WORLD CLIMATE RESEARCH PROGRAMME

ARCTIC CLIMATE SYSTEM STUDY (ACSYS)

INITIAL IMPLEMENTATION PLAN

SEPTEMBER 1994

WCRP-85

WMO/TD-No. 627
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

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ARCTIC CLIMATE SYSTEM STUDY
(ACSYS)

INITIAL IMPLEMENTATION PLAN

SEPTEMBER 1994
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LIST OF ACRONYMS

AARI - Arctic and Antarctic Research Institute (Russian Federation)
ACSYS - Arctic Climate System Study (WCRP)
AIDJEX - Arctic Ice Dynamics Joint Experiment
AIRS/MHS - Advanced Infrared Radiometer Sounder (Atmospheric Infrared Sounder)/Microwave Humidity Sounder
AITP - Arctic Ice Thickness Project (WCRP)
AMIP - Atmospheric Model Intercomparison Project
AMMS - Advanced Multichannel Microwave Sensor
AOVP - Arctic Ocean Variability Project (ACSYS)
APDA - Arctic Precipitation Data Archive (ACSYS)
ARDB - Arctic Run-off Database (ACSYS)
Argos - Satellite-borne data relay and platform location system
ARM - Atmospheric Radiation Measurement (programme)
ATSR - Along Track Scanning Radiometer
AVHRR - Advanced Very High Resolution Radiometer
BASE - Beaufort and Arctic Storms Experiment (Canada)
BSRN - Baseline Surface Radiation Network
CART - Cloud and Radiation Testbed
CAS - Commission for Atmospheric Sciences (WMO)
CD-ROM - Compact disk - Read-only memory
CEAREX - Co-ordinated Eastern Arctic Experiment
CIMO - Commision for Instruments and Methods of Observation (WMO)
CLIVAR - Study of Climate Variability and Predictability (WCRP)
CLS - Collecte Localization Satellites (France)
CME - Community Modelling Effort (U.K.)
CMM - Commission for Marine Meteorology (WMO)
CTD - Conductivity, Temperature, and Depth (Instrument)
ECMWF - European Centre for Medium-range Weather Forecasts
EOS - Earth Observing System
ERS - Earth Resources (or Remote-sensing) Satellite
ESMR - Electrical Scanning Microwave Radiometer
FGGE - First GARP Global Experiment
FIRE - First ISCCP Regional Experiment
FRAM - Fine Resolution Antarctic Model
GARP - Global Atmospheric Research Programme
GCM - General Circulation Model or Global Climate Model
GDSIDB - Global Digital Sea-Ice Data Bank (WMO/CMM)
GEWEX - Global Energy and Water Cycle Experiment (WCRP)
GPCC - Global Precipitation Climatology Centre
GRDC - Global Run-off Data Centre
GTS - Global Telecommunication System
HIRS - High-resolution Infrared Radiation Sounder
IABP - International Arctic Buoy Programme
ICSU - International Council of Scientific Unions
IHP/OHP - International Hydrological Programme/Operational Hydrological Programme
IOC - Intergovernmental Oceanographic Commission (Unesco)
IOS - Institute of Ocean Sciences (Canada)
ISCCP - International Satellite Cloud Climatology Project (WCRP)
JERS - Japanese Earth Resources Satellite
JSC - Joint Scientific Committee for WCRP (WMO/ICSU/IOC)
LANDSAT - Land (earth resources) Remote Sensing Satellite (NASA)
LEADEX - Lead Experiment
LIDAR - Light Detection and Ranging (instrument)
MAGS - Mackenzie GEWEX Study (Canada)
MODIS - Moderate Resolution Imaging Spectrometer (NASA/GSFC)
MSU - Microwave Sounding Unit
NASA - National Aeronautics and Space Administration (U.S.A.)
NCAR - National Centre for Atmospheric Research (U.S.A.)
NMC - National Meteorological Centre
NOAA - National Oceanic and Atmospheric Administration (U.S.A.)
NODC - National Oceanographic Data Centre
NSA/AAO - North Slope of Alaska/Adjacent Arctic Ocean
NSIDC - National Snow and Ice Data Centre (U.S.A.)
NWP - Numerical Weather Prediction
OCCAM - Ocean Circulation Climate Advanced Modelling (U.K.)
POLEX - Polar Experiment (FGGE)
RADARSAT - Radar Satellite (Canada)
SalArgos - Argos-located buoy equipped with temperature and conductivity sensors
SAR - Synthetic Aperture Radar
SCARAB - Scanner for Radiative Budget
SHEBA - Surface Heat Budget of the Arctic Ocean
SMMR - Scanning Multichannel Microwave Radiometer
SPOT - Système pour l'Observation de la Terre (satellite) (France)
SSM/I - Special Sensor Microwave/Imager
TIROS - TV Infrared Observational Satellite
TOVS - TIROS Operational Vertical Sounder
UKMO - United Kingdom Meteorological Office
ULS - Upward-Looking Sonar
UV - Ultra-Violet (Irradiation)
UV-B - 280-320 nm UV Wavelength Interval
WCRP - World Climate Research Programme
WDC - World Data Centre
WGNE - Working Group on Numerical Experimentation (JSC/CAS)
WMO - World Meteorological Organization
WOCE - World Ocean Circulation Experiment (WCRP)
FOREWORD

Climate models generally suggest that global climate change is greatly amplified in the Arctic. Conversely, it is increasingly believed that the Arctic plays a significant role in global climate control, chiefly through its influence on the large-scale thermohaline circulation of the ocean (the "conveyor belt") and on the global heat budget (e.g., the snow and ice albedo feedback). However, the observational base, our knowledge of the controlling physical processes, or our ability to model the role of the Arctic in global climate are not presently sufficient to realistically assess the principal issues linking the Arctic with global climate.

Therefore, in 1991, the Joint Scientific Committee (JSC) for the WCRP, taking into account the plans developed for the GARP Polar Experiment (POLEX), the results of the Meeting of Experts on Sea Ice and Climate Modelling (WCP-77), and the subsequent work of the WCRP Working Group on Sea Ice and Climate (WCRP-18 and 41; WCP-128), chaired by Professor Norbert Untersteiner, initiated an inquiry into the need for and feasibility of an Arctic Climate System Study under the WCRP. In 1992, the Study Group for this effort, chaired by Professor Ernst Augstein, prepared the "Scientific Concept of the Arctic Climate System Study (ACSYS)" (WCRP-72), and concluded that an Arctic Climate System Study was now both timely and feasible. Shortly thereafter, the JSC established the ACSYS project and appointed an ACSYS Scientific Steering Group. This present initial implementation plan is an early product of that steering group. The intent is to lay out a practicable programme to over the next decade assess the role of the Arctic in global climate. Five areas are emphasized: 1) ocean circulation, 2) sea-ice climatology, 3) the Arctic atmosphere, 4) the hydrological cycle, and 5) modelling.

K. Aagaard
Chairman
WCRP ACSYS
Scientific Steering Group
EXECUTIVE SUMMARY

1. Scientific goal and main objectives of ACSYS

The scientific goal of ACSYS, which started its main observational phase on 1 January 1994 and will continue for a ten-year period, is to ascertain the role of the Arctic in global climate. To attain this goal, ACSYS seeks to develop and co-ordinate national and international Arctic science activities aimed at the three main objectives:

(i) understanding the interactions between the Arctic Ocean circulation, ice cover and the hydrological cycle;

(ii) initiating long-term climate research and monitoring programmes for the Arctic;

(iii) providing a scientific basis for an accurate representation of Arctic processes in global climate models.

2. Arctic Ocean circulation programme

There are numerous indications of a potentially strong feedback between changes in the upper Arctic Ocean and its ice cover and changes in the global heat balance. There are also indications that changes in intermediate and deep water formation in high northern latitudes may lead to alteration of the large-scale thermohaline circulation of the world ocean; the former are in turn linked to sea-ice formation. The Arctic Ocean also provides an important closure in the global hydrological cycle, again with consequences for climate and the global energy flux. In order to model the global climate satisfactorily, it is therefore likely that we must realistically represent the role of the Arctic Ocean in the global climate system. The Arctic Ocean Circulation Programme of ACSYS is designed to provide the information necessary to do this; it has four components.

1) The Arctic Ocean Hydrographic Survey will collect a high-quality hydrographic database representative of the Arctic Ocean, with the goal of determining the general circulation and its time scales, and the rate of transformation of the different water masses, as well as to provide insight into the processes responsible for maintaining the circulation and transformation of water masses. The strategy is to map, over the course of the ACSYS decade, the pertinent physical and chemical properties of the Arctic Ocean, including a variety of transient and steady-state tracers. The goal is to keep the same standards of accuracy and resolution as those of the WOCE Hydrographic Programme, and appropriate calibration and intercomparison procedures will be an integral part of the programme.

2) The Arctic Ocean Shelf Studies are aimed at understanding how the shelves processes partition salt and fresh water components, and how the resulting buoyancy fluxes are coupled to the ocean interior; at defining the dynamics and thermodynamics of the shelves waters sufficiently to permit realistic modelling of the Arctic Ocean climate system; and at determining the variability on the shelves and how this variability affects the interior ocean. The approach is threefold: to conduct a set of
seasonally distributed shelf surveys in the Barents, Kara, Laptev, and Chukchi Seas; to ascertain the seasonal and interannual variability of the shelf circulation and its waters; and to conduct a series of field experiments sufficient to document key processes.

3) The Arctic Ocean Variability Project is designed to assess the variability of the circulation and density structure of the Arctic Ocean, including exchanges with the surrounding seas; to indicate the rates and variability of the processes important in maintaining present ocean conditions; and to provide a basis for further monitoring of climate change in the Arctic. The strategy is to maintain an array of drifting instrumented oceanographic buoys which will telemeter conditions in the mixed layer and pycnocline; to deploy and recover annually or biannually a set of bottom-moored instruments at selected sites in the deep basins and along the principal topographic boundaries of the Arctic Ocean; and to directly measure through moored instrumentation and satellite remote sensing the variability of the exchanges through the major straits connecting the Arctic Ocean with the seas to the south.

4) The Historical Arctic Ocean Climate Database Project aims to establish a universally available digital hydrographic database for the Arctic Ocean for analysis of climate-related processes and variability, and to provide a data set suitable for initialization and verification of Arctic climate and circulation models. Two co-ordinated efforts are involved, one to assemble a data set based on the work of European and North American investigators, and the other to fully make available the extensive measurements of Russian scientists. The over-arching goal of the ACSYS historical database effort is to assemble a digital data set of the broadest possible temporal and spatial scope, but with sufficient quality control to warrant its issuance as a unified data set.

3. Arctic sea-ice programme

The ACSYS sea-ice programme includes three main components:

(i) establishing an Arctic basin-wide sea-ice climatology database;

(ii) monitoring the export of sea ice through the Fram Strait;

(iii) Arctic sea-ice process studies.

In order to investigate the natural variability, as well as to improve and verify sea-ice models, an extended sea-ice database encompassing both surface measurements and satellite observations over the Arctic Ocean is required. Passive microwave satellite measurements have been reliably used to map the sea-ice extent and concentration since 1972. The processed data are archived in the World Data Centre-A for Glaciology and are available in CD-ROM format. Remote sensing capability will continue to be supported by NASA for the next few decades. A Global Digital Sea-ice Data Bank based on historical sea-ice data is being developed for the WMO Commission for Marine Meteorology by the Arctic and Antarctic Research Institute, St. Petersburg, Russian Federation, and WDC-A for Glaciology, Boulder, Colorado, U.S.A.
One of the main tasks of the ACSYS Arctic sea-ice programme is to establish a climatology of ice thickness and ice velocity. To achieve this goal, ACSYS will use data supplied by the WCRP Arctic Ice Thickness Project, the International Arctic Buoy Programme, sonar profiling naval submarines and unmanned vehicles, airborne oceanographic lidars, and polar satellites carrying appropriate instruments.

As an element of the WCRP Arctic Ice Thickness Project, a moored array of upward-looking sonars has already been installed in the Fram Strait for measuring the draft of the drifting ice. The ice volume transport is deduced from the mean ice draft and locally observed ice concentrations and drift velocities. Systematic SAR and other satellites images are used to obtain the necessary information on sea-ice concentrations in the strait. The ice velocities are determined from in-situ and Acoustic Doppler Sonar current measurements.

ACSYS includes a special field experiment to improve the description in a Lagrangian framework of mechanical and thermal processes determining sea-ice thickness. With that end in view, the experiment is designed to study ice thickness changes along the path of an ice-floe.

4. Arctic Atmosphere Programme

The Arctic atmosphere provides the dynamic and thermodynamic forcing of the Arctic Ocean circulation and sea ice. Through the cloud and radiation fields, it also provides an essential heat sink for the climate system, so maintaining the large-scale global temperature gradient and providing a source of cold polar air masses important for the atmospheric general circulation. Correct representation in coupled models of the interactions between the troposphere, the atmospheric boundary layer and the sea ice and upper ocean and especially of the role of radiation and cloud, is essential for proper simulation of climate and climate change. An improved atmospheric database is needed, in particular to develop increased understanding of Arctic processes, for verification of atmospheric circulation models over the polar region and to provide the observations necessary to estimate the forcing fluxes for sea ice and ocean.

To help achieve this, ACSYS will:

(1) Encourage and promote field campaigns to increase understanding of the physical processes which take place in the Arctic and provide the basis for better physical parameterization schemes in models.

(2) Promote a re-analysis of Arctic historical data based on use of both a state-of-the-art NWP assimilation system and, where appropriate, high quality single field analyses, especially of surface temperature and pressure. The aim will be to provide a synthesis of available atmospheric data throughout the depth of the atmosphere for studies of atmospheric processes and model verification and to assist in the derivation of improved data sets of the atmospheric forcing on sea ice and ocean over the Arctic. Maintenance of the current network of Arctic drifting buoys and improved satellite retrievals of surface properties and the surface radiation budget will be essential to these tasks.
Develop a polar clouds and radiation programme with particular emphasis on improved techniques for satellite retrievals of cloud and radiation properties. These will require concurrent in-situ and satellite measurements, using both aircraft and surface-based instrumentation, and improved modelling of Arctic cloud and radiation fields.

The ACSYS Arctic atmosphere programme will build on a number of existing or planned supporting field programmes. In particular, the U.S.A. Atmospheric Radiation Measurement and Surface Heat Budget of the Arctic Ocean programmes, the U.S.A. Arctic FIRE Experiment, and the Canadian Beaufort and Arctic Storms Experiment.

5. Hydrological Cycle in the Arctic Region

The two major components of the hydrological programme of ACSYS are the compilation of an Arctic hydrological database and the development of hydrological models of selected Arctic regions. Co-ordination of existing data collection and modelling efforts will be an essential function of ACSYS.

In support of the development of research-quality hydrological data sets, ACSYS will include a Solid Precipitation Climatology Project, which will interface with the WMO/CIMO Solid Precipitation Intercomparison Project. Primary ACSYS efforts within this project will be:

(1) the documentation and intercomparison of solid precipitation measurement procedures used in high latitudes, and

(2) the development of methodologies for determining areal (regional) distributions of precipitation from station data.

The ACSYS Solid Precipitation Climatology Project will also include the development and assessment of satellite remote sensing methods for determining snow-water equivalent, snow depth and snow extent.

ACSYS will co-ordinate the development of an Arctic Precipitation Data Archive (APDA) containing daily, monthly and annual total precipitation (both liquid and solid) data from all observing stations in the Arctic, including ice stations. The APDA will cover a period of at least 15 years (1978 onward) and will draw upon existing precipitation data collections. Quality control and standardization of the station data will be achieved in conjunction with the Solid Precipitation Climatology Project.

An Arctic Run-off DataBase (ARDB) will be organized by ACSYS through an international exchange of hydrological data. The ARDB will contain both historical (1978 onward) and current information on daily water discharges at each of the gauge-sites where hydrometric observations are made in the Arctic. ARDB is envisaged as a separate project implemented within the Global Run-off Data Centre (GRDC) in Koblenz, Germany, and will share with GRDC a commonality of procedures and technical facilities. The preparation of an ARDB catalogue and the submission of data to ARDB should begin during 1994-1995.
Macroscale modelling within the ACSYS hydrological programme will include atmospheric and surface (catchment) components. As part of the ACSYS Arctic re-analysis and data assimilation effort, it is proposed that precipitation over the data-sparse Arctic Ocean be estimated through the atmospheric water vapour flux convergence simulated by atmospheric models of one or several NWP centres. In collaboration with such centres, ACSYS will:

1. undertake a comparative assessment of model-derived and selected station measurements, and

2. compile model-derived precipitation statistics for multi-year periods on a regional basis.

Hydrological modelling will include the adaptation to the Arctic of macroscale hydrological models developed in the framework of GEWEX, and the development of physical or parametric mesoscale hydrological models for selected Arctic river catchments. Formulation of the ice phase will be a major element of such modelling efforts. The hydrological modelling will interface with on-going and planned national programmes in Canada (Mackenzie GEWEX Study), Russia ("GGI-90" model), Europe ("Europamodel") and Japan. Intensive hydrological observation periods of one to several years will be required in support of the model development.

