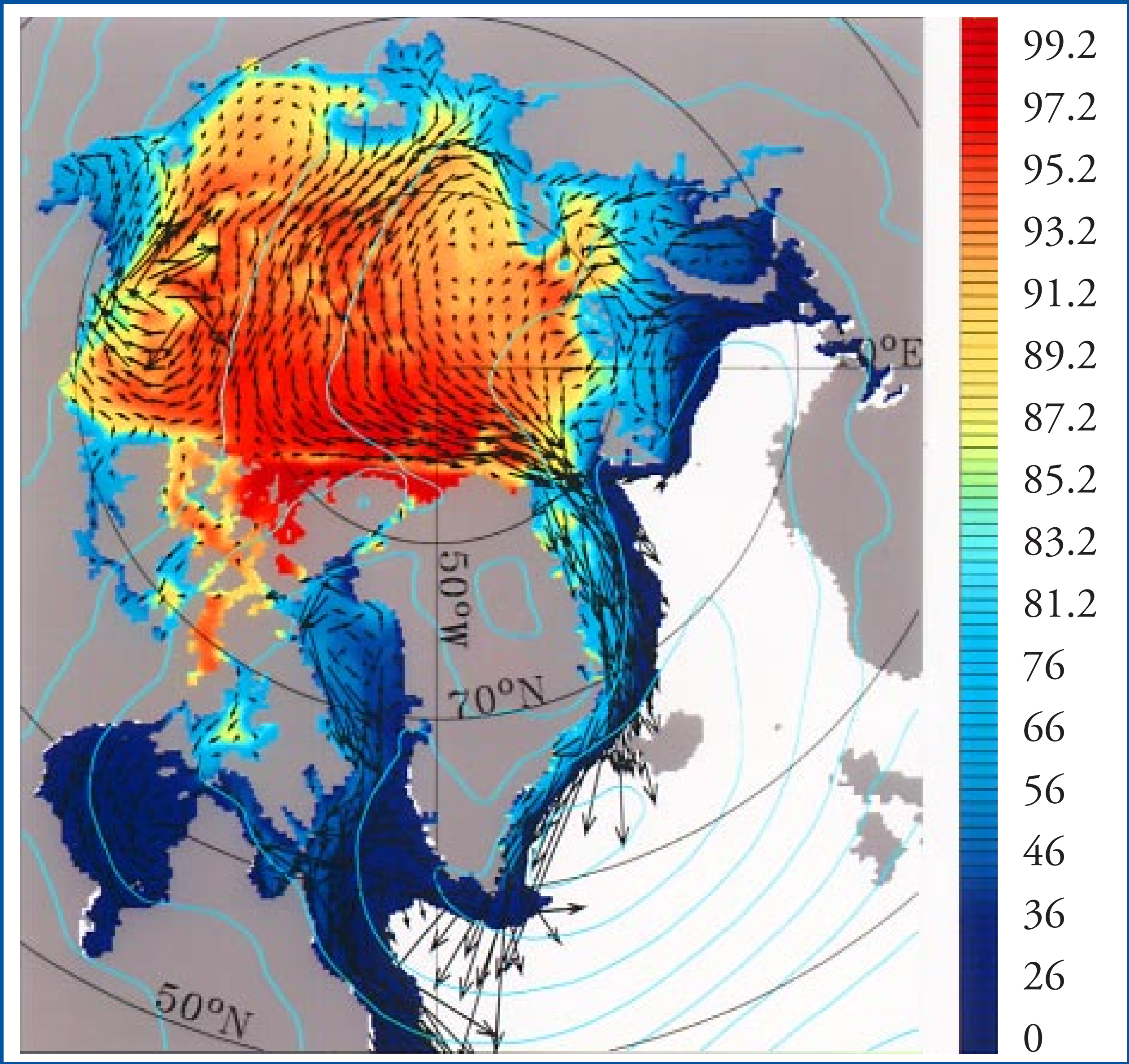
Modeling the Arctic System



A Workshop Report on the State of Modeling in the Arctic System Science Program

Front cover: Simulated Arctic sea-ice compactness (%) and velocity (cm/s) with sea-level pressure overlaid (blue line) based on results averaged for 1990 – 94 from a sea-ice model driven by observed atmospheric forcing and modeled ocean circulation.

