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Arctic Climate Change

The ACSYS Decade and Beyond

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Dedication

Dr. Victor Savtchenko (22.07.1937–15.08.2008)

This book is dedicated to the memory of Victor (Gavrilovitch) Savtchenko, a scientist and coordinator of international climate science, who, in turn, dedicated a significant part of his life, knowledge and energy towards formulating the founding ideas and setting the stage for two major research projects of the World Climate Research Programme (WCRP), namely the Arctic Climate System Study (ACSYS) and the Climate and Cryosphere (CliC) Project.

Victor was born on 22 July 1937 in Poltava in the former Soviet Union. Now this city and the region surrounding it is a part of Ukraine. In 1969 Victor completed a postgraduate course of the Leningrad Hydrometeorological Institute (at present the Russian State Hydrometeorological University), and joined the Arctic and Antarctic Research Institute (AARI) in Saint Petersburg. In 1970 in his successfully defended dissertation for the academic degree of the Candidate of Science, he elegantly used sophisticated mathematical apparatus for a study of internal waves in fluids. This project solidified the characteristic style of his research that combined an accurate mathematical description of the simplified but essential features of complex phenomena with a deep and all-embracing understanding of their overarching complexity. Victor has kept this style of scientific investigation for his entire life and it proved to be particularly fruitful in theoretical studies of ocean and atmosphere interactions. Because of his affiliation with AARI, all scientific work of Victor had a strong focus on the role of the Arctic and Southern Oceans in climate variability and change.

For more than a decade Victor was the head of the Modelling Laboratory in the AARI's Department of Ocean – Atmosphere Interactions. He participated in several field expeditions to the Arctic and Antarctic. Main results of his studies are summarised in the Doctor of Science thesis, defended in 1989, in a well-known monograph 'Impact of heat fluxes from the ocean on oscillations of climate in high latitudes' (co-authored with close colleague Andrey Nagurny), and in over 60 research articles in leading scientific journals.

In 1978, Victor started to work for the World Meteorological Organization in Geneva, serving as senior scientific officer of the Global Atmospheric Research Programme, until 1981, and, in 1989–1999, as senior scientific officer of WCRP. His scientific insight and managerial support were decisive in the establishment of the WCRP Arctic Climate System Study (ACSYS). In the 1990s, while ACSYS was still underway, Victor started to work on a new global project to address the role of frozen water in the climate system. He was the one who recalled the now famous term ‘cryosphere’ and insisted on including it in the title of the new project, the Climate and Cryosphere (CliC).

Victor was a kind, sensitive, and modest person. Even for those who knew him well, it may come as a surprise that this very serious scientist and seasoned program manager had a charming hobby of collecting toy owls. Victor Savtchenko passed away on 15 August 2008 in Divonne-Les-Bains, France, at the age of 71. We are very grateful to Victor for his devoted service to climate and polar science and for his very significant contributions to founding ACSYS and CliC, two successful projects of the WCRP.

Geneva Vladimir Ryabinin

Foreword

The Arctic is a region of rapid changes caused by global warming, resulting in rising atmospheric and oceanic temperatures, and declining sea ice cover and thickness, with significant impacts on ecosystems and human settlements. Therefore, a better understanding of climate processes in the Arctic is fundamental to assess major impacts of these changes in the Arctic and within the entire Earth system due to a variety of feedback processes.

The ACSYS project was fundamental in raising the awareness of the role of the Arctic in the global climate system. It has greatly advanced our understanding of the processes acting in the Arctic due to development of improved observing systems, using both in situ and remote sensing techniques, and numerical models describing the various components of the climate system and their interaction. ACSYS activated nearly 250 scientists from 19 countries for its final conference, with many more researchers, who participated in the respective field work and modelling activities.

ACSYS was designed as a ten-year project, which started in 1994 and finished at the end of 2003. It has provided a valuable legacy of data sets, model components and understanding, which is used as a basis for ongoing research within the framework of the bi-polar Climate and Cryosphere (CliC) project of the WCRP, as well as for many projects during the International Polar Year 2007–2009. This book represents an account of this legacy and its relevance for current Arctic climate research.

We express our thanks to the impressive number of scientists that have contributed to the success of the ACSYS project. This book could not have been realised without the huge support of the authors who submitted their chapters for this volume. We further acknowledge the following scientists for their help in reviewing the individual chapters of this book: Sabine Attinger (Helmholtz Centre for Environmental Research, Leipzig, Germany), Jens Hesselbjerg Christensen (Danish Climate Centre, Copenhagen, Denmark), Klaus Dethloff (Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany), Wolfgang Dierking (Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany), Peter S. Guest (Naval Postgraduate School, Monterey, USA), Stefan Hagemann (Max Planck Institute for Meteorology, Hamburg, Germany), Peter M. Haugan (University of Bergen, Norway), Daniela Jacob (Max Planck Institute for Meteorology, Hamburg,

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Chapter 1
The Origins of ACSYS

Victor Savtchenko†

Abstract This chapter briefly reviews, in a historical perspective, the science background for establishing an internationally coordinated Arctic Climate System Study (ACSYS) under the auspices of the World Climate Research Programme (WCRP).