6. ACSYS Modelling Programme

Climate variations in polar regions arise from the interaction between atmosphere, sea ice and ocean. In order to understand and predict this interaction, a number of numerical modelling experiments have to be performed with a hierarchy of sea ice (only) and coupled sea-ice/ocean or atmosphere/sea-ice/ocean models.

The ACSYS modelling strategy includes optimization of the different models for the Arctic region using as many observations as possible, and response experiments to investigate the influence of the river run-off on the oceanic circulation, the dependence of the fresh water export to the North Atlantic upon processes occurring in the Arctic Ocean, and its influence on the global "conveyor belt" circulation through modification of the deep water formation. A special emphasis will be placed upon the question to what degree is the high sensitivity of polar regions to CO$_2$ increases due to inadequate model components or to real positive feedbacks.

These model experiments will be performed with large-scale climate-oriented models. Since these models use various parameterizations of sub-grid processes, improved process models are required to better represent small-scale physics in large-scale models. These process investigations should address small-scale sea-ice deformation (ridge building), shelf processes, plume dynamics, run-off disposition, lead and polynya processes (interaction of oceanic and atmospheric boundary layers), open-ocean convection, fluxes between basins, and parameterization of clouds, radiation, precipitation and surface albedo of sea ice for all seasons.
1. SCIENTIFIC GOAL AND MAIN OBJECTIVES OF ACSYS

The Arctic Climate System Study (ACSYS) aims to answer two related questions:

- Is the Arctic climate as sensitive to global changes as models seem to suggest?
- What is the sensitivity of global climate to Arctic processes?

These questions arise from a variety of observational facts and modelling results. We already know that:

- Water mass formation in the north polar region closes a major path in the global thermohaline circulation of the ocean, often referred to as the "conveyor belt circulation";

- Sea-ice formation in the Arctic, together with fresh water input from Canadian and Russian rivers, controls the salinity of superficial waters and the formation of intermediate and deep waters, while sea-ice albedo is a significant factor of the global radiation balance and climate;

- Although coupled atmosphere-ice-ocean models exhibit vastly different climate sensitivities in the Arctic, presumably because their representations of air/sea-ice interaction processes differ from one another, they are consistent in indicating that the largest temperature rise induced by an increase in greenhouse gases occurs in the Arctic. Some models show a shutdown of the conveyor belt circulation in the North Atlantic, with considerable climatic consequences.

However, major gaps in our knowledge remain. We do not know how accurate model simulations are, since their representation of much of the physics is incomplete and they do not resolve important ocean current systems. Atmospheric models, both in research and operational weather forecasting, suffer from serious errors in computed surface temperatures. Ocean models can show circulations opposite to those observed. Some of the difficulties arise from the sparsity of observational data available for model validation and the relatively poor spatial resolution of current models.

We do not know how sensitive the Arctic ice cover may be to climate changes. We can see that sea ice responds on very short notice to weather events, yet the scanty ice thickness data available to date show little evidence of systematic change during this century. We also wonder how easily the large fresh water reservoirs in the Arctic ice sheets could be released as a result of possible climate change?
We do not know the sensitivity of climate to Arctic river run-off, nor do we have adequate estimates of the mean and variability of discharge to the Arctic Ocean from the large number of smaller ungauged rivers and streams. The climate scenarios now available from global models provide ambiguous estimates of possible changes in air temperature and precipitation over Arctic terrestrial regions, where run-off to the Arctic Ocean originates.

We do not know whether the Arctic hydrospheric processes could significantly modify the global conveyor belt circulation under altered climatic conditions. While the Arctic is probably too small to contribute a dominating amount of heat, salt or fresh water to the global thermohaline circulation as a whole, and while the contribution of the Arctic to the global carbon cycle is at present small, the potential importance of Arctic processes lies in their ability to reduce or block deep water formation in the North Atlantic. A change in the conveyor belt circulation would produce significant changes both in the transport of heat and salt and possibly also in the uptake of greenhouse (and other) gases by the ocean. Models predict that the largest warming will occur in the Arctic. There is as yet little evidence for such a response.

These questions can be answered. Hitherto, the Arctic atmosphere-ice-ocean system has not been studied in a sufficiently comprehensive manner primarily for logistic reasons. As our understanding of the role of the Arctic has developed, it has become increasingly evident that a co-ordinated study of the Arctic system is needed and is feasible. The scale and multidisciplinary nature of the study require a co-operative international effort.

The scientific goal of ACSYS is to ascertain the role of the Arctic in global climate. To attain this goal, ACSYS seeks to develop and co-ordinate national and international Arctic science activities aimed at three main objectives:

- understanding the interactions between the Arctic Ocean circulation, ice cover and the hydrological cycle;

- initiating long-term climate research and monitoring programmes for the Arctic;

- providing a scientific basis for an accurate representation of Arctic processes in global climate models.

The rationale for the ACSYS proposal is the expectation that a consolidated science and implementation plan, based on a broad scientific consensus, will constitute a sound justification for the provision of adequate resources and logistics to carry out research on the Arctic climate system.

The Initial Implementation Plan which follows is a statement of the main tasks and objectives of the Arctic climate system study. These objectives can only be achieved through participation of scientists from different countries, and the co-ordination of national ACSYS activities.
2. ARCTIC OCEAN CIRCULATION PROGRAMME

There is great scientific interest in the potentially strong feedback between changes in the hydrographic properties and ice cover of the upper Arctic Ocean, and changes in the global heat balance (cf. Moritz et al., 1990, for a recent discussion and overview). At present, the Arctic Ocean is markedly stratified between 50 and 150 m, with a resulting very low effective vertical diffusion rate in the upper water column (Wallace et al., 1987). Perturbations of the vertical structure of the Arctic Ocean would almost certainly also change the convective and diffusive fluxes of salt and sensible heat across the pycnocline and the mixed-layer interface (Aagaard et al., 1981). The resulting changes in vertical flux would be expected to change the ice cover significantly, since studies suggest that the present sea-ice configuration is quite sensitive to small changes in oceanic heat fluxes (Maykut, 1986). A significant change in the Arctic ice cover would in turn affect the large-scale surface and atmospheric radiation budgets (Fletcher, 1965; Curry et al., 1993), the atmospheric circulation and the transport of CO₂ through the air-sea interface (Anderson et al., 1990).

There is also evidence that intermediate and deep waters formation in high northern latitudes is a major driving factor of the large-scale thermohaline circulation of the world ocean (e.g., Reid, 1981; Gordon, 1986), and that several stable regimes of the global circulation may exist. The causes and nature of the transitions between such regimes is of considerable interest (Bryan, 1986; Manabe and Stouffer, 1988). Increasingly, the paleoclimatic evidence points toward the existence of large changes in both the atmosphere and the ocean circulations which may occur on surprisingly short time intervals (e.g., cf., Broecker et al., 1985, for an early discussion, or more recently Taylor et al., 1993). In this connection we note that the production of large amounts of sea ice in the Arctic Ocean, as well as the presence of a relatively fresh surface layer and anomalously saline deep waters, have a major influence on the convective gyres in the Greenland, Iceland, and Labrador Seas. In effect, the Arctic Ocean appears to condition these gyres, and to effect substantial control over convective and mixing processes (Aagaard et al., 1985; Swift and Koltermann, 1988; Aagaard and Carmack, 1989; Heinze et al., 1990; Aagaard et al., 1991). Changes in ice production, changes in the formation rate and properties of water masses in the central Arctic Ocean and adjoining shelf seas, or changes in the export of water and ice to the convective regions of the North Atlantic, could easily alter the Atlantic thermohaline circulation cell, which appears to be very finely tuned at its northern end (Aagaard and Carmack, 1989; Schlosser et al., 1991). Either a weakening or strengthening of the thermohaline cell would affect climate, particularly in the northern hemisphere (Manabe and Stouffer, 1988). A weakening of the thermohaline circulation has in fact been proposed as the mechanism responsible for major paleoclimatic disturbances such as the Younger Dryas interruption of the last deglaciation (Broecker et al., 1985).

The Arctic also provides an important closure in the global hydrologic cycle, again with consequences for climate and the global energy flux. For example, Wijffels et al. (1992) have used the inflow to the Arctic through the Bering Strait as a specified boundary condition for estimating the global fresh water transport by the oceans, with unexpected results for net meridional transport in both the Pacific and the Atlantic. Essentially, Wijffels et al. argue that the excess fresh water added to the
North Pacific from the atmosphere (equal to the convergence of the atmospheric water vapour flux over the North Pacific) drains through the Arctic into the North Atlantic. Analogous arguments regarding the role of the Arctic in global geochemical balances have been advanced by Codispoti (1979) and Walsh et al. (1989), for example. Furthermore, the chemical signature has been used to identify and trace the upper waters, the surface mixed layer and the halocline waters (e.g., Östlund and Hut, 1984; Anderson and Jones, 1992; Schlosser et al., 1994).

These considerations suggest that in order to model the global climate in a satisfactory way, we must understand the role of the Arctic Ocean in the global climate system. However, we have an entirely inadequate description of the present state of the Arctic Ocean and its circulation, and only a fragmentary understanding of the processes that maintain that state. To progress significantly, we must both expand the observational database and improve our mechanistic understanding of Arctic processes.

2.1 Arctic Ocean Hydrographic Survey

2.1.1 INTRODUCTION AND OBJECTIVE

The objective of the ACSYS hydrographic survey is to collect a high quality database covering the Arctic Ocean, in order to determine the general circulation and the rate of transformation of the different water masses, as well as to provide insight into the processes responsible for maintaining this circulation. The survey programme will illuminate a variety of scales and phenomena, from basin-wide flow to details of mixing.

The strategy is to map, over the course of a decade, the pertinent physical and chemical properties of the Arctic Ocean, including a variety of transient and steady-state tracers, to the same standards of accuracy and resolution as the WOCE Hydrographic Programme. Considerable variability in the circulation and mixing almost certainly exists in the Arctic Ocean on shorter than decadal time-scales (Anderson et al., 1994), but by the use of tie points between different sections in different years, and modelling, the mapping will meet the need for a modern full-parameter description of the Arctic Ocean.

2.1.2 RESOURCES AND MEASUREMENTS

Traditionally, ice stations or air-mobile survey teams have been used to investigate the permanently frozen central Arctic Ocean. However, the former technique provides little opportunity for specific site selection and for rapid coverage of the desired sections, while the latter method limits the parameters which can be measured and their accuracy. For hydrographic work of the required coverage and quality, there is at present no viable alternative to the capabilities of a well-equipped modern research vessel. Furthermore, recent campaigns using ice-breaking research vessels have shown the feasibility of oceanographic work within large areas of the interior of the Arctic Ocean (Anderson et al., 1989; Anderson et al., 1994). Indeed, the cost per station appears to compare very favorably with other approaches. There are today several research vessels capable of cruising in the central Arctic Ocean, most of them listed in Table 2.1.
<table>
<thead>
<tr>
<th>Name of vessel</th>
<th>Country</th>
<th>Scientific equipment*</th>
<th>Maximum number of scientists</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louis St. Laurent</td>
<td>Canada</td>
<td>H and L</td>
<td>26+</td>
</tr>
<tr>
<td>Polarstern</td>
<td>Germany</td>
<td>H and L</td>
<td>55</td>
</tr>
<tr>
<td>Academician Fedorov</td>
<td>Russia</td>
<td>H and L</td>
<td>80</td>
</tr>
<tr>
<td>Oden</td>
<td>Sweden</td>
<td>L</td>
<td>39</td>
</tr>
<tr>
<td>Polar Sea</td>
<td>U.S.A.</td>
<td>H and L</td>
<td>30</td>
</tr>
<tr>
<td>Polar Star</td>
<td>U.S.A.</td>
<td>H and L</td>
<td>30</td>
</tr>
</tbody>
</table>

* H = heavy equipment, L = light equipment

| Table 2.1 | Summary information on research vessels capable of working in the central Arctic Ocean. |

The strategy for the Arctic Ocean hydrographic survey is principally based on the use of the vessels indicated in Table 2.1, to carry out sections crossing all the deep basins of the Arctic Ocean and extending up onto the adjacent shelves as indicated tentatively in Figure 2.1. For scientific, logistical and safety reasons, the majority of this work will be performed by vessels working in pairs. Only in parts of the Arctic Ocean adjacent to the northern Canadian Archipelago and northern Greenland, is it likely that the ice will consistently be so heavy as to limit ship-borne sections. In this region, the hydrographic work may therefore have to be supported by aircraft.

Generally, the minimum requirements for a typical two-ship operation will call for a station spacing of about 50 km over the abyssal plain, and 10-20 km in areas of large topographic relief. At each station, the sampling programme will include a full-depth CTD profile and discrete water samples at 30-40 levels for a full abyssal-depth station, with emphasis on resolving the structure of the upper 500 m. Additional specialized profiles, e.g., of velocity (using either a hull-mounted or wire-mounted Acoustic Doppler Current Profiler), will be included wherever practicable. Parameters to be determined from each discrete water sample include salinity, oxygen, nutrients (phosphate, nitrate, and silicate), the carbon system (total carbonate, alkalinity, and total and dissolved organic carbon), and a suite of stable and transient tracers (CFC-11, -12 and -113, carbon tetrachloride, tritium, He-3 and -4, C-13 and -14, O-18), possibly supplemented by other radioisotopes, e.g., Ar-39, and by selected trace metals. Temperature, salinity, and pressure measurements should be accurate to respectively 0.002°C, 0.002 and 2db, with precision of one-half these.

The ship-borne work will be supplemented by hydrographic coverage of the upper 1000 m of the water column extending 150 km to either side of the ship track by means of a portable CTD deployed by helicopter. The spacing of these stations will be such as to resolve sub-mesoscale eddies, which have a scale of 10-20 km.
2.1.3 PLANNED OBSERVATIONAL PROGRAMMES

The 1987 Polarstern cruise and the 1991 International Arctic Ocean Expedition concentrated on the western Eurasian basin. As the next step in executing a composite Arctic Ocean hydrographic survey, Canada and the U.S.A. will undertake a joint campaign in 1994. Two ships will concentrate on work in the eastern Canada basin (Figure 2.1). While these three expeditions will together contribute significantly to the ACSYS goal of mapping the Arctic Ocean hydrography, an additional set of four compound sections (Figure 2.1) are planned over the next decade. Two of these will be accomplished in 1996 or 1997, and the last two in 1998-1999. Together with the 1987, 1991, and 1994 sections, these constitute a minimum requirement for the ACSYS Arctic Ocean Hydrographic Survey. The coverage emphasizes the basin margins, where boundary currents and shelf-basin and interbasin exchanges occur, but it also provides a description of the interior of the basins sufficient to define the integrated effects of shelf and boundary processes on the interior ocean, including a definition of the circulation and replacement time scales based on transient tracer measurements. The planning is predicated on full and co-ordinated use of the various scientific facilities and personnel available internationally (Table 2.1), and its execution will provide a basis for understanding the large-scale circulation and water mass transformation in the Arctic Ocean. Further work can then concentrate on more detailed and process-oriented efforts.

Figure 2.1 Planned oceanographic sections with a full sampling programme for high quality hydrographic and tracer measurements.
2.1.4 Data availability

It is essential for a joint international programme to produce consistent data that can be easily accessed. Therefore, ACSYS will work towards the use of comparable measurement techniques on all participating vessels, as well as appropriate intercalibration exercises. The data collected is the possession of the individual principal investigator for a time period after each cruise, but an open communication is supported. This time period is recommended to be two years. Within this time period, the data cannot be published or cited without permission of the principal investigator. Following each cruise, it is recommended that a short cruise report be prepared giving station locations, water sampling summaries, and other pertinent information. The ACSYS Project Office will assist the Chief Scientist in preparation and distribution of these cruise reports. Final data reports will be the responsibility of the operational groups, but data summaries will be made available by the Project Office at the appropriate time. The final data sets will be deposited with national or international data centres in a manner which ensures easy access by the international scientific community.

2.2 Arctic Ocean Shelf Studies

2.2.1 Introduction

The broad, shallow continental shelves that surround the Arctic Ocean and comprise about a third of its surface area are important sources of both positive (fresh water) and negative (brine-enriched water) buoyancy fluxes (McDonald and Carmack, 1991). Just as the Arctic Ocean itself acts as an estuary of the world ocean, so the shelves act as estuaries for the Arctic Ocean. Inputs of fresh water to the shelves by river inflow, ice melt, and net precipitation increase the stability of Arctic surface waters, thereby promoting winter ice growth and suppressing deep convection both in the Arctic Ocean and, by advection out of the Arctic Ocean, in the North Atlantic (Aagaard and Carmack, 1989). At the same time, the production of cold, salty waters by freezing on the Arctic shelves serves to cool and deepen the Arctic halocline, which further favours ice growth by providing a cold insulating layer which shields Arctic ice from underlying warm water of Atlantic origin (Aagaard et al., 1981; Melling and Lewis, 1982). Arctic shelves are also sites where changes in ice thickness and duration of the ice season are expected to be most pronounced, should global warming occur.

