

Investigating the Arctic Marine Environment During a Period of Rapid Change

Development, Accomplishments, and Outlook for OAII

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Increased concern about the Arctic system's sensitivity to global change and the role of Arctic processes in global change led to the creation of the National Science Foundation (NSF) Arctic System Science (ARCSS) program in 1988. The Ocean–Atmosphere–Ice Interactions (OAII) component of ARCSS was established in 1991 following a research community workshop held at Lake Arrowhead, California, in 1990. After this workshop the OAII Science Steering Committee (SSC) expanded its membership and, with the support of NSF, accepted responsibility for producing an ARCSS/OAII science plan. Additional component milestones included OAII all-hands meetings held in May 1997, October 1999, and November 2001. A continuing theme has been the OAII SSC's commitment to a "bottom-up" approach to developing new initiatives in which the community at large is encouraged to suggest research that relates to the marine environment of the Arctic system within the context of global change.

The timing for OAII was propitious because recent observations suggest that the Arctic is undergoing remarkable changes extending from the atmosphere into the ocean and impacting human populations and living resources. The changes continue. The last decade has been one of generally reduced ice cover. For example, the summer of 2002 had the lowest levels of ice extent and area in the passive microwave record since observation began in 1978. The observed changes are in general agreement with models suggesting that increased greenhouse gases will cause the greatest warming in the troposphere and adjacent ocean and land of the Arctic.

Recent changes must, however, be placed in the context of decadal-scale variation produced by drivers such as the Arctic Oscillation (AO), underscoring the need to build on and continue time-series observations. Indeed, recognition that the pervasive system changes noted during the

past decade may be associated with a positive state of the AO has added intellectual excitement and provided theoretical underpinning to interpretation of the observed changes.

Additional positive developments in recent years include improved access for U.S. scientists arising from the construction of a research icebreaker, the USCGC *Healy*, and increased funding for Arctic logistics at NSF. Technological advances, including autonomous chemical instrumentation, improved satellites, and a new generation of autonomous and remotely operated vehicles, have also improved the outlook for Arctic research. Positive developments also include the release of formerly classified data from thousands of former Soviet Union and Western oceanographic stations in the Arctic as a result of the Gore–Chernomyrdin Commission's efforts. Finally, the aggregate international resources devoted to Arctic research may, at last, be on the increase after the lean decades of the recent past.

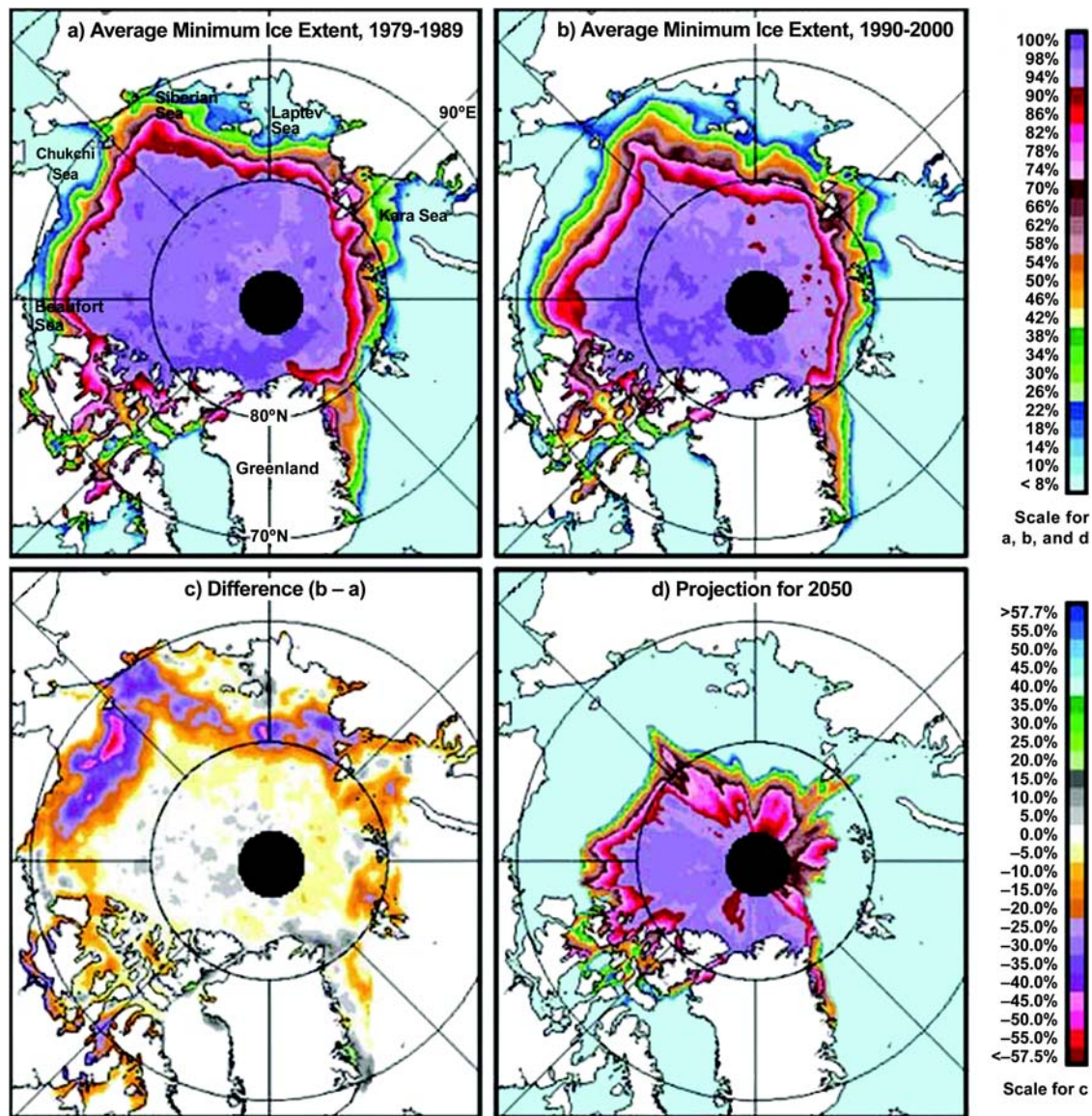
Completed and Ongoing OAII Research Projects

