would be structured to allow global and regional analyses of glacier changes and to take advantage of different intensities of measurements at various sites. With reference to the tier system proposed for global terrestrial observations, the following sites and reported observations are envisioned:

- Tier 1 (large transects): reporting details to be determined later;
- Tier 2 (extensive and process-oriented glacier mass balance studies within major climatic zones): annual reporting;
- Tier 3 (regional glacier mass change within major mountain systems, i.e., reduced stake networks): annual reporting;
- Tier 4 (long-term observations of glacier length change at about 10 sites selected according to size and dynamic response within each of the mountain ranges: pluriannual reporting (frequency to be determined); and,

- Tier 5 (glacier inventories repeated at time intervals of a few decades by using satellite remote sensing): continuous upgrading and analyses of existing and newly available data.

The launch of two new environmental satellites (Landsat 7 and Terra) in 1999 marked a major advance in capabilities for global mapping and measurements of glaciers and ice sheets. Plans to use these remote-sensing capabilities, and to integrate these capabilities with existing field glaciology programmes, are entering an operational phase. An international consortium for Global Land Ice Measurements from Space (GLIMS) has been organized to undertake image analysis and other tasks that cannot optimally or readily be done from one institution. GLIMS will use data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument and focus on glaciers other than the polar ice sheets, whereas a Landsat-7 global glacier observation project has a heavy emphasis on polar ice sheets. Systematic mapping and interpretation with glacier models for selected glaciers will deliver invaluable information on the global extent of glacier advances in recent centuries.

For other important variables such as lake ice conditions and snow water equivalent, there are currently no co-ordinated efforts within GCOS, and in some cases national observation programmes are dwindling. Some countries, such as Canada, are in the process of defining a cohesive national observing network for observing all components of the cryosphere, including observations required for using the cryosphere as an indicator of climate change. For the strategy to be successful, certain important aspects must be considered.

Operational daily observations of sea-ice and snow-cover extent are well in hand, but products for other parameters (particularly sea-ice thickness, snow depth/water equivalent) still only exist on a regional or research basis. The necessary tools for remote sensing are becoming more widely available and tested over a range of conditions, although there are new ones, such as altimetry and scatterometry, that can be exploited more fully. It is crucial to ensure that, as operational systems evolve and change, there is adequate temporal overlap to inter-calibrate the sensors for consistent time series. CliC should co-ordinate closely with the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM) Working Group on Polar Seas and other Sea Ice Regions (POSSIR), and with other WMO Commissions as appropriate.

Indices and statistics such as those identified in 9.1.2 for snow cover need to be compiled on a consistent basis for a representative global network of stations, over a long record. Corresponding indices are needed for sea ice and fresh-water ice conditions.

There is a need to sustain, and in some cases enhance current *in situ* observations of cryospheric variables, particularly glacier mass balance and snow water equivalent. CliC should work closely with key national agencies and TOPC to formulate goals for realistically attainable, representative networks that will serve all aspects of CliC.

Groups such as the Mountain Agenda (Messerli and Ives, 1997; Mountain Agenda, 1998), the nascent Mountain Forum (www.mtnforum.org) and the IGBP (Becker and Bugmann, 1996) have drawn attention to the importance of mountain hydrology and ecology and the value of integrated catchment hydrology/altitudinal gradient studies. CliC should co-ordinate with these groups to explore the potential for expanded or new GTNets addressing cryosphere-related parameters.

10 REMOTE SENSING IN CliC

Satellite remote-sensing methods provide invaluable and often unique observational data for a range of climate and cryosphere studies, including: process-oriented studies; analyses of large-, regional-, and even global-scale spatio-temporal variability; monitoring and detection of climate change; and as essential validation and/or assimilation data for numerical models. Numerous satellite-derived cryospheric data sets or products have already been developed, and more are under development or planned using data from present and near-future sensor systems.

10.1 PRESENTLY-AVAILABLE SATELLITE PASSIVE MICROWAVE-DERIVED CRYOSPHERIC DATA PRODUCTS

The large-scale variability of the sea-ice and snow covers can be studied at up to decadal time-scales using existing satellite data sets. Microwave-derived time series of snow and ice parameters are now among the longest continuous satellite-derived geophysical records, extending over 20 years. The Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) provided data from 1978-87, and the follow-up Special Sensor Microwave Imager (SSM/I) onboard Defence Meteorological Satellite Program (DMSP) satellites F8, F10, F11, F13 have provided data since 1987. Consistently-gridded (25 x 25 km cells) SMMR and SSM/I brightness temperature data sets are produced and distributed by the National Snow and Ice Data Center (NSIDC) at no cost to the science community, and constitute one of the key baseline data sets used to monitor cryospheric variability. Currently two products are distributed: (i) an Equal-Area Scalable Earth (or EASE)-grid of global daily SSM/I brightness temperatures (ascending and descending orbits separated), and (ii) a polar-stereographic gridded product of daily-averaged brightness temperatures (SMMR and SSM/I) with geographic coverage of the northern and southern polar regions.

The sea-ice parameters derived from multi-frequency, microwave brightness temperature (T_B) data include ice concentration (the percent of ice-covered ocean) from which total ice area (the area of ice-covered ocean) and total ice extent (the area within the ice-ocean margin) is derived. Time series analyses of these parameters derived from SMMR and SSM/I data have indicated decreases of ~3% per decade in the Arctic (Maslanik et al., 1996; Parkinson et al., 1999). There has been essentially no change (Johannessen et al., 1995; Bjørgo et al., 1997) or even a slight increase (Heygster et al., 1996; Cavalieri et al., 1997) in the Antarctic.

Because open water, first-year ice, and multi-year ice (having survived at least one summer) have different radiative properties, algorithms applied to multi-channel T_B data can separate these components, at least in winter when the signatures are relatively stable. The potential to monitor inter-annual variations in the Arctic multi-year ice fraction from microwave data has been explored (Comiso, 1990), but has remained under realized until recently (Johannessen et al., 1999). Johannessen et al., (1999) show that the multi-year ice area in winter decreased ~14% between 1978 and 1998, and note that inter-annual variations in ice thickness and multi-year ice area appear to be closely associated, though validation data sets remain fragmentary.

In addition to validating the accuracy of retrieved parameters, a key issue is establishing the sensor data homogeneity required to provide consistent data sets of sea ice and other cryospheric parameters (Walsh, 1995). For passive microwave-derived sea-ice data, this involves combining data from similar sensors aboard different satellites (Stroeve et al., 1998). The difficulties experienced in combining SMMR and SSM/I data have underscored the importance of an adequate overlap period for inter-calibration at the geophysical parameter level. An overlap period of one year is recommended (Cavalieri et al., 1999). The problem of data homogeneity is even more pronounced when incorporating data derived from other sensors and sources.

Significant progress is being made towards understanding microwave signatures of ice sheets. The signatures are strongly affected by conditions beneath the surface, and contain information on depth-hoar and ice-layer intensity, snow temperatures and wetness, and snow accumulation rate (Steffen et al., 1999; Abdalati and Steffen, 1998). The relationship between emission (polarization) and accumulation in Greenland is consistent with that expected from earlier work, using 4.5 cm-wavelength (6.7 GHz) data. For 19 GHz and 37 GHz the link between microwave emission and accumulation rates in the dry-snow area of the Greenland ice sheet is significant; however, the emissivity is also dependent on the extent of hoar development. As a result, accumulation estimates based on passive microwave observations in the low-accumulation dry-snow areas will require successful parameterization of hoar formation.

Estimates of snowmelt on glaciers and ice sheets have been derived from passive microwave satellite data (Abdalati and Steffen, 1997). By comparing passive microwave satellite data and field observations, variations in melt extent have been detected by establishing melt thresholds in the cross-polarized gradient ratio (XPGR). The XPGR, defined as the normalized difference between 19-GHz horizontal channel and 37-GHz vertical channel of the SSM/I, exploits the different effects of snow wetness on different frequencies and polarizations and gives a distinct melt signal. Using this XPGR melt signal, seasonal and interannual variations in snowmelt extent of the ice sheet can be studied. A notable increasing trend in melt area of 4.4% per year has been observed for the Greenland ice sheet between 1979 and 1991. This came to an abrupt halt in 1992 after the eruption of Mt. Pinatubo. The relationship between the warming trend and increasing melt trend between 1979 and 1991 suggests that a 1° C temperature rise corresponds to an increase in melt area of 73,000 km^2. Following a decrease due to the 1991 cooling attributed to Mt. Pinatubo, the increase in melt area of the Greenland ice sheet continued.

Since the launch of SMMR in 1978, significant advances have been made in the development of algorithms for retrieval of snow cover information such as depth (e.g., Kunzi et al., 1982; Chang et al., 1987), water equivalent (e.g., Hallikainen et al., 1992; Goodison and Walker, 1993); areal extent (e.g., Grody and Basist, 1996), and wet/dry state (Walker and Goodison, 1993). SMMR and SSM/I data have been used to derive snow cover extent estimates that generally correspond well with NOAA AVHRR snow cover data (Armstrong and Brodzik, 1999). The only existing passive microwave-derived global snow cover data set was generated by NASA using SMMR data, providing information on snow extent and snow depth (Chang et al., 1990). It is generally agreed within the passive microwave snow research community that no single depth or water equivalent algorithm will produce representative values on a global basis due to spatial variations in land cover, terrain and physical snow cover characteristics. Efforts to address this limitation have focused on the development and validation of more complex algorithms that, for example, take into account effects of snow metamorphism (Josberger and Mognard, 1999), variations in forest density (Foster et al., 1997), or apply a regional approach (Goodison and Walker, 1995; Tait, 1998). Such advances in algorithm development and validation are needed before a reliable climatological snow cover data series on a global or hemispheric basis can be produced from SMMR-SSM/I data. The issue of sensor data homogeneity is again important for snow cover products derived from SMMR and SSM/I data.

There has been limited application of satellite passive microwave data to derive data sets for other cryospheric elements, mainly due to the fact that the resolution is too coarse (e.g., 25 km) for deriving information for elements such as glaciers, lake ice, and river ice. The capability of SSM/I 85 GHz data (12.5 km resolution) for discriminating ice covered areas from open water areas has been shown for large lakes in North America, such as Great Slave Lake in northern Canada (Walker and Davey, 1993) and Lake Superior (Pilant, 1995). An SSM/I derived time series (1987-1998) of lake ice freeze-up and break-up for Great Slave and Great Bear Lakes in northern Canada is being compiled as part of the Mackenzie Basin GEWEX study (MAGS) (Stewart et al., 1998). The use of SMMR and SSM/I data for frozen ground applications has been investigated, with results indicating that areas of frozen and thawed ground/soil can be discriminated (e.g., Zuerndorfer et al., 1990; England, 1992; Judge et al., 1997).