The shelves can be conceptually divided into an inner and outer domain, corresponding to the boundary between landfast and moving pack ice, and into summer and winter realizations. River inflow enters from the continent, is processed first within the inner and then the outer domain, and is finally exported as a surface layer to the ocean interior. In terms of net buoyancy export, this river throughflow is largely transparent to shelf processes, even though it exerts control on brine production (McDonald and Carmack, 1991). In addition, within each domain, ice forms and melts each year. If new ice and its brine products are separated, e.g., by shelf drainage, before melting and re-mixing the following summer, then there will be a net upward flux of buoyancy over the Arctic Ocean, which is then available for export to the North Atlantic. To determine the net buoyancy flux associated with the freeze/melt cycle requires knowledge of both the net ice removal from the shelf and
brine drainage into the interior. The former is directly measurable, but probably not the latter without heroic efforts. Therefore, brine drainage is probably best determined as a residual in shelf budgets.

2.2.2 OBJECTIVES

The objectives of the shelf component of the ACSYS programme are to:

- understand and model how the Arctic shelves partition salt- and fresh water components, and how the shelves couple the resulting buoyancy fluxes to the ocean interior;

- define the dynamics and thermodynamics of the shelves sufficiently to permit realistic modeling of the Arctic Ocean climate system;

- determine the variability of processes and conditions on the Arctic shelves and how this variability affects the structure and variability of the interior Arctic Ocean.

2.2.3 OBSERVATIONAL PROGRAMME

2.2.3.1. Shelf surveys

Three separate but complementary activities are planned to study the role of Arctic shelves in global climate. The first is a set of shelf surveys in the Barents Sea (where Atlantic water is modified), in the Kara Sea (where much of the lower halocline water originates (e.g., Jones and Anderson, 1986)), in the Laptev Sea (where much of the shelf ice production of the Arctic occurs), and in the Chukchi Sea (where the Pacific inflow occurs and the upper halocline water is formed (e.g., Jones and Anderson, 1986)). These surveys will complement the corresponding measurements planned for the deep Arctic basins. Three to five sections across each shelf, with 10-15 hydrographic stations per section, are required. The shelf measurements must include most of the same hydrographic parameters and tracers as the basin surveys, and in general these should be sampled both in the ice and the water column. A unique aspect of the shelf surveys, however, is that they should be conducted both in the late summer and in the late winter, placing additional demands on logistical support, including significant use of aircraft.

2.2.3.2 Shelf variability study

The adjacent shelf seas supply the Arctic Ocean both with ice and a variety of characteristic shelf waters. On interannual time scales, measurements in the interior of the Arctic Ocean will reflect the net output of these various shelves and therefore provide a measure of the variability of shelf processes. However, it is unlikely that such interior measurements will provide a sufficient definition of shelf processes and their variability to allow the development of a full predictive capability for the Arctic Ocean climate system. Direct measurements of the variability of the shelf waters are therefore also required in selected shelf areas.
The goal of the shelf variability study is to obtain decadal-scale time series of the annual and interannual variability of shelf hydrography, buoyancy fluxes and ice cover. This will both provide a necessary context in which to understand the detailed shelf surveys, and a means to a mechanistic understanding of the shelf system and its role in Arctic climate. Seasonal hydrographic mappings repeated at least twice during the ACSYS decade, together with moored measurements of temperature, salinity, velocity, and ice thickness and velocity in the shelf survey areas (Section 2.2.3.1: the Barents, Kara, Laptev, and Chukchi Seas) are the major components of this work. Additionally, the activity will be extended to the Beaufort Sea, where many of these measurements have been made since 1980, providing a special basis of comparison. Two to four mooring sites occupied over the decade in each of the designated shelf areas are required. The shelf variability study will be co-ordinated with the Arctic Ocean variability project (Section 2.3).

2.2.3.3 Shelf process experiments

The third element in the ACSYS shelf observational programme is a series of shelf process experiments designed to document key processes and assist their incorporation in models. These include:

- Forcing of shelves by wind storms in autumn and early winter and the consequences for salt budgets;
- The role of shelf-break currents on transport and horizontal mixing, and the exchanges associated with upwelling of offshore waters onto the shelf;
- Heat and salt fluxes associated with the opening and re-freezing of polynyas and flaw leads;
- The role of under-ice topography in the vertical transfer of heat, salt, and momentum; and
- The role of canyons in the cross-shelf exchange of water masses.

2.2.4 DATA AVAILABILITY

Needs and plan for data management parallel those of Section 2.1.4.

2.3 Arctic Ocean Variability Project

2.3.1 INTRODUCTION

Defining the variability of the system is a means to understanding the mechanisms and processes which control the system. Remarkably, however, there has been very little monitoring of the Arctic Ocean to date, apart from ice drift measurements and hydrographic stations on shelves, primarily in the Russian sector. For example, there is only a handful of time series from moored instruments extending for more than a few months, and this primarily at sites adjacent to the continental margin in the Beaufort Sea or in passages connecting to oceans in the south, principally the Bering and Fram straits.
2.3.2 Project Goals

It is planned that ACSYS will include an Arctic Ocean Variability Project (AOVP) to provide:

- An assessment of the variability of the circulation and density structure of the Arctic Ocean;
- An indication of the rates of processes important in maintaining present ocean conditions;
- A basis for further monitoring of climate change in the Arctic.

The AOMP is planned to continue throughout the ACSYS decade of 1994-2004. Its primary focus will be the circulation and structure of the Arctic Ocean, and exchanges with the surrounding oceans. A key to the success of the project is the sustained availability of the logistical support necessary to service instrumentation in the field, generally on an annual or biennial basis.

2.3.3 Project Plans

Experience with applicable techniques has come primarily from the deployment of instrumented buoys drifting with the sea ice and from bottom-moored arrays. With respect to drifting buoys, the sensor packages have incorporated a number of different oceanic instruments to measure relative velocity, temperature and salinity. Data are normally transmitted via CLS/Service Argos. An early example of this effort is the Arctic Oceanographic Buoy Programme of the University of Washington, which originally used buoys equipped with a 300 m long cable (Morison, 1989; Morison et al., 1982). Changes in depth induced by the variable ice drift velocity can be used to enhance the vertical span of the measurements. Steele and Morison (1993) have calculated the local heat flux from the Atlantic layer to the ice at various locations in the Arctic Ocean using this technique. Recent experience suggests that the surface fluxes of momentum, heat, and salt can be monitored from surface drifters by making single-depth measurements of velocity, temperature, and salinity in the mixed layer. The key is to obtain the high-frequency statistics of the velocity at a fixed depth. The concept has been discussed and demonstrated by McPhee (1989, 1992), McPhee and Steele (1990), and McPhee et al. (1987). Drifting buoys have also been developed to determine the ice mass balance, e.g. the alpha buoy of Untersteiner and Thorndike (1984), which measures heat flux in the ice with a thermistor string and changes in ice thickness with a differential pressure sensor. The first main component of AOVP will therefore be to maintain an array of at least 30 drifting oceanographic buoys in the Arctic Ocean to study the variability of the mixed layer and the pycnocline, together with surface fluxes and their variability. Each buoy will, at a minimum, measure temperature, salinity, and velocity at one level in the mixed layer and at 2-3 levels in the pycnocline. Array maintenance will depend upon annual replacements of buoys. Normally, such replacement is most easily done from aircraft during the spring, and it may be best combined with the deployment of the IABP buoys.
The second mainline activity of the AOVP is the maintenance of a basic network of bottom-moored arrays. Such arrays were first deployed in the deep Arctic Ocean in 1979 (Aagaard, 1981). Because of deep-reaching ice keels, in-situ measurements are normally not possible in the upper 40-50 m. However, acoustic sensors can fill part of this observation gap. They include an upward-looking sonar for ice thickness measurements and an acoustic doppler profiler for velocity monitoring at each mooring. Both methodologies have been successfully utilized in the Arctic during the last few years. In addition, 4-6 pairs of stable temperature-salinity sensors and a similar number of current meters should be deployed at each mooring. Such moorings can be installed and recovered either from a temporary ice camp, using aircraft support, or from ice-breakers. Assessment of variability within the Arctic Ocean itself by this means should be done at a minimum of two sites within each of the four major basins (Canada, Makarov, Nansen, and Amundsen). These sites should be sufficiently removed from the continental shelves and the open boundaries so as to be representative of the net integrated effects of the major boundary processes. In addition, variability at 6-8 sites along the continental slope and over the ridges separating the basins should be measured, since much of the transport in the Arctic Ocean appears to occur within topographically trapped boundary currents concentrated along the basin margins (Aagaard, 1984; Aagaard, 1989; Jones et al., 1991). Whenever possible, the moored measurements should be complemented by full-column hydrography and tracer measurements in sections passing through the monitoring sites. At a minimum, this should be done annually or biennially during the servicing of the moorings. A start on this part of the AOVP has been made through the Canada/U.S.A. Arctic Ocean Climate Station project.

Finally, it is essential to determine the variability of the main exchanges with surrounding seas, both with regard to transport and to water mass properties. In the context of global climate change, the variability of fluxes through the Fram Strait and their effect on the large-scale thermohaline circulation are particularly important (Aagaard and Carmack, 1989). Other through-flows may also be of first-order importance. One of these is the flow through the Bering Strait, which carries the excess precipitation over the North Pacific into the Atlantic Ocean (Wijffels et al., 1992). It is also possible that significant amounts of water from the Norwegian Sea may enter the Arctic Ocean through the Barents Sea, with important consequences for the structure of the Arctic Ocean and its variability (Rudels, 1987; Blindheim, 1989). This possibility will be explored in conjunction with work on the Barents and Kara shelves, as well as the outflow from the Canada Basin through the Canadian Arctic Archipelago. At present, variability studies of a few years duration are being carried out in the Fram and Bering straits, but these need to be extended in time and placed on a firmer footing continuing through the ACSYS decade. The work presently being carried out provides the detailed information necessary to plan an efficient ACSYS effort, and thus serves as a prototype study for the final ACSYS experimental design. In the case of the Fram Strait, the present work is combined with that of the sea-ice monitoring effort (Section 3.2.2), and this symbiotic arrangement is expected to continue.
While the emphasis of the AOVP will be on the variability of the velocity and density (temperature and salinity) fields, other key measurements will be included as appropriate. For example, a capability for monitoring ice thickness is easily added to moored arrays by including an upward-looking sonar (ULS). Similarly, sediments traps can be incorporated into the same arrays to monitor the downward particle fluxes and thereby contribute to carbon cycle studies.

A number of other techniques can in principle be applied for the purpose of the AOVP, but these are still in an exploratory or developmental phase, and they can therefore not presently be considered as a mainline activity within the AOVP. An example is acoustic tomography, which could in principle be used to monitor both the spatially integrated density field and its derivatives (e.g. vorticity). In particular we note that both the acoustic transmission time in the ocean and the signal attenuation by the ice cover can potentially provide important information. Successful high-latitude tests of acoustic tomography have been conducted in the Greenland Sea, showing that the gyre-scale temperature field can indeed be observed by this technique (Worcester et al., 1993). Plans are also being developed for an international Arctic acoustic thermometry programme, that would call for the long-term deployment of sources and receivers around the periphery of the Arctic Ocean. Another new technique is the Lagrangian description of the circulation using acoustically tracked sub-surface floats. Several transmission studies have been conducted, the most recent one in the Beaufort Sea, which suggest that the technique is applicable, at least regionally. However, the long-range tests required before embarking upon a basin-scale tracking project have yet to be conducted.

2.4 Historical Arctic Ocean Climate Database

2.4.1 BACKGROUND AND OBJECTIVES

Arctic Ocean studies have until recent years had much of an exploratory character, with little baseline information or statistical background on which to develop theories and measurement programmes. There are still many areas for which no modern data are available. However, there is a significant body of physical and chemical oceanographic data held by various scientific institutions, which could form a collection covering many of the geographical and seasonal categories of a climatological description of the Arctic Ocean.

Arctic Ocean research in the former Soviet Union has been extensive, and there is a great deal to be gained from combining western and Russian data to expand both the geographical and temporal coverage of the Arctic Ocean. The opportunity now exists to assemble a data set which will bring the historical information available for the Arctic closer to the level of other oceans. Such an undertaking should be carried out in an international framework in order to ensure the widest possible access to data and worldwide distribution of the final product. Implementing this work under the ACSYS will provide the necessary international guidelines to the design and implementation of the project.
The objectives of this effort are to:

- Establish a universally available digital hydrographic database for the Arctic Ocean for analysis of climate-related processes and variability, and for the preparation of atlases and other data products;

- Provide a data set suitable for initialization and verification of Arctic climate and circulation models.

2.4.2 DATA SOURCES

2.4.2.1 Western data sources

The assembly of an Arctic Ocean database has been going on informally as part of basin-scale investigations by scientists in North America and Europe. Using existing archives, the Institute of Ocean Sciences in Canada (IOS) has organized the collection of a considerable body of accurate CTD and chemical data from recent field programmes, including the collected data of 25 years of Canadian research. The data coverage is approaching the point where climatologically meaningful basin-scale studies can be undertaken.

Extensive Arctic data catalogues giving details on data type, quality and source already exist at a number of locations. However, the gap between finding where a database is located and actually obtaining the data in a useful format is often daunting. The goal of the effort centered at IOS is not primarily to produce a catalogue or an atlas, although such documents may be published as part of the project, but rather to introduce the existing data into the World Data Centre network and record them on CD-ROM files which can be searched and sorted efficiently. To date, the following data sets have been gathered:

- Relevant data holdings of the U.S.A. National Oceanographic Data Centre (NODC);

- CEAREX-1 collection of U.S.A. and Canadian data from the Eastern Arctic; these were initially assembled on CD-ROM in 1991 by the National Snow and Ice Data Centre, Boulder, Colorado, U.S.A.

- AIDJEX data;

- An extensive set of observations made around Canadian and U.S.A. coastal waters by IOS Arctic groups and the University of Washington.

Additional data from European sources, particularly Germany, Norway, and Sweden are being added, and IOS, Canada will be the responsible institution for assembling these data into a unified set for ACSYS.
2.4.2.2 Russian data sources

There are many areas which have been studied only by Russian scientists, and their collaboration in the design and implementation of the Arctic Ocean database is essential. Not only do these data provide the broadest spatial coverage, but they also provide the best indication of temporal variability over much of the water column.

The Russian data sources include:

- Gridded Arctic Ocean data analyzed by the Arctic and Antarctic Research Institute (AARI), from data held by the Russian Federation (including the data collected by the former Soviet Union);

- Oceanographic observations at the drifting "North Pole" stations in the Polar basin (over about 80 station years during 1950-1991);

- Quasi-synoptic oceanographic surveys of the Polar basin and the northern shelf seas using aircraft landings during 1948-1993 (Figure 2.2);

- Annual oceanographic surveys of the Russian shelf seas during summer. These involve standard sections and are available from 1950-1993.

A portion of the gridded data, based primarily on observations during the early 1970s and before, have recently been assembled at IOS in parallel with the Western data collection (Section 2.4.2.1). These Russian data are on a 100 km x 100 km grid and are available for winter and summer at eight depths: 0, 100, 300, 500, 1000, 2000, 3000, and 4000 m.

2.4.3 DATABASE DESIGN

The over-arching goal of the ACSYS historical database effort is to assemble a digital hydrographic data set of the broadest possible spatial and temporal scope, but with sufficient quality control to warrant its issuance as a unified data set.

Particularly important in this effort is to provide sufficient spatial and temporal resolution over a wide area to meet the needs of modern high-resolution numerical models, for example, to resolve the structure of the halocline, lying between the surface mixed layer and the Atlantic layer (the vertical resolution cited in Section 2.4.2.2 is inadequate for this purpose).

As measurements exist since the early 1950’s, at least in the upper 500-1000 m of the ocean, every effort should be made to incorporate the full temporal coverage in the database.
Fig. 2.2. Russian hydrographic stations based on aircraft landings in the spring of 1979.
3. ARCTIC SEA-ICE PROGRAMME

The most unusual property of the Arctic Ocean is its permanent sea-ice cover. This thin layer of ice alters the surface properties of the ocean, such as its ability to reflect or absorb sunlight, its interaction with the atmosphere, and its ability to support various forms of life. Because these, and other, sea-ice properties play a role in the global heat balance and the thermohaline circulation of the ocean, it is important to understand the processes that sustain the ice pack.

It has often been argued that the ice cover represents a fragile balance between various energy fluxes, with the implication that changes in other parts of the climate system could alter the present equilibrium in the Arctic, leading to a different sea-ice regime. The argument emphasizes the sensitivity of several global processes to sea ice, and the sensitivity of the sea-ice pack to the climate.