Keywords Arctic • ACSYS • Climate • WCRP • Sea ice • Ocean • Polar • Snow • Atmosphere • Ocean

The First Implementation Plan (FIP) of the WCRP was published in November 1985 (WCRP 1985). Based on the Scientific Plan (WCRP 1984), the FIP proposed activities needed to achieve the goals of the Programme and to efficiently develop the work among the WCRP projects according to their areas of expertise.

The scientific objectives (or 'streams') of the Programme were defined as follows:

- Establishing the physical basis of long-range weather prediction
- Understanding the predictable aspects of global climate variations over periods of several months to several years
- Assessing the response of climate to natural or man-made influences over periods of several decades

The first and second objectives were considered to be the necessary 'stepping stones' towards achieving the third objective. The WCRP activities were organized through six sub-programmes, namely:

- Atmospheric Climate Prediction Research (ACP)
- Coupled Atmosphere-Ocean Boundary Layer Research (CAOB)
- Cryosphere Research

V. Savtchenko
†Deceased 15 August 2008

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- Tropical Ocean and Global Atmosphere (TOGA) project
- World Ocean Circulation Experiment (WOCE)
- Climate Sensitivity Assessment (CSA)

The ACP and the CAOB research activities constituted the basis for achieving the first objective of the WCRP. The Cryosphere Research and TOGA projects were designed to achieve the second objective. The WOCE and the CSA projects, together with the activities planned for the first and second ‘streams’, constituted elements of a scientific strategy for the achievement of the third objective of the WCRP.

The Cryosphere Research sub-programme was a forefather of both the ACSYS and the WCRP Climate and Cryosphere (CliC) projects. The sub-programme was focused on modelling the large-scale interaction between the atmosphere and sea ice. It concentrated on the study of seasonal and interannual variations of sea ice and on the determination of oceanic and atmospheric forcings which control them, with a view to incorporate the scientific advances in the knowledge of sea-ice processes into fully interactive atmosphere–ocean–ice models required for the assessment of long-term climate variations and impacts. The term ‘cryosphere’ was treated as the combination of the sea-ice cover of the polar oceans and the ice sheets over Greenland and the Antarctic continent. The consideration of snow was included in the study of hydrological processes in relation to the development of atmospheric climate models, i.e. in the Atmospheric Climate Prediction Research sub-programme (the first ‘stream’ of the WCRP).

The World Meteorological Organization (WMO)/International Council of Scientific Unions (ICSU) Joint Scientific Committee (JSC) for the WCRP recognized, at an early stage, the significant climate impact of sea ice as it affects the interaction between the ocean and the atmosphere as well as the surface albedo. The JSC-IV (1983) pointed out that since the extent of sea ice shows noticeable interannual as well as seasonal variations, sea-ice processes could be important for all three ‘streams’ of climate research. The observed extent of sea ice is, in particular, an important boundary condition to be specified for long-range weather prediction. The JSC-IV agreed that satellite observations of sea ice should be one key component of a comprehensive strategy for monitoring climate and the factors controlling its long-term variations.

It was underlined in the FIP that sea ice played a significant role in the fluctuations of the global ocean–atmosphere system on seasonal and longer time scales and constituted, therefore, an important interactive component of the climate system. It was stressed that the major obstacle, which hampered the development of interactive global atmosphere–ocean–ice models, was the lack of adequate observations to describe or to infer:

- Forcing fields, such as the ocean surface current and heat flux; the surface wind and air temperature and the incoming radiation flux at the surface
- Sea-ice state variables, such as the ice concentration, velocity, thickness and internal stress
- Physical processes, which determine mechanical properties of natural sea-ice fields

Existing or planned multi-national programmes (such as the Marginal Ice Zone Experiment and the Greenland Sea Project) addressed the above-indicated problems only partially. Information about the extent, concentration and age of sea ice on the global scale was expected to be provided by planned satellite missions with passive and/or active microwave sensors. Nevertheless, it was absolutely clear that substantial augmentation of existing programmes was needed to meet the observational requirements for large-scale sea-ice modelling in the Arctic Ocean basin and around the Antarctic continent. Therefore, the JSC-VI (1985) agreed on establishing an international research programme on sea ice and climate as an integral part of WCRP. A JSC Working Group on Sea Ice and Climate (WGSI) was constituted to design a strategy for global sea-ice research and to advice on a scientific strategy for the development of the fully interactive atmosphere–ocean–ice models. Prof. N. Untersteiner (Polar Science Centre, University of Washington, Seattle, USA) chaired the Group.