A list of OAII projects and their principal investigators is maintained on the OAII web site (<http://arcss-oaii.hpl.umces.edu>). These projects can be divided into two broad classes: medium to large multidisciplinary or interdisciplinary efforts and smaller, individual projects aimed at filling key gaps in priority research areas.

The following medium to large projects have been implemented under the ARCSS/OAII aegis:

- Northeast Water Polyna Study (NEW), 1991–1995;
- Investigations of the Western Arctic (IWA), 1992–1995;
- U.S./Canada Arctic Ocean Section (AOS), 1994–1997;
- Surface Heat Budget of the Arctic Ocean

Average yearly minimum perennial ice concentrations from 1979 to 1989 (a) compared with 1990–2000 (b), the differences between these two periods (c), and a projection of minimum perennial ice concentrations for 2050 (d).



- (SHEBA), 1995–2003; and
- Western Arctic Shelf–Basin Interactions (SBI), 1999–2009.

In addition, OAI was instrumental in establishing the Study of Environmental Arctic Change (SEARCH), an interagency and international research program. The first SEARCH-supported research involves a collaboration with Arctic-CHAMP (Community-wide Hydrological and Analysis Program), which is supported by ARCSS, and the Arctic and Subarctic Ocean Flux (ASOF) program, which is supported by the European Commission. This research will include the establishment of an instrument array at the entrances to the Arctic Ocean for monitoring ocean and hydrological fluxes, which are an important determinant of the global “thermo-

haline” (overturning) circulation and the ability of the ocean to sequester atmospheric carbon dioxide.

Although the five medium to large OAI projects received major support from ARCSS/OAI, they were collaborative efforts that involved other nations and other government agencies as well.

Northeast Water Project

The Northeast Water Polynya Study (NEW) examined a polynya located on the continental shelf off northeast Greenland at high latitude (about 80°N). Much of the focus was on how carbon is processed in a seasonally open water area, with a view towards enhancing predictions

of how the ecosystem and various biological processes would change if warming increased the amount of open water at high northern latitudes.