The coupled Arctic Ocean/Sea Ice model has been developed with support from the Department of Energy and the National Science Foundation and is being run by Wieslaw Maslowski, Yuxia Zhang, and Albert Semtner at the Naval Postgraduate School. Detailed information is available at <http://vislab-www.nps.navy.mil/~braccio/maslowski/arctic.html>.

Modeling the Arctic System

A Workshop Report on the State of Modeling in the Arctic System Science Program

from the ARCSS Modeling Workshop
15 – 16 January 1996
Boulder, Colorado

Funded by the National Science Foundation
Arctic System Science Program

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This report is published by ARCUS with funding provided by the National Science Foundation under Cooperative Agreement OPP-9404321. The opinions, findings, conclusions, and recommendations contained in this document do not necessarily reflect the views of NSF.

The workshop report may be cited as:
Modeling the Arctic System: A Workshop Report on the State of Modeling in the Arctic System Science Program. The Arctic Research Consortium of the U.S., Fairbanks, Alaska. February 1997. 141 pp.

Appendices

Foreword

This report is the product of a workshop organized by the Arctic Research Consortium of the United States (ARCUS) and held in Boulder, Colorado in January 1996. ARCUS was tasked by the National Science Foundation (NSF) to organize a workshop to provide recommendations to the NSF Arctic System Science (ARCSS) Program and the ARCSS Committee, the committee representing the arctic research community. Important goals of the workshop were to develop modeling recommendations and priorities and to determine important ARCSS synthesis efforts. Oral and poster presentations from the workshop are included in the report as are overviews of modeling activities within ARCSS.

The workshop was planned and led by the interdisciplinary Modeling Working Group (page 14). The Modeling Working Group (MWG) was created in 1995, as recommended in the report *Arctic System Science: A Plan for Integration* (1993), and was tasked with proposing mechanisms to devise the most efficient strategies for achieving ARCSS modeling goals.

We would like to extend appreciation to Gordon Bonan and John E. Walsh who were co-chairs of the MWG at the time of the workshop, as well as to the present co-chairs, Amanda Lynch and F. Stuart Chapin. The overviews of modeling within GISP2, PALE, OAII, and LAII were prepared by Mark Twickler, Starley Thompson, Richard Moritz, and John Hobbie, respectively. They contribute greatly to the body of information about ARCSS modeling efforts. Kristjan Bregendahl, of ARCUS, contributed extensively to the development of this publication, with both editorial and technical publications expertise. Finally, on behalf of the arctic scientific community, we thank the Office of Polar Programs at NSF for financial support and for the opportunity given to participate actively in this planning process.

Wendy Warnick
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Reference

Arctic System Science: A Plan for Integration. 1993. Arctic Research Consortium of the United States, Fairbanks, Alaska.

Executive Summary

Modeling can be understood as an integration of known information about a system. Hence it is an indispensable tool in the development of a conceptual understanding of the Arctic system. Until now, modeling efforts have been pursued largely independently within each program of the NSF Arctic System Science Program (ARCSS). While considerable progress has been made in modeling the Arctic system with this approach, a high priority in the coming years will be greater integration of modeling with data synthesis and data gathering efforts, and between modelers in different programs and projects. Workshop participants reached a strong consensus, however, that a single, grand system model is inappropriate and, possibly, unfeasible. General types of models considered appropriate included some use of integrated system models, together with process models that encompass the physical, chemical, biological, and social domains. The development of conceptual models, and models useful for policy-making, were considered to be a key gap in current efforts.