The most studied global process involving sea ice is the global heat balance. Here, the potential for positive feedback is evident: warmer temperature implies less sea ice, which, in turn, implies more absorbed solar radiation, and even warmer temperatures (the sea-ice albedo - temperature feedback). In climate models, this process is responsible for the frequently quoted prediction that the largest temperature changes associated with increases in the atmospheric CO₂ occur in the Arctic. It is important to keep in mind that these destabilizing processes are held in check by the stabilizing effect of the infrared radiation from the ice surface: the warmer the ice, the more rapidly it is cooled by radiation.

In a gradually warming climate, as the mean surface temperature in the Arctic approaches the freezing point, the positive albedo - temperature feedback becomes increasingly important. On the other hand, the stabilizing effect of the infrared radiation remains about the same. This suggests that at some point, there will be a runaway transition to an Arctic Ocean that is ice free in the summer and perhaps even in the winter. Such a transition could occur on the time scale of decades.

These considerations identify the stability of the ice pack in the Arctic Ocean as an attractive scientific problem, viz., to follow the ice pack as it tries to maintain equilibrium with an atmosphere the composition of which is changing in a specified way. Thus, we are not trying to predict the (unpredictable) time dependent response of a non-linear dynamical system, but only the equilibrium state corresponding to a slowly changing external force. The possibility that a transition to an ice-free Arctic would be irreversible, only adds to the interest to the problem.

To make a creditable prediction about the stability of the ice pack over the next few decades, we must improve both theories and observations of the processes involved. In particular, we need to reach a position where predictions of changes in the ice regime over short time scales, say seasons, years, and decades, can be tested against observations. At present, this is not possible. For example, the historical record of ice thickness is not adequate to define interannual or decadal variations. Neither is the record of ice production or export through the Fram Strait. The paragraphs that follow describe efforts that are underway or are needed to fill these observational gaps, and to assemble a climatological archive to document the ice pack and support studies of its interactions with the other parts of the climate system.
3.1 Basin-wide Sea-ice Climatology Database

Long-term observations of sea-ice extent, concentration, thickness and velocity are required for investigating the natural (seasonal and interannual) variability and to determine anthropogenic influences. The data also form the basis for sea-ice model improvement and verification (Barry et al., 1993). The surface fluxes on a large scale for ocean models in polar regions can be determined only through sea-ice models.

Sea-ice climatology studies need to be supported by a corresponding knowledge of atmospheric and, to a lesser extent, oceanic conditions. The most relevant variables are the surface pressure and temperature, poleward fluxes of heat and moisture, clouds and outgoing visible or infrared radiation. It would be impossible to interpret the sea-ice climatology without such information (see chapter 4).

3.1.1 Sea-ice Extent and Concentration

The extent of sea-ice can be defined by identifying the position of the ice edge as a function of longitude and latitude. It is important that investigators agree eventually on an operational definition of the ice edge, but a precise definition is not important at this point. Passive microwave observations from ESMR, SMMR, and SSM/I have been reliably used to map the ice extent since 1972. The SSM/I instrument or an equivalent remote sensing capability will continue to be supported by NASA for the next few decades.

Using passive satellite microwave measurements, in principle the sea-ice surface can be classified into open water (open water in the WMO definition has a few percent of free ice concentration), first-year ice, and old ice using a combination of polarization and spectral gradient information. In fact, second-order conditions affect the retrievals. Some examples of this are: the "open water" proportion can consist of some mixture of ice free water and thin ice or even meltwater ponds overlying thick ice; snow cover on first-year ice can bias the spectral gradient between high frequency and lower frequency data to yield some proportion of "multi-year ice" within 100% first-year ice; and emission from water in the atmospheric column can affect the retrievals of both ice concentration and ice type. However, when one or more of these secondary factors can be defined by some other means, errors in the algorithms can be reduced, and additional information can be extracted, such as proportion of open water versus young ice. Passive microwave radiometers flown on aircraft just above the surface and underneath a satellite can provide useful information in interpreting the satellite signal.

Parkinson and Cavalieri (1989) estimate that the uncertainty in locating the ice edge is about 30 km, i.e. one SMMR pixel. (This is only an estimate, but Steffen and Schweiger (1991) have made an intercomparison with Landsat-derived ice concentrations. Their findings showed a seasonal dependence of the accuracy of passive-microwave derived ice concentration). They estimate that the total area covered by ice can be measured within about \(0.3 \times 10^6\) km\(^2\). From the work of Gloersen and Campbell (1991), random errors in estimates of the ice area appear somewhat smaller, perhaps \(0.1 \times 10^6\) km\(^2\). During the annual cycle, the total ice area in the Arctic fluctuates between about \(6 \times 10^6\) km\(^2\) and \(14 \times 10^6\) km\(^2\) (Gloersen et al., 1992). The interannual variability in the maximum and minimum ice areas is
about $1 \times 10^6$ km$^2$. These numbers imply that the seasonal cycle in the extent of sea ice can be measured quite accurately, and that variations from year to year can be resolved to one significant figure. This precision is adequate for monitoring the ice extent, given current uncertainties in sea-ice and coupled climate models.

The microwave data are processed by NASA, archived in the National Snow and Ice Data Centre, Boulder, Colorado, U.S.A., and are available in CD-ROM format. For ACSYS, the only action required is to reaffirm the importance of this data set.

Historical Arctic sea-ice data archived by various national services in the form of daily or weekly sea-ice charts (based on air reconnaissances, satellite observations, ship and shore reports) are now being digitized and will be merged into an Arctic subset of the Global Digital Sea-Ice Data Bank (GDSIDB) being developed by the WMO/CMM Steering Group for the GDSIDB (WMO, 1993). Available historical data on snow cover over the Arctic Ocean will be included into the GDSIDB.

3.1.2 Ice Thickness

A substantial part of the fresh water flux at the sea surface is represented by the net freezing/melting rate which can only be obtained basin-wide from improved dynamic-thermodynamic sea-ice models. Information on sea-ice thickness is crucial in order to improve existing models for the sea-ice dynamics.

The WCRP Arctic Ice Thickness Project (AITP), based on the use of moored upward-looking sonars (ULS), was launched in 1988 (WCRP-41) and underwent rapid progress with a significant increase in ULS deployments in 1991 and a further increase in 1992. Altogether nineteen ULS moorings were deployed in 1993: thirteen on the European side and six on the Pacific side of the Arctic Ocean (Figure 3.1). Additional ULS deployments on the Siberian shelf and in the Kara Sea are needed to complete a best possible array. Maintaining a permanent array over a period of at least ten years is an attainable objective for the AITP.

As the ice canopy moves, the stationary sonars sense the ice draft along a track of about 1000 km or more per year. However, it is not possible to construct detailed maps of the ice thickness for the entire Arctic this way. A more realistic objective is to collect statistics that characterise the ice thickness in a few selected regions. One may characterise the ice thickness in terms of an ice thickness distribution. Recent observations have shown that the upward-looking sonars can resolve both the annual cycle of the thickness distribution at one location, and differences in the thickness distribution between different regions.

There are several other ways to measure ice thickness and various research projects have been organised to use them. Observations from submarines, unmanned under-ice vehicles and aircraft can all be used effectively for this purpose. The flux of ice mass can be estimated by a combination of ULS series with velocities derived from buoy drifts or from SAR and AVHRR estimates. These efforts will also contribute to the ACSYS goal.
Figure 3.1 The present Arctic upward-looking sonar array.
3.1.3 ICE MOTION

The International Arctic Buoy Programme (IABP) co-ordinates the systematic deployment of, and data processing for, a substantial number of sea-ice buoys in the Arctic Ocean. The locations of the buoys are determined by satellite tracking with adequate precision and sampling rate for resolving the largest features of the field of motion. ACSYS will rely on this programme which is well established under the auspices of WMO-IOC Data Buoy Co-operation Panel.

Data from the IABP have special relevance to other ACSYS projects. In particular, the field of motion can be integrated over time to indicate the origins of ice passing over a particular upward-looking sonar device.

The available record (1979-present) of basin-wide ice motion data indicates large interannual variations in the velocity field, that can be related to variations in the atmospheric pressure field. These variations affect the regional distribution of ice, the local convergence and divergence, the flux of ice through the Fram Strait and the advection of the ice edge.

Figure 3.2 shows the mean annual field of sea-ice motion based on past drifting buoys, ice stations, and beset ships observations. Horizontal sea-ice divergence and subsequent interstitial freezing are the principal mechanisms for replenishing the ice cover in the Arctic basin. The regional pattern of mean annual horizontal divergence of sea ice is illustrated on Figure 3.3. The net creation of ice surface is about $0.9 \times 10^6$ km$^2$ per year, roughly balancing the annual export through the Fram Strait. I.P. Romanov’s privately published book and atlas (1993) summarize results of systematic measurements of snow and ice thickness, ice motion, and ice melting collected by some Russian scientists during several, almost synoptic (see Figure 2.2), spring airborne surveys of the Arctic Ocean in 1972-1984, as well as from ice drifting stations, air reconnaissances, and ice-breakers’ voyages in 1948-1988.

Other sources of information on sea-ice motion are consecutive SAR or AVHRR images, from which the translation (drift) of single floes can be determined. In contrast to the Lagrangian information from a few buoys, remote sensing data provide quasi-Eulerian information on the velocity field of sea ice with easy calculation of divergence/convergence patterns.

3.2 Monitoring the Export of Sea Ice through the Fram Strait

3.2.1 INTRODUCTION

About 95% of the ice that leaves the Arctic Ocean passes through the Fram Strait (Vinje and Finnekåsa, 1986) which is therefore the key location for monitoring the ice export from the Arctic Ocean, a very important climatic variable, which may be interpreted as a measure of the Arctic sea-ice production. Long-term series of the ice thickness observations are needed, not only in the Fram Strait but also in other strategic locations, for better understanding of the linkage between the different areas and reliable estimations of decadal trends. The ice flux will serve as an effective constraint on model simulations of Arctic climate.
Figure 3.2. The mean annual field of sea-ice motion derived from the trajectories of drifting buoys, ice stations, and beset ships, 1893-1993. The contour lines are isochrones, in years, of mean arrival time in the Fram Strait.

Figure 3.3. The mean annual field of the horizontal sea-ice divergence.
A long-term record of ice mass flux through the Fram Strait can be obtained by combining appropriate ice thickness and ice velocity observations. It is believed that the interpolated velocity fields from the IABP drifting buoy array in a rapidly moving ice flow are not sufficiently accurate for this purpose, although a closer look at this question would be useful. The safest strategy will therefore be to enhance the present generation of the upward-looking sonar instruments by adding the capability to determine the ice velocity from the Doppler shift associated with the ice motion, or to infer velocity from sequential satellite-borne SAR or AVHRR imagery.

The two first annual time-series of ULS measurements in the central section of the Fram Strait reveal a bimodal distribution of the ice draft with a long tail (Figure 3.4) extending as far as 28 m that represents the maximum ice keel depth. The annual mean ice thickness, corrected for footprint error, was 3 m at that location in 1990-91.

3.2.2 Monitoring Array Design

A proper selection of monitoring sites in the Fram Strait may be crucial to obtain a correct estimation of the ice outflow. A number of different aspects need to be considered in this respect. The mixing between the southbound cold Transpolar Current and the northbound warm West-Spitsbergen Current causes considerable ice melting between 80° and 81°N (Östlund and Hut, 1984; Vinje and Finnekåsa, 1986). Further south, at 79°N, a pulsating westward inflow of warmer water has been observed under the ice in the East-Greenland Current (Kvambekk and Vinje, 1992). This indicates that the ice melting caused by westward moving eddies from the West-Spitsbergen Current takes place over a relatively wide latitudinal range in the Fram Strait. A systematic, topographically induced effect on the local mean ice thickness has been observed at 78°N (Figure 3.4), thus excluding this latitude as representative. Divergence areas in the East-Greenland Current seems to occur periodically down-stream around 79°N. Nevertheless this location seems to be the best for measuring the ice mass export from the Arctic Ocean, since the ice stream is relatively narrow throughout the seasons.

The marked cross-flow variations in both ice thickness and drift velocity (Wadhams, 1983; Vinje and Finnekåsa, 1986) suggest that at least four moorings at appropriate spacing are necessary to obtain a proper description of the ice thickness distribution (Figure 3.5).

3.2.3 Data Management

The ACSYS repository for ULS ice thickness measurements will be at the Norwegian Polar Institute. Data must meet uniform standards, and will be submitted to the repository as soon as they have been fully processed and corrected. Data standards, including footprint corrections and sea surface referencing, will be promulgated through the repository after recommendations from investigators.
Figure 3.4  ULS measurement results from the Fram Strait for the period July 1990-August 1991. A and B locations were 79°13'N, 03°17'W and 78°02'N, 04°47'W.

The marked difference in the ice draft distribution as well as the ice concentration for the two locations as shown by the lower graphs for April (left) and August reflects the effect of flow divergence, indicated by the mean drift pattern of buoys in the area.
In accord with general ACSYS data policy, ice thickness measurements will be made available by the repository to all ACSYS investigators, but they cannot be published or cited without permission of the principal investigator for a period of up to two years. After that time, the data will be deposited with national or international data centres in a manner which ensures easy access by the international scientific community.

Figure 3.5  Proposed ULS mooring positions in the Fram Strait along 79°N, at one, three, five, and seven degrees W (filled circles) to obtain an optimal coverage with regard to a combination of the observed cross-strait profiles of velocity, ice thickness and ice concentration.

Thick line: Median ice edge at the end of March
Broken line: Median ice edge at the end of September
Thin line: Depth contours (km)
Insert: Cross-strait velocity profile (m/s) at 79°N.
3.3 Integrated Studies of Ice-Atmosphere-Ocean Interactions

The atmospheric and oceanic boundary layers and sea ice form a complex interactively coupled system. Improved understanding is needed of the interactive processes by which this heterogeneous system adjusts to external perturbations. To accomplish this, improved understanding is required of:

- the role of the ice thickness distribution and melt ponds for the surface energy balance over sea ice and the subsequent impact of the surface state on the evolution of the Arctic cloudy boundary layer;
- the influence on spectral surface albedo of ice thickness, melt pond area and depth, lead fraction, ice age, salinity and density;
- the formation of open water areas as a function of ice pack characteristics and wind forcings, and the contribution of surface energy transfers in cyclogenesis;
- the absorption, internal absorption and transmission of solar radiation in sea ice;
- the aggregate effect of leads on the fluxes of momentum, heat, and moisture into the Arctic atmosphere and the exchange of water between the leads and the underlying mixed layer;
- mixed layer processes, including the processes of ice bottom accretion and ablation and the impact of brine rejection and bottom melting on the rate at which the ocean can loose heat to the ice, the impact of brine rejection and melt water on the stability of the Arctic Ocean and the horizontal exchange of heat and salt below the ice cover.

Concurrent measurements of the above processes made over an aggregate of sea-ice types and thicknesses will permit understanding the thermodynamic interactions between sea ice, the atmospheric boundary layer and the upper ocean. This is one of the primary aims of the U.S.A. Surface Heat Budget of the Arctic Ocean (SHEBA) programme (section 4.5.3). Contributions to our understanding of these processes will also be made by other programmes and experiments outlined in section 4.5 and by that in section 3.4 below. Such measurements are an essential requirement for developing models that can address the mutual adjustments of the upper ocean, ice cover and atmosphere to perturbations of the climate system.

3.4 Sea-Ice Process Studies

3.4.1 LAGRANGIAN DRIFT EXPERIMENT (STUDY OF ICE THICKNESS CHANGES ALONG THE PATH OF AN ICE-FLOE)

Mechanical and thermal processes combine to determine ice thickness. A theoretical framework for integrating these effects has existed for many years but,
until recently, observations documenting the evolution of the ice thickness distribution were not available. ACSYS will include a special field experiment to improve the description of these processes in a Lagrangian framework.

The project consists in following a particular ice-floe of some 200 km in diameter for a period of two years. The ice thickness distribution will be measured several times during this period using an upward-looking sonar on a submarine. The sampling strategy will be based on criss-crossing the region with enough passes to obtain an accurate statistical representation of the under-ice topography (assuming the ice thickness statistics are isotropic, there is no need to produce a map of thickness itself). The ice floe will also be instrumented with many ice thickness gauges, to determine how ice growth and melt rates depend on thickness. These gauges would be read manually three or four times a year. Synthetic aperture radar data for the region will be used to follow the details of ice motions and their relationship to the formation of leads and pressure ridges. The experiment will require establishing an ice station that will be occupied by a small field party for successive limited periods of time.
4. ARCTIC ATMOSPHERE PROGRAMME

4.1 Introduction

The atmospheric circulation over the Arctic region and its representation in general circulation models is important to studies of global climate because:

- High latitudes constitute a heat sink for the global climate system which must be represented correctly in models if the strength of the atmospheric circulation is to be adequately simulated;

- Polar air masses, interacting with warmer air from lower latitudes provide the temperature contrast which drives baroclinic instability;

- Surface winds provide the dynamic forcing on sea ice and ocean; transport of ice may exert a strong influence on heat exchange in the North Atlantic and thus affect ocean circulation and climate;

- The surface radiation and turbulent heat fluxes provide the thermodynamic forcing on sea-ice and the oceanic circulation, controlling the formation and melting of sea ice; proper representation of the surface heat fluxes requires adequate simulation of the atmospheric circulation, cloudiness, and atmospheric boundary layer;

- Climate change simulations show that the Arctic is a region of high climatic sensitivity to increased concentrations of greenhouse gases.