The WGSI suggested that ocean circulation studies in the ice-covered Southern Ocean be brought into the framework of the WOCE, while a specific Arctic Basin project might eventually be needed to improve predictions of climatic changes of the air–sea ice system. These recommendations of the Group were endorsed by the JSC-VII (1986). In 1988, the WGSI completed its assessment of sea-ice science issues relevant to the climate problem and put forward a programme of proposed activities that, it considered, should be carried out in the WCRP framework (WCP-18). The JSC-X (1989) expressed its agreement with the assessment done by the Group of the state of affairs in international polar sciences and outstanding priorities from the point of view of climate research. The Committee agreed that WCRP efforts should be focused on promoting the implementation of the following specific polar climate research projects identified by the Group:

- Polar radiation reference stations (to acquire standard downward shortwave and longwave radiation flux data)
- Coordinated global sea-ice modelling studies and intercomparison of results
- Arctic and Antarctic Ice-Thickness Monitoring Projects (based on upward-looking sonar measurements from under-ice moorings)
- Arctic Ice-Ocean Station Network (to acquire long-term series of systematic hydrographic, ocean current and sea-ice observations from a small number of sites in the Arctic basin)
- Arctic and Antarctic Drifting Ocean Data Buoys Programmes

The Sea-Ice Numerical Experimentation Group (SINEG) was established by the JSC-X in order to promote (by means of coordinated numerical experiments) the development of sea-ice models and coupled atmosphere–ice–ocean models for climate research, and the assessment of the sensitivity of models to internal parameterizations and external forcing fields. Prof. P. Lemke (Alfred Wegener Institute for Polar and Marine Research (AWI), Bremerhaven, Germany) was appointed the convener of the SINEG.

The fourth session of the WGSI held in November 1989 (WCP-41) reviewed various aspects of the role of sea ice in the climate system, corresponding WCRP sea-ice research priorities, and the status of implementation of WCRP sea-ice observation and modelling projects. The Group noted that polar oceanic processes play a dominant role in the production of the deep and bottom water masses of the world ocean and therefore in the formation of the global thermohaline circulation, which is responsible for planetary-scale redistribution of heat and freshwater. The Group further noted that studies of the Antarctic deepwater formation and corresponding sea-ice processes were part of the WOCE but that international large-scale Arctic Ocean circulation studies had not been undertaken yet. In order to lay the foundation for an Arctic Ocean monitoring programme and to begin collection of long-term series of hydrographic and tracer data in the Arctic basin, the Group agreed to promote international cooperation for the implementation of deep ocean measurements of temperature, salinity, currents and tracer concentrations by exploiting opportunities afforded by sea-ice studies in the Arctic.

To reflect the new research priorities, the Group was reconstituted under its previous name – Working Group on Sea Ice and Climate – as a joint body of the JSC and the Committee on Climatic Changes and the Ocean (CCCO) formed by the Intergovernmental Oceanographic Commission (IOC)/Scientific Committee on Oceanic Research (SCOR). The Working Group on Sea Ice and Climate was charged with the tasks of promoting the implementation of specific WCRP sea-ice research projects and developing appropriate activities for improving the understanding of the freshwater balance of polar regions and its relationship to deepwater formation in the ocean (JSC-XI 1990). Prof. E. Augstein (AWI, Bremerhaven, Germany) chaired the Group.

The International Conference on the Role of the Polar Regions in Global Change was held in June 1990 at the University of Alaska, Fairbanks, USA. Many papers presented at the conference emphasized the potentially significant and complex influence of the Arctic Ocean sea-ice processes on the dynamics of the global climate system, in particular the relation between circulation, salinity structure and freshwater budget of the Arctic Ocean and the North Atlantic deepwater production (International Conference 1991).

It was evident that the role of the Arctic Ocean processes in the maintenance and change of the global climate system would be much better understood if observational data required for refining parameterizations of physical processes and for validation of coupled atmosphere–ice–ocean models could be collected in the Arctic and made available for the international climate research community. It was also evident that consideration of the impact of the Arctic Ocean on the climate represented a gap in WCRP activities. At the same time, there was no doubt that the WCRP was the most adequate international body to address the appropriate Arctic topics. Informal discussions on the subject held by the chairman of the WGSI with some leading climate scientists showed that a special Arctic component of WCRP with strong hydrographic, sea-ice and atmospheric elements was highly desirable from a scientific point of view and feasible, taking into account the changes that happened in the international political climate. As a first step towards outlining an Arctic experiment within the WCRP framework, an ad hoc workshop was organized in Mainz, Germany, in December 1990 to prepare an appropriate proposal for consideration by the JSC.