10.2 PRESENTLY AVAILABLE NOAA AVHRR-DERIVED POLAR DATA PRODUCTS

The NOAA AVHRR-based Polar Pathfinder (APP) project aims to produce a consistent set of remotely-sensed data products of surface temperature, albedo, cloud fraction and sea-ice motion, each a key component of the climate and cryosphere system (Barry, 1998). The APP is part of the NOAA/NASA Pathfinder programme in which new data sets from several sources are produced in support of long-term climate studies. The APP component has and continues to generate multi-year, gridded products for high northern and southern latitudes (greater than ~50º) using data from 1983-1996. These provide a basis to study spatial and temporal patterns of variability in the polar regions.

The parameters can be analysed individually or in combination with others. The grid cells range from 1.25 to 25 km, in a scheme which is consistent with microwave-derived ice and snow cover data products, thereby facilitating analysis using an integrated, multi-sensor approach. For example, these data products have already contributed toward providing the first comprehensive view of sea-ice transport throughout the Southern Ocean. Other Antarctic phenomena such as the break-up or "calving" of enormous parts of floating ice shelves are monitored using NSIDC's Polar 1-km AVHRR data set.

Since 1966, NOAA has mapped the areal extent of snow cover in the Northern Hemisphere on a weekly basis using optical satellite imagery (e.g., AVHRR, GOES) (Matson et al., 1986). This data set (both hard copy charts and digital gridded data) is the longest satellite-derived record (> 30 years) of snow extent, and has been used as the basis for many analyses of snow cover variability and change on a hemispheric and continental basis (e.g., Robinson et al., 1993; Brown, 1995). The NSIDC has regridded the NOAA data set onto a 25-km grid, in an azimuthal, equal area projection (the NSIDC EASE-Grid), covering the period January 1971 to August 1995. This data product is available as a 2 volume CD-ROM (NSIDC, 1996). The availability of snow extent information in EASE-Grid format has also facilitated the validation of SMMR and SSM/I derived snow cover information in the same format (e.g., Armstrong and Brodzik, 1999).

10.3 PRESENT SATELLITE RADAR DATA FOR CRYOSPHERIC STUDIES

The variability of several sea-ice and land-ice phenomena and parameters can be studied using data from satellite-borne active microwave sensors (radars). Since 1991, Synthetic Aperture Radar (SAR) data have been acquired from the European Space Agency's (ESA) European Remote Sensing satellites (ERS-1 and ERS-2), including an overlapping "Tandem Mission" period in 1995. These high-resolution (~25 m) backscatter data are acquired along 100 km swaths, which is a limiting factor for regional and larger-scale studies. Since 1995, the Canadian Radarsat has generated SAR data sets (including wide-swath (500 km) images with similar spatial resolution to that of ERS SAR). Radarsat's greater spatio-temporal sampling capabilities can provide data more commensurate with the CliC goals.

Satellite SAR data have much higher spatial resolution and completely different imaging mechanisms which complement passive microwave data. Sea-ice phenomena and parameters that can be studied from SAR backscatter data include open and refrozen leads and polynyas, sea-ice roughness (and type), and sea-ice motion, at scales two orders of magnitude smaller than passive microwave data. SAR data can serve as independent observations for comparison with sea-ice parameters derived from passive microwave or visible- and thermal-band imagery. Sea-ice parameter retrieval, and hence product generation, from SAR data remains a research topic (e.g., Sandven et al., 1999), though some applications such as sea-ice motion fields (and thereby derived parameters such as divergence and shear) are relatively well developed (e.g., Kwok et al., 1998). The RADARSAT Antarctic Mapping Project (RAMP) acquired SAR images covering the whole of Antarctica, at a resolution 30 times finer than previously available, between September and October 1997 *(Figure 10.1)*. SAR data are also used to study land-ice topography and phenomena such as glacier surges; the use of SAR interferometric techniques to produce full, three-dimensional flow patterns for glaciers has been a research highlight.

However, despite considerable research and the generation of very large amounts of ERS and Radarsat SAR data from the polar regions since 1991, there are no generally-available SAR-derived cryospheric data products providing comprehensive spatio-temporal coverage comparable with those derived from NOAA-AVHRR, SMMR or SSM/I data. Both ERS and Radarsat SAR data are prohibitively expensive for the science community to produce real climatologies. Applications are necessarily limited mainly to case studies. It is important for a programme such as CliC to have reasonable access to archival SAR data for climatological studies.

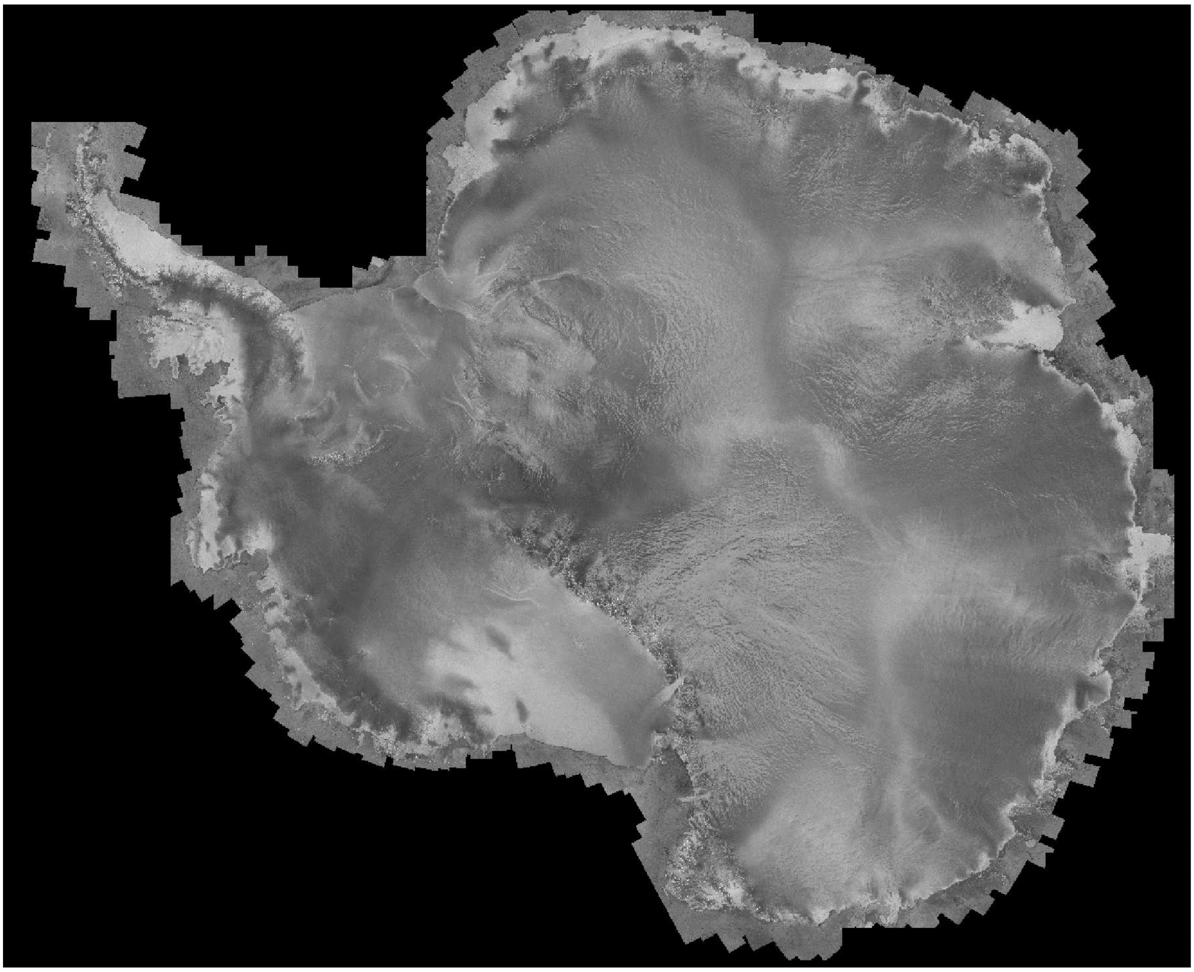


Figure 10.1: Five-kilometre mosaic of the Antarctic ice sheet compiled from RADARSAT SAR images. These images were acquired as part of the RADARSAT Antarctic Mapping Project that is a collaboration between NASA and the Canadian Space Agency to completely map the Antarctic with RADARSAT-1. (© Canadian Space Agency)

10.4 INNOVATIVE TECHNIQUES FOR CRYOSPHERIC STUDIES

10.4.1 Using Present Remote Sensing Data

Several innovative techniques recently began to provide cryospheric data sets from available satellite data. For example, large-scale cryospheric features may be studied using 50km resolution data from the ERS Wind Scatterometer. The backscatter data provide the basis to study ice motion from changes in the patterns of spatially-averaged surface roughness, which can potentially be related to ice deformation and ice type (Gohin and Cavanie, 1994). There have also been some very promising analyses of sea-ice motion from the relatively high frequency (thereby higher spatial resolution) 85 GHz channel passive microwave data (e.g., Agnew et al., 1997; Emery et al., 1997; Kwok and Rothrock, 1999). The synergy from combining passive microwave-derived ice motions with AVHRR- and SAR-derived estimates and *in situ* data holds considerable promise (Agnew et al., 1999; Shokr and Agnew, 1999). The accuracy of the displacement fields using this approach may be comparable to those derived from data from the International Arctic Buoy Programme, but with greater spatial coverage (Schmidt and Hansen, 1999).

Innovative methods to estimate spatially averaged sea-ice thickness using spaceborne altimetry appear promising (Peacock et al., 1998) and may be applied to continuous ERS altimeter data sets since 1991. Methods to map ice sheet topography and estimate thickness from satellite altimetry are not particularly new. However, research is progressing towards improving the accuracy and consistency between sensors needed to more reliably determine the inter-annual variability and trends in the mass balance of the Greenland and Antarctic ice sheets (e.g., Wingham et al., 1998a). The potential to use scatterometer and passive microwave data for mapping the large-scale variability in boreal freeze-thaw patterns and perhaps permafrost is also being explored (Scipal and Wagner, 1998; Mognard et al., 1998).