Guidelines for model output archival have been addressed in the Model Output Protocol (page 12). While the group producing the information clearly has first priority for publication, synthesis and integration efforts require timely exchange. Models are often developed over long periods of time, sometimes under the auspices of different funding agencies and even the private sector; model and model output availability must be addressed on a case-by-case basis. It remains for the PIs to nominate a model output availability strategy in each proposal that is appropriate for them but does comply with the Protocol.

A less tangible goal of the workshop was to promote interaction among modelers from different ARCSS components and non-ARCSS modelers. This goal was certainly met and, in particular, it recognized the importance of these interactions to improve the representation of the Arctic in Global Climate Models (GCMs) and Climate System Models (CSMs).

There remains a need for specific scientific goals to drive the modeling activities within ARCSS. In addition, cross-disciplinary integration by modeling must be assessed carefully for readiness to ensure that such modeling is scientifically sound, productive, and efficient.

Workshop Recommendations

Workshop Goals

The workshop was organized by the Arctic Research Consortium of the United States (ARCUS) to provide guidance to the ARCSS Modeling Working Group (MWG), which reports to the ARCSS Committee, and to develop recommendations on synthesis and integration for the NSF ARCSS Program. The goals of the workshop are outlined below.

1. **To develop guidelines and priorities and a sense of the most useful phasing for development of ARCSS modeling efforts.**
   a. What is the overall goal of ARCSS modeling?
   b. What are the current modeling priorities?
   c. How should ARCSS modeling activities be phased over the next three to five years?
      - What can be done immediately, relatively easily?
      - What would the next projects be?
   d. What are we not prepared to do now?
      - What kinds of efforts should not be funded by ARCSS?
      - What efforts are not worth support for the results to be gained?
      - What do we have insufficient data or understanding to attempt now?

2. **To develop guidelines for the archiving of model output**
   a. What model output should be archived, and by whom?

3. **To determine which data synthesis efforts are most important for modeling activities**

4. **To establish a funding policy on modeling-only projects (projects with no field work or data analysis component), that use existing data for model validation and development.**

ARCSS Modeling Recommendations

According to *Arctic System Science: A Plan for Integration* (1993), the primary mandate of the NSF Arctic System Science (ARCSS) Program is to understand the physical, chemical, biological, and social processes of the Arctic system that contribute to or are influenced by global change. In this way it will be possible to:

- advance the scientific basis for predicting environmental change on a decade-to-centuries time scale, and
- formulate policy options in response to anticipated impacts of changing climate on humans and social systems.

The development and application of various forms of models are important means to better understand the Arctic system, to predict the response of the Arctic to environmental change, and to formulate policy options. Thus, credible integrative models of the Arctic system, or sub-components, are essential to the ARCSS Program if its overall goal is to be achieved.

The overall ARCSS modeling effort has been envisioned as inclusive, with broad overlap between projects undertaken through ARCSS research. The research has been conducted through the Paleo-environmental Studies (GISP2[1] and PALE[2]); Studies of the Contemporary Environment (OAII[3] and LAII[4]); the Human Dimensions of the Arctic System [HARC], a proposed initiative that will integrate and synthesize across all programmatic boundaries; and Synthesis, Integration, and Modeling Studies [SIMS], neither a program nor a component, but rather a programmatic emphasis that advances integration and synthesis across all the ARCSS programs and with other large arctic research programs. The ARCSS modeling effort would conform to ARCSS general objectives if it emphasized studies aimed at gaining insight into and making predictions about the Arctic system, culminating in the development of models that can be used to extrapolate our knowledge over broad areas and yield quantitative and qualitative information about the future response of the Arctic system to change.