The workshop developed the ACSYS proposal (Position Paper 1991), which was considered by the JSC-XII (1991). The main scientific goals of the ACSYS were defined as follows:

- To provide a scientific basis for a realistic representation of the Arctic region in coupled global climate models
- To suggest and possibly implement an effective climate monitoring scheme in the Arctic
- To develop regional coupled ocean–ice models and to carry out sensitivity studies and climate change computations for specified atmospheric and lateral boundary conditions
- To improve the treatment of Arctic clouds and radiation transfer in atmospheric and coupled climate models

Responding to the ideas in the proposal, the JSC-XII agreed to consider a coordinated research project to study the large-scale dynamics of the Arctic Ocean and sea ice, and the energy and freshwater budgets of the Arctic basin and adjacent regions. The Committee believed that a comprehensive statement of the scientific concept of the proposed Arctic Climate System Study should be prepared, which could convince the scientific community to participate and science funding agencies to support corresponding activities. For this purpose, the Committee established an ad hoc Study Group to consider the scientific goals and conditions for implementation of ACSYS, including logistic and organizational aspects. Prof. E. Augstein was appointed the chairman of the Study Group. The Study Group prepared the ACSYS concept document (WCRP-72) which was approved by the fifth session of the WGSI (WCRP-65). It was proposed that ACSYS comprises the following four main elements:

- Study of the structure and circulation of the Arctic Ocean
- Observation and modelling of sea ice
- Air–sea interaction
- Freshwater cycle in the Arctic region

The JSC-XIII (1992) welcomed the comprehensive approach developed by the Study Group for a multi-disciplinary study of the Arctic climate system to investigate the large-scale dynamics of the Arctic Ocean and sea ice, and the energy and freshwater budgets of the Arctic basin and adjacent regions. The Committee decided to undertake the ACSYS as a new project of the WCRP. To lead the implementation of the project, the JSC established an ACSYS Scientific Steering Group (SSG). Consequently, the Committee disbanded the WGSI. It was agreed that the ACSYS SSG should also assume the responsibility for oversight of sea-ice research and monitoring projects previously taken by the WGSI. Prof. K. Aagaard (NOAA Pacific Marine Environmental Laboratory, USA) was appointed the chair of the ACSYS SSG. The JSC-XIII further agreed that the SINEG would have an important role in supporting the ACSYS modelling efforts and should continue with appropriately modified terms of reference. The Committee emphasized that, in proposing the establishment of ACSYS, the importance of Antarctic science was not being overlooked or considered a lower scientific priority. The reason for focusing on an Arctic study in the WCRP was to take advantage of the then available and planned facilities in the Arctic basin. The JSC-XIII requested the ACSYS SSG to keep Antarctic science in mind and, when appropriate, to apprise the Committee of the possible need for WCRP initiatives in the Antarctic.[1]

The JSC-XIII underlined that an urgent task for the ACSYS SSG was the preparation of an internationally agreed implementation plan for the experiment. Responding to this request and building on the Scientific Concept of ACSYS, the SSG prepared the Initial Implementation Plan (IIP) for the ACSYS (WCRP-85). The main observational phase of the experiment began formally on 1 January 1994 and has been scheduled for a 10-year period, i.e. until 31 December 2003. The scientific goal of ACSYS was to ascertain the role of the Arctic in global climate. To attain this goal, ACSYS sought to develop and coordinate national and international Arctic science activities aimed at three main objectives:

- Understanding the interaction 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 IIP outlined the following five main areas of the ACSYS activity:

- Arctic Ocean circulation programme
- Arctic sea-ice programme
- Arctic atmosphere programme
- Study of the hydrology of the Arctic region
- Modelling of basin-wide ocean-ice processes and ocean–ice–atmosphere interaction

The first session of the ACSYS SSG (SSG-I 1993) reviewed the activities and terms of reference of the SINEG. In view of the orientation of SINEG's efforts towards coupled sea-ice/ocean modelling, both in the Arctic and the Antarctic, the SSG agreed that the SINEG should be renamed as the ACSYS Sea-Ice/Ocean Modelling Panel (SIOM) with appropriately modified terms of reference. Prof. P. Lemke was nominated to serve as the convener of the Panel. The SIOM Panel was converted into the ACSYS Numerical Experimentation Group in 1998, with expanded terms of reference. In 1999, Prof. P. Lemke stepped down as chair of the ACSYS NEG, and Dr. Gregory M. Flato from the Canadian Centre for Climate Modelling and Analysis became the new chair.

[1] The ACSYS SSG followed this advice and developed (in the late 1990s) a proposal focused on global cryospheric studies within the WCRP. The proposal was approved by the JSC as a core WCRP CliC project.