10.4.2 Using Future Remote Sensing Data

Several future techniques, remote-sensing systems, data sets and methodologies for cryospheric studies may become reality within the coming decade. ESA has already approved one such dedicated system, CryoSat, as part of their Earth Explorer Program. The goals of CryoSat are to measure fluctuations in sea and land ice masses (thickness) at large space and time scales, in order to determine their fluctuations to within the limit set by SAR and interferometric techniques in synergy with radar altimetry (Wingham et al., 1998b). Satellite laser altimetry (e.g., NASA's planned Geoscience Laser Altimeter (GLAS)) will also provide valuable data to map sea and land ice elevations and will yield new data on cloud properties.

The NASA Gravity Recovery and Climate Experiment (GRACE) mission, to be launched in July 2001, will map the Earth's gravity field at 2-4 week intervals. This will enable changes in water storage to be estimated, as originally discussed by Chao et al., (1987), providing valuable information on snow storage (Rodell and Famiglietti, 1996). Trupin et al., (1992) examined contributions of glacier melt to changes in day length, polar motion and displacements of the Earth's centre of mass from a satellite-reference frame. They concluded that glacier melt-induced secular trends in polar motion excitation residuals were potentially detectable by laser ranging measurements. They also noted the potential for detecting changes in the Earth's gravity due to changes in ice masses that will be realized through the GRACE mission.

Finally, the potential to monitor ocean temperature and perhaps sea-ice thickness in a synoptic mode in the Arctic Ocean may be also realized using a proposed network of undersea acoustic sensors. Acoustic techniques have been used in other oceans, and a pilot experiment has shown that transmission across the Arctic basin is possible. Moreover, because sea ice has a dampening effect on acoustic waves, this attenuation may contain information about the sea-ice cover, including its thickness (Johannessen et al., 1999; Mikhalevsky et al., 1999).

11 CROSS CUTTING ISSUES

11.1 OBSERVATIONAL FRAMEWORK

Observations of the various cryospheric components differ greatly in their degree of organization and comprehensiveness. An overview was presented by Barry (1984), while a recent summary focusing on observations in Canada (Barry, 1995) provides more specific information on gaps. Trenberth (1995) identifies some priority recommendations for cryospheric monitoring.

The observational framework for CliC is provided by:

i) the WMO meteorological and hydrological networks;
ii) continuing WCRP programmes for Antarctic buoys (IPAB) and for sea-ice thickness in both hemispheres (ASITP, AnSITP), as well as the separate Arctic buoy programme (IABP);
iii) elements of GCOS/GTOS/GOOS relating to the cryosphere. Specific current projects are the Global Terrestrial Network for Glaciers (GTNet-G) of the World Glacier Monitoring Service (WGMS) and the Global Terrestrial Network for Permafrost (GTNet-P) of the International Permafrost Association; and,

iv) programmes and projects of international organizations with cryospheric interests (particularly IASC, ICSI, IGBP, IPA, SCAR and SCOR), and of some other groups/institutions identified in WCRP (1998b), and as shown in Table 3.

Other current and proposed initiatives include: the Surface Heat Budget of the Arctic Ocean (SHEBA) modelling phase, the Western Arctic Shelf Basin Interactions (SBI) programme, and the proposed Study of Environmental Arctic Change (SEARCH) – all components of the US/NSF Arctic Systems Science (ARCSS) programme. It will be crucial for CliC to develop “A Cryospheric Observing System” plan in conjunction with GCOS, analogous to that developed for the oceans by the Ocean Observing System Development Plan (Smith et al., 1995).

11.2 MODELLING STRATEGY

A CliC modelling strategy must address improved parameterization in models of the direct interactions between all components of the cryosphere, the atmosphere, and the ocean. This must be done at a variety of scales from the regional to the global; and with a hierarchy of models ranging from those of individual processes to fully coupled climate models. It will also be essential to provide the improved data sets needed for validation of models and parameterization schemes.

Specific modelling requirements include:

i. comparison of present atmospheric models (AMIP II, PMIP) and coupled climate models (CMIP) where the cryosphere is either a boundary condition or a prognostic model component;

ii. comparison of present cryospheric models (SIMIP, SNOWMIP, PILPS, EISMINT) and evaluation of future development needs;

iii. the contribution of cryospheric model components to long-range weather prediction (e.g., seasonal prediction of ECMWF);

iv. assessment of the contribution of the cryosphere to long-term climate variability;

v. further development of process models (e.g., glacier flow, dynamics of the grounding line of ice shelves); and,

vi. input of modelling activities into a model data bank (model physics, model code, data from standard run, including forcing and response, and specific sensitivity experiments).

A variety of specific modelling applications and requirements for model development, have been identified in the previous sections. Such developments include improved interactive modelling of the atmosphere and the elements of the cryosphere, especially with respect to sea level change (ice mass balance), the surface energy budget and surface hydrology, including iceberg calving and fresh-water runoff. Improved formulation of surface albedo and its dependence on surface type, surface temperature, vegetative cover, etc., are also required, particularly in regions of ice and snow melt.

Continued efforts are needed to understand and represent the stable atmospheric boundary layer, including that over sloping terrain, especially ice sheets. In ocean modelling there must be considerable improvement in the treatment of THC source mechanisms and processes, and subsequent circulation characteristics, such as plume and flow rates, characteristics, paths and entrainment.

Simplified versions of the existing sophisticated permafrost/frozen ground models are required for use in climate GCMs. Important processes to be included are:

- the coupling of frozen ground processes to surface hydrology in land-surface schemes; and,
- effects of the thawing of perennially frozen ground, including the release of methane providing feedback to atmospheric greenhouse gas concentrations, the development or enlargement of swampy areas, and changes in vegetation and surface energy balance.

11.3 INFRASTRUCTURE FOR CliC DATA MANAGEMENT

The development of a plan for CliC data and their management will build directly on the ACSYS experience in developing the Arctic Precipitation Data Archive (APDA) (WCRP, 1997), the deliberations of the ACSYS Data Management and Information Panel (ACSYS DMIP) (WCRP, 1998a) and other WCRP projects (WCRP, 1995). It is important to recognise that the CliC data requirements will necessitate the continuation of many ACSYS data collection and archiving activities and their expansion to encompass Antarctic and other cryospheric data needs. Metadata for all Antarctic scientific research are now being assembled in the Antarctic Master Directory. The U.S. National Science Foundation is now supporting an Antarctic Glaciological Data Center at the NSIDC/WDC for Glaciology in Boulder, Colorado, USA.

The projected scope of CliC activities described will likely entail the collection and/or assembly of data sets related to: global sea ice, snow cover, fresh-water ice, glaciers, ice caps, the Greenland and Antarctic ice sheets and shelves, seasonally and perennially frozen ground, and sub-sea permafrost. The WCRP requirements for cryospheric data have been specified in several reports (see Appendix F in WCRP, 1998c). GCOS/GTOS requirements are detailed in reports of the Terrestrial Observations Panel for Climate (TOPC) (GCOS, 1997). The general status of observational data for the CliC cryospheric elements is summarised in the report prepared by the 1997 Meeting of Experts (WCRP, 1998b, Appendix C, Table 2).

12 INFRASTRUCTURE FOR CliC

The cryosphere is of scientific interest to many scientific organisations, with diverse scientific interests. Development of a scientific programme that is complementary to other initiatives and draws on expertise of other organisations will be necessary.

The Meeting of Experts on Cryosphere and Climate (WCRP, 1998b) identified various existing activities of relevance to the CliC endeavour. It did not find any important overlaps; rather it recognised a variety of gaps in ongoing programmes (Grassl, 1999). These include information on sea-ice thickness and ice volume, sea-ice motion in the Southern Ocean, representative mass balance data for mountain glaciers and ice caps, altimetry data and mass balance data for the Greenland and Antarctic ice sheets. Comprehensive data are also lacking on the distribution of global snow depth and snow water equivalent, as well as on fresh-water ice conditions, that can potentially be derived by optimal blending of *in situ* and satellite data. Information is also needed on trends in the extent of permafrost and seasonally frozen ground, in active layer thickness and permafrost temperatures. Further identified deficiencies exist in the parameterization of cryospheric processes in climate models and their validation and comparison.

There is a need for co-ordination between the proposed CliC and the other activities, especially to achieve a global perspective of cryosphere research. There are three broad categories of polar and cryospheric programmes, agencies and organisations that need to be considered. These are other WCRP and WMO programme components, IGBP, SCAR, SCOR and IASC projects, and other climate-related activities of other groups (Table 3).

[3]Table 3: Observational Cryospheric Programmes for the Northern (n) and Southern (s) Hemispheres

CYROSPHERIC ELEMENTS CLIMATE PROCESSES	**Ice Sheets**	**Ice Shelves**	**Glaciers, Ice Caps**	**Sea Ice**	**Snow**	**Frozen Rivers, Lakes**	**Frozen Ground**
Sea Level Change	MAGICS (**n**) PARCA (**n**) ISMASS (**s**) WAIS (**s**)		MAGICS (**n**) GLIMS (**n&s**)		ITASE (**s**)		
Ocean Surface Processes and Deep Water Formation	MAGICS (**n**) ISMASS (**s**) WAIS (**s**)	FRISP (**s**) iAnZone	MAGICS (**n**) GLIMS (**n&s**)	ACSYS (**n**) CRYSYS (**n**) ASITP (**n**) IABP (**n**) CLIVAR (**n&s**) iAnZone (**s**) ASPeCt (**s**) AnSITP (**s**) IPAB (**s**)	ACSYS (**n**) ASPeCt (**s**)		
Snow and Glacier Hydrology	PARCA (**n**) ITASE (**s**)		MAGICS (**n**) CRYSYS (**n**) GLIMS (**n&s**)		MAGS (**n**) CRYSYS (**n**)	CRYSYS (**n**)	CRYSYS (**n**)
Land Surface Processes					CRYSYS (**n**) GAME (**n**)	CRYSYS (**n**) GAME (**n**) MAGS (**n**)	CRYSYS (**n**) GAME (**n**) MAGS (**n**) CALM (**n**)

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[3] See List of Acronyms in Appendix 4

The establishment of a Working Group on Polar Seas and Other Sea Ice Regions (POSSIR) has been proposed under the Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology (JCOMM). Its tasks would include the co-ordination of relevant operational polar observing systems. A JCOMM/GOOS Meeting of Experts on a polar regions Strategy in December 1999 took note of WCRP ACSYS, CliC and the existing GDSIDB activities. If POSSIR is established, a formal linkage with CliC will clearly be desirable.