To this end, the first ARCSS modeling workshop, *Modeling the Arctic System*, was held in Boulder, Colorado on 15-16 January 1996. The specific goals of the workshop are listed on page 5. The workshop numbered approximately 50 participants from within and outside the ARCSS community. At the workshop, overviews of modeling efforts within GISP2, PALE, OAII, LAII, and HARC were given during the first session. During the remainder of the workshop, major topics included sessions on the following: Overviews of System Models (two presentations), Components of a System Model (four presentations), Broad Linkages Between Components (nine presentations), Process Models (three presentations), Data Sets and Modeling (four presentations), and Poster Session (seven posters).

In addition, the workshop featured several plenary sessions and moderated discussions to develop recommendations for an ARCSS modeling plan. There was a strong consensus that a single grand system model is inappropriate to the ARCSS modeling goals. There was much less consensus, however, regarding the specific modeling efforts ARCSS should promote. While some thought

1. GISP2, Greenland Ice Sheet Project Two
2. PALE, Paleoclimates of Arctic Lakes and Estuaries
3. OAII, Ocean/Atmosphere/Ice Interactions
4. LAII, Land/Atmosphere/Ice Interactions

General Circulation Models held the most promise others argued that process models were more important to the ARCSS program. In many ways, the workshop discussions followed specific disciplinary lines as the participants promoted the research interests with which they were most familiar.

Modeling of cross-disciplinary phenomena in the arctic is a laudable objective. Such modeling must be driven by clear and compelling scientific goals that are more specific than a desire to understand and predict the future of the Arctic system. A case can be made that the specific scientific goals have not yet been articulated in a way that would enable development of a guide for ARCSS modeling. The ARCSS Modeling Working Group and reports prepared by it will be more viable entities when the ARCSS Committee and the ARCSS Program have established specific scientific goals germane to the advances made through ARCSS Program research. Such goals are the only way to determine what kinds of models to develop.

Moreover, the cross-disciplinary integration implicit in ARCSS modeling cannot and should not be accelerated beyond the ability of the science and the scientists to provide sound building blocks (descriptions of well-understood physical, chemical, and social processes) and motivators that justify the efforts of integration. Integration needs to be undertaken carefully and only when there are compelling and achievable benefits to be realized. There is little point in building complex models to solve as-yet-unformulated problems. In this regard, it should be emphasized that cross-disciplinary integration (by modeling or otherwise) will likely be a slow and difficult process if done in a scientifically sound manner. Many of the sub-field activities within ARCSS may not be ready for such integration. It is important that the integration by modeling be a "bottom-up" rather than "top-down" process. The scientists who are directly involved with modeling are often in the best position to assess readiness for integration, and these scientists must make their cases in proposals for ARCSS funding. Readiness and conformance to specific scientific goals of ARCSS should be the criteria for funding of modeling activities within ARCSS.

The remainder of this report will be a synopsis of major workshop themes. This report should be viewed as a workshop summary rather than as a comprehensive blueprint for ARCSS modeling.

Broad Science Themes in Support of ARCSS Goals

Various ARCSS-related committees, working groups, workshops, and publications have outlined the important questions for ARCSS to address (see *Arctic System Science: A Plan for Integration* (1993), and the specific science plans for each ARCSS component). It was agreed at the workshop that the overall goals of the ARCSS program remain appropriate. In addressing these questions, modeling within the ARCSS program should strive for improved predictive understanding of the natural variability and anthropogenic changes in the Arctic environment and how the Arctic affects the earth system. There is a further need for specific cross-disciplinary goals to guide ARCSS modeling.

