Invited keynote address

The cryosphere: an early indicator and global player

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Ice at or below the surface of the planet Earth is an important part of the climate system. The solid phase of water has two unique characteristics which make it both an early indicator of climate change and a global player. First, if warmed to the melting point at 0°C, higher air temperatures and/ or higher long-wave back radiation just increase the melting rate but not – as with all other surfaces – the temperature, which stays at 0°C. Small ice caps and mountain glaciers thus become early indicators of a changed climate. Second, if seawater is cooled to the freezing point at about −1.8°C, the sea ice formation process ejects salt causing the denser water to sink, thereby filling the global ocean interior with very cold water. The location where most of this deep convection occurs is strongly dependent on the freshwater balance and thus on the average salinity of ocean basins. Present ocean configuration and ocean topography, as well as precipitation distribution, make the northern North Atlantic more saline than any other high latitude ocean part and thus the site with most of this deep water formation. Sea ice formation is therefore of high significance for the European climate. Since it drives the near surface warm North Atlantic current northward off the European coast in compensation for southward deep water flow in the western Atlantic, northwestern Europe is warmer by about 4°C than the same latitudes on the eastern Pacific coast of America.

Since I restrict myself to climate-related aspects of the cryosphere, I will not speak about reactions of the biosphere and high latitude populations to global change, but I will include cryospheric processes outside the polar latitudes.

A few facts: the cryosphere

- **is the largest freshwater reservoir:** 98% of all freshwater is fixed in the Antarctic and Greenland ice sheets as well as in the other small ice caps and mountain glaciers;
- **contains the brightest natural surface:** fresh powder snow reaches an albedo of about 90% as compared to about 15 to 20% for grassland;
- **is responsible for a positive feedback:** melting of high albedo surfaces (snow and ice) increases absorption of solar radiation which in turn increases temperature and accelerates melting of nearby snow and ice surfaces;
- **emits least heat to space:** the low surface temperatures of Greenland and Antarctica cause the lowest emissions to space both in winter and summer for their respective hemispheres;
- **insulates the ocean from heat loss:** sea ice reduces all three heat losses of a surface (long-wave net radiation, sensible heat flux, latent heat flux); the latter two to a small fraction of the values for an open ocean area;
- **fixes large amounts of carbon dioxide (CO_2) and methane (CH_4):** organic material in permafrost is to a large part emitted as CO_2 and CH_4 after the melting of permafrost;
- **changes by more than a factor of two within an annual cycle:** for example, Northern Hemisphere snow cover reaches $46.5 \cdot 10^6$ km^2 in late January and is lowered to $3.9 \cdot 10^6$ km^2 in September;
- **creates the cold interior of the global ocean:** Antarctic bottom water and North Atlantic deep water formed by deep convection are the main water masses of the global ocean, with temperatures mostly below about 3°C even in tropical latitudes.

Some recent findings

This selection of examples tries to avoid overlap with other presentations in this volume. Therefore, the following three examples will be briefly presented: remote sensing of mountain glacier retreat; stability investigations of the thermohaline