In the case of WCRP projects, it is critical that science initiatives within CliC are co-ordinated with, and complementary to, those initiated or planned, especially those of ACSYS, CLIVAR and GEWEX. It may be appropriate to have one- or two-way representation or points of contact on steering groups and/or working groups, with agreed schedules for any deliverables that may be required (from ACSYS/CliC to CLIVAR, for example). Current models for this include ACSYS - GEWEX, two-way, and CLIVAR-ACSYS one-way representation. In the case of ACSYS/CliC - GCOS/TOPC, there is already good cryospheric representation on the latter, where glacier and permafrost monitoring networks have been proposed.

WCRP's International Programme for Antarctic Buoys (IPAB) and the WCRP Antarctic Sea Ice Thickness Project (AnSITP) are at present supervised by the ACSYS Scientific Steering Group. These Groups will become part of CliC. Similarly, ACSYS/CliC are well represented in relevant WMO activities, within JCOMM for the Global Digital Sea Ice Data Bank (GDSIDB), and within CIMO for the Solid Precipitation Measurement Intercomparison.

WCRP also has close co-operation with several IGBP components including Past Global Changes (PAGES) and Biospheric Aspects of the Hydrological Cycle (BAHC). PAGES addresses issues relating to climate change, including the response of ice sheets and sea level, principally on two time scales – around 2000 years, and 250,000 years (IGBP, 1998). A number of component activities relate to ice coring, but others in the terrestrial, marine and modelling realms are also important for CliC. The BAHC project refers to the value of snowline monitoring and the importance of water balance in mountain catchments, some of which involve snow cover and glaciers (IGBP, 1997). The Mountain Agenda (1998) group has drawn attention to the critical role of mountains as "water towers for the twenty-first century". WCRP and the Inter-American Institute (IAI) have agreed to co-operate in climate research and the IAI will consider supporting, within available resources, scientific activity and research in South and Central America relevant to WCRP (Inter-American Institute, 1999).

The Scientific Committee for Antarctic Research (SCAR) and the Scientific Committee for Ocean Research (SCOR) have a number of important Antarctic programmes and projects. These are well summarised by P. Clarkson (WCRP, 1998b, Appendix B.8) and E. Fahrbach (WCRP, 1998b, Appendix B.11). Close co-ordination between CliC and some of these efforts will be needed.

There are several relevant scientific unions and commissions within ICSU. These include the International Permafrost Association (IPA), the International Commission on Snow and Ice (ICSI) and the International Association of Hydrological Sciences (IAHS). A link to planned ICSI model comparisons would be useful. ACSYS/CliC is already represented in the IAHS and ICSI as well as on the Standing Committee on Data, Information and Communication of the IPA. Also under ICSU are the World Data Centers, which include WDCs for Glaciology in Boulder (USA) and Lanzhou (China), and the World Glacier Monitoring Service (WGMS) through the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

The International Arctic Science Committee (IASC) oversees several important science activities. These include the Mass Balance of Arctic Glaciers and Ice Sheets (MAGICS) (see J. Hagen in WCRP, 1998b, Appendix B.7), and the Barents Sea and Bering Sea Impact Studies (BASIS and BESIS), as described in the IASC Project Catalogue, 2000 (www.iasc.no/ProjectCatalogue/catalogue.htm).

CliC might also become attractive for consortia of scientists co-operating at present in climate-related Arctic and Antarctic research activities like WAIS (West Antarctic Ice Sheet), FRISP (Filchner-Ronne Ice Shelf Programme), and EISMINT (European Ice-Sheet Modelling Initiative). The possibility of establishing a partnership for observations of global snow and ice, analogous to the recently established Partnership for Observations of Global Oceans (POGO) (see http://igos.partners.org) is an idea that might be explored via ICSI.

The next IPCC review includes cryospheric processes as a component of Working Group I. Working Group II specifically addresses many of the cryospheric impacts of climate change in the chapter Polar Regions. It is essential that CliC interact in the presentation and identification of scientific issues, needs, and gaps.

12.1 STRATEGIES FOR COOPERATION

There are various options for establishing linkages with other WCRP and external programmes. These include:

(i) participation of invited experts from related programmes in ACSYS/CliC SSG meetings and science conferences;

(ii) establishing links between the IACPO Director and corresponding GEWEX and CLIVAR project office directors;

(iii) letters of agreement from the parent bodies (such as SCAR, SCOR, IGBP) of specialist groups or projects to contribute to CliC with invited experts representing these groups to attend ACSYS/CliC SSG meetings;

(iv) participation of CliC representatives in other programmes, such as ASPeCt or iAnZone, or in their SSGs;

(v) formal representation of other programmes on the CliC SSG;

(vi) co-sponsorship of the CliC project by WCRP and other organizations like SCAR, with joint funding support; and,

(vii) full integration of international co-ordinated activities as sub-projects of WCRP CliC.

Each option affords various benefits and may have certain drawbacks. The particular mode(s) that CliC should adopt has not been determined, but options will be considered by the joint ACSYS/CliC SSG at its first meeting.

13 NEXT STEPS

On behalf of the Task Group, R.G. BARRY presented this Science and Co-ordination plan to the JSC-XXI meeting in Tokyo, 13-17 March 2000. The JSC approved the establishment of the CliC Project within the WCRP and the formation of a combined ACSYS /CliC SSG until the end of 2003, when the present ACSYS project ends. New members selected for the combined SSG will replace those retiring from the ACSYS SSG in 2000/2001. The new members will be chosen so as to provide links with, and co-ordination to, the other programmes and activities identified in Section 12. Initially, the work of the ACSYS/CliC SSG should focus on co-ordination issues, planning, and on an implementation timetable for key elements of the science strategy. The new Director of the International ACSYS/CliC Project Office will play a major role in co-ordinating the CliC plans with GEWEX and CLIVAR activities that relate to the cryosphere.

National programme managers in countries with significant interest in cryosphere-climate issues will be briefed in relevant aspects of the Science and Co-ordination Plan. Following this briefing, the CliC SSG and WCRP Director should consider the organization of a CliC International Science Conference to seek national commitments to support an Implementation Plan for the Climate and Cryosphere Project.

14. REFERENCES

1. Abdalati, W., and K. Steffen, 1995. Passive microwave-derived melt regions on the Greenland ice sheet. Geophys. Res. Lett., 22, 787-790.
2. Abdalati, W., and K. Steffen, 1997. Snowmelt on the Greenland ice sheet as derived from passive microwave satellite data. J. Climate, 10(2), 165-175.
3. Abdalati, W., and K. Steffen. 1998. Accumulation and hoar effects on microwave emission in the Greenland ice-sheet dry-snow zones. J. Glaciol., 44(148), 523-531.
4. Agnew, T.A., H. Le and T. Hirose, 1997. Estimation of large scale sea ice motion from SSM/I 85.5 GHz Imagery. Ann. Glaciol., 25, 305-311.
5. Agnew, T.A., H. Le and M. Shokr, 1999. Characteristics of large winter leads over the Arctic Basin from 85.5 GHz DMSP SSM/I and NOAA/AVHRR imagery. Canadian J. of Remote Sensing, 25(1), 12-20.
6. Allison, I., and 10 others, 1998. Antarctic Sea Ice Processes and Climate: Preliminary Plan. SCAR Report 15, 11-26.
7. Anderson, L.G., E.P. Jones and B. Rudels, 1999. Ventilation of the Arctic Ocean estimated by a plume entrainment model constrained by CFCs. J. Geophys. Res., 104, 13423-13429.
8. Anderson, L.G., K. Olsson and M. Chierici, 1998a. A carbon budget for the Arctic Ocean. Global Biogeochemical Cycles, 12, 455-465.
9. Anderson, L.G., K. Olsson, E.P. Jones, M. Chierici and A. Fransson, 1998b. Anthropogenic carbon dioxide in the Arctic Ocean: Inventory and sinks. J. Geophys. Res., 103, 27707-27716.
10. Anisimov O.A., N.I. Shiklomanov and F.E. Nelson, 1997. Global warming and active-layer thickness: results from transient general circulation models. Global and Planetary Change, 15(3-4), 61-78.
11. Anisimov, O.A., and F.E. Nelson, 1996. Permafrost distribution in the Northern Hemisphere under scenarios of climatic change. Global and Planetary Change, 14, 59-72.
12. Anisimov, O.A., and F.E. Nelson, 1997. Permafrost zonation and climate change in the Northern Hemisphere: results from transient general circulation models. Climatic Change, 35, 241-258.
13. Armstrong, R.L., and M.J. Brodzik, 1999. A twenty-year record of global snow cover fluctuations derived from passive microwave remote sensing data. Proc., American Meteorological Society 5th Conference on Polar Meteorology, Dallas, Texas, January 10-15, 1999.
14. Barry, R.G., 1984. Snow and ice. In E. F. Westrum, Jr., ed., CODATA. Directory of Data Sources for Science and Technology (CODATA Bulletin No. 53), Pergamon Press, 87.
15. Barry, R.G., 1985. The Cryosphere and Climate Change in Detecting the Climatic Effects of Increasing Carbon Dioxide (ed.) M.C. MacCracken, F.M. Luther, DOE/ER 0235, US Dept of Energy, Washington DC, pp. 109-148.
16. Barry, R.G., 1995. Observing systems and data sets related to the cryosphere in Canada: A contribution to planning for the global climate observing system. Atmos. – Ocean 33, 771-807.

17. Barry, R.G., 1996. The parameterization of surface albedo for sea ice and snow cover. Progr. Phys. Geogr., 20, 61-77.

18. Barry, R.G., 1997. Satellite-derived data products for the Polar Regions. EOS 78(5): 52. Part II. The Polar Pathfinder Group. The Polar Pathfinders: Data Products and Science Plans. EOS Electronic Supplement 96149e.

19. Barry, R.G., J. Brown and J.A. Heginbottom, 1995. Workshop on Permafrost Data and Information, Oslo, Norway. Glaciol. Data Report, GD-28, WDC-A for Glaciology, University of Colorado, Boulder.

20. Barry, R.G., R.L. Armstrong, J.A. Maslanik and T.A. Scambos, 1998. Cryospheric research and data products from the National Snow and Ice Data Center. Arctic Research of the United States, 12, 64-69.