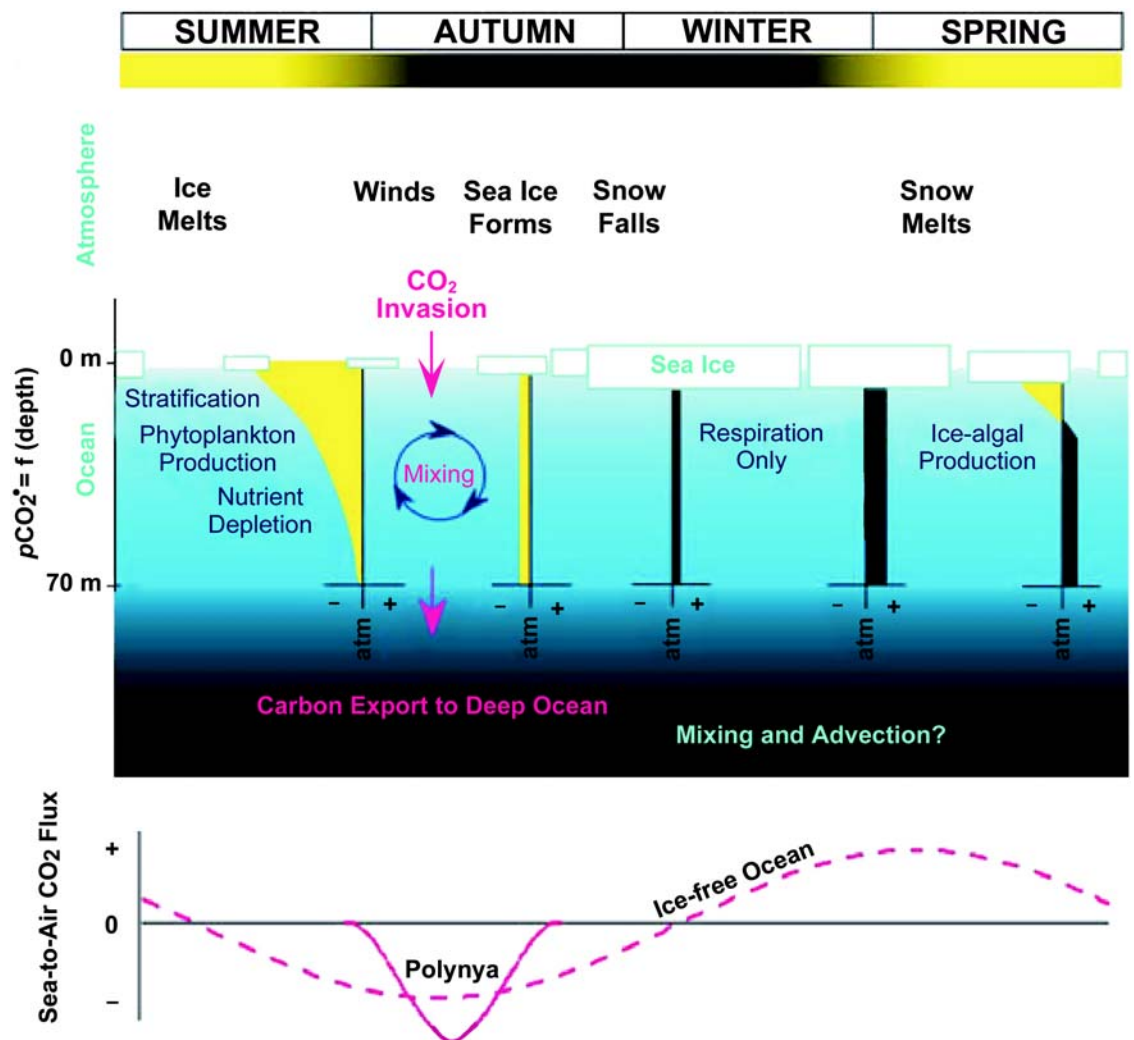
This first OAI project was inherently international, with the Arctic Ocean Science Board endorsing it as the first major project of the International Arctic Polynya Program and with the first expedition in 1991 led by Germany. Thus, in addition to U.S. scientists receiving support from OAI, many other researchers were supported by Canada, Denmark, Germany, Greenland, Poland, and several other countries. Research platforms included Germany's *Polarstern* and the U.S. Coast Guard's *Polar Sea*.

The OAI-supported results shed considerable new light on primary and secondary productivity, carbon dioxide fluxes, carbon/nutrient ratios, pelagic-benthic coupling in the NEW polynya, and biogeochemical cycling in the NEW polynya. For example, the results represented the first assessment of new primary production throughout

an entire season in the Arctic. A surprising result was that advection of zooplankton onto the shelf in the polynya was low, resulting in a low abundance of herbivorous zooplankton. Comparison of these results with later work in another high-Arctic polynya, the North Water polynya in northern Baffin Bay, suggests that the absence of close coupling between phytoplankton and zooplankton in the NEW polynya helps to account for its lower overall productivity. NEW investigators also suggested, based on considerations of physical, chemical, and biological processes, that high-latitude polynyas are efficient sinks for atmospheric carbon dioxide.

Data on physical variables and particle fluxes were successfully recovered from four moorings, providing the first suite of year-round oceanographic observations from the NEW polynya. These moorings documented features such as a wintertime mixing event that helped to replenish nutrients and reset the ecosystem for the higher

A conceptual model for carbon cycling in the NEW polynya suggesting that it is relatively efficient at sequestering atmospheric carbon dioxide.



productivity observed at most trophic levels during 1993.

Many additional NEW results are reported in a special volume of the *Journal of Geophysical Research* (vol. 100, no. C3, 1995) and in a special volume of the *Journal of Marine Systems*. Note that during the summer of 2002 the ice cover in the Arctic Ocean in general and in the NEW study region was markedly reduced, suggesting that the NEW investigators were on the right track when they suggested the need to learn more about high-latitude open water ecosystems. This line of research continues with the implementation of additional international polynya projects (<http://www.fsg.ulaval.ca/giroq/now/wel.htm>).