The ACSYS Arctic Atmosphere Programme focuses specifically on atmospheric characteristics and processes that are required to be studied in order to increase our understanding of, and ability to model, the interactions between the troposphere, the atmospheric boundary layer, and the sea-ice/upper ocean, which together form a complex and heterogeneously coupled system. Current gaps in our understanding include: the interactions among cloud evolution, atmospheric and boundary layer dynamics, and the surface characteristics; the role of leads and polynyas in heat and moisture exchange between the atmosphere and ocean; formation of wintertime cold-core anticyclones and interactions with the development of temperature and humidity inversions and boundary layer clouds; and the interactions between coastal storms and ice-edge processes.

To address these issues, it is essential for ACSYS to develop an improved atmospheric database, which will allow the validation of atmospheric models, improved understanding of the interaction of the atmospheric circulation with the underlying surface, and the foundation for improved treatment of Arctic atmosphere processes in climate models and determination of Arctic temperature trends and variability. Two different types of data sets are required to achieve these goals:

i) data sets obtained from field campaigns that provide increased understanding of physical processes and the foundation for improved parameterizations in climate models; and
ii) large-scale analyses of meteorological and surface characteristics to validate existing models, provide surface forcing for sea-ice/ocean models, and to conduct diagnostic studies relating surface fluxes to the large-scale atmospheric circulation.

4.2 Arctic Atmosphere Historical Data Set

4.2.1 ARCTIC ATMOSPHERE RE-ANALYSIS

State-of-the-art analysis and assimilation systems used for weather forecasting can potentially provide the most comprehensive data sets for studies of the Arctic atmospheric circulation and its climate. They also provide estimates of surface forcing fields over sea ice. However, the central Arctic is of peripheral interest for most numerical weather prediction operations and existing meteorological analyses suffer from serious systematic errors in the Arctic due to a number of factors:

- the sparsity of atmospheric sounding data over the central Arctic basin and related difficulties in quality control and in determining the appropriate weights for observations versus first guess fields over such data-sparse regions;

- uncertainties in satellite-derived surface temperatures and soundings arising because surface-cloud discrimination in the Arctic is complicated by the high albedo of snow and ice-covered surfaces;

- the simplistic representation of sea ice in NWP models (generally taken as a slab of ice of fixed thickness with 100% concentration over a grid square);

- uncertainties and inadequacies in physical parameterizations used in assimilation models, particularly regarding Arctic clouds, radiation and atmospheric boundary layer processes;

- numerical problems involved with filtering fields at the northernmost rows of grid point models.

Whilst archives of past operational analyses are available, they lack consistency on account of successive changes introduced in models and data assimilation systems. A particular example is seen in Figure 4.1 which shows time series of monthly mean surface temperatures at the North Pole from the United Kingdom Meteorological Office (UKMO) Numerical Weather Prediction analysis system over the period July 1986 to December 1992. The decrease in summertime temperatures between 1987 and 1988 and the continuance of these low values through 1989 and 1990 is unrealistic and can be associated with a change in the assimilation scheme. The return in 1991 to summer temperatures close to the melting point of ice coincides with introduction of a new operational model. Other NWP models show similarly spurious changes. An example from the U.S.A. National Meteorological Centre (NMC) model is given in Figure 4.2, showing artificially high winter temperatures from 1983
Figure 4.1 Monthly mean surface temperatures at the North Pole extracted from the NWP analyses of the UKMO.

Figure 4.2 Monthly mean surface temperatures at the North Pole extracted from the NWP analyses of the U.S.A. NMC.

Figure 4.3 Monthly mean surface temperatures from the AMIP run of the Hadley Centre AGCM, averaged over the northern polarmost grid points of the model.
to 1986. These operational archives are clearly inadequate to validate the mean climate and its variability simulated in long climate model runs such as shown in Figure 4.3 (monthly mean temperatures obtained at polarmost latitudes in the course of a ten year integration of the Hadley Centre climate model implemented for the WGNE Atmospheric Model Intercomparison Project; see Gates, 1992). Neither do they provide a consistent long term archive for deriving the thermodynamic forcing on sea ice (see also section 4.3).

Consistency can only be achieved by a re-analysis of historical data using a single assimilation system. For ACSYS, the most promising approach would be to carry out such a re-analysis for the region between (say) 40°N and the pole using a state-of-the-art quality control and assimilation system, together with a realistic representation (empirical or otherwise) of sea-ice properties. ACSYS will seek to develop such a system which would be implemented at a cooperating NWP Centre.

Such a re-analysis project is a major undertaking. Global re-analyses are now in progress at both the National Meteorological Centre (U.S.A) and the European Centre for Medium Range Weather Forecasts (ECMWF). These are expected to produce the best and most consistent analyses to date of global climate over the recent past. Verification of these analyses over the Arctic can be partially accomplished by comparing with satellite retrievals and measurements from field analyses that were not assimilated into the analyses, as well as with independently-derived regional analyses (section 4.2.2).

The database for producing daily gridded analyses over the Arctic Ocean of basic atmospheric dynamic and thermodynamic quantities has been enhanced over the past decade by the surface pressure and temperature data obtained from drifting sea-ice surface buoys (Thorndike et al., 1983) and to some extent from satellite-derived atmospheric temperature retrievals (e.g., Claud et al., 1991). Improved methods of 4-dimensional data assimilation and initialization, such as those employed by the ECMWF in their routine initialized analyses, have provided a plausible data set for diagnostic and climatological studies of Arctic circulation features which will be enhanced by the re-analyses currently underway. However, it is doubtful that these re-analyses will be able to address the special needs of ACSYS for very high quality analyses over the Arctic, particularly with regard to determination of surface fluxes, because of the sparsity of sounding data, uncertainties in satellite retrievals, and inadequacy of model parameterizations in the Arctic. A goal of ACSYS is to provide the foundation for improved meteorological analyses in the Arctic with special emphasis on surface fluxes, directed towards an improved re-analysis of the Arctic atmosphere historical data set. To address the lack of atmospheric sounding data over the Arctic, refinements to satellite retrievals of temperature and humidity profiles need to be made (e.g., Francis, 1994). The ARM, SHEBA and FIRE programmes (see section 4.5) should provide the foundation for better parameterizations of sea ice, radiation, clouds, and the atmospheric boundary layer in NWP models. Improved formulations of sea ice and improved procedures for initialization/updating of sea-ice fields from observations will also be sought by ACSYS for use in the proposed Arctic re-analysis.
4.2.2 **ARCTIC REGIONAL ANALYSES**

Historical data sets based on regional analyses of single variables will continue to be essential for defining current climate at high latitudes and for monitoring and detection of climate change. Surface air temperature is of especial interest in this context. At present, production of a high quality analysis of 2 m air temperature for the Arctic basin is a research task. Surface temperature variations are different in the Arctic from those in mid-latitudes. During the dark winter months, October through March, the diurnal signal is small and the typical differences between the surface snow temperature and 2 m air temperature are often of the order 1°C. However, surface air temperatures during the Arctic night are generally higher by 1°-10°C under overcast conditions than under clear skies. During the summer melt season, June through August, the 2 m air temperature rarely departs from the melting temperature. This leaves only a few months when short-wave radiation has a significant impact on the 2 m air temperature. The unique Arctic environment may call for analysis techniques different from those employed in mid-latitudes. For example, recent studies show that clear-sky AVHRR images can be used to estimate surface temperatures with errors of about 2°C (Key and Haefliger, 1992; Lindsay and Rothrock, 1994). Analyses of cases with a cloudy atmosphere suggest that TOVS can be used to obtain temperature with errors of a few degrees. The recommended strategy is to combine the satellite data, coastal station reports, and drifting data buoy air temperatures (see section 4.3.3) to produce the fields of daily averaged surface temperature from which appropriate climatologies may be derived.

4.3 **Atmospheric Forcing of Sea ice and Ocean**

4.3.1 **INTRODUCTION**

An important task for ACSYS is the derivation of improved data sets of atmospheric forcing. A goal of ACSYS is to provide daily values of all components of the surface fluxes of heat, fresh water, and momentum on a horizontal scale of 1°, over several annual cycles. The atmospheric forcing of sea ice and ocean is effected through the surface wind stress (dynamic forcing) as well as fields of solar and long-wave radiation, sensible and latent heat, and of precipitation (discussed in sections 5.2.1 and 5.2.3), each of which contributes to the thermodynamic or buoyancy forcing. The determination of atmospheric forcing is required for:

- driving sea-ice and ocean models;

- verification of internally-generated boundary fluxes in coupled atmosphere-ocean-ice model computations;

- diagnostic studies of, for example, the polar energy balance.

In the past, surface conditions for integrating stand-alone sea-ice models have been obtained by specifying fluxes, using available climatological data or in-situ measurements of relevant atmospheric parameters. Currently, the dynamical forcing can be effectively obtained from the corresponding operational NWP product. The fields of surface temperature and humidity can also be taken from the NWP analyses.
At present, the reliability of dynamical forcing deduced from NWP analyses (surface wind field) is considerably better than that of the thermal forcing (surface temperature and humidity), though this can be expected to be overcome if a special re-analysis effort for ACSYS is undertaken. The largest uncertainties are associated with errors in the NWP computations of surface radiation. Because of this, an approach based on model data, coupled with use of surface radiation budget data based on retrievals from satellite data and in-situ data must be used.

4.3.2 Surface Radiation Budget

Surface ice/snow temperatures and albedo are an integral part of the surface radiation balance. Two approaches should be used to determine surface ice/snow temperatures and albedo on the time and space scales required by ACSYS: satellite retrievals, and NWP models. Satellite retrievals of surface temperature and albedo are hampered particularly by cloud discrimination difficulties particularly during the polar night; it is anticipated that SHEBA and FIRE (section 4.5) will markedly improve satellite retrievals of these quantities. Further, new instrumentation for the Earth Observing System (EOS) (which will be available by the end of the century) should vastly increase the accuracy of satellite retrievals in polar regions (see section 4.4.4). Although sophisticated sea-ice models are increasingly being included in global climate models (GCMs), accurate sea-ice predictions are less critical to the short-term forecasts made by the NWP centers. As already noted (section 4.2), ACSYS will seek to provide an improved representation of sea ice for use in NWP models in the context of the proposed Arctic atmosphere re-analysis.

Existing in-situ measurements of incoming short-wave and long-wave radiation are relatively sparse and of short duration or uncertain quality. Radiation measurements from the former Soviet Union's drifting ice stations will provide climatological information and will be useful in validation of surface retrievals of the incoming radiation. Because of the large dependence of the surface short-wave and long-wave radiation fluxes on cloud characteristics, satellite cloud retrieval schemes and NWP cloud parameterizations must be improved before reliable determinations of the surface incoming fluxes can be made on the time and space scales required for ACSYS. More accurate satellite cloud retrievals and model cloud parameterizations in the Arctic is a major aim of the ACSYS strategy and forms a component of the ACSYS cloud and radiation programme described in section 4.4 below. It is also a goal of SHEBA, ARM, and FIRE (see section 4.5).

4.3.3 Surface Turbulent Fluxes

The wind stress provides the primary driving mechanism for sea-ice motion and ocean currents. Turbulent heat fluxes are significant components of the surface energy budget, and the surface evaporative flux is required to determine the total fresh water flux. In the absence of direct eddy correlation measurements, which are very rare in the Arctic, surface turbulent fluxes are calculated from the so-called bulk methods, which require as input the surface air wind speed, temperature and humidity (at approximately 10m) along with the surface snow/ice temperature.
The International Arctic Buoy Programme has contributed to significantly improve surface pressure and wind fields provided by NWP models. An error analysis for the surface geostrophic wind shows the rms error for vector winds to be smaller than 2 m s\(^{-1}\). In principle, the same array of drifting buoys that monitor atmospheric pressure could serve to define the surface air temperature fields. Unfortunately, only about 30% of the buoys are specially equipped to measure the 2 m temperature. Temperature data from the remaining buoys are susceptible to large errors. Further efforts are required to improve the buoy temperatures. To achieve ACSYS goals, it is essential that the current array of Arctic drifting buoys be maintained, as well as the real-time transmission of data through the GTS. These data should be archived through the World Data Centre System.

NWP surface winds are the preferred source of wind speed data to determine the surface fluxes. Unfortunately, surface air temperature and humidity values produced by the NWP models are not currently of sufficient accuracy for use in determining surface turbulent fluxes. The models themselves do not generally assimilate surface temperature and humidity data, and temperature and humidity soundings are very sparse over the Arctic Ocean, though there is a relatively good radiosonde network surrounding the Arctic basin. (All available Arctic basin and adjacent land surface station soundings from the late 1950s to 1988 have been assembled, quality-checked and issued on three CD-ROMs (Serreze et al., 1992)). Therefore, the NWP fields of surface air temperature and humidity are almost entirely the product of the internal physics of the model (e.g., boundary layer, clouds and radiation), which are inadequate over the Arctic. Improvement of boundary layer, cloud and radiation parameterizations for global climate models (and implicitly for NWP models) over the Arctic is a major goal of SHEBA and ARM (see section 4.5). Consistency of analysis can only be provided by a re-analysis of the available historical data using a single assimilation system, as discussed in section 4.2 above, validated against high quality regional analyses of surface air temperature (section 4.2.2).

Surface latent and sensible heat fluxes over the Arctic Ocean are relatively small when compared with surface radiation fluxes, particularly during summer. In fact, the magnitude of the turbulent heat fluxes is probably within the range of error in the estimates of the net surface radiation flux. However, there is one aspect of turbulent heat flux in the Arctic that is of particular importance in understanding the exchange of energy between the atmosphere and ocean, namely leads. Although leads occupy only a small fraction of the ice pack, their role in the overall surface energy budget of the Arctic Ocean is substantial. Open water areas in the sea ice are of major significance for the ocean-atmosphere exchange of heat and moisture, particularly during winter. Field measurements taken in winter during the AIDJEX Lead Experiment (Andreas et al., 1979) showed that the turbulent heat fluxes from leads can exceed 400 W/m\(^2\) for sensible heat and 130 W/m\(^2\) for the latent heat flux. Typical wintertime air-sea temperature differences of 20-40°C over leads create heat fluxes up to two orders of magnitude larger than over pack ice (Andreas, 1980), and the net heat loss from a small percentage of open water and thin ice can exceed that from the surrounding ice pack. Recent measurements and modelling efforts associated with LEADEX are increasing our understanding of the surface fluxes of heat and moisture in the presence of leads and its transfer in the atmosphere. What remains to be accomplished is the development of a parameterization of surface heat and moisture flux from leads, as a function of modeled or observed lead fraction and the observed or parameterized lead width distribution.
4.4 Polar Clouds and Radiation Programme

The downward fluxes of short-wave (solar) and long-wave (atmospheric) radiation are principally modified by the presence of clouds and aerosol. In polar regions, the distribution and optical thickness of clouds and aerosol layers can only be systematically observed over the whole region by remote sensing from satellites. Satellite cloud retrievals, combined with radiative transfer models, provide an important technique for derivation of the surface radiative fluxes. However, substantial differences (which have been attributed to ice crystal precipitation) have been noted between surface-based and ISCCP cloud climatology in the Arctic, and the wintertime ISCCP results need confirmation. These errors in satellite-retrieved cloud properties result in corresponding errors in the surface radiation fluxes. In order to improve these derivations, there is a need for new cloud retrieval methods, including assimilation of satellite data into numerical model runs; utilisation of new satellite techniques and instrumentation; and improved methods of characterising the surface properties of ice and snow. A particular difficulty with current ISCCP surface temperature estimates is the lack of a satisfactory automatic cloud masking procedure for the Arctic (Schweiger and Key, 1992; see also Lindsay and Rothrock, 1994).

The success of routine cloud and radiative flux retrievals is also dependent on good quality observational data either from in-situ surface observations or from aircraft. Provision of such ground truth is essential so that the accuracy of the retrievals can be assessed and improved. There is also a need for improvements in our knowledge of polar clouds and their modelling, including better understanding of the life cycles of Arctic clouds and their interactions with the radiation field.

4.4.1 Concurrent In-situ and Satellite Measurements for Calibration and Validation of Retrieval Algorithms

Accurate values of surface temperature are necessary to estimate cloud height and optical thickness from satellite measurements. The retrieval of ice surface temperature is hampered by lack of full information on the optical properties of the atmosphere column for validation. Measurements of surface skin temperature in conjunction with radiosonde measurements of temperature and humidity under clear sky conditions are needed in all seasons to solve this problem. Reference in-situ measurements of incoming and outgoing short-wave irradiances under clear and cloudy conditions, atmospheric temperature and humidity, as well as aerosol, clear sky ice crystals ("diamond dust") and cloud properties are needed throughout the period of solar illumination to validate surface albedo measurements inferred from satellite radiometry data. For both surface temperature and albedo, verification data should be representative of an area similar in size to the field of view of satellite radiometers, i.e. about 1 km². Aircraft surveys will be an important tool for this purpose.