21. Barry, R.G., and J.A. Maslanik, 1993. Monitoring Lake Freeze-up/Break-up as a Climatic Index. Snow Watch '92, WDC-A Glaciological Data Report 25, 66-79.

22. Barry, R.G. B.E. Goodison and E. LeDrew (ed.), 1993. Snow Watch '92 – Detection Strategies for Snow and Ice. WDC-A for Glaciology, Glaciological Data Report GD-25, Boulder, Colorado, USA, 273 pp.

23. Becker, A., and H. Bugmann, (eds.) 1996. Predicting Global Change Impacts on Mountain Hydrology and Ecology: Integrated Catchment Hydrology/Altitudinal Gradient Studies. IGBP Report 43, Stockholm.

24. Bentley, C.R., 1998. Rapid sea-level rise from a West Antarctic ice-sheet collapse: a short-term perspective. Journal of Glaciology, 44, 157-163.

25. Bjørgo, E., O.M. Johannessen and M.W. Miles, 1997. Analysis of merged SMMR-SSMI time series of Arctic and Antarctic sea ice parameters. Geophys. Res. Lett., 24, 413-416.

26. Boer, G.J., G.M. Flato and D. Ramsden, 2000. A transient climate change simulation with greenhouse gas and aerosol forcing: Projected change in the 21st century. Climate Dynamics, in press.

27. Bromwich, D.H., et al., 1994. Simulation of the modern Arctic climate by the NCAR CCM1. J. Climate, 9, 1299-1318.

28. Bromwich, D.H., R.I. Cullather and M.L. van Woert, 1998. Antarctic precipitation and its contribution to the global sea-level budget. Ann. Glaciol., 27, 220-226.

29. Brown, J., and C. Haggerty, 1998. Permafrost digital databases now available. EOS 79(52), 634.

30. Brown, J., O.J. Ferrians Jr., J.A. Heginbottom and E.S. Melnikov, 1997. International Permafrost Association Circum-Arctic Map of Permafrost and Ground Ice Conditions. U.S. Geological Survey Circum-Pacific Map Series, Map CP-45.

31. Brown, R.D., 1995. Spatial and temporal variability of North American snow cover, 1971-1992. Proc. 52nd Eastern Snow Conference, Toronto, Ontario, June 7-8 1995, 69-78.

32. Brown, R.D., 1997. Historical variability in Northern Hemisphere spring snow covered area. Ann. Glaciol., 25, 340-346.

33. Budd, W.F., and R.C. Warner, 1996. A computer scheme for rapid calculations of balance-flux distributions. Ann. Glaciol., 23, 21-27.

34. Budd, W.F., P.A. Reid and L.J. Minty, 1995. Antarctic moisture flux and accumulation from global atmospheric analyses. Ann. Glaciol., 21, 149-156.

35. Cavalieri, D.J., C.L. Parkinson, P. Gloersen, J.C. Comiso and H.J. Zwally, 1999. Deriving long-term time series of sea ice cover from satellite passive-microwave multi-sensor data sets. J. Geophys. Res. 104, 15,803- 15,814.

36. Cavalieri, D.J., P. Gloersen, C.L. Parkinson, H.J. Zwally and J.C. Comiso, 1997. Observed hemispheric asymmetry in global sea ice changes. Science 278, 1104-1106.

37. Chang, A.T.C., J.L. Foster, D.K. Hall, H.W. Powell and Y.L. Chien, 1990. Nimbus-7 SMMR Derived Global Snow Cover and Snow Depth Data Set: Documentation, Product Description and User's Guide. The Pilot Land Data System, NASA Goddard Space Flight Center.

38. Chang, A.T.C., J.L. Foster and D. K. Hall, 1987. Nimbus-7 SMMR derived global snow cover parameters. Ann. Glaciol., 9, 39-44.

39. Chao, B.F., W.P. O'Connor, A.T.C. Chang, D.K. Hall and J.L. Foster, 1987. Snow load effect on the Earth's rotation and gravitational field, 1979-1985. J. Geophys. Res., 92 (B9), 9415-9422.

40. Church, J.A., J.M. Gregory, Ph. Huybrechts, M. Kuhn, C. Lambeck, M.T. Nhuan, D. Qin and P.L. Woodworth, 2001. Changes in sea level. Chapter 11 in: IPCC Third Scientific Assessment of Climatic Change, J. Houghton and D. Yihiu (eds.), Cambridge University Press (in press).

41. Clark, M.P., and M.C. Serreze, 1999. Snowfall responses over the USA to phase and amplitude variations in the tropospheric wave train. Interactions between the Cryosphere, Climate and Greenhouse Gases, ed., M. Tranter, Int. Assoc. Hydrol. Sci. Publ. No. 256, 45-54.

42. Comiso, J.C., 1990. Arctic multi-year ice classification and summer ice cover using passive microwave satellite data. J. Geophys. Res. 95, 13, 411-13,422.

43. Crane, R.G. (ed.), 1993. Workshop on Cryospheric Data Rescue and Access. Glaciol. Data Report GD-25, WDC-A for Glaciology, University of Colorado, Boulder, pp. 275-294.

44. de Wolde, J.R., R. Bintanja and J. Oerlemans, 1995. On thermal expansion over the last hundred years. J. Climate, 8, 2881-2891.

45. Diaz, H.F., and N.F. Graham, 1996. Recent changes in tropical freezing heights and the role of sea surface temperature. Nature, 383, 152-155.

46. Doake, C.S.M., H.F.J. Corr, H. Rott, P. Skvarca and N.W. Young, 1998. Break-up and conditions for stability of northern Larsen Ice Shelf, Antarctica. Nature , 391 (6669), 778-781.

47. Drewry, D.J., S.R. Jordan and E. Jankowski, 1982. Measured properties of the Antarctic ice sheet: surface configuration, ice thickness, volume and bedrock characteristics. Ann. Glaciol., 3, 83-91.

48. Duguay, C.R., and P.M. Lafleur, 1997. Monitoring ice freeze-up and break-up of shallow tundra lakes and ponds using ERS-1 SAR data. Proceedings GER'97 - International Symposium: Geomatics in the Era of Radarsat, May 24-30, 1997, Ottawa, Ontario (CD-ROM Vol. 1).

49. Dyurgerov, M., and M. Meier, 1997. Mass balance of mountain and subpolar glaciers: a new global assessment for 1961-1990. Arct. Alp. Res., 29, 379-391.

50. Ebert, E.A., and J. Curry, 1993. An intermediate thermodynamic sea ice model for investigating ice-atmosphere interactions. J. Geophys. Res., 98(C6), 10,085-10,109.

51. Echelmeyer, K.A., W.D. Harrison, C. Larsen and J.E. Mitchell, 1994. The role of the margins in the dynamics of an active ice stream. J. Glaciol., 40(136), 527-538.

52. Emery, W.J., C.W. Fowler and J.A. Maslanik, 1997. Satellite-derived maps of Arctic and Antarctic sea ice motion. Geophys. Res. Lett., 24, 897-900.

53. England, A.W., 1992. Radiobrightness of diurnally heated, freezing soil. IEEE Transactions on Geoscience and Remote Sensing, 28, 464-476.

54. Ferrick, M.G., and T.D. Prowse, 2000. Two communities join forces to study ice-covered rivers and lakes. EOS 81(10), p. 108.

55. Fitzharris, B., 1996. The Cryosphere: Changes and their Impacts. In: Climate Change 1995, Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Cambridge University Press, 241-265.

56. Flato, G.M., G.J. Boer, W.G. Lee, N.A. McFarlane, D. Ramsden, M.C. Reader and A.J. Weaver, 2000. The Canadian Centre for Climate Modeling and Analysis Global Coupled Model and its Climate. Climate Dynamics (in press).

57. Foster, D.J. Jr., and R.D. Davy, 1988. Global snow depth climatology. USAF publication USAFETAC/TN-88/006, Scott Air Force Base, Illinois, 48 pp.

58. Foster, J., A. Chang and D. Hall, 1997. Improved passive microwave algorithms for North America and Eurasia. Proc. of the Third International Workshop on Applications of Remote Sensing in Hydrology, Greenbelt, Maryland, U.S.A. October 1996, 63-70.

59. Fricker, H.A., R.C. Warner and I. Allison, 2000. Mass budget of the Lambert Glacier-Amery Ice Shelf system, East Antarctica: a comparison of computed balance fluxes and measured fluxes. J. Glaciol (in press).

60. GCOS, 1997. GCOS/GTOS plan for Terrestrial Climate-related Observations. Version 2.0. GCOS-32. WMO/TD No. 796, WMO, Geneva, 130 pp.

61. Giovinetto, M.B., and H.J. Zwally, 1995. An assessment of the mass budgets of Antarctica and Greenland using accumulation derived from remotely sensed data in areas of dry snow. Zeit. Gletscherkunde Glazialgeologie, 31, 25-37.

62. Gloersen, P., et al., 1993. Arctic and Antarctic sea ice, 1978-1987. Satellite passive microwave observations and analysis. NASA SP-511, NASA, Washington, DC, 290 pp.

63. Gloersen, P., C.L. Parkinson, D.J. Cavalieri, J.C. Comiso and H.J. Zwally, 1999. Spatial distribution of trends and seasonality in the hemisphere sea ice covers: 1978-1996. J. Geophys. Res., 104(C9), 20,827-20,835.

64. Gohin, F., and A. Cavanie, 1994. A first-try at identification of sea ice using the three beam scatterometer of ERS-1. Int. J. Rem. Sens., 154, 9-19.

65. Goodison, B.E., and A.E. Walker, 1993. Use of snow cover derived from satellite passive microwave data as an indicator of climate change. Ann. Glaciol., 17, 137-142.

66. Goodison, B.E., and A.E. Walker, 1995. Canadian development and use of snow cover information from passive microwave satellite data. In, Passive Microwave Remote Sensing of Land-Atmosphere Interactions (Choudhury, B.J., Kerr, Y.H., Njoku, E.G., and Pampaloni, P., eds.), VSP, Utrecht, The Netherlands, 245-262.

67. Goodison, B.E., I. Ye Frolov and V.M. Kotlyakov, 1998b. The role of the cryosphere in the climate system. In: Proceedings of the Conference on the World Climate Research Programme: Achievements, Benefits and Challenges (Geneva, 26-28 August 1997). WMO/TD-No. 904.