Investigations of the Western Arctic Project

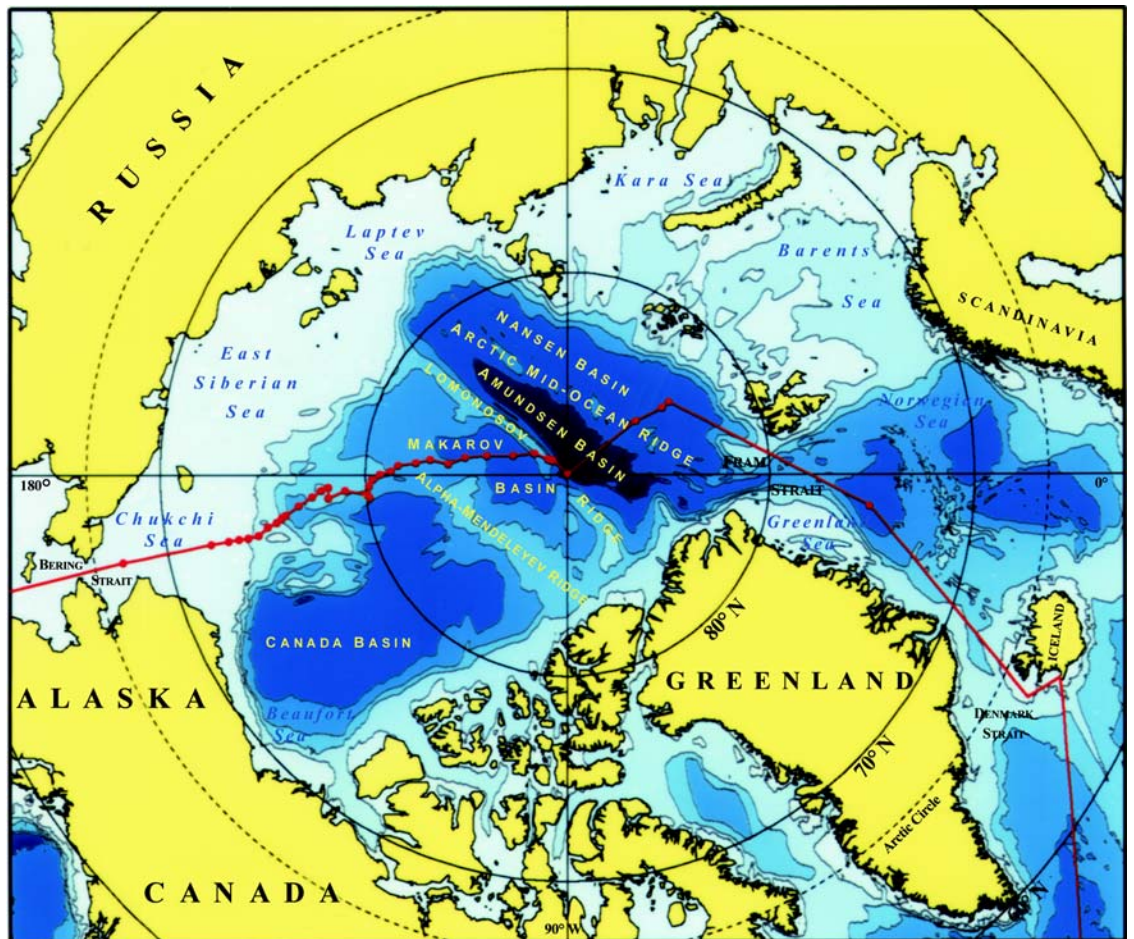
The Investigations of the Western Arctic (IWA) experiment was known initially as the Western Arctic Mooring (WAM) experiment. Under the aegis of this project, an international effort to continue the monitoring of transports through

Bering Strait and the Barrow Canyon region has been maintained. Recently the temperature, salinity, and current sensors have been supplemented by water sampling devices and by in-situ nutrient analyzers. The results have helped to document a significant warming and freshening of the Bering Strait inflow to the Arctic Ocean, which may be accompanied by a change in the nutrient inputs. For example, maximum salinities in the inflow have decreased by approximately 1.5 psu. IWA also provided new information on the formation and transport of halocline waters formed in the northeastern Chukchi Sea and on the flux and dispersal of fresh water carried onto this shelf in the Siberian Coastal Current. This program also documented water mass transports in Barrow Canyon and their response to the wind regime. Several expeditions to the Bering–Chukchi–Beaufort region were also supported under the IWA aegis.

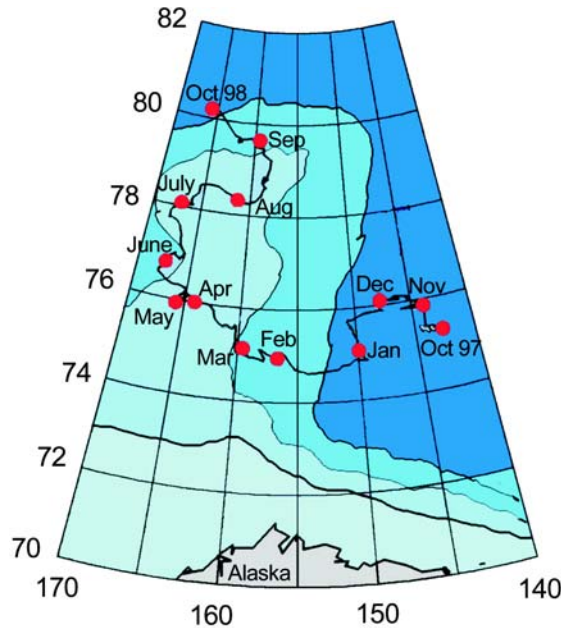
Arctic Ocean Section

The 1994 Arctic Ocean Section (AOS) project was an international program that received major

Station location track for the 1994 Arctic Ocean Section (AOS) expedition that crossed the Canada Basin.