4.4.2 Aircraft Measurements of Radiation Transfer and Optical Properties

Systematic aircraft surveys, synchronised ideally, with the overpasses of relevant satellites, in representative weather and seasonal conditions will constitute an important ground-truth basis for radiation and cloud/surface properties. These measurements should include:
cloud microphysical and radiation flux measurements made concurrently from aircraft and the surface in order to test various formulations of cloud-radiation interactions;

- optical properties of clouds, clear-sky ice crystals and Arctic aerosol;

- vertical distribution of cloud particulate matter and cloud optical thickness.

4.4.3 In-situ Measurements of the Surface Radiation Budget

Comprehensive field observations are required for all seasons as well as continuous series of reference surface radiation flux measurements spanning at least one annual cycle. Systematic backscatter lidar measurements are also required to determine the altitude, range and optical thickness of cloud and aerosol layers. Three to five ground-based measurement stations, meeting the standards of the WCRP Baseline Surface Radiation Network (BSRN), are needed in the Arctic. Where possible, the BSRN measurements should be supplemented with surface UV-B observations at the same sites.

4.4.4 Combined Satellite Retrievals of Atmospheric and Surface Properties: Refined Instrumentation and Techniques

There is a need to assess both what additional geophysical parameters can be measured in the Arctic using the current suite of satellite radiometers, particularly using multi-sensor algorithms, and the potential utility of new instruments not yet on satellites. The instruments that have been most utilised in the remote sensing of the Arctic atmosphere and sea ice are SSM/I, HIRS2/MSU and AVHRR. Issues related to the SSM/I include validation of algorithms to retrieve sea-ice type (first year or multi-year ice), and the simultaneous retrieval of sea-ice and atmospheric water vapour characteristics. New work suggests that some thickness estimate is possible for young ice categories. Future satellite and space platforms may carry updated versions of the AVHRR instrument optimised for cloud identification, and new vertical sounders like HIRS for estimating the particle size and cloud height. These may be supported by the multi-angular views of the ATSR, enabling some three-dimensional representation of cloud fields. Multi-spectral sensing techniques, such as provided by NOAA-AVHRR, have shown some potential for distinguishing clouds from the underlying ice and snow fields. Issues related to the AVHRR include the validation of ISCCP retrievals and cloud properties, surface temperature, surface albedo and surface solar radiation fluxes, and the analysis of sea-ice motion. Microwave imaging data could be useful to improve information on lead fraction, once the concentration algorithms are improved. SAR is a potentially useful sensor for the Arctic that has been under-utilized to date. Both SAR and AVHRR can provide detailed ice motion information to complement buoy data (Maslanik et al., 1994). Further, combined analysis of high-resolution SAR data and lower resolution AVHRR and SSM/I data can provide important information on the appearance of surface characteristics over a range of spatial scales. Substantial work with new instruments could be done with aircraft above the Arctic basin.
Additional satellite sensors already flying or soon to be launched include SCARAB, to determine radiative fluxes at the top of the atmosphere; LANDSAT and SPOT for analysis of sea-ice motion and surface albedo on small scales; multangle and multiband radiometer on ATSR to determine bidirectional surface reflectances; ERS-1, JERS-1 and RADARSAT SAR for sea-ice motion and type (first year or multi-year), ice concentration and polynyas; AIRS/MHS and AMMS for atmospheric water characteristics; laser altimeters to measure sea-ice characteristics and snow depth; and MODIS to measure the properties of clouds, atmospheric structure and surface variations.

4.4.5 STUDIES OF CLOUD LIFE CYCLES AND PHYSICAL PROCESSES

Improved understanding is needed of cloud life cycle processes as related to the formation, maintenance and dissipation of Arctic clouds. Current climate models show substantial disagreement amongst themselves and with observations of Arctic cloud properties. A necessary first step is to accurately model the Arctic cloud properties in the present-day climate. To model the cloud-radiation feedback mechanism (and to understand future climate scenarios), we must understand how cloud fraction and vertical distribution, water vapour and cloud water content, cloud particle concentration and size and cloud phase will change as atmospheric temperature and chemical composition change. It is clear that improved model parameterizations of cloud microphysical processes, radiative transfer, boundary layer turbulence, cloud fraction and shallow convection in atmospheric models are required to adequately model the Arctic clouds and their associated feedback processes. Understanding and modelling boundary layer clouds in the Arctic are made particularly complex because of the low temperatures and low water vapour content, frequent temperature and humidity inversions. Tackling these problems will require systematic studies that include synthesis of aircraft data of the type outlined in 4.4.2 above with surface and satellite measurements and with large-scale analyses of atmospheric fields during different seasons and under different synoptic conditions.

4.5 Supporting National and Multinational Programmes

Elements of a response to the needs outlined in sections 3.3 and 4.4 above are now emerging through several national and international field programmes planned for the mid-1990s to study Arctic surface processes, and cloud properties and their radiative impacts.

4.5.1 U.S.A. ATMOSPHERIC RADIATION MEASUREMENT PROGRAMME

The Atmospheric Radiation Measurement Programme (ARM) of the U.S.A. Department of Energy aims to improve the handling of radiative transfer in GCMs, especially as influenced by clouds. This is being done in part through the provision of a testbed for the study of cloud and cloud radiative transport processes over areas corresponding to a typical GCM grid element, and through comparisons of the acquired data with the results of model parameterizations of clouds, cloud
microphysical properties, and cloud-radiative interactions. Three CART (Cloud and Radiation Testbed) sites are currently planned, one of which is the NSA/AAO (North Slope of Alaska/Adjacent Arctic Ocean) site. The ARM experimental programme is already underway at the first CART site, located in the Southern Great Plains of the U.S.A., north of Oklahoma City. Long-term measurements are scheduled to start at the Tropical Western Pacific CART site (in the vicinity of Papua-New Guinea) next year (1995). It is currently expected that the major research effort at the NSA/AAO CART site will begin in 1997 in parallel with the SHEBA experiment (see 4.5.3).

CART sites have a planned life of ten years. Most ARM facilities constituting the NSA/AAO CART site will likely be near and/or inland from Barrow and nearby villages, on the rim of the Arctic Ocean. However, the ARM measurements in the Adjacent Arctic Ocean proposed to be made in the perennial ice pack in conjunction with SHEBA can only be made for 12-18 months, the planned lifetime of the SHEBA ice camp.

A generic CART site includes:

1) a central facility with instrumentation for making low-, medium- and high-spectral-resolution measurements of radiative fluxes, as well as for characterizing the surface around and the atmospheric column above the facility (various profiling instruments);

2) a set of auxiliary stations surrounding the central facility within a several kilometer radius equipped with video-based multi-spectral whole-sky imagers for computer reconstruction of the 3-dimensional cloud field over the central facility;

3) an extended array of automated observing stations distributed over roughly a 200 x 200 km² area (at lower latitudes) to collect radiometric, meteorological, surface and surface flux data;

4) several boundary facilities on the periphery of the extended area equipped with wind, temperature, cloud and humidity profilers for characterizing the flows into and out of the extended CART site.

Because of logistical and related budgetary constraints, the NSA/AAO CART site is likely to depart from this model to a significant extent, taking advantage of the infrastructure available only at Barrow and other North Slope villages, as well as the infrastructure anticipated to be provided by other programmes such as SHEBA (section 4.5.3).

The instrumentation under consideration for the central facility includes (but is not limited to) high- and medium-resolution interferometers in the 4-20 micrometer spectral range (extension to yet longer wavelengths has been recommended); a cloud radar; a microwave radiometer for measuring column densities of liquid water and water vapour; a micro-pulse laser ceilometer; a radar wind-profiler with a radio acoustic sounding system (for measuring humidity profiles); a multi-wavelength rotating shadow-band radiometer; a balloon-borne sounding system; broadband pyranometers, pyrheliometers and pyrgeometers; standard meteorological sensors; surface albedo...
and surface flux instrumentation. Since it is proposed that the central facility be close to the NOAA Climate Monitoring and Diagnostics Laboratory station near Barrow, it is expected that relevant information on near-surface concentrations of trace gases and aerosols will be available from that source. Periodic instrumented aircraft measurements aloft, as well as existing satellite sensing systems will augment the ground-based NSA/AAO CART measurements.

To fulfil its goal of improving the performance of the radiation and cloud process models and parameterizations used in general circulation models, ARM primarily uses CART data and data acquired from other sources (satellites, etc.) relevant to the CART sites to evaluate radiation and cloud process models, and to guide the development of improved models. As appropriate, ARM activity also includes:

- modelling and diagnostic studies of other existing data sets relevant to the representation of clouds in GCMs;
- development of needed advanced instrumentation for high precision radiometric observations, as well as for cloud and water vapour profiling;
- the application of ARM data to related research programmes.

4.5.2 BEAUFORT AND ARCTIC STORMS EXPERIMENT

The Beaufort and Arctic Storms Experiment (BASE) is the atmospheric component of the Canadian GEWEX programme Mags (Mackenzie GEWEX Study). The objective of BASE is to improve understanding of weather systems in the Canadian Arctic, particularly as related to precipitation. The BASE field experiment is being conducted from approximately September 1 until November 15, 1994 in the region within a few hundred kilometers of the mouth of the Mackenzie river, based at Inuvik airport. The following observational facilities are planned for BASE: research aircraft, Doppler radar, cloud radar, boundary layer wind profiler, mesonet stations on land, offshore buoys and enhanced rawinsondes.

4.5.3 SURFACE HEAT BUDGET OF THE ARCTIC OCEAN (SHEBA) PROGRAMME

SHEBA is a U.S.A. programme with a scientific focus on the surface heat balance of the central Arctic Ocean. The long-range objective of SHEBA is to improve the understanding of polar processes, including the cloud-radiation and ice-albedo feedback mechanisms, leading to better models of the role of the Arctic Ocean in climate change. The principle obstacle to progress in understanding these processes and the stability of the Arctic Ocean sea ice is the lack of appropriate data sets needed to document Arctic climate, to develop, test and implement improved formulations of Arctic processes and to apply remote sensing data to process studies and climate monitoring.
The essence of SHEBA is to conduct a year-long field experiment on a drifting ice camp in the Arctic Ocean, combined with modelling and remote sensing analysis. This field experiment is currently planned for the period April 1997 through September 1998. The observational programme will be designed to emphasize the interactions of the surface radiation balance, mass changes of the sea ice, the storage and retrieval of energy and salt in the mixed layer of the ocean, the formation and radiative properties of clouds and their interplay with the radiation balance, and the relationships between the air-sea-ice system and the signals received by satellite-borne sensors. Special emphasis will be placed on the use of modern surface-based technology, such as precision radiometers, multiband LIDAR, cloud radar, ocean turbulence clusters, autonomous underwater vehicles, and photoelectric devices to measure subsurface radiation. Dedicated aircraft will conduct regular surveys of the surface conditions and take a variety of measurements in the cloudy atmospheric boundary layer. Observations at the ice camp will be augmented by a number of strategically placed automatic data buoys.

SHEBA will supplement the ground truth database in the Arctic to help refine satellites-derived diagnostics of the Arctic climate system at larger space and time scales. The three satellite instruments that are most relevant in this context are SSM/I, TOVS and AVHRR. A key issue raised by the exploitation of SSM/I data is the simultaneous retrieval of sea-ice characteristics and atmospheric water vapour. Preliminary diagnostics of TOVS retrievals indicate that new algorithms are required in the Arctic. Issues related to AVHRR include the ISCCP retrievals of cloud properties, surface temperature, surface albedo and surface solar radiation fluxes. SHEBA may also provide an opportunity to fly prototype satellite instruments on aircraft before these instruments are deployed in space, e.g. AIRS/MHS and AMMS for atmospheric water vapour or MODIS for cloud properties, atmospheric aerosols and surface characteristics.

The SHEBA modelling effort will focus on the improvement of climate simulations, making use of in-situ and remotely-sensed data sets. A long-term goal of SHEBA is to develop enhanced models of polar air-sea-ice interactions, and to integrate these models in full coupled global atmosphere-ocean climate models that can address the climate processes occurring in the Arctic and their impact on global climate. To work towards this goal, a hierarchy of models will be developed, ranging from simplified energy balance models up to detailed physical process models and three-dimensional regional models of the coupled atmosphere-ice-ocean system.

4.5.4 U.S.A. ARCTIC FIRE EXPERIMENT

An ISCCP regional experiment is currently being planned in conjunction with the SHEBA field experiment (see 4.5.3) in the Beaufort Sea during spring and summer 1997. The focus of this experiment will be to understand the physical processes occurring in the summertime Arctic cloudy boundary layer and to improve our ability to remotely sense properties of the Arctic clouds, atmosphere and underlying surface. This experiment will rely heavily on instrumented aircraft that will measure atmospheric turbulence, radiation, and cloud properties. These measurements will be supported by the surface-based observations made in conjunction with SHEBA and ARM.
5. HYDROLOGICAL CYCLE IN THE ARCTIC REGION

5.1 Introduction

The fresh water cycle in the Arctic region is an important component of the planetary water cycle. Exchanges between the atmosphere, ocean and Arctic river basins involve of the order of 10,000 km³ of fresh water every year or about 0.25 million m³/s (0.25 sverdrup).

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 interannual differences, let alone long-term climatic trends. The objective of ACSYS (in co-operation with other relevant programmes such as the WCRP Global Energy and Water Cycle Experiment) is to assemble complete and accurate enough data to determine the variability of the Arctic hydrological cycle as well as regional differences; to assess the role and contributions of the various atmospheric, oceanic and land surface processes that influence the fresh water budget, and to provide a basis for further diagnostic studies of long-term climate change. The specific objectives of the ACSYS hydrological programme are:

- Determining the elements of the fresh water cycle in the Arctic region and their time and space variability;
- Quantifying the role of atmospheric, hydrological and land surface processes in the exchanges between different elements of the hydrological cycle;
- Developing mathematical models of the hydrological cycle under specific Arctic climate conditions, suitable for inclusion in coupled climate models;
- Providing an observational basis for the assessment of possible long-term trends of the components of the fresh water balance in the Arctic region under changing climate.

The hydrological programme of ACSYS involves two major components:

1) Assemblage of a regional database for all components of the fresh water balance over the Arctic region, including the Arctic Ocean basin and the catchments of Arctic rivers;

2) Development of hydrological models of selected Arctic river basins and their validation against appropriate observational data sets.
5.2 Research-quality Arctic Hydrology Data Sets

Precipitation and run-off are the main fresh water components of the hydrological cycle in the Arctic region. ACSYS will collect available regional information on precipitation and run-off, as required for the computation of the water budget of the Arctic land, the assessment of river water discharges to the Arctic Ocean, and testing of hydrological models and coupled land-atmosphere models. The problem is that the network of precipitation and river gauging stations in the Arctic is very sparse in relation to the considerable variability of hydrological phenomena at high latitudes.

For the purpose of ACSYS, consistent data sets need to be assembled by drawing upon national archives and applying a uniform processing procedure for both real-time and historical data.

5.2.1 ACSYS SOLID PRECIPITATION CLIMATOLOGY PROJECT

Precipitation is comparable to run-off as a source of fresh water for the Arctic Ocean. Unfortunately, the spatial and temporal distributions of precipitation in the Arctic are poorly known. Large year-to-year fluctuations and lower-frequency variations are known to exist over land areas, resulting in highly variable run-off values. Factors contributing to uncertainties 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. Over the central Arctic Ocean, even the climatological seasonal cycle of precipitation is not well known, as long records at fixed observing stations simply do not exist.

The existing precipitation network in the Arctic region includes about 100 stations in northern Canada, 25 in Alaska, 20 in Greenland and more than 100 in the Arctic zone of Russia. Precipitation data obtained in Canada and in Russia are the most readily suitable for ACSYS purposes. The data for approximately 130 Russian stations situated in the Arctic watersheds, from the beginning of record to 1983/84, are being quality-checked for release by the National Snow and Ice Data Centre (NSIDC), University of Colorado, Boulder, CO, U.S.A. Daily precipitation and snow pack data from Alaska and Greenland are recorded in standard synoptic reports and cannot be easily extracted. For the period 1977-1989 these GTS data are held at the National Centre for Atmospheric Research, Boulder, Colorado, U.S.A.

Many different instruments and observation methods are used for precipitation measurements in the region. Only in Russia and in Finland is a single type of precipitation gauge used; four types of gauges are used in the U.S.A.; five in Canada; three in Norway. Consequently, difficulties are expected in reconciling these different observation sources and assembling a consistent climatological data set. Furthermore, considerable errors (up to 80%) affect solid precipitation measurements in the Arctic zone. A standard methodology to correct solid snowfall data from the operational meteorological network is being developed by the WMO/CIMO Solid Precipitation Measurement Intercomparison Project. This work has not yet been extended to the Arctic region.
ACSYS recognizes the need to develop better methods for estimating solid precipitation over the Arctic. The development of these methods should proceed in parallel with the assemblage of the Arctic precipitation data archive (Section 5.2.3). ACSYS will participate in joint efforts with other programmes to:

1. organize an international co-operative project for the intercomparison of existing solid precipitation measurements and instruments in Arctic regions, and
2. evaluate new approaches to regional estimates of solid precipitation in the Arctic.