68. Goodison, B.E., P.Y.T. Louie and D. Yang, 1998a. WMO Solid Precipitation Measurement Intercomparison: Final Report. WMO/CIMO Report No.67, WMO/TD No. 872, World Meteorological Organization, Geneva, 306 pp.

69. Goodison, B.E., R.D. Brown and R.G. Crane, (co-ordinators) with contributions from R. Alley, R. Bales, D. Barber, R.G. Barry, R.D. Brown, C. Bentley, T. Carrol, D. Cline, C.R. Duguay, G.M. Flato, D.K. Hall, R. Harrington, J. Kargel, H. Kieffer, S. Munro, C. Parkinson, B. Raup, A. Rothrock and M. Sharp, 1999.Cryospheric Systems.National Aeronautics and Space Agency, EOS Science Plan, Chapter 6, 261-307. http://www.eospso.gsfc.nasa.gov/sci_plan/chapters.html.

70. Gow, A.J., S.F. Ackley, W.F. Weeks and J.W. Govoni, 1982. Physical and structural characteristics of Antarctic sea ice. Ann. Glaciol., 3, 113-117.

71. Grassl, H., 1999. The crysophere: an early indicator and global player. Polar Res., 18(2), 119-125.

72. Grody, N.C., and A.N. Basist, 1996. Global identification of snowcover using SSM/I measurements. IEEE Transactions on Geoscience and Remote Sensing, 34 (1), 237-249.

73. Groisman, P. Ya, T.R. Karl and R.W. Knight, 1994a. Changes of snow cover, temperature and radiative heat balance over the Northern Hemisphere. J. Climate, 7, 1633-1656.

74. Groisman, P. Ya, T.R. Karl and R.W. Knight, 1994b. Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. Science, 263, 198-200.

75. Haeberli, W., M. Hoelzle and D. Suter (eds), 1998. Into the Second Century of World Glacier Monitoring - Prospects and Strategies. Studies and Reports in Hydrology, 56. UNESCO Publishing, Paris, 227 pp.

76. Hallikainen, M., and P. Jolma, 1992. Comparison of algorithms for retrieval of snow water equivalent from Nimbus-7 SMMR data in Finland. IEEE Transactions on Geoscience and Remote Sensing, 30 (1), 124-131.

77. Harris, S. 1986. Permafrost distribution, zonation and stability along the eastern ranges of the Cordillera of North America. Arctic, 39, 29-38.

78. Higham, M., M. Craven, A. Ruddell and I. Allison, 1997. Snow accumulation in the interior of the Lambert Glacier basin, Antarctica. Ann. Glaciol., 25, 412-417.

79. Huybrechts, P., 1990. 3-D model for the Antarctic ice sheet - a sensitivity study on the glacial-interglacial contrast. Clim. Dynam., 5, 79-92.

80. Huybrechts, P., and J. de Wolde, 1999. The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming. J. Climate, 12(8), 2169-2188.

81. Huybrechts, P., D. Steihage, F. Wilhelms and J. Bamber, 2000. Balance velocities and measured properties of the Antarctic ice sheet from a new compilation of gridded data for modeling. Ann. Glaciol., 30, (in press).

82. IGBP, 1997. Predicting global change impacts on mountain hydrology and ecology: Integrated catchment hydrology/altitudinal gradient studies. Workshop Report. Global Change Report, No. 43, IGBP, Stockholm, 61 pp.

83. IGBP, 1998. Past Global Changes (PAGES). Status Report and Implementation Plan. IGBP Report 45, IGBP, Stockholm, 236 pp.

84. Inter-American Institute, 1999. Letter of Understanding between the Inter-American Institute for Global Change Research (AIA) and the World Climate Research Programme (WCRP) in the field of climate research. IAI Newsletter, issue 20, pp. 11-12.

85. IPCC, 1996. Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (Houghton, J.T. et al., (eds.), Cambridge University Press, Cambridge and New York, 572 pp.

86. Jacobs, S.S., and J.C. Comiso, 1993. A recent sea-ice retreat west of the Antarctic Peninsula, Geophys. Res. Lett., 20(12), 1171-1174.

87. Johannessen, O.M., E.V. Shalina and M.W. Miles, 1999. Satellite evidence for an arctic sea ice cover in transformation. Science, 1937-1939.

88. Johannessen, O.M., M.W. Miles and E. Bjørgo, 1995. The Arctic's shrinking sea ice. Nature, 376, 126-127.

89. Josberger, E.G., and N.M. Mognard, 1998. A passive microwave snow depth algorithm with a proxy for snow metamorphism. Proc., Fourth International Workshop on Applications of Remote Sensing in Hydrology, Santa Fe, New Mexico, USA.

90. Judge, J., J.F. Galantowicz, A.W. England and P. Dahl, 1997. Freeze/thaw classification of prairie soils using SSM/I radiobrightnesses. IEEE Transactions on Geoscience and Remote Sensing, 35(4), 827-831.

91. Kaser, G., 1999. A review of the modern fluctuations of tropical glaciers. Global Planet. Change, 22, 93-103.

92. Kunzi, K.F., S. Patil and H. Rott, 1982. Snow-cover parameters retrieved from Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) data. IEEE Transactions on Geoscience and Remote Sensing, GE-20 (4), 452-467.

93. Kwok, R., and D.A. Rothrock, 1999. Variability of Fram Strait ice flux and North Atlantic Oscillation. J. Geophys. Res., 104, 5177-5189.

94. Kwok, R., A. Schweiger, D.A. Rothrock, S. Pang and C. Kottmeier, 1998. Sea ice motion from satellite passive microwave data assessed with ERS and buoy motions. J. Geophys. Res., 103, 8191-8214.

95. Leemans, R., and W. Cramer, 1991. The IIASA Database for Mean Monthly Values of Temperature, Precipiation, and Cloudiness on a Global Terestrial Grid. Research Report RR-91-8, International Institute for Applied Systems Analysis, Laxenburg, Austria, 62 pp.

96. Lewis, E.L., et al., 2000. The Freshwater Budget of the Arctic Ocean, Kluwer Publishers, Dordrecht, in preparation.

97. Manabe, S., R.J. Stouffer and M.J. Spelman, 1991. Transient responses of a coupled ocean-atmosphere model to gradual changes of atmospheric CO2. Part I: Annual mean response. Journal of Climate, 4, 785-818.

98. Maslanik, J.A., M.C. Serreze and R.G. Barry, 1996. Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. Geophys. Res. Lett., 23, 1677-1680.

99. Matson, M., C.F. Ropelewski and M.S. Varnadore, 1986. An Atlas of Satellite-Derived Northern Hemisphere Snow Cover Frequency. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Data and Information Service, Washington, D.C.

100. Meier, M.F., 1984. Contribution of small glaciers to global sea level. Science, 226, 1418-1421.

101. Meier, M.F., and D.B. Bahr, 1996. Counting glaciers: Use of scaling methods to estimate the number and size distributiuon of the glaciers of the world. In S.C. Colbeck (ed) Glaciers, Ice Sheets and Volcanoes. A Tribute to Mark F. Meir. US Army CRREL Special Report 96-27, pp. 89-94.

102. Messerli, B., et al., 1997. Mountains of the World. A Global Priority. Parthenon Publishing, New York, 493 pp.

103. Mikhalevsky, P.N., A.N. Gavrilov and A.B. Baggeroer, 1999. The Transarctic Acoustic Propagation Experiment and climate monitoring in the Arctic. IEEE J. Ocean. Eng. (in press).

104. Mognard N.M., S. Baillarin and Y.H. Kerr, 1998. Monitoring of the boreal regions from 1992 to 1996 with the Special Sensor Microwave Imager. Proc., IGARSS'98, ISBN 0-7803-4406-5 (CD-Rom edition), Seattle, USA, July 6-10, 1998.

105. Mountain Agenda, 1998. Mountains of the World: Water Towers for the Twenty-first Century. Institute of Geography, University of Berne, 32 pp.

106. Murphy, J.M., 1994. Transient response of the Hadley Centre coupled ocean-atmosphere model to increasing carbon dioxide. Part I: Control climate and flux correction. Journal of Climate, 8, 36-56.

107. National Snow and Ice Data Center, 1996. Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea Ice Extent. Volumes 1.0-2.0.

108. Oerlemans, J., 1996. Quantifying global warming from the retreat of glaciers. Science, 264, 243-45.

109. Parkinson, C.L., and D.J. Cavalieri, 1989. Arctic sea ice 1973-1987: Seasonal, regional and inter-annual variability. J. Geophys. Res., 94(C10), 14199-14223.

110. Parkinson, C.L., 1991. Inter-annual variability of the spatial distribution of sea ice in the north polar region. J. Geophysical Research, 96(C3), 4791-4801.

111. Parkinson, C.L., D.J. Cavalieri, P. Gloersen, H.J. Zwally and J.C. Comiso, 1999. Arctic sea ice extents, areas, and trends, 1978-1996. J. Geophys. Res., 104(C9), 20,837-20,856.

112. Pavlov, A.V., 1997. Permafrost - climatic monitoring of Russia: methodology, results of observations and forecast. Earth Cryosphere, N 1, 47-58

113. Peacock, N.R., S.W. Laxon, R. Scharoo, W. Maslowski and D.P. Winebrenner, 1998. Geophysical signatures from precise altimetric height measurements in the Arctic Ocean, Proc. IGARSS'98, ISBN 0-7803-4406-5 (CD-Rom edition), Seattle, USA, July 6-10, 1998.

114. Pilant, D., 1995. SSM/I Time Series Observations of Great Lakes Ice and Snow. Proceedings of the 52nd Eastern Snow Conference, 7-8 June 1995, Toronto, Canada, 21-28.

115. Retzlaff, R., and C.R. Bentley, 1993. Timing of stagnation of Ice Stream C, West Antarctica, from short-pulse radar studies of buried surface crevasses. J. Glaciol., 39(133), 533-561.

116. Robinson, D.A., A. Frei and M. Serreze, 1995. Recent variations and regional relationships in Northern hemisphere snow cover. Ann. Glaciol., 21, 71-76.

117. Robinson, D.A., F.T. Keimig and K.F. Dewey, 1991. Recent variations in Northern Hemisphere snow cover. In Proceedings, 15th NOAA Annual Climate Diagnostics Workshop, Asheville, North Carolina, October 29 - November 2, 1990. Asheville, NC, National Oceanic and Atmospheric Administration, 219-224.

118. Robinson, D.A., K.F. Dewey and R.R. Heim, 1993. Global snow cover monitoring: an update. Bull. Am. Meteorol. Soc., 74, 1689-1696.