The ACSYS Conference on the Dynamics of the Arctic Climate System (WCRP-94) in Gothenburg, Sweden, in November 1994 reviewed the ACSYS IIP. The Conference fully concurred on the importance of the ACSYS goal and found ACSYS to be a well-focused and technically feasible project. The polar science community and science funding agencies of countries active in Arctic climate research and global change investigations gave strong support to the ACSYS. A number of additions and refinements to the IIP were proposed.

Subsequently, the ACSYS SSG reviewed and evolved the IIP, taking into account national contribution to the project and logistic coordination with other international programmes. The end product, which is regularly updated, is available on the ACSYS Web site (http://acsys.npolar.no) under the title 'ACSYS Implementation and Achievements'.

In a paper published in 1994 when ACSYS was launched as the only WCRP regional experiment, K. Aagaard and E. Carmack, discussing effects of the Arctic Ocean on global climate, put the following two questions:

- Is the Arctic Ocean, in fact, an important cog in the global climate machinery?
- Can realistic changes in the density structure and circulation of the Arctic Ocean effect significant changes on a much larger spatial scale?

They foresaw that getting answers to the fundamental questions would require a decade or two.

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Part I
Observations

Chapter 2
Advances in Arctic Atmospheric Research

James E. Overland and Mark C. Serreze

Abstract The previous decade and a half saw major advances in understanding of the Arctic atmosphere and the ability to project future climate states based on reanalysis datasets, field studies, and climate models. Limitations continue to be the lack of direct observations of the Arctic troposphere. The balance of evidence now argues for an anthropogenic component to Arctic change. Today, we see positive Arctic-wide temperature trends in all seasons with an Arctic amplification relative to lower latitude changes, but with strong regional modulations from natural variability. These include a positive index of the Arctic Oscillation (AO) in the early 1990s, a record negative phase of the AO during the winter of 2009/2010, and increased prominence of an Arctic Dipole (AD) climate pattern. The negative AO period showed linkages between Arctic and subarctic weather. Despite deficiencies in climate models used for the International Panel of Climate Change (IPCC), all models project increased temperatures and sea ice loss by mid-century, amplified through Arctic feedback processes.

Keywords Arctic atmosphere • Energy balance • Climate change • Arctic Oscillation

2.1 Introduction

The previous decade and a half (1995–2010) was an active period for Arctic research based on retrospective analyses, field studies, and the development and application of improved coupled atmosphere–sea ice–ocean global climate models for change

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detection and projections. The past 15 years also saw major shifts in atmospheric climate patterns, with strengthening of the polar vortex between the 1980s and early 1990s linked to a positive trend in the index of the Arctic Oscillation (AO) (Serreze et al. 2000; Overland et al. 2004a), a record negative phase of the AO during the winter of 2009/2010, and increased prominence of the Arctic Dipole climate pattern (Wu et al. 2006). Along with increased recognition of the role of atmospheric variability and change in driving extreme seasonal minima in sea ice extent, such as the record September minimum observed in 2007 (Stroeve et al. 2008), there was increased awareness of impacts of sea ice loss on emerging Arctic amplification of air temperature changes and that sea ice loss may be affecting patterns of atmospheric circulation with potential impacts beyond the Arctic (Serreze et al. 2008; Francis et al. 2009; Budikova 2009; Screen and Simmonds 2010; Kumar et al. 2010; Deser et al. 2010; Overland and Wang 2010; Petoukhov and Semenov 2010). In this chapter, we discuss several trends in climate research from the ACSYS period to the present, rather than claiming to be comprehensive in all areas of Arctic meteorology. We refer readers to the primary journal sources for in-depth review.

One fascinating story of the last two decades was the rise and fall of the Arctic Oscillation as the key organizing principle for understanding variability in Arctic atmospheric circulation (Kerr 1999); the AO was defined as the first principal component of variability in monthly winter sea level pressure fields with the positive phase associated with anomalously low Arctic surface pressures and a strong cyclonic polar vortex. The AO turned from a predominantly negative phase in the 1970s to a strong positive phase in the first half of the 1990s, with some authors considering it to be a manifestation of global warming (Palmer 1999; Feldstein 2002), but since the late 1990s, the AO index has been variable, and it has often been replaced by another climate pattern, the Arctic Dipole (AD). Winter 2009–2010 had an extreme negative phase of the AO associated with a meridional flow pattern; evidence arose of linkages between Arctic climate and midlatitude weather (Cattiaux et al. 2010; Seager et al. 2010; Overland et al. 2011). A shortcoming of the AO framework is that it represents a single geographic center of variability, while Arctic circulation variability often shows more than one center of action at a given time.