A first task will be to establish a working group to co-ordinate internationally the documentation and intercomparison of techniques used to measure solid precipitation in the Arctic. This activity will require an interface with the WMO/CIMO Solid Precipitation Measurement Intercomparison Project. Because the main emphasis of CIMO is on the operational use of solid precipitation data in middle latitudes, the ACSYS effort will complement CIMO by providing a WCRP complement to the WMO project. The Arctic focus of ACSYS also gives this effort a geographical thrust that complements CIMO, although much of the information acquired by CIMO will clearly be useful to the ACSYS effort. The countries that have devoted the largest effort to the problems of solid precipitation measurement are Canada and Russia (Groisman et al., 1991; Groisman and Easterling, 1994). It is expected that the experiences of these two countries will provide a starting point for:

1. a more comprehensive documentation of measurement procedures used to obtain data in the existing archives, and
2. a systematic intercomparison and assessment of the various procedures.

The intercomparison should include data on snow depth (water equivalent) obtained from snow course surveys, many of which have been made on an irregular basis.

The second task of the project is a development of methodology for an assessment of areal (regional) distribution of solid precipitation in the Arctic based on station data. Regions of particular interest are those corresponding to the major river drainage basins of the Arctic. A tool for possible use in the regional extrapolations is a high-resolution limited-area atmospheric model driven laterally by analyzed fields obtained from a large-scale (or global) data assimilation scheme. It may also be possible to make effective use of the inverse approach by using catchment run-off to obtain estimates of regional precipitation. The use of such an inverse approach will require collaboration between meteorological and hydrological participants within ACSYS.

Finally, ACSYS should encourage the development and assessment of remote-sensing methods for estimation of solid precipitation (snow-water equivalent, snow depth, snow extent). Candidate tools include visible, infrared and passive microwave satellite radiometry. Visible- and infrared-derived products are currently used to produce weekly operational charts of snow extent by the U.S. National Weather Service and Environment Canada. These charts have been examined for homogeneity and compiled into a data set spanning more than twenty years.
(Robinson et al., 1993), although they provide no information on snow depth or mass. Single-channel passive microwave algorithms have been used to map snow-water equivalent (Chang et al., 1990), but the accuracy of such estimates is severely limited in heavily-vegetated (e.g. forested) areas and uncertain even in areas of sparse vegetation. Other passive microwave products are being prepared for 1988-89 at the National Snow and Ice Data Centre (Boulder, Colorado, U.S.A.) from the Special Sensor Microwave Imager (SSM/I) as part of the NASA Pathfinder project (Armstrong and Hardman, 1992). Satellite-derived fields offer sufficient advantages in spatial and temporal coverage that thorough assessments of their utility for climate studies appear to be appropriate within the framework of the ACSYS Solid Precipitation Intercomparison Project.

5.2.2 ARCTIC RIVER DISCHARGE DATA

At present, river discharge measurements are made at about 110 stations in the Arctic (80 stations in Russia, 10 in Canada and Alaska, and 20 in Scandinavian countries). River gauging methods applied in these countries generally provide an accuracy of ± 5-10%. Exceptions are gauging stations in the lower reaches of rivers running across low coastal plains, where the errors in estimating the river flow may be as large as ± 15-20% on account of the complicated hydraulic conditions resulting from the backflow of sea water and long periods of freezing. Because of such difficulties, gauging stations are not numerous. Arctic river discharge estimations are thought to be fairly reliable and consistent with each other.

The time span of discharge measurements in river basins entirely contained within the Arctic polar region varies from 10 to 40 years. For the majority of the large river basins of Russia and Canada that span several latitude zones, river flow measurements (even within the Arctic region) extend over more than 40 years. Discharge data are regularly published in the hydrological yearbooks of the countries concerned. However, historical information available in archives is generally not widely accessible in a consolidated database.

In order to provide impetus for the collection of the required hydrological information for ACSYS, it is reasonable to organize an international hydrological data exchange through a special Arctic Run-off Database (ARDB). The ARDB should contain both historical (since 1978) and current information on daily water discharges of Arctic rivers at each of the gauge-sites where hydrometric observations were made or are made. The existing historical archives of daily river run-off data at gauging stations in the Arctic would be expected to constitute the main contribution to this database. The acquisition of additional river run-off data at sites in low coastal plains of the Russian Arctic, where hydraulic conditions are complicated by backflow from the sea and long periods of freezing, would require a special methodology yet to be developed and further basic research.

The ARDB would also collect on-going daily observations on an annual basis as well as relevant auxiliary data on basin location and size, observation period, sources of information and other material, as appropriate.
The organization of the ARDB would be based on procedures developed by the Global Run-off Data Centre (GRDC) in Koblenz (Germany), operating under the auspices of the WMO. At present, the GRDC is archiving diurnal (or at least mean monthly) water discharge data from 2930 observation sites in 131 countries. Nevertheless, GRDC data holdings on Arctic rivers are currently rather poor (about 15 sites). Data at the GRDC are stored in digital format and available in the form of diskettes, tables or graphs. In the future, it is envisaged to establish direct data links between GRDC and various international organizations and national administrations, in particular the WMO Secretariat in Geneva.

It is assumed that the ARDB would be a separate project implemented within the GRDC and would use the same technical facilities. Some additional equipment may be necessary for data delivery in the formats required by climate modellers. Basic data may be submitted to the GRDC in any convenient form including CD-ROM, diskettes, magnetic tapes or even tables. The schedule for the creation of the ARDB is split in two stages:

(a) preparation of a catalogue on data availability (1994);

(b) submission of historical and current information from all Arctic river basins (1995).

During the first stage, the GRDC will develop the general structure of ARDB as well as formats for catalogue and output products. The annual submission of Arctic river run-off data to the ARDB project is planned to begin in 1996 and continue thereafter. The creation of the special ARDB facility within GRDC will be supported by Germany’s National Committee for IHP/OHP.

5.2.3 Arctic Precipitation Data

To provide the observational basis for further development in hydrological modelling of Arctic rivers, a comprehensive Arctic Precipitation Data Archive (APDA) is required. In order to constitute the APDA, ACSYS will draw upon from existing precipitation data collections.

Appendix A of the Scientific Concept of ACSYS (WCRP-72) contains a summary of snow cover data available from national agencies. Particularly noteworthy for ACSYS are the monthly (and some daily) station data held by the Canadian Climate Centre, daily and monthly precipitation data held by the Alaskan State Climatologist’s Office, and the extensive collections held at various Russian institutes (Russian data holdings include precipitation measurements made at drifting ice stations). Various countries of northern Europe also hold data sets that would be of use to ACSYS. International collections include the global precipitation data set (7300 stations) compiled by the University of East Anglia, the World Monthly Station climatology, the North American data set compiled by Groisman and Easterling (1994), and the Global Precipitation Climatology Centre (GPCC) data set assembled in Offenbach (Germany) under the auspices of WCRP. The international collections generally contain only monthly data and often do not include the lower-order stations that report only to national agencies.
The APDA should cover the period from 1978 (by analogy with ARDB) and contain daily, monthly and annual total precipitation (both liquid and solid) data from all observation stations (including drifting ice stations) within the Arctic zone. When available, data on depth and density of the snow pack, as well as water equivalent of the snow cover, are also to be incorporated.

The implementation of APDA should be co-ordinated by a leading agency or institute participating in ACSYS, with the co-operation of the countries within the geographical scope of the project.

5.3 Macroscale Atmospheric-Hydrological Modelling in the Arctic

5.3.1 Model-Derived Arctic Precipitation

Hydrological analyses for northern land areas can always draw upon existing station data. Over the Arctic Ocean, however, the only information available is derived from measurements at manned Arctic drifting stations, the number of which rarely exceeds 3 at any particular time. An alternative approach is to make an estimation of atmospheric precipitation over the Arctic basin based on the total atmospheric water vapour flux convergence from the atmospheric fields analysed by NWP centres.

In favour of this approach are the impressive advances made in numerical weather prediction and rainfall forecasts in mid-latitudes and the existence of a relatively dense aerological-sounding network surrounding the Arctic basin. Potential problems are the degraded performance of atmospheric moisture-sensing instruments at very low temperatures that could compromise the quality of atmospheric data at high latitudes, and the tendency of numerical weather prediction models to reproduce their own model-generated water vapour distribution within a few hours after updating with new observations. The implementation of this component of the ACSYS precipitation programme will require:

a) Identifying one or several NWP centres that would undertake an assessment of model-derived precipitation fields and area-averaged moisture flux divergence fields against direct measurements at stations where orographic and instrumental biases are considered to be relatively small;

b) Accumulating computed precipitation statistics that could be compared with snow course measurements and river discharge data over a period of several years, so as to overcome sampling errors associated with interannual variability.

Because data assimilation procedures (and the models themselves) undergo significant changes over the years, this task would best be implemented as part of the broader ACSYS re-analysis project described in section 4.2. ACSYS co-operation with the other re-analysis projects will also be desirable.
The use of weather prediction models as a means of obtaining precipitation over the Arctic parallels the ACSYS approach for obtaining surface heat and radiative fluxes. Indeed, the case for a special Arctic re-analysis and data assimilation effort is strengthened by the need for several data fields. The ACSYS re-analysis project would provide realistic climatologies of precipitation (e.g., snowfall) and energy fluxes with immediate applications to forcing ice/ocean model simulations and to diagnostic studies of interannual variations in the Arctic.

5.3.2 Hydrological Modelling at River-Catchment Scale

Water exchanges in the land-atmosphere system constitute an important feature of Arctic climate. A region-wide study of the hydrological cycle must rely on macroscale models for simulation and data synthesis. Unfortunately, macroscale models of the hydrological cycle have not yet been developed for Arctic conditions. Interdisciplinary co-operation with the GEWEX programme, particularly the Canadian Mackenzie GEWEX Study (MAGS) in the Mackenzie river basin, and international co-operation among Arctic countries, will be essential to progress in this domain. A scientific strategy suitable for ACSYS would include:

- Adaptation of macroscale hydrological models developed in the framework of GEWEX to Arctic (high-latitude) climate conditions;

- Development of physical (conceptual) or parametric mesoscale hydrological models for selected river catchments within the Arctic region.

Russian scientists are planning to develop a macroscale hydrological model for one of the large river basins in Siberia (Yenisei or Kolyma). It is also envisaged to adapt existing models (e.g., the Europamodel) for this purpose. A suitable scientific co-operation framework would need to be established with European, and, if possible, Japanese institutions interested in the modelling of natural processes and corresponding organizations in Canada (National Hydrology Research Centre) and Russia (State Hydrological Institute, and Arctic and Antarctic Research Institute). In the U.S.A., hydrologic modelling of northern Alaskan rivers (e.g., the Kuparuk) is a focus of the terrestrial component of the National Science Foundation's Arctic System Science programme.

It is also desirable to proceed with the adaptation of the Watflood and Hydrotel models for small watersheds in the Mackenzie basin, being undertaken in Canada as part of MAGS. Furthermore, the Russian "GGI-90" model should be adapted to some mid-size watershed (Pyasina or Nizhnyaya-Taimyra rivers) and one or two small watersheds up to 100 km² in drainage area. A detailed study of the hydrological cycle under various water regimes and the derivation of model parameters would require the organization of intensive hydrological observations in several experimental plots within these river catchments in Canada and in Russia, running for periods of one to several years.
6. ACSYS MODELLING PROGRAMME

6.1 Problems and Objectives

An ultimate goal in climate modelling is to optimize and apply fully coupled models of the atmosphere/sea-ice/ocean system; as indicated in section 6.4, this effort will be co-ordinated by the WCRP research programme on Climate Variability and Predictability (CLIVAR). Because of the complexity of such an undertaking, progress in developing an optimized fully coupled model will require development of a hierarchy of models applied to the Arctic region to understand and predict the interaction of the atmosphere, sea ice and ocean in more detail. A number of numerical modelling experiments need to be performed, using sea-ice (only) and coupled sea-ice/ocean or atmosphere/sea-ice/ocean models.

The first priority should be placed on model optimization in order to describe realistically the observed annual and interannual variability. Response studies should follow to investigate the influence of the river run-off on the oceanic circulation, the dependence of the fresh water export to the North Atlantic upon processes occurring in the Arctic Ocean, and the extent to which the high sensitivity of polar regions to CO₂ increase may be due to inadequate model description of the oceanic circulation, sea-ice and atmospheric processes, or to real positive feedbacks.

This coupled modelling approach will provide the interdisciplinary integration of the ACSYS project, since data are required of oceanic (Chapter 2), sea-ice (Chapter 3) and atmospheric (Chapter 4) variables, and river run-off (Chapter 5), from monitoring and process studies, for model forcing and verification.

6.1.1 Ocean

The dynamics of the Arctic Ocean appear to be dominated by two important processes which do not occur in other ocean basins: mixing driven by shelf-slope flows and deep water formation in the open ocean. The details of these processes are mainly local, unlike Sverdrupian (wind-driven) processes elsewhere, but the effects are basin-wide, which makes the Arctic a unique problem for ocean modellers. In particular, the Arctic mean flow is weak but with an energetic eddy activity superimposed. Neither shelf-slope processes nor open-water convection is accurately reproduced by large-scale models, as their spatial resolution usually precludes the description of small-scale features. The difficulty of observing such small-scale transient phenomena has further detered modellers from undertaking the relevant process-resolving simulations, so that little progress has been made towards suitable parameterizations.

6.1.2 Ice

On the geophysical scale, sea ice is a thin, broken layer floating on the polar oceans, that may be modified in thickness and concentration by various dynamic and thermodynamic processes. Sea ice constitutes a boundary between two much larger geophysical fluids, the atmosphere and the ocean, and influences their interaction considerably. The details and consequences of the role of sea ice in mediating between atmosphere and ocean are still not fully understood.
Due to its high albedo and insulating properties, sea ice modifies the heat, salt and momentum exchange between atmosphere and ocean. Since the sea ice is generally melted far away from the creation area, the ice drift induces a significant net buoyancy flux at the ocean surface. Because of its low salinity and negative latent heat, the motion of sea ice constitutes a very effective means to transport heat and salt. The pattern of ice motion and net freezing rate are rather sensitive to the rheological aspects applied in the constitutive law characterizing the sea ice as a solid state material (Owens and Lemke, 1990; Ip et al., 1991; Flato and Hibler, 1992).

In dynamic sea-ice models it is generally assumed that the sea ice can be treated as a two-dimensional continuum, which is characterized by five variables, i.e. the fields of snow and ice thickness, compactness and horizontal velocity. The prognostic equations are derived from conservation equations for snow and ice mass and compactness, and from a momentum balance, including internal ice stress.

A variety of large-scale sea-ice models have been applied to the Arctic and Antarctic sea-ice cover, ranging from very simple thermodynamic to highly sophisticated dynamic-thermodynamic models (Barry et al., 1993; Flato and Hibler, 1992; Häkkinen, 1993). These experiments suggest that the effects of sea-ice dynamics cannot be omitted for realistic simulations of the sea-ice cover, i.e. thickness, concentration and motion. Furthermore, the experiments show that the dynamic-thermodynamic sea-ice model is less sensitive to short-time perturbations than the thermodynamics-only model (Lemke et al., 1990). From the paleoclimate experiments it is evident that this is also true for modifications of the atmospheric and deep ocean boundary conditions. The reduced sensitivity can be explained by the specific interaction between the dynamics and the thermodynamics of the sea-ice model. In regions where the thermodynamics reduces the ice thickness, the ice gets weaker and the dynamics (under favourable conditions, i.e. convergence) can readily increase the ice thickness (by importing ice into the region). In regions where the dynamics reduces the ice cover (divergence), the thermodynamics (under favourable conditions, i.e. cooling) can easily increase the sea-ice thickness. These interactions produce a negative, i.e. stabilizing, feedback, which in previous CO₂ experiments was not included. The reduced sensitivity of a more realistic sea-ice model will obviously modify the large polar response that has been observed in the numerical experiments with coupled circulation models. In order to improve the results of the sea-ice model and to reduce computing time, modifications and fine-tuning of process parameterizations within the surface energy balance, the heat conduction and the dynamic codes seem to be necessary.