119. Robinson, D.A., and G. Kukla, 1985. Maximum surface albedo of seasonally snow-covered lands in the Northern Hemisphere. J. Clim. Appl. Met., 24, 402-411.

120. Rodell, M., and J. Famiglietti, 1999. Detectability of variations in continental water storage from satelite observations of the time dependent gravity field. Water Resources. Res., 35, 2705-2723.

121. Rothrock, D.A., Y. Yu and G.A. Maykut, 1999. Thinning of the Arctic sea-ice cover. Geophysical Research Letters, 26(23), 3469-3472.

122. Sandven, S., O.M. Johannessen, M.W. Miles, L.H. Pettersson and K. Kloster, 1999. Barents Sea seasonal ice zone features and processes from ERS-1 SAR: SIZEX92. J. Geophys. Res., 104, 15,843-15,857.

123. Schmidt, G.A., and J.E. Hansen, 1999. Role of sea ice in global change pondered. EOS, Trans. American Geophysical Union 80, 317-339.

124. Scipal, K., and W. Wagner, 1998. Monitoring Freeze-Thaw Cycles over Northern Canada. Proceedings of the 2nd European Conference on Applied Climatology, 19-23 October 1998, Vienna, Austria (CD-ROM Proceedings).

125. Shine, K.P., A.H. Henderson-Sellers and R.G. Barry, 1984. Albedo - climate feedback: the importance of cloud and cryosphere variability. In: A.L. Berger and C. Nicolis, eds. New Perspectives in Climate Modelling. Elsevier, Amsterdam, pp. 135-155.

126. Shokr, M., and T. Agnew, 1999. Sea Ice Parameters Retrieval Using Synergistic Observations from SSM/I 85.5 GHz and AVHRR, Proc. of the International Geoscience and Remote Sensing Symposium (IGARSS'99), June 28-July 2, 1999, Hamburg Germany.

127. Skinner, W.R., 1993. Lake Ice Conditions as a Cryospheric Indicator for Detecting Climate Variability in Canada. Snow Watch ’92, WDC-A Glaciological Data report 25, 204-240.

128. Smith, N.R., G.T. Needler and the Ocean Observing System Development Panel, 1995. An Ocean Observing System for Climate. The Conceptual Design. Climatic Change, 31, 475-494.

129. Steele, M., and G.M. Flato, 1999. Growth, Melt, and Modelling: A Survey. In: The Freshwater Budget of the Arctic Ocean, NATO ASI, in press.

130. Steffen K., W. Abdalati and I. Sherjal, 1999. Faceted crystal formation in the northeast Greenland low-accumulation region, J. Glaciol. 45, (149) 63-68.

131. Steffen, K., W. Abdalati and J. Stroeve, 1993. Climate sensitivity studies of the Greenland ice sheet using satellite AVHRR, SMMR, SSM/I and *in situ* data. Meteorol. Atmos. Phys., 51, 239-259.

132. Stewart, R.E., H.G. Leighton, P. Marsh, G.W.K. Moore, H. Ritchie, W.R. Rouse, E.D. Soulis, G.S. Strong, R.W. Crawford and B. Kochtubajda, 1998. The Mackenzie GEWEX Study: The Water and Energy Cycles of a Major North American River Basin. Bulletin of the American Meteorological Society, 79(12), 2665-2683.

133. Stroeve, J.C., A.W. Nolin and K. Steffen, 1997. Comparison of AVHRR-derived and *in situ* surface albedo over Greenland. Rem. Sens. Environ., 62, 262-276.

134. Stroeve, J., X. Li and J.A. Maslanik, 1998. An intercomparison of DMSP F-11 and F-13-derived sea ice products. Rem. Sens. Environ., 64, 132-152.

135. Tait, A., 1998. Estimation of snow water equivalent using passive satellite microwave radiation data. Rem. Sens. Environ., 64, 286-291.

136. Thompson, D.W.J., and J.M. Wallace, 1999. Annular modes in the extratropical circulation. J. Climate, in press.

137. Thompson, L.G., E. Mosley-Thompson, M. Davis, P.N. Lin, T. Yao, M. Dyurgerov and J. Dai, 1993. Recent warming: Ice core evidence from tropical ice cores with emphasis on central Asia. Global Planet. Change, 7, 145-156.

138. Trenberth, K.E., 1995. Long-term climate monitoring by the Global Climate Observing System. Report of Breakout Group B- Climate responses and feedbacks. An editorial. Climatic Change, 31, 163-180.

139. Trupin, A.S., M.F. Meier and J. Wahr, 1992. Effect of melting glaciers on the Earth's roation and gravitational field: 1965-1984. Geophys. J. Int., 108, 1-15.

140. Vaughan, D.G., J.L. Bamber, M. Giovinetto, J. Russell and A.P.R. Cooper, 1999. Reassessment of net surface mass balance in Antarctica. J. Climate, 12, 933-946.

141. Vernekar, A.D., J. Zhou and J. Shukla, 1995. The effect of Eurasian snow cover on the Indian monsoon. J. Climate, 8, 248-266.

142. Vinnikov, K. Ya., R.J. Stouffer, D. Cavalieri, J.E. Walsh, C.L. Parkinson, D.J. Cavalieri, J.F.B. Mitchell, D. Garrett and V.F. Zakharov, 1999. Global Warming and Northern Hemisphere Sea Ice Extent. Science, 286, 1934-1937.

143. Walker, A.E., and B.E. Goodison, 1993. Discrimination of a wet snow cover using passive microwave satellite data. Ann. Glaciol., 17, 307-311.

144. Walker, A.E., and M.R. Davey, 1993. Observation of Great Slave Lake ice freeze-up and break-up processes using passive microwave satellite data. In: Proc. 16th Canadian Symposium on Remote Sensing, Sherbrooke, Quebec, 7-10 June 1993, 233-238.

145. Walsh, J.E., 1995. Long-term observations for monitoring of the cryosphere. Clim. Change 31, 369-394.

146. Walsh, J.E., 1978. A data set of northern hemisphere sea ice extent, 1953-76. Glaciological Data. Report GD-2, National Snow and Ice Data Center, University of Colorado, Boulder, CO., 49-51.

147. Walsh, J.E., 1993. Temperature Variations in Northern High Latitudes, 1960-1990.

148. Warner, R.C., and W.F. Budd, 1998. Modelling the long-term response of the Antarctic ice sheet to global warming. Ann. Glaciol., 27, 161-168.

149. Warrick, R.A. et al., 1996. Changes in sea level. Chapter 7 in: Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, Houghton, J.T. et al., (eds.), 359-405. Cambridge University Press, Cambridge and New York.

150. Warrick, R.A., C. Le Provost, M.F. Meier, J. Oerlemans and P.L. Woodworth, 1996. Changes in sea level. In J.T. Houghton et al., eds. Climate Change 1995. The Science of Climate Change, pp. 359-405.

151. Washburn, A.L., 1973. Periglacial Processes and Environments. St Martin's Press, New York.

152. WCRP, 1995. Report of the ninth session of the WCRP/GEWEX Working Group on Data Management for the Global Precipitation Climatology Project (GPCP), College Park, Maryland, USA, 24-26 May 1995. WCRP Informal Report No. 7/1995, Geneva, 20 pp.

153. WCRP, 1997. Proceedings of the workshop on the implementation of the Arctic Precipitation Data Archive (APDA) at the Global Precipitation Climatology Centre (GPCC), Offenbach, Germany, 10-12 July 1996. (Ed.: R.G. Barry, T. Fuchs and B. Rudolf). WCRP-98, WMO/TD No. 804, Geneva, 126 pp.

154. WCRP, 1998a. Report of the first session of the ACSYS Data Management and Information Panel, St. Petersburg, Russian Federation, 10-12 March 1998. WCRP Informal Report No. 7/1998.

155. WCRP, 1998b. Proceedings of a meeting of experts on cryosphere and climate, Cambridge, UK, 3-5 February 1997. (Ed.: R.G.Barry). WCRP-102, WMO/TD No. 867.

156. WCRP, 1998c. Arctic Climate System Study (ACSYS). Summary Report of the Sixth Session of the WCRP ACSYS Scientific Steering Group. WCRP Informal Report No. 8/1998, Appendix F: WCRP Satellite Data Requirements.

157. WCRP, 1999a. Summary report on the first session of the WCRP (JSC/ACSYS) Climate and Cryosphere (CliC) Task Group (Utrecht, the Netherlands, 8-11 July 1998). WCRP Informal Report No. 4/1999 (Ed.: R.G. Barry). WMO, Geneva, 27 pp.

158. WCRP, 1999b. Hydrological Cycle in the Arctic Region. In: ACSYS Implementation and Achievements (revised draft). Available from: www.npolar.no/acsys/impplan/index.htm.

159. Williams, R.S. Jr., and J.G. Ferrigno (in press). Introduction, Satellite Image Atlas of Glacier of the Worlds. U.S. Geological Survey Professional Paper 1386-A.

160. Wingham, D.J., et al., 1998b. CryoSat: A mission to determine fluctuations in the mass of the earth’s land and marine ice fields. Proposal to European Space Agency.

161. Wingham, D.J., A.L. Ridout, R. Scharoo, R.J. Arthern and C.K. Shum, 1998a. Antarctic elevation change from 1992 to 1996. Science, 282, 456-458.

162. Worby, A.P., R.A. Massom, I. Allison, V.I. Lytle and P. Heil, 1998. East Antarctic Sea Ice: A Review of its Structure, Properties and Drift. In: M. Jeffries (ed.), Antarctic sea ice properties, processes and variability, AGU Antarctic Research Series, 74, 41-68.

163. Wu X., W.F. Budd and T.H. Jacka, 2000. Simulations of Southern Hemisphere warming and Antarctic sea-ice changes using global climate models. Ann. Glaciol., 29 (in press).

164. Zhang, T., R.G. Barry, K. Knowles, J.A. Heginbottom and J. Brown, 1999. Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere. Polar Geography 23(2), 147-169.

165. Zhou Z., and J. Oerlemans, 1997. Contribution of glacier melt to sea-level rise since AD 1865: a regionally differentiated calculation. Climate Dynamics, 13, 835-845.

166. Zuerndorfer, B.W., A.W. England, C.M. Dobson and F.T. Ulaby, 1990. Mapping freeze/thaw boundaries with SMMR data. Journal of Agriculture and Forest Meteorology, 52, 199-225.