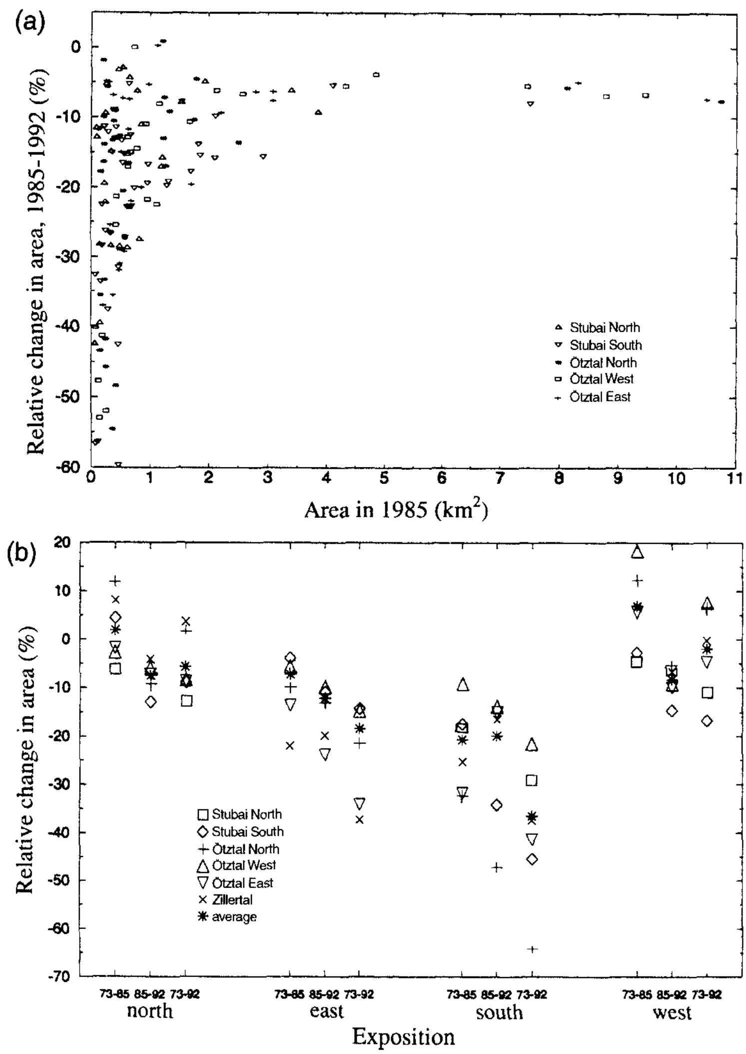

Fig. 1. Glacier retreat in the Austrian Alps: (a) relative change in area in 1992 versus area in 1985 as a function of glacier area; (b) change in area with exposition (from Paul 1997, with permission of author).

overturning in the Atlantic; and selection of a sea ice rheology code best suited for global climate models.

Alpine glacier retreat: Small valley glaciers react comparably rapidly to temperature and precipitation changes. Their retreat depends strongly on their length, mean slope, ratio of accumulation to entire surface area and orientation. Landsat images with sufficiently high spatial resolution exist since 1973 for a trend analysis. As one of my students (Paul 1997) has shown, for many glaciers in the eastern Alps, the 19 year period from 1973 to 1992 was one of strong retreat with clear dependencies on orientation and size of the glaciers. As Fig. 1 demonstrates, even the 1985 to 1992 period gave clear signals. The main reason for the retreat in this area with no significant change of annual precipitation during the recent decades was a rather rapid warming.

Thermohaline circulation changes in the Atlantic: At present the meridional overturning of the Atlantic drives the so-called global ocean conveyor belt. Palaeoclimatic evidence points to rapid changes of the deep water formation rate in the high latitude Atlantic, the core region of the conveyor belt. As also shown by modelling studies (e.g. Rahmstorf 1996) the stability diagram (see Fig. 2) of the conveyor contains a large

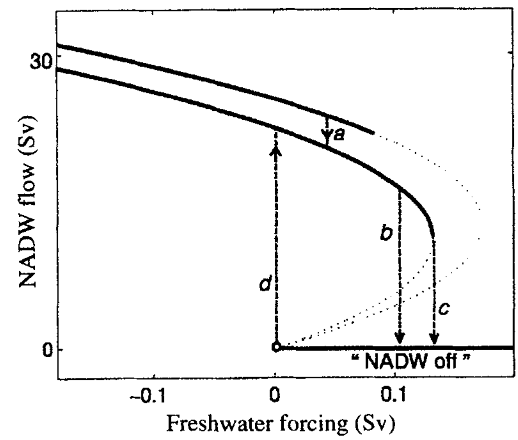

Fig. 2. North Atlantic deep water (NADW) formation rate as a function of additional freshwater input into the Atlantic north of 30°S (modified from Rahmstorf 1999, with permission of the author). Solid lines show stable equilibrium states; unstable states are dotted. Note the strong hysteresis as well as the different mechanisms responsible for the cessation of deep water formation. Transition mechanisms include: a) local convective instability; b) polar halocline catastrophe; c) advective spin-down; and d) start-up of convection and NADW formation.