The drift track taken by the Surface Heat Budget of the Arctic Ocean (SHEBA) ice station, 2 October 1997 to 9 October 1998.



support from the United States and Canada. The OAI program and the Office of Naval Research (ONR) provided support for U.S. participants. This effort produced the first comprehensive treatment of the properties of the Canada Basin, including pollutants and associated biological processes. It also helped to document how major changes in the hydrography of the Arctic Ocean have been unfolding since the late 1980s. The AOS results suggested that many previous estimates of the biological productivity of the Polar Basin were too low, partly because of insufficient recognition of the role of ice algae. Furthermore, heterotrophic microbes were found to be far more active in these perennially cold waters than previously thought. This project was comprehensive and included coordinated observations from two icebreakers on geological structure, biogeochemical cycling in Canada Basin sediments, tracer chemistry, biogeochemical cycling, the “microbial loop” etc. Although many of the results are reviewed in a special issue of *Deep-Sea Research* (vol. 44, no. 8, 1997), results continue to be published in a variety of journals.

Surface Heat and Radiation Budget of the Arctic Ocean

The SHEBA (Surface Heat Budget of the Arctic Ocean) project is governed by two broad goals:

- Enhancing our understanding of the ice–albedo and cloud–radiation feedback mechanisms, and

- Using this understanding to improve the treatment of sea ice in large-scale models.

The centerpiece of the SHEBA program was a year-long international and interdisciplinary field experiment. On 2 October 1997 the Canadian Coast Guard icebreaker *Des Groseilliers* was frozen into the pack ice of the Beaufort Sea, the first such science platform “besetting” in over a century.

For the next year this ship drifted with the ice pack as an interdisciplinary team of researchers made a comprehensive suite of measurements of the atmosphere, ice, and ocean. These measurements included profile properties of the atmosphere, cloud fraction and properties, atmospheric boundary layer, surface radiation fluxes, albedo, snow properties, ice mass balance, ice stress, ocean boundary layer, and thermohaline structure of the upper ocean. Because of the large variability of surface properties, SHEBA measurements were made at multiple sampling sites and in spatial surveys using aircraft, submarines, and satellite remote sensing. This was done to sample a region large enough to represent the surface “footprint” of a single grid cell in a high-resolution climate model. The “besetting” of the *Des Groseilliers* also presented a remarkable opportunity to collect invaluable data on a full year’s cycle of biology and hydrology in the upper ocean under the auspices of the Joint Ocean Ice Study (JOIS), which was organized by and received major support from Canada.

The SHEBA experiment further documented the thinning of the ice cover in the Arctic and the freshening of the surface layers and shed new light on the roles of atmospheric moisture, leads, and melt ponds. Data collected during the SHEBA/JOIS drift also revealed that freshwater runoff has been stored in the Canada Basin in response to the highly positive AO conditions during the 1990s, leading SHEBA researchers to suggest that hydrological feedback may be as important as ice–albedo feedback in changing the Arctic’s upper ocean. This freshening also seems to have had a dramatic impact on the biological structure of ice communities. Other biological studies conducted during the SHEBA drift documented the seasonal cycles of zooplankton, heterotrophic microbes, and community respiration and production. The SHEBA biological results generally confirm the findings of the AOS project, which found that canonical estimates of productivity within the permanent ice pack are too low, but that microbial activity was lower, suggesting

significant temporal variability on the interannual (or shorter) time scale.

The SHEBA field work was quite successful, in large part because of the interdisciplinary approach and cooperative spirit that developed aboard the *Des Groseilliers*. SHEBA results have been disseminated in many conference presentations and journal articles and in a special section of the *Journal of Geophysical Research* (October, 2002). SHEBA is now in Phase III, its final phase, which will officially continue through 2003. This phase emphasizes synthesis, analysis, and modeling of the data from the Phase II field experiment. While the SHEBA program officially ends in 2003, the analysis of the data set and its assimilation into large-scale models will continue into the future. The year-long observational data set is a key legacy of the SHEBA program. These data are available through the Joint Office of Science Support, University Corporation for Atmospheric Research (<http://www.joss.ucar.edu/cgi-bin/codiac/projs?SHEBA>). The data will be archived for long-term access at the Arctic System Science Data Coordination Center, National Snow and Ice Data Center (<http://arcss.colorado.edu>). More information on SHEBA may be found at <http://sheba.apl.washington.edu> and in companion articles in this issue of *Arctic Research of the United States*.