From 1982 to1999, the Arctic Ocean became cloudier and warmed in spring, but cooled and become less cloudy in winter. By contrast, since the dawn of the new millennium, autumn has become the season with the strongest positive temperature anomalies. This is in large part a result of a retreat of summer sea ice extent, resulting in increased heat uptake in the ocean mixed layer in newly sea-ice-free ocean areas; this heat is then transferred back to the atmosphere in autumn (Serreze et al. 2008; Screen and Simmonds 2010; Deser et al. 2010). This process of Arctic amplification has long been predicted by global climate models. This warming, while strongest at the surface, has impacted atmospheric temperatures and geopotential heights well up into the troposphere (Overland and Wang 2010).

A yearlong surface energy budget and boundary-layer climate assessment over the sea ice of the western Arctic was established using observed values during the SHEBA (Surface Heat Budget of the Arctic) experiment from October 1997 to October 1998. Many of the SHEBA results were summarized in a special issue of *Journal of Geophysical Research*.

Reanalysis fields of atmospheric variables became standard tools of climate research. Reanalysis represents blending of a short-term model forecast with observations through a data assimilation process. Examples are tropospheric pressure heights and winds. Modeled or forecast variables, typically those at the surface (e.g., precipitation, radiation, and turbulent fluxes), are not directly influenced by observations of that variable. Research through previous decade focused primarily on the Reanalysis of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the European Center for Medium-Range Weather Forecasts (ECMWF). A shortcoming of these reanalysis products is the lack of direct tropospheric observations over the Arctic. Next-generation reanalyses include ERA-Interim and MERRA, the Modern Era Retrospective-Analysis for Research and Applications, a product of the National Aeronautics and Space Administration.

A major question as recently as 5 years ago was whether the recent Arctic warming was unique in the instrumental record and whether such a trend will continue. Arctic temperature anomalies in the 1930s and 1940s were as positive as those in the 1990s, and the events of the early 1990s are associated with a positive persistence of the AO, considered a manifestation of natural variability. Attribution of Arctic change is difficult because one is assessing changes relative to large natural variability in an energetic atmospheric circulation. In the last 5 years, however, there are both observational and model evidence for systematic changes in the Arctic. An observational surprise was the 39% reduction in sea ice extent in summer 2007 relative to climatology, with sea ice extents for 2007 through 2010 all below the two standard deviation level based on a 1979–2000 reference level. Other surprises include breakdown of the strong polar vortex (positive AO) in recent years replaced by more meridional (north-south) flow as indicated by an AD climate pattern in spring and summer, and the record negative phase of the AO and NAO value (a regional manifestation of the AO) in winter 20009–2010. Persistent trends in many Arctic variables, including sea ice extent, the timing of spring snow melt, increased shrubbiness in tundra regions, and ocean temperatures, as well as Arctic-wide increases in air temperatures, can no longer be associated only with dominant climate variability patterns. Arctic-wide warming is occurring twice as fast as most other regions on the planet (Fig. 2.1). The next sections discuss these results in more depth.

2.2 Energy Fluxes

Differential solar heating drives an equator to pole gradient in atmospheric temperature and hence pressure heights, driving the general circulation of the atmosphere which transports heat poleward. Differential heating also results in a poleward oceanic heat transport. The Arctic can be viewed as the Northern Hemisphere heat sink as part of the planetary heat engine. The large-scale energy budget of the Arctic was reviewed by Serreze et al. (2007), and the surface energy budget observed at SHEBA was described by Persson et al. (2002). The January