6.1.3 Atmosphere

Considered in isolation, current models of atmosphere, sea-ice and ocean sub-systems have significant deficiencies. Deficiencies in atmospheric models, particularly when applied over the Arctic Ocean, include simulation of surface temperature and pressure fields (Walsh and Crane, 1992), clouds and radiation (Curry and Ebert, 1992), precipitation, and boundary layer processes. Components of the modelled surface energy, momentum and fresh water fluxes over the Arctic Ocean are thus likely to have serious errors. An issue of particular concern for sea-ice dynamics is the absence of the Beaufort Sea Anticyclone during the cold portion of the year in many (but not all) atmospheric models (e.g. Walsh and Crane, 1992).
In summary, large-scale models use various parametric representations for processes that are not simulated explicitly. A better understanding of these sub-grid scale processes requires both detailed model simulations and observations. Process oriented work should focus on the following main topics:

- small-scale sea-ice deformation (ridge building);
- shelf processes and plume dynamics;
- lead and polynya processes (interaction of atmospheric and oceanic boundary layers);
- open-ocean convection;
- fluxes between basins;
- atmospheric processes (clouds, radiation, precipitation), and
- parameterization of the surface albedo of sea ice for all seasons.

6.2 Arctic Numerical Experimentation Programme

6.2.1 Sea-ice models

i) Large-scale formulations of sea-ice dynamics and properties

In modelling sea ice as a single component, high priority should be given to sensitivity experiments run with different sea-ice models and/or parameterizations on the same spatial grid, with the same forcing, initial values and verification data. These studies should investigate in priority:

- How many ice thickness categories need to be resolved by the model?
- Which shape of the yield curve is realistic?
- What is the optimal parameterization of ice rheology?
- Which is the optimal albedo parameterization, including the dependence on melt ponds, ice thickness, snow cover and snow temperature?
- How does the model dispose of the absorbed solar radiation, including melting on the top, bottom or side surface of the ice, heating of the ice, enlargement of brine pockets, storage in leads or in the mixed layer beneath the ice?

Preliminary experiments with different treatments of sea-ice dynamics have been performed by Ip et al. (1991, see Figure 6.1). The optimal sea-ice model should in principle be determined by inverse modelling based on all data available on Arctic sea-ice concentration, thickness and drift. The implementation of the ACSYS sea-ice programme (Chapter 3) will significantly improve the required database. Therefore, a success in the derivation of the optimal sea-ice model for climate research seems to be highly realistic in the near future.
Figure 6.1
Average monthly velocity fields for March 1992 obtained with different treatments of sea ice dynamics: (a) elliptical; (b) square; (c) Mohr-Coulomb; (d) cavitating fluid; (e) incompressible Mohr-Coulomb; (f) free flight. A velocity vector one grid cell long is approximately 0.12 ms⁻¹. From Ip et al., 1991.
ii) Small-scale models of sea-ice deformation

Sea ice in polar regions can be found with a range of thicknesses which evolve through dynamic and thermodynamic processes. The main cause of thickness diversity is the deformation of the ice-pack which forms thick ice through ridge building and thin ice within leads.

In large-scale sea-ice models, ridging is not represented explicitly but is taken into account in a parametric form through the constitutive law. In order to improve the sea-ice rheology assumed on the geophysical scale, model experiments of sea-ice deformation (ridging and rafting) should be conducted on small scales. The energy expended in deformation is largely determined by the ridging process. Thus the investigation of the energetics of pressure ridging is important for the determination of ice strength on the geophysical scale. Promising preliminary studies of this topic have been conducted recently by Hopkins et al. (1991).

6.2.2 OCEAN PROCESS MODELS

Large-scale ocean models have been improved and compared to observations under WOCE. Nevertheless, particular processes relevant for the Arctic Ocean have not been treated adequately. Studies of ocean processes do not normally require international co-ordination. However, the impetus of a large-scale programme such as ACSYS is useful to ensure that the relevant process studies are indeed undertaken, and to provide an international forum for model intercomparisons and validation against observations.

i) Shelf processes

On the Eurasian shelves, both dense (saline) and fresh waters are exchanged across the shelf edge. Under freezing conditions, off-shore winds lead to enhanced, continuous brine rejection which creates convective plumes descending across the shelf-break. Future model studies on the role of shelf-induced convection should address:

- the determination and parameterization of the entrainment rate of descending plumes,
- the abundance and statistics of convective plumes in relation to external forcing, water properties and topography,
- the integrated effect of convective plumes on the formation of oceanic intermediate and deep water masses (for large-scale model parameterizations).
There is increasing evidence that turbulent boundary layers on the continental slope influence the ocean interior through intrusions from convergent flow in the boundary layer created by inhomogeneities in the surrounding stratification (Garrett, 1989; Salmun et al., 1991). The resulting "filling-box" behaviour of the ocean interior produces an effect identical with, and of the same order of magnitude as, vertical eddy diffusion since isopycnals are forced apart or together by the convergent or divergent flow. Parameterization of this process is urgently needed for enclosed basins such as the Arctic, to achieve an accurate simulation of the stratification.

Intrusions also occur when coherent eddies spin off the topography. Modelling studies in other basins demonstrate that adequate horizontal and vertical resolution are vital if the eddies produced by general circulation models are to have the right energy level; this process appears to involve several vertical baroclinic modes. Each vertical mode has its own (horizontal) deformation radius, whose size shrinks with the order of the mode. To resolve the first few deformation radii is a severe requirement, and most eddy-resolving models (FRAM, CME, etc.) can only just resolve the first baroclinic mode. Thus eddy studies must use adequate resolution if they are to reproduce Arctic features adequately; grid spacings as small as 5 km are probably necessary in the weakly stratified basins.

Another important process which has received relatively little attention and is still poorly understood, is the production of buoyant water by mixing the river run-off with the oceanic water masses. Considerable mechanical energy is needed to break down the strong haline stratification on the shelves. Winds, tides and instabilities of strong coastal boundary currents may provide effective mixing mechanisms through nonlinear interactions (Holloway, 1986). The relative importance of these mechanisms should be investigated with small-scale models as well as basin-scale models.

ii) Open-ocean convection

Convective processes in the open ocean have not yet been adequately observed. Based largely on theoretical considerations, quantitative estimates have been made of open-ocean convection rates in penetrative plumes (Killworth, 1983; Rudels, 1989, 1990). In the future, numerical simulations will be developed with high resolution, non-hydrostatic numerical models (Jones and Marshall, 1993; Madec et al., 1991). These experiments should give insight into the probability of occurrence of convection events under various conditions, the space and time-scales of such events in relation to surface forcing, and their integrated effect on the large-scale thermohaline structure and circulation. Use could be made of observational data and process simulations to develop parameterizations suitable for large-scale models that are unlikely ever to resolve the narrow plume scales. Work on the parameterization of plume ensembles is in progress at the U.K.M.O. (Alves, private communication) and within the U.K. OCCAM project.

iii) Inter-basin connections

The resolution of ocean circulation models is equally inadequate to deal with narrow sills and gaps between ocean basins, through which considerable flow of dense water may occur. Poorly resolved sills (e.g. with one grid point representing the sill) typically allow only 1% of the maximum possible hydraulic flow, thus causing
drastic underestimation of, for example, the flux of water into the North Atlantic through the Denmark Strait. Since the representation of the thermohaline circulation depends on completing the water pathway accurately, and considering that many sills are too narrow to be resolved by ocean circulation models, work is needed on the parameterization of flows through sills.

6.2.3 Coupled sea-ice/ocean models

Sea ice influences the ocean circulation through its effects on the surface momentum and buoyancy fluxes. The buoyancy flux forcing of the ocean seems to be the dominating part of the interaction, since the sea-ice motion creates pronounced inhomogeneities in the spatial pattern of net freezing or melting. This spatial distribution of net salt/fresh water fluxes is rather sensitive to the rheology (i.e. dynamical parameters) and transport simulated by the models. Furthermore, 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.

Several experiments with coupled sea-ice/ocean models have already been conducted for the Arctic Ocean (Hibler and Bryan, 1987; Semtner, 1987; Aukrust et al., 1992). These experiments have shown a significant improvement of the simulation of the seasonal variation of the sea-ice edge in the North Atlantic sector (see Figure 6.2). For a realistic simulation of the present circulation and structure of the Arctic Ocean, improvements are required in both the sea-ice and the ocean parts of these models. The model improvement includes the optimization of several processes which drive the circulation of the Arctic Ocean, i.e. the formation of dense water on the shelves during off-shore winds, the advection of ice produced on the shelves and exported from the Arctic basin, and the drainage of dense shelf water into the deep Eurasian basin affecting the deep water properties of the Greenland Sea via exchanges through the Fram Strait. Perhaps the greatest deficiency of present large-scale models is the use of relatively coarse resolutions and associated large viscosities. The enhanced computer power in the near future should lead to a dramatic improvement in the realism of the model results.

The sea-ice/ocean modelling programme should aim to reproduce the simulation of the observed mean state and the natural variability of the Arctic Ocean and the surrounding seas. Sensitivity experiments are required to investigate the dependence of model results on certain process parameterizations (sea-ice rheology, convection, etc.).

Furthermore, sensitivity studies are required to assess the influence of changes in river run-off on the oceanic structure, vertical heat fluxes and sea-ice thickness distribution and to investigate the dependence of the fresh water export into the North Atlantic on processes in the Arctic basin (sea-ice dynamics) and on the shelves, as well as changes in boundary/forcing conditions.

Higher resolution (nested) models are required to investigate the interaction of sea ice and ocean in the Greenland Sea and to examine the dependence of the exchange with the North Atlantic and the Arctic basin on deep water formation.
Figure 6.2  Simulated and observed 50% concentration limits for both the coupled ice-ocean model and the ice-only model. From Hibler and Bryan, 1987.
6.2.4 Small- and Mesoscale Coupled Models

i) Sea-ice/atmosphere models

Modelling difficulties are compounded considerably by coupling two or more sub-systems. The coupling of imperfect models (e.g. atmosphere and sea ice) invariably results in serious model drift. Problems that are relatively minor when modelling an individual system may be amplified in a coupled model with nonlinear feedbacks. For example, improper simulation of cloud properties in an atmospheric model is a problem, but this problem by no means dominates the solution, because the fixed lower boundary conditions (sea surface temperature) keep the solution stable. However in a coupled atmosphere/sea-ice model, incorrect clouds will dominate the solution because of the sensitivity of the surface energy balance and thus sea-ice thickness to clouds. An additional example of an enhanced difficulty that arises in coupled models is illustrated for the case of surface albedo. Sea-ice models frequently use a summertime melting ice albedo as high as 0.64, which substantially exceeds the observed values that are typically 0.50 (Robinson et al., 1992). Because of model "tuning", reasonable ice characteristics can be determined using an incorrect surface albedo. However, use of an incorrect summertime surface albedo would have profound effects in a coupled sea-ice/atmosphere model, completely altering the way in which clouds affect the summertime radiation balance. Changes to the radiation balance are merely the first-order effects; higher order effects would be expected as the modified atmospheric radiation balance modifies the atmospheric boundary layer structure and cloud characteristics, which further modify the radiation balance and affect the sea-ice characteristics. This is but one example of the increased sensitivity of a coupled system to certain model parameters; it is clear that particular attention must be paid to the interface between two sub-models and to designing parameterizations that will allow the appropriate feedbacks to occur between the two sub-systems.

To address the issue of coupling atmosphere with sea-ice models, two approaches have been used. One-dimensional models of the coupled atmosphere/sea-ice/upper ocean system have been utilized by Curry and Ebert (1992) and Moritz et al. (1992) to address the thermodynamic coupling between the atmosphere, sea ice, and upper ocean. Walsh et al. (1993) have begun using a high-resolution limited-area atmospheric mesoscale model coupled to a thermodynamic-dynamic sea-ice model. The rationale for constructing a high-resolution regional model of the Arctic atmosphere and sea ice is that the treatment of orography, the cloudy boundary layer, and sea-ice dynamics is limited in global climate models by both vertical and horizontal model resolution. A regional model of the Arctic climate, when driven by analyzed lateral boundary conditions, has the additional advantage particularly during model development of minimizing the impact of model biases or errors from sub-polar latitudes. Utilization of a limited area model of the coupled atmosphere/sea-ice system will allow exploration of coupled model sensitivities and feedbacks and development of suitable parameterizations for global coupled models.
ii) Lead and polynya processes

Strong interactions between the cold atmosphere and the relatively warm ocean take place in leads and polynyas. The fluxes of heat and moisture into the atmosphere and the production of dense water due to the freezing of ice are the most important parts of this interaction. The dependence of these processes on atmospheric and oceanic conditions and the sea-ice concentration should be determined with coupled atmosphere-ocean boundary layer models, including radiation and clouds (Ebert and Curry, 1993; Maykut, 1986; Martin and Cavalieri, 1989). Since most of the ocean-atmosphere exchange in the Arctic takes place through leads and polynyas, the integral effect of these processes on the structure and circulation of the Arctic Ocean needs also to be investigated.

6.3 Data Requirements for Arctic Model Initialization, Forcing and Validation

A high priority objective of ACSYS is the development of a standard forcing and verification data set for the atmosphere/sea-ice/ocean system covering a period of at least 5 to 10 years. There are relatively long data sets of Arctic sea-ice velocities (International Arctic Buoy Programme) and concentrations (passive microwave remote sensing) which can be used for sea-ice model verification. An optimization of the various algorithms used for estimating the ice concentration from satellite imagery still seems to be necessary before the data can be applied for model tuning.

The most important sea-ice variable for discriminating between different dynamical parameterizations is ice thickness. Unfortunately only very limited thickness data are available (McLaren, 1989; Bourke and McLaren, 1992; McLaren et al., 1992; Wadhams, 1992). Enhancing this data set is a first priority for model optimization. The release of additional ice thickness data from submarine cruises in the Arctic would also be very beneficial. An optimal data set would be the monthly evolution of the thickness distribution on a 100 km x 100 km grid. A minimum data set are the seasonal values of the mean ice thickness at a limited number of stations (10 to 20) such that the geographical distribution is well captured. The sea-ice data discussed here can be used for initialization and verification of dynamic-thermodynamic sea-ice models. An observational programme to obtain these data is presented in Chapter 3.

For the initialization and verification of coupled sea-ice/ocean models a major expansion of the Arctic Ocean database (structure and circulation) is equally needed (see Chapter 2). For the initialization, temperature and salinity data are required on a grid of approximately 100 km x 100 km on the standard Levitus-levels (preferably improved to 10 m in the upper 100 m). These should be provided at least seasonally (4 values per annual cycle) and preferably monthly. It is recognized, that deeper levels are unlikely to be available seasonally. In this case it is important that the data are vertically stable, especially at junctions vertically between seasonal and annual values. These data can also be used for model verification. In addition, velocity time series are required. Remotely sensed data (surface temperature and surface elevation) are also very useful, as well as tracer data which contain information on the flow field.

At model boundaries, ocean temperatures, salinities and velocities are required. Inflow values are absolutely necessary. This includes also river run-off. Outflow values are desirable.
In most investigations, the forcing of sea-ice/ocean models has been inferred from atmospheric climatologies. Recently, the daily output of numerical weather prediction models has been successfully used to drive sea-ice models (Serreze et al., 1990; Riedlinger and Preller, 1991; Preller and Posey, 1989; Stössel, 1992). These data include winds, air temperature and humidity. Because of model deficiencies, solar radiation, clouds and precipitation are still taken from climatologies. The database for these climatologies is in the Arctic still rather sparse. This situation calls for an enhancement of the observational data, but also for an improvement of the model performance concerning cloud cover in polar regions.

NWP analyses provide the most coherent forcing data set available, although there are still some problems in polar regions due to the low density of observing stations. Since NWP models prescribe a 100% ice cover poleward of the climatological ice edge, a re-analysis using the observed sea-ice concentration will actually be needed to produce a truly realistic boundary forcing data set (see section 4.2).

6.4 Global Climate Interactions with the Arctic

Two sets of problems concerning the role of the Arctic in the climate system can be addressed with coupled atmosphere-ocean circulation models: the influence of the Arctic on natural climate variations and the impact on the response of the climate system to global warming. These model investigations will be promoted and co-ordinated by the WCRP research programme on Climate Variability and Predictability (CLIVAR). The contribution of ACSYS to these activities should be to ensure that polar processes are properly represented in the coupled model. This includes the delivery of an optimized dynamic-thermodynamic sea-ice model and accurate ocean physics, tailored for the Arctic area.

Global warming experiments with global atmosphere-ocean general circulation models have shown a magnified response in polar regions. Whether this is due to inadequacies in the sea-ice component or to a real phenomenon due to positive feedbacks special to the Arctic is not clear yet. Coupled circulation models so far have used thermodynamic sea-ice formulations and, if at all, a simplified advection scheme. Presently dynamic-thermodynamic models (e.g. the cavitating fluid model of Flato and Hibler, 1992, or various versions of the original Hibler viscous-plastic model) are being implemented at the Max-Planck Institute of Meteorology in Hamburg, Germany, at the United Kingdom Meteorological Office, and NCAR, U.S.A. The use of even more sophisticated sea-ice schemes could provide a better evaluation of the role of the Arctic sea-ice in the climate system.

Investigations concerning the role of the Arctic on the natural climate variability should also realistically model the fresh water budget of the Arctic basin and the fresh water export into the North Atlantic in view of its likely influence on the global conveyor belt circulation.
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