Western Arctic Shelf–Basin Interactions Project

The Western Arctic Shelf–Basin Interactions (SBI) project is in Phase II of three planned phases. This project focuses on biogeochemical cycling in the outer shelf and upper slope portions of the Chukchi and Beaufort Seas and their interactions with the Arctic Ocean. SBI is, in part, a response to the recognition that the extensive Arctic shelves are crucial to determining the character of the Arctic marine ecosystem and to the maintenance of the halocline, the salt gradient in the upper 200 m that is so important to the dynamics, thermodynamics, and ecosystem structure of the Arctic Ocean proper. While we understand the importance of these processes and know that some of them are undergoing significant change, the shelves and slopes of the Arctic are poorly sampled, with even seasonally resolved data from these shelves being sparse and in many cases absent. Thus, we lack a mechanistic understanding sufficient to enable us to develop tools for predicting change in this region. At the same

time the recent changes observed in the Arctic system may be having significant impacts. For example, accelerated coastal erosion may be increasing the material fluxes onto the shelves of the Arctic Ocean. In addition, the changes in characteristics of the Bering Strait inflow that have been noted previously, if prolonged, could have a significant influence on the thermohaline structure of the Arctic Ocean and on nutrient cycling.

SBI Phase I was devoted to retrospective data analysis, modeling, and field experiments that were an appropriate prelude to the main field effort that is occurring during Phase II. One interesting result arising from the Phase I paleoceanography studies was evidence for rapid climatic change in the western Arctic that is not reflected in the records from the Greenland ice cores. SBI Phase II began in earnest during the spring and summer of 2002 with two major process cruises on the Coast Guard research icebreaker *Healy* and with mooring/hydrography cruises on the Coast Guard icebreaker *Polar Star* and the University of Alaska's *Alpha Helix*. All cruises went well and provided important new data on the plumes of bioactive material originating on the outer shelf and slope and on the biological and physical processes that produce and modify this transport of bioactive material to the interior of the Arctic Ocean. The Phase II data are in the early stages of analysis, but it is already clear that these data will provide important new insights into the variable timing of phytoplankton blooms in the study region, the regeneration of nutrients over the outer shelf, and the effect of the halocline in restricting the biological signals originating over the shelf largely to the upper 250 m in the adjacent Arctic Ocean.

Additional SBI information is available in a separate article in this issue of *Arctic Research of the United States* and on the SBI web site (<http://sbi.utk.edu>).

Study of Environmental Arctic Change

The Study of Environmental Arctic Change (SEARCH) originated within OAI and was initially motivated by the striking changes observed in the Arctic Ocean's structure and circulation beginning in the early 1990s. The frontal boundary between the eastern and western halocline types had migrated from roughly over the Lomonosov Ridge to roughly parallel to the

Alpha and Mendeleev Ridges, and cores of relatively warm Atlantic water have been observed over the Lomonosov and Mendeleev Ridges.

It soon became apparent, however, that these maritime changes had counterparts on the land and in the atmosphere. For example, there has been a trend of decreasing atmospheric pressure over the Arctic Basin, air temperature has risen over the Russian Arctic, and permafrost is thawing in many regions. In addition, the need to compare the present-day changes with the paleo record is obvious. Thus, SEARCH has evolved into a program that will transcend the ARCSS components and that should help propel us into a more interdisciplinary approach to investigating the Arctic system in the context of global change.

The SEARCH project has a Scientific Steering Committee that collaborates with an interagency working group formed under the auspices of the U.S. Interagency Arctic Research Policy Committee (IARPC). This working group includes EPA, the Smithsonian Institution, NSF, NOAA, NASA, DOD, and DOI. A SEARCH science plan has been published, along with an implementation plan that includes input from all ARCSS components. SEARCH research has begun to support research projects involving the Arctic system's hydrologic cycle and the North Atlantic overturning circulation. More information on SEARCH can be found at <http://psc.apl.washington.edu/search/index.html>.

Synthesis, Integration, and Modeling

Because the ARCSS program focuses on the Arctic system, Synthesis, Integration, and Modeling (SIM) includes integral activities within OAI. For example, Phase I of the SBI experiment included physical and biological models that should help inform the Phase II field work. An early response to the need for SIM was the convening of an OAI modeling workshop. OAI investigators also participated in an ARCSS modeling workshop in 1996. A partial list of OAI simulation, integration, and modeling results includes:

- A Lagrangian model of the Bering and Chukchi Sea ecosystem that agreed well with observations and suggested a significant role for dissolved organic carbon storage in the Arctic halocline;
- A study of the thermodynamics of the Arctic mixed layer suggesting the importance of

solar radiation entering the ocean through leads and thin ice;