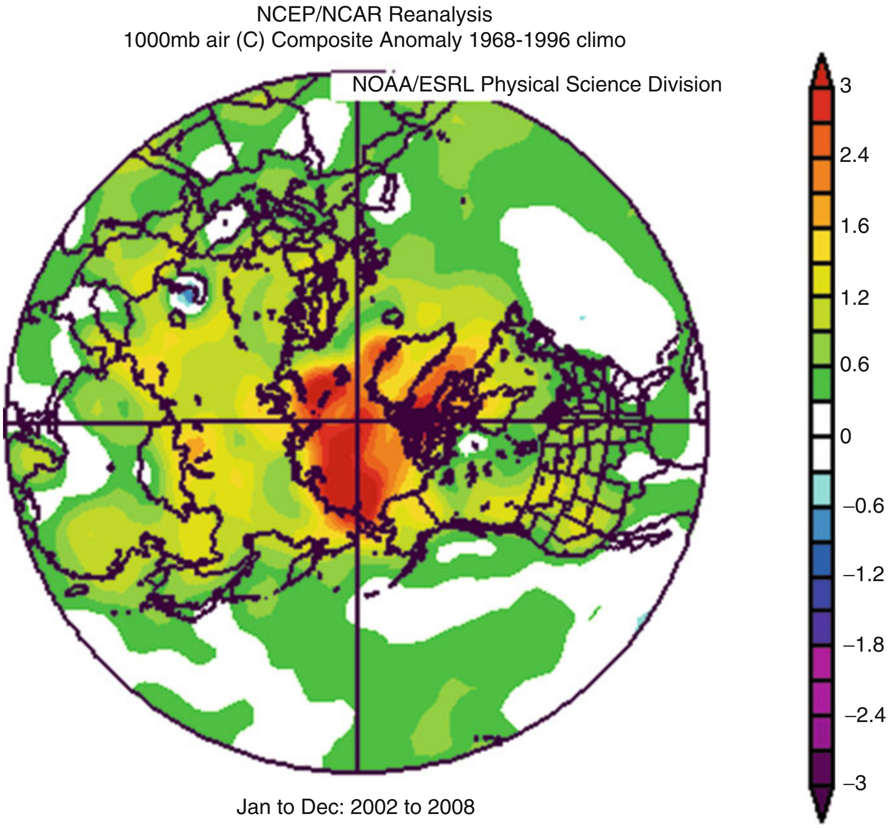

Fig. 2.1 Near surface (1,000 hPa) air temperature anomaly multiyear composites (°C) for 2002–2009. Anomalies are relative to 1968–1996 mean and show a strong Arctic amplification of recent temperature trends (Data are from the NCEP–NCAR Reanalysis through the NOAA/Earth Systems Research Laboratory, generated online at www.cdc.noaa.gov)

and July energy budget of the polar cap, taken as the region poleward of 70°N, is shown in Fig. 2.2, using ERA-40 reanalysis data. At the top of the atmosphere, the longwave energy (LW) loss radiation is 230 $W\,m^{-2}$ in summer and 180 $W\,m^{-2}$ in winter, while the summer net shortwave (SW) radiation flux is 240 $W\,m^{-2}$ downward. The transfer of energy from the south into the Arctic (given by $\nabla \cdot F$) is about the same for summer and winter, 80–90 $W\,m^{-2}$. These radiative and advective transports give a net increase in energy storage of the Arctic Ocean mixed layer (the net surface heat flux) in July of 100 $W\,m^{-2}$ associated with sea ice melt and sensible heat gain, while in January, the surface has a net loss of 60 $W\,m^{-2}$ linked to ice growth and oceanic sensible heat loss. In winter, the radiative loss at the top of the atmosphere is about equal to the sum of the contributions from radiative loss at the surface and horizontal advection.

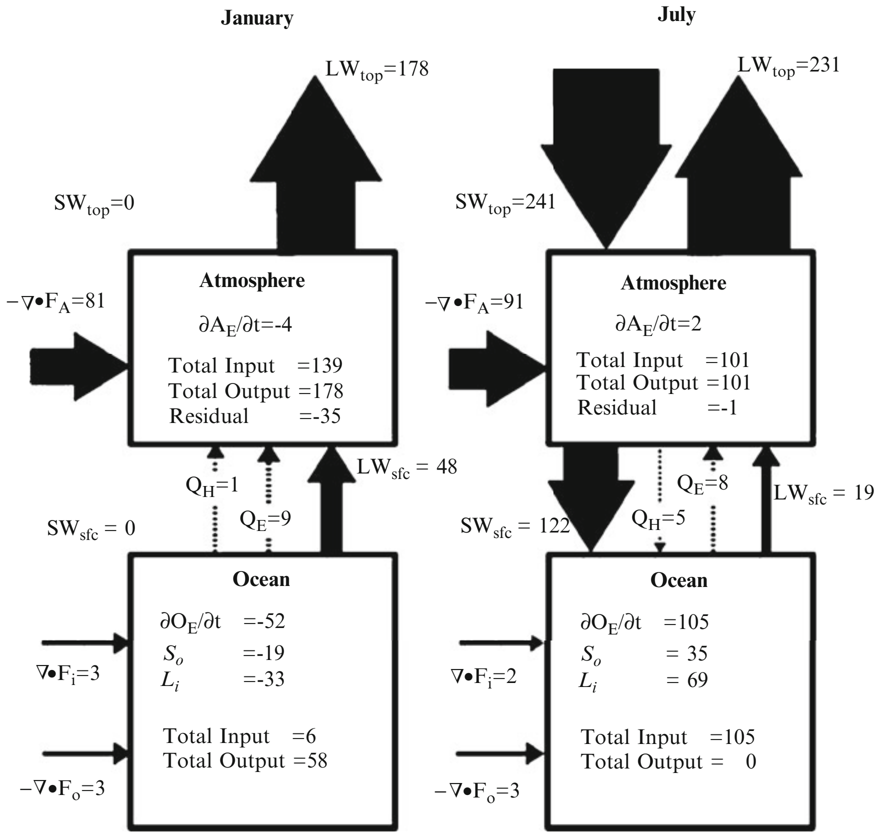

Fig. 2.2 Schematic of the Arctic energy budget for January and July (After Serreze et al. 2007). Symbols are defined in the text. Units are in W m^{-2}. The width of the arrows is proportional to the size of the transports