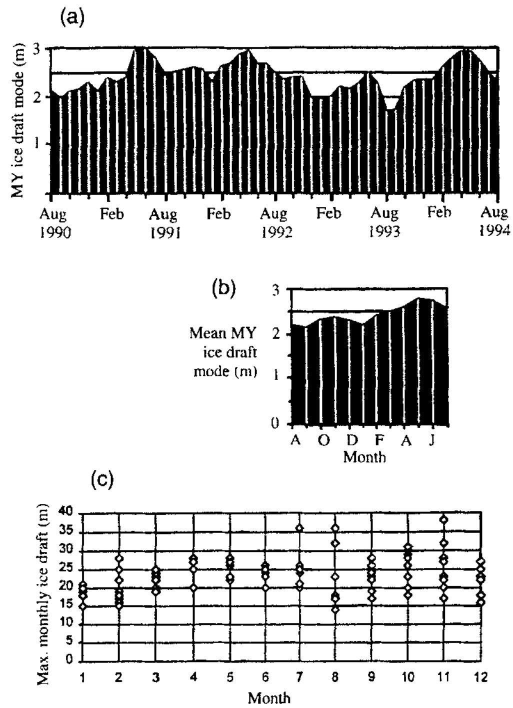

Fig. 3. (a) First multi-year time series of sea ice draft in Fram Strait; (b) the annual cycle; and (c) the maximum draft during different months (T. Vinje and N. Nordlund, pers. comm.). Ice thickness = draft × 1.136. Ice export per year = ca. 2.8 × 10^3 km^3.

hysteresis. The addition of freshwater north of 30°S in the Atlantic – only 0.1 Sverdrup (1 Sv = 10^6 m^3 s^{-1}) is sufficient – stops deep water formation, which will only start again if all the additional freshwater input is removed. The cryosphere (for example, due to additional melt-water from decaying ice sheets) has exerted this influence in the past, but a change in precipitation and/or evaporation over the Atlantic would also suffice. Much more research is needed to find out

Table 1. Similarities and contrasts among polar regions. NH and SH indicate whether the intersection of a cryospheric element with a climate process is specific to the Northern or the Southern Hemisphere, or occurs in both.

Climate processes/ cryospheric elements	Ice sheets	Ice shelves	Glaciers, ice caps	Sea ice	Snow	Frozen rivers, lakes	Frozen ground
Sea level change	NH: trend SH: catastrophic		NH				
Deep water formation		SH		NH, SH			
Surface energy balance:							
Albedo	NH, SH			NH, SH	NH, SH	NH	
Latent and sensible heat		SH		NH, SH	NH, SH	NH	NH
Oceanic surface buoyancy flux:							
Precipitation					NH, SH		
Melting/ablation, freezing/accumulation	NH	SH	NH	NH, SH	NH, SH	NH	
Iceberg calving	NH	SH					
Soil moisture (run-off)					NH	NH	NH
Radiative processes (through changed atmospheric composition)							NH

Table 2. The state of observational data for the Northern (NH) and Southern (SH) hemispheres, and international research programmes/groups/institutions that have contributed or will contribute to the data. D− indicates absence of necessary data; D+ indicates availability of some data; Do indicates lack of information on the data required.

Climate processes/ cryospheric elements	Ice sheets	Ice shelves	Glaciers, ice caps	Sea ice	Snow	Frozen rivers, lakes	Frozen ground
Sea level change	D− MAGICS ISMASS WAIS		NH: Do/− MAGICS SH: D−				
Deep water formation		D− FRISP		NH: D+ ACSYS CLIVAR SH: D− iAnZone ASPECt			
Surface energy balance:							
Albedo	NH: Do SH: D+ GEWEX			D+ ACSYS GEWEX	D+ GEWEX	Do	
Latent and sensible heat		D− FRISP		NH: Do ACSYS SHEBA SH: D− ASPECt WCRP	D+ ECMWF NCEP	D+ ECMWF NCEP	Do ECMWF
Oceanic surface buoyancy flux:							
Precipitation					D− Snowdrift		
Melting/ablation, freezing/accumulation	D− MAGICS ISMASS WAIS	D− FRISP	NH: Do/− MAGICS SH: D−	D+ NH: ACSYS SH: ASPECt WCRP iAnZone	Do NH: ACSYS SH: ASPECt		
Iceberg calving	Do/+	Do/+					
Soil moisture (run-off)					Do GEWEX	Do GEWEX	Do GEWEX
Radiative processes (through changed atmospheric composition)							D− IGAC

whether the global warming by an enhanced greenhouse effect would bring us nearer to such a rapid change.

Sea ice dynamics in climate models: The coupling of ocean – sea ice and the atmosphere as well as of soil, vegetation and atmosphere is among the major challenges of climate modelling. Sea ice dynamics is an important part in this coupling. The Sea Ice Modelling Panel (SIOMP) of the Arctic Climate System Study (ACSYS) of the World Climate Research Programme (WCRP) conducted sea ice dynamics model intercomparisons and found that only the viscous-plastic model could reproduce the observed sea ice thickness distribution in the Arctic (Lemke et al. 1997). Global climate models therefore should adopt this code for a more realistic representation of sea ice in global coupled climate models.