- Modeling studies of the thermodynamic interactions between the atmosphere and sea ice that suggest that the ice thickness in the central Arctic may undergo large (approximately 1 m) fluctuations on time scales of 1–15 years in response to varying atmospheric heat flux;
- Models of dense water formation and transport on and off Arctic shelves and their relation to halocline maintenance, showing the potential importance of small baroclinic eddies (15–25 km in diameter), the influence of alongshelf currents and canyons, and the effects of ambient stratification and shelf-break topography;
- Modeling of convection with thermobaric effects, indicating that dense bottom plumes flowing out of Denmark Strait can be detected by remote sensing;
- A comparison between numerical models and data that suggests that existing models do a poor job of simulating freezing and melting along the North American coastline, perhaps because of large interannual variability;
- A coupled ice–ocean model suggesting that a realistic atmospheric forcing field for the 1979–1993 period, which may change in response to the Arctic Oscillation or North Atlantic Oscillation, can account for the recently observed dramatic, large-scale changes in sea ice and oceanic conditions;
- Analysis of global climate model simulations suggesting that the Arctic Oscillation can be responsible for much of the recently observed trends in sea ice and in the Arctic Ocean and that this type of variability is present in paleoclimatic data from the Arctic;
- Improvement in the Community Climate System Model relating to the effects of cloud water on solar and longwave radiation based on measurements obtained during SHEBA; and
- Incorporation of sea ice albedos measured during SHEBA into the new sea ice component of the Community Climate System Model, which will be used for climate change scenarios developed for the IPCC (Intergovernmental Panel on Climate Change).

Since ARCSS/OAI data are available to all approximately two years after collection and are

archived at the National Snow and Ice Data Center, OAI results are likely to resonate in models long after the projects that produced these results have ended.

Priorities for Future OAI Research

Chemical Exchanges Between the Land, Surface Ocean, Ice, Snowpack, and Lower Troposphere

To date, OAI has not supported a project focused on interactions between surface processes, the biosphere, and the atmosphere. However, it is now clear that fluxes of trace gases, aerosols and aerosol precursors, and pollutants between the upper Arctic Ocean and the overlying troposphere can significantly impact both the Arctic atmospheric composition and the underlying biosphere. This gap has been recognized and discussed for several years at a variety of OAI meetings, and some research relating to these topics has been conducted by international partners during OAI-sponsored programs. Major gaps in our knowledge of these topics remain, however, and OAI is now poised to begin a research program. To develop community consensus and to explore and define research priorities, a workshop called "Changing Environmental Controls on Coupled Chemical Exchange between the Ocean, Ice, and Atmosphere in the Arctic" was held in November 2002 at Purdue University. The workshop brought together 24 investigators to identify prospective collaborators, determine and evaluate scientific priorities, creatively address logistics, and make recommendations for a coordinated study.

The workshop participants recommended a coordinated field, laboratory, and modeling study of air-surface exchange processes in the Arctic, named Ocean-Sea Ice-Snowpack-Atmosphere Interactions Research (tentatively OASIS). This project would emphasize chemical coupling between these reservoirs and would include the following objectives:

- Understanding the solar influence on physical, chemical, and biologically mediated exchange processes involving halogens, nitric oxide, ozone, volatile organic compounds, persistent organic pollutants, mercury, sulphur species, and carbon dioxide in the Arctic and their links to climate change;

- Understanding the influence of OASIS exchange processes on physical and radiative characteristics of clouds and hence on climate;
- Determining the impact of past changes in environmental pollution on OASIS exchange processes as part of the development of a capability to predict future changes;
- Determining the impact of changes in ice cover characteristics and temperature on chemical OASIS exchange and the associated feedbacks on climate; and
- Determining the impact of chemical OASIS exchange on tropospheric chemistry and climate as well as on the surface and biosphere and their feedbacks.

A workshop summary presentation is available at <http://www.chem.purdue.edu/arctic/ArcticWorkshop.htm>. This site will be periodically updated as an OASIS science plan and management structure are developed.

Nearshore Processes

As a partial response to the need for intensified interdisciplinary research within ARCSS, the OAI all-hands meeting held in Salt Lake City during November 2001 was concurrent with meetings of the Land-Atmosphere-Ice Interactions (LAI) component of ARCSS and with the ARCSS-sponsored Russian-American Initiative for Land-Shelf Environments in the Arctic (RAISE). All three groups recognized the importance of studying the coasts and adjacent inner shelves of the Arctic system, where most of the human populations and living resources are located. This zone is already heavily impacted by warming (resulting in coastal erosion and permafrost warming, for example) and by energy development.

Accordingly a steering group has been formed and an initial document outlining the science issues involved in a Land-Shelf Interactions (LSI) project has been distributed and discussed by the OAI, LAI, and RAISE steering committees at a joint meeting held in San Francisco in December 2002. This plan is now being considered by the ARCSS Advisory Committee. The overall objective is to develop a coordinated, interdisciplinary research program that would support land-, river-, and sea-based researchers who would focus on the impacts of climate change on human and biological communities and related physical and chemical systems in the

coastal and nearshore regions of the Arctic system. The questions of interest to LSI include the following:

- What are the impacts of coastal erosion?
- What is the fate of the peat and dissolved organic matter transported to the nearshore environment by coastal erosion and runoff?
- How important are trace gas releases from thawing permafrost?
- How may changing runoff patterns influence the coastal–nearshore system?
- How has the coastal–nearshore zone been influenced by previous climate change?