Measured energy fluxes at the surface in the Beaufort Sea for the SHEBA year are shown in Fig. 2.3. In Fig. 2.3a, F_{tot} is the total vertical heat flux and Q* is the sum of the longwave and shortwave contributions, separated out in Fig. 2.3b as Qs and Ql. Albedo is α, Hs and Hlb are sensible and latent heat flux, and C is the conductivity flux from the ocean through the sea ice to the surface. At the SHEBA site, the total surface flux varied from −25 to +12 W m^{-2} in winter to +37 to +129 W m^{-2} in July (Persson et al. 2002). Most variability is from changes in cloud cover. These mean observed flux magnitudes are considerably smaller than the Arctic-wide estimates by Serreze et al. (2007) in Fig. 2.2, but the Arctic-wide estimates include additional sensible heat flux from open water areas in the Atlantic sector north of 70°N. As in the Arctic-wide estimates, radiative terms dominate the surface energy budget in

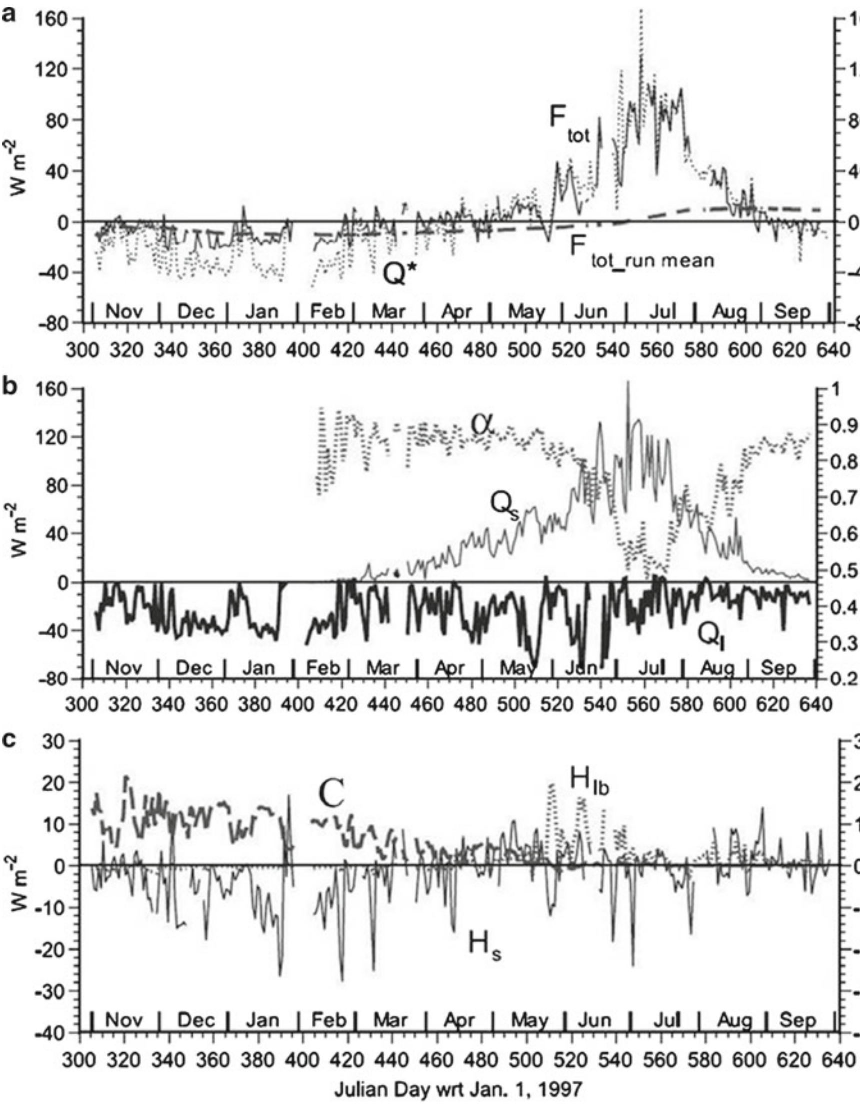

Fig. 2.3 Surface energy budget at the SHEBA camp site (After Persson et al. 2002). (**a**) Ftot is the total vertical heat flux, and Q* is total radiative flux. (**b**) Qs is the shortwave, and Ql is the long-wave contribution. Albedo is a. (**c**) Hs and Hlb are sensible and latent heat flux, and C is the conductivity flux from the ocean through the sea ice to the surface. The cumulative mean for Ftot starts on 1 November 1997

winter and summer; turbulent fluxes are five to ten times smaller in magnitude and are generally of opposing sign to the net radiation. By October, accumulation of excess energy, Ftot-run_mean, was equivalent to melting of nearly 1 m of sea ice.