The Arctic Climate System Study

The different projects of WCRP are normally global since both the atmosphere and the ocean circulate globally. Only the Arctic Climate System Study (ACSYS) has a regional focus, i.e. it

Table 3. The state of modelling for the Northern (NH) and Southern (SH) hemispheres, and international research programmes/groups/institutions that have contributed or will contribute to modelling efforts. M+ indicates that some modelling activities are underway; M− indicates insufficient modelling efforts; Mo indicates lack of information on sufficient modelling activities.

Climate processes/ cryospheric elements	Ice sheets	Ice shelves	Glaciers, ice caps	Sea ice	Snow	Frozen rivers, lakes	Frozen ground
Sea level change	Mo/+ EISMINT		NH: Mo MAGICS SH: M−				
Deep water formation		M+ FRISP iAnZone EISMINT		M+ ACSYS iAnZone ice–ocean coupling			
Surface energy balance:							
Albedo	Mo EISMINT			M+ ACSYS iAnZone	Mo WGNE: Albedo $\alpha = \alpha$ (T, surface type)	Mo GEWEX	
Latent and sensible heat		M+ FRISP EISMINT iAnZone		M+ ACSYS iAnZone	Mo WGNE: subgrid parameter-ization (Land)	M+ ECMWF NCEP	Mo ECMWF
Oceanic surface buoyancy flux:							
Precipitation					Mo		
Melting/ablation, freezing/accumulation	Mo/+ EISMINT	M+ FRISP EISMINT iAnZone	NH: Mo MAGICS SH: M−	M+ ACSYS IAnZone	Mo/+ ACSYS iAnZone		
Iceberg calving	M−	M−					
Soil moisture (run-off)					Mo WGNE	Mo GEWEX	Mo WGNE
Radiative processes (through changed atmospheric composition)							Mo CLIVAR ACC

concentrates on the Arctic Ocean and sea ice. Its objectives are:

- to provide the scientific basis for the representation of the Arctic region in coupled global atmosphere–ocean models;
- to develop an effective climate monitoring scheme in the Arctic;
- to carry out scenario computations for specified large-scale atmospheric conditions, in order to evaluate possible impacts of climate change in the Arctic region.

ACSYS formally implements its goals since 1994 although some scientific activities had already started in the early '90s. A good example of early achievements is provided in Fig. 3, which displays the first multi-year time series of sea ice draft in Fram Strait measured with upward looking sonars mounted on top of ocean moorings. It underlines the importance of sea ice export through Fram Strait into the Atlantic. 2800 km^3 are exported per year which is – if compared to river run-off – roughly 20 times the discharge of the Congo River. Astonishingly, the thickest ice is exported in summer and interannual changes are large, spanning the range from about 2000 to 4000 km^3, thus contributing to large salinity anomalies in Greenland Sea waters.

Table 4. Existing international programmes/projects/activities. Status: I = implementation; IP = implementation plan exists.

Acronym	Full title	Hemisphere	Status	Focus	Sponsoring institution
ACSYS	Arctic Climate System Study	NH	I	Arctic Ocean circulation and sea ice	WCRP
IABP	International Arctic Buoy Programme	NH	I	Drifting buoys on sea ice	Operational and research institutions
IPAB	International Programme of Antarctic Buoys	SH	I	Drifting buoys on sea ice	WCRP
ANSITP	Antarctic Sea Ice Thickness Project	SH	I	Sea ice thickness from upward-looking sonars	WCRP
iAnZone	International Antarctic Zone Program	SH	I	Coupling of the circum-Antarctic Ocean and the atmosphere	SCOR (ICSU)
CALM	Circumpolar Active-Layer Monitoring Programme	NH	I	Active layer thickness in continuous permafrost areas	IPA (ICSU)
GCD	Global Geocryological Data Base	Both	I	Retrieval, documentation, archiving and distribution of permafrost data	IPA (ICSU)
MAGICS	Mass Balance of Arctic Glaciers and Ice Sheets in Relation to the Climate and Sea Level Changes	Both, focus on NH	I	Circumpolar mass balance studies	IASC
CLIVAR-D5	Southern Ocean Thermohaline Circulation Focus in CLIVAR	SH	IP	Southern Ocean variability and climate variability	WCRP
ASPECt	Antarctic Sea-Ice Processes and Climate	SH	IP	200 years of past Antarctic climate and environment change	SCAR (ICSU)
ISMASS	Ice Sheet Mass Balance and Sea Level	SH	IP	Mass balance of the Antarctic Ice Sheet	SCAR (ICSU)
WAIS*	West Antarctic Ice Sheet Initiative	SH	I	Understanding the dynamics of the WAIS	USA consortium
FRISP*	Filchner-Rönne Ice Shelf Project	SH	I	Understanding ice shelf–ocean interaction	European consortium
EISMINT*	European Ice Sheet Modelling Initiative	SH	I	Understanding the dynamics of ice sheets, including ice shelves	Mainly European consortium
CRYSYS*	Canadian contribution to NASA's EOS on the Cryospheric System	NH	?	Use of the cryosphere to monitor climate change	Canadian initiative