Because of the concentration of human populations and resources in the coastal and nearshore environment, LSI will have a strong contingent of researchers interested in the Human Dimensions of the Arctic System (HARC). The HARC component of ARCSS has already hosted an online workshop dealing with LSI-related issues. During this workshop it was recognized that changes in oceanographic conditions, such as the sea ice regime and the extent of brackish water, may have a significant impact on the concentration and availability of living resources. Additional information on LSI (including a draft science plan) is available at the RAISE/LSI web site (<http://arctic.bio.utk.edu/RAISE/index.html>).

OAI Outreach Activities

Although this report emphasizes OAI research, it is important to note that the scientific activities went hand in hand with significant outreach efforts. These included articles and programs in the national and local media presenting OAI research to the general public. For example, reporters participated in the SHEBA drift experiment and in the SBI fieldwork, resulting in coverage on national TV and radio, as well as a large number of print articles. K–12 teachers have also participated in OAI research through NSF’s Teachers Experiencing Antarctica and the Arctic (TEA) program. OAI researchers have developed educational web sites, educational games, and contests dealing with the Arctic, assisted with K–12 curriculum development, and made many presentations to K–12 students and the public at large. In addition, to facilitate and stimulate outreach, examples of outreach activities are provided on the OAI website (<http://arcss-oai.hpl.umces.edu>).

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SHEBA: The Surface Heat Budget of the Arctic Ocean

This article was prepared by Donald K. Perovich, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire; Richard C. Moritz, Polar Science Center, University of Washington, Seattle; and John Weatherly, U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Central to almost all aspects of Arctic system science is the problem of projecting the variations of Arctic climate during the next 100 years and beyond. Such projections are based on simulations performed with global numerical models of the climate system that represent the atmosphere, the oceans, land surfaces, the snow cover, and the sea ice cover. These simulations indicate that physical processes occurring in the Arctic ocean–atmosphere–ice system produce climate feedback mechanisms involving thermodynamic coupling of the sea ice, snow cover, and Arctic clouds.

Two key processes are the ice–albedo and cloud–radiation feedback mechanisms. These feedbacks strongly influence the simulated Arctic climate; however, there is wide variation in the response of different climate models to perturbations, such as enhanced atmospheric greenhouse gases. Through its effect on the circulation of the atmosphere and ocean, the high sensitivity of the Arctic climate extends the uncertainty surrounding future climate scenarios to hemispheric and global scales.

The uncertainties associated with Arctic climate sensitivity have long been recognized by the Arctic research community. The combination of the importance of the Arctic sea ice cover to climate and the uncertainties of how to treat the sea ice cover led directly to SHEBA: the Surface Heat Budget of the Arctic Ocean. SHEBA is a large, interdisciplinary project that was developed through several workshops and reports. SHEBA was governed by two broad goals: understand the ice–albedo and cloud–radiation feedback mechanisms and use that understanding to improve the treatment of the Arctic in large-scale climate models. The SHEBA project was sponsored jointly by the National Science Foundation’s Office of Polar Programs Arctic System Science program and the Office of Naval Research’s High Latitude Dynamics program. From a programmatic perspective, it was critical that SHEBA be

an interdisciplinary experiment: one where a diverse group of researchers come together, each bringing their own particular expertise, to work on the common goals of the program. Achieving this interdisciplinary teamwork was one of the major successes of SHEBA.

Background

The ice–albedo feedback is a straightforward concept. The albedo is simply the fraction of the incoming sunlight that is reflected. Interestingly, snow has the largest albedo of any naturally occurring material on earth, while water has one of the smallest. The snow-covered sea ice reflects most (about 80%) but not all of the incident sunlight. This absorbed sunlight leads to melting, which in turn lowers the albedo, resulting in more absorbed sunlight, increasing melting, and the process continues. The ice–albedo feedback has been understood qualitatively for over 100 years. The challenge for SHEBA was to quantitatively define it in a form suitable for large-scale climate models. The ice–albedo relationship is significant because it is a positive feedback, so a small change can be amplified into a large difference.

The cloud–radiation feedback is more complex. During the long night of the Arctic winter, clouds act as a blanket, trapping thermal radiation and warming the surface. However, in summer, the sun is up, and clouds have two opposing effects on the surface heat budget: again, they act as a blanket, but they also act as an umbrella, reducing the amount of sunlight and cooling the surface. Prior to SHEBA we did not know even qualitatively—let alone quantitatively—which of these cloud effects is stronger, or whether Arctic cloud variables tend to increase or decrease in response to changes in the surface heat budget. Knowledge of these relationships is essential to evaluating the net interaction between Arctic clouds and the ice cover.