Appendices

APPENDIX 1

TERMS OF REFERENCE OF THE CliC TASK GROUP

The JSC-XIX 1998 endorsed the proposal of the ACSYS SSG-VI (WCRP Informal Report No. 8/1998) for a broader programme on cryosphere and climate in the WCRP. As a first step, a task group ("The WCRP Climate and Cryosphere Task Group" (CliC)) was established to develop a science and co-ordination plan for presentation at the JSC-XXI (March 2000, Tokyo). The detailed responsibilities were set down as follows:

(i) The Task Group is responsible to the JSC through the ACSYS Scientific Steering Group;

(ii) The Task Group will develop a science and co-ordination plan for the WCRP Climate and Cryosphere (CliC) project. The Group members will propose studies of cryospheric elements where there are notable gaps in present programmes. They will seek to enhance links between global and regional cryospheric studies and will ensure accurate and appropriate treatment in climate models of cryospheric processes and the interactions of the cryosphere with atmosphere, oceans and land surface. Preparation of the global and regional cryospheric data sets necessary for forcing and validating climate models and for diagnostic studies of the cryosphere's role in climate will be organized. The Task Group will interact with other WCRP efforts (in particular, GEWEX and CLIVAR) and they will establish approprate co-ordination mechanisms with other projects that can contribute to WCRP research on climate and the cryosphere.

(iii) The Task Group shall also set out the framework in which CliC can be implemented in the WCRP (noting that ACSYS will be maintained as a distinct component of the WCRP until its agreed end date in 2003);

(iv) A progress report shall be given to the 20th session of the Joint Science Committee (JSC-XX) in March 1999, and a draft science and co-ordination plan delivered for review at its 21st session in March 2000.

The ACSYS Scientific Steering Group was asked by the JSC-XIX to select suitable members for the task group and to prepare arrangements for the first meeting.

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LIST OF ACRONYMS

AAO	Antarctic Oscillation
ACC	Anthropogentic Climate Change; Antarctic Circumpolar Current
ACSYS	Arctic Climate System Study (WCRP)
ACW	Antarctic Circumpolar Wave
ADACIT	ACSYS Data Centre for Ice Thickness
AES	Atmospheric Environmental Service (Canada)
AGCM	Atmospheric General Circulation Model
AIO	Atmosphere-Ice-Ocean
ALBW	Adélie Land Bottom Water
AMIP	Atmospheric Model Intercomparison Project (WCRP)
AMSR	Advanced Microwave Scanning Radiometer
AnSITP	Antarctic Sea Ice Thickness Project (WCRP)
AO	Arctic Oscillation; or Arctic Ocean
APDA	Arctic Precipitation Data Archive
APP	AVHRR-based Polar Pathfinder project (NOAA)
ARCSS	Arctic Systems Science (NSF)
ASI	Atmosphere Snow and Ice
ASITP	Arctic Sea Ice Thickness Project (WCRP)
ASL	Atmosphere Snow and Land
ASPeCt	Antarctic Sea-Ice Processes, Ecosystems and Climate (GLOCHANT)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer (Terra/EOS)
AVHRR	Advanced Very High Resolution Radiometer
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
BASIS	Barents Sea Impact Study (IASC)
BEDMAP	Bedrock Map of Antarctica (not a true acronym). Project to compile and map ice thickness data for Antarctica (SCAR).
BESIS	Bering Sea Impact Study (IASC)
BOREAS	Boreal Ecosystem-Atmosphere Study
CALM	Circumpolar Active Layer Monitoring Program
CCCMA	Canadian Centre for Climate Modelling and Analysis
CEOP	Co-ordinated Enhanced Observing Period (GEWEX)
C-GA	Cryosphere-Global Atmosphere
C-GO	Cryosphere-Global Ocean
CIMO	Commission for Instruments and Methods of Observation (WMO)
CliC	Climate and Cryosphere (WCRP)
CLIVAR	Climate Variability and Predictability (WCRP)
CMIP	Coupled Intercomparison Model Project
CMM	Commission for Marine Meteorology (WMO)
CryoSat	Cryosphere Satellite (ESA)
CRYSYS	Cryospheric System to Monitor Global Change in Canada
CSE	Continental Scale Experiment (GEWEX)

CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DecCen	Decadal-to-Centennial
DMSP	Defense Meteorological Satellite Program (US)
EASE	Equal-Area Scalable Earth grid
ECHAM	GCM based on the ECMWF weather forcast model (Max Planck Institute for Meteorology, Hamburg)
ECMWF	European Centre for Medium Range Weather Forecasting (UK)
ECOPS	European Committee for Ocean and Polar Sciences
EISMINT	European Ice Sheet Modelling Initiative
ENSO	El Niño-Southern Oscillation
EOS	Earth Observing System (NASA)
EPICA	European Project for Ice Coring in Antarctica (ECOPS)
ERS	European Remote Sensing satellite (ESA)
ESA	European Space Agency
ESE	Earth System Enterprise (NASA)
FAGS	Federation of Astronomical and Geophysical Services
FRISP	Filchner-Ronne Ice Shelf Programme (SCAR)
GAME	GEWEX Asian Monsoon Experiment
GCM	General (or Global) Circulation Model
GCOS	Global Climate Observing System
GDSIDB	Global Digital Sea-Ice Data Bank (WMO)
GEWEX	Global Energy and Water Cycle Experiment (WCRP)
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GISP	Greenland Ice Sheet Project (or Programme)
GLAS	Geoscience Laser Altimeter System (NASA)
GLIMS	Global Land Ice Measurements from Space
GLOBE	Global Learning and Observations to Benefit the Environment (NSF)
GLOCHANT	Group of Specialists on Global Change and the Antarctic (SCAR)
GOALS	Global Ocean-Atmosphere-Land System (CLIVAR)
GOES	Geostationary Operational Environmental Satellite
GOOS	Global Ocean Observing System; or Global Ozone Observing System
GPCC	Global Precipitation Climatology Centre (WCRP)
GRDC	Global Runoff Data Centre (WMO auspices)
GRIP	Greenland Ice-core Project (or Programme) (ESF)
GTNet-G	Global Terrestrial Network for Glaciers
GTNet-P	Global Terrestrial Network for Permafrost
GTOS	Global Terrestrial Observing System
HSSW	High Salinity Shelf Water
IABP	International Arctic Buoy Programme
IACPO	International ACSYS/CliC Project Office
IAHS	International Association of Hydrological Sciences (ICSU)
IAI	Inter American Institute
iAnZone	International Antarctic Zone (SCOR affiliated programme)
IASC	International Arctic Science Committee

ICAPP	Ice Core Circum-Arctic Paleoclimate Programme
ICESat	Ice, Cloud and land Elevation Satellite (NASA)
ICSI	International Commission on Snow and Ice (IAHS)
ICSU	International Council for Science
IGAC	International Global Atmospheric Chemistry Programme (IGPB)
IGBP	International Geosphere-Biosphere Programme of UNESCO (ICSU)
IOC	International Oceanographic Commission (of UNESCO)
IOS	Initial Observing System (GCOS)
IPA	International Permafrost Association
IPAB	International Programme for Antarctic Buoys (WCRP)
IPCC	Inter-governmental Panel on Climate Change (WMO, UNEP)
ISLSCP	International Satellite Land Surface Climatology Project (GEWEX)
ISMASS	Ice Sheet Mass Balance and SeaLevel Contributions (GLOCHANT)
ISW	Ice Shelf Water
ITASE	International Trans-Antarctic Scientific Expeditions (GLOCHANT)
ITCZ	Intertropical Convergence Zone
ITEX	International Tundra Experiment
JCOMM	Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology
JSC	Joint Scientific Committee (WCRP)
LSP	Land Surface Process
MAGICS	Mass Balance of Arctic Glaciers and Ice Sheets in relation to Climate and Sea Level Changes (IASC)
MAGS	Mackenzie GEWEX Study (Canada)
MAAT	Mean Annual Air Temperature
NADW	North Atlantic Deep Water
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration (US)
NEG	Numerical Experimentation Group
NH	Northern Hemisphere
NOPEX	Northern Hemisphere Climate Processes Land Surface Experiment (BAHC)
NOAA	National Oceanic and Atmospheric Administration (US)
NSF	National Science Foundation (US)
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction
OGCM	Ocean General Circulation Model
PAGES	Past Global Environmental Changes (IGBP)
PARCA	Program in Arctic Regional Climate Assessment (NASA)
P-E	Precipitation minus Evaporation
PICE	Palaeoenvironments from Ice Cores (SCAR-GLOCHANT)
PILPS	Project for Intercomparison of Land-surface Parameterization Schemes
PMIP	Paleoclimate Model Intercomparison Project

PNA	Pacific NorthAmerican (teleconnection pattern)
POGO	Partnership for Observations of Global Oceans
POSSIR	Working Group on Polar Seas and other Sea Ice Regions (JCOMM)
RAMP	RADARSAT Antarctic Mapping Project (NASA and Canadian Space Agency)
RCM	Regional Climate Model
SAR	Synthetic Aperture Radar
SBI	Western Arctic Shelf Basin Interactions (ARCSS)
SCA	Snow Covered Area
SCAR	Scientific Committee on Antarctic Research (ICSU)
SCOR	Scientific Committee on Oceanic Research (ICSU)
SCP	Science and Co-ordination Plan
SEARCH	Study of Environmental Arctic Change (ARCSS proposed)
SH	Southern Hemisphere
SHEBA	Surface Heat Budget of the Arctic Ocean (ARCSS)
SIMIP	Sea Ice Model Intercomparison Project (ACSYS)
SMMR	Scanning Multichannel Microwave Radiometer
SNOWMIP	Snow Model Intercomparison Project (under ICSI snow climate WG)
SSG	Scientific Steering Group
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SWE	Snow Water Equivalent
THC	Thermohaline Circulation
TOGA	Tropical Oceans and Global Atmosphere Programme (WCRP)
TOPC	Terrestrial Observation Panel for Climate (GCOS/GTOS)
UKTR	UK Met Office High Resolution GCM Transient Experiment
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAF	United States Airforce
WAIS	West Antarctic Ice Sheet Initiative
WCRP	World Climate Research Programme
WDC	World Data Center
WG	Working Group
WGMS	World Glacier Monitoring Service
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment (WCRP)
WSBS	Weddell Sea Bottom Water
XPGR	Cross-polarised gradient ratio

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