*National or multi-national activities with research topics falling within the CLIC domain (incomplete).

Another achievement is the sea ice model intercomparison which has led to a recommendation for climate model sea ice codes (Lemke et al. 1997): modelled sea ice dynamics using the viscous-plastic model are nearest to observations of sea ice extent and thickness and should thus be adopted for global coupled climate models.

No overlaps, but still some gaps

Soon after the start of ACSYS, discussions for a broader approach of research on climatically relevant cryospheric processes were initiated inside and outside WCRP. An expert meeting on Cryosphere and Climate organized by WCRP and hosted by the British Antarctic Survey in Cambridge, UK, from 3 to 5 February 1997, developed recommendations for WCRP concerning the broadening of climate-related cryospheric research (WCRP 1998).

One of the main findings was that despite the large number of programmes/projects/activities, there were nearly no overlaps but still some gaps in climate-related research of cryospheric processes. This is detailed in Tables 1 to 3, which first show the processes relevant in the different cryospheric elements and the contrasts between the hemispheres, and then point to data gaps and insufficient modelling. The major recommendation to WCRP was that a global activity on cold regions and climate within WCRP should be developed whereby already successfully implemented projects should not be disrupted.

The recommendations of the meeting led to the establishment of a Task Group on Climate and

Cryosphere (CLIC) by the Joint Scientific Committee (JSC) for WCRP.

Climate and Cryosphere: a WRCP initiative

With the establishment of the JSC/ACSYS Task Group on Climate and Cryosphere (CLIC) at the nineteenth session of JSC in Cape Town, South Africa, in March 1998, a global Climate and Cryosphere project of WCRP became highly probable. That the CLIC Task Group is also charged with the formulation of a coordination plan can easily be understood if one looks at Table 4 which lists existing international programmes/ projects/activities engaged in climate-related cryospheric research. Coordination will be facilitated by the fact that many of the ongoing activities are sponsored by committees or associations of the International Council for Science (ICSU) which is also a sponsor of WCRP, in addition to WMO and UNESCO's IOC.

The two major goals of CLIC – as far as I can see them now – will be:

- understanding climatically relevant cryospheric processes, including their role as early indicators of climate variability and climate change;
- understanding and predicting – to the extent possible – the influence of the cryosphere on global climate.

A first outline of the science plan was drafted at the first CLIC Task Group meeting which took place in Utrecht, The Netherlands, from 8 to 11 July 1998. The report of the meeting, including the outline, will be discussed by the ACSYS Scientific Steering Group in Tokyo in November 1998 before it is submitted to the JSC for WCRP in March 1999 in Kiel, Germany.

Outlook

The improved understanding of seasonal to interannual climate variability, as it is expressed by seasonal climate anomaly predictions related to tropical sea surface temperature anomalies, which are available now from global modelling centres, shifts the main climate research topics to other processes and to longer time scales. Cryospheric processes thus come more into the focus of climate research. For example, improved seasonal predictions in the Asian monsoon area may need better data on central Asian snow cover. The understanding of the Arctic oscillation depends on improved data and modelling of sea ice – ocean – atmosphere interaction; and the understanding of the influence of the enhanced greenhouse effect on global thermohaline ocean circulation needs, in addition to oceanographic information, data on the long-term behaviour of snow extent, run-off or calving from ice sheets.

It is time for CLIC, and since all institutions implementing or planning projects on climatically relevant cryospheric processes have indicated their preparedness to cooperate, I see no major obstacles for the proper coordination of the existing activities and the filling of the gaps identified in a new global WCRP project Climate and Cryosphere.

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