Great advances have been made in the characterization of global climate model biases in the Arctic, and in the development of algorithms to improve their performance. These global models include atmosphere, ocean, and coupled climate system models, and their use has been directed toward a better understanding of how past, present, and future changes in the Arctic system interact and feed back to effect local and global climate. This work has been extended to include regional climate system models, which include representation of the atmospheric, terrestrial, oceanic, and cryospheric environments at high resolutions, allowing detailed investigations of the Arctic climate system, and providing a regional context for physical, chemical, biological, and sociological process models. Process models focus on specific Arctic system processes and feed backs. They include terrestrial ecosystem and community models that provide a better understanding of how terrestrial, fresh water, and marine biotic communities are linked to and respond to other Arctic system components. In addition, models of hydrologic and biogeochemical cycles provide better understanding of biological and geophysical processes controlling the distribution, abundance, and long-term fate of terrestrial, atmospheric, and oceanic fresh water and its biogeochemical components. Models of land-based ice sheets and sea ice add crucial links to the understanding of the Arctic hydrological system. Finally, a key set of models are those investigating human interactions and societal processes. These models have the potential to enhance our understanding of human responses to and effects on Arctic system components encompassing past, present, and future time frames.

Interrelationships between modeling efforts is a key issue. It is not necessary that a model be part of an "Arctic System Model" to contribute valuable knowledge toward a systematic understanding of the system. While each process model is an artificial construct within a large Arctic system, they can and should provide important insight into the processes they encompass. Further, they are not completely independent and may provide insight into the interactions and feedbacks between systems, and hence lead to integrative modeling efforts. Eventually, such modeling efforts accumulate to form a stronger basis for understanding the Arctic system. In addition, this process can represent multiple time slices of a continuum, by incorporating paleoclimate studies (e.g., PALE and GISP2) and predictive studies.

General Types of Modeling Studies Recommended for ARCSS

There are multiple approaches to addressing the broad science themes of the ARCSS program. The ARCSS modeling effort must be inclusive with broad overlap between or among programs. Moreover, it should emphasize studies aimed at gaining insight into and making predictions about the Arctic system, culminating in the development of models that can be used to extrapolate our knowledge over broad areas and yield quantitative and qualitative information about the future response of the Arctic system to change. It is vital that the manner in which a scientist uses models to support these goals be left to the discretion of the individual scientist.

We recommend modeling efforts that cross several broad categories, as follows:

Model Verification

Numerous models exist or are being developed that differ in scientific maturity. To enhance verification of model output, ARCSS modeling should strive to:

- Resolve discrepancies between observations (present day and from paleoclimatic reconstructions) and model outputs and, where appropriate, model-to-model output.
- Successfully simulate past, as well as present, environments.
- Narrow uncertainties (range) between different model projections of the same variables.

In doing so, modeling efforts should carefully document initial conditions and parameterizations in order to better understand the key processes and feedbacks within the Arctic system.

Insight

Understanding the processes required to successfully simulate past, present, and future environments is fundamental to the ARCSS modeling program. Insight moves beyond mere process modeling of environmental parameters and also includes human dimensions and policy related modeling. In order to focus on model verification and validation within a realm of model uncertainty, we should promote studies to:

- Test the importance of particular processes.
- Test various scaling hypotheses and scale-related problems.

- Determine the robustness of a particular simulation or prediction, given parameter uncertainty.
- Test alternative parameterizations of a particular process.

Forecasts and Reconstructions

ARCSS models used in an environmental context different from that of today should:

- Determine relationships between the Arctic and global climate systems.
- Provide predictions about future anthropogenic effects on the Arctic environment and potential feedbacks to the global environment. A necessary component of this is the identification of natural climate variability.
- Reconstruct past environmental changes to better understand the responses of the Arctic to a wide variety of global climatic conditions.
- Show relevance to human/landscape scale changes.

Guidance for Data Collection Efforts

The relationship between data collection efforts and modeling is often misunderstood and overlooked. Dialogue between these communities is key to developing reliable models in ARCSS. Thus, studies are needed to:

- Identify data needed to narrow model uncertainty.
- Integrate and guide field programs and help prioritize data collection efforts.
- Identify new data products necessary for model testing (e.g., remote sensing).

Types of Models to Support

The breadth of modeling activities represented at the ARCSS Modeling Workshop was impressive, ranging from highly focused disciplinary models such as sea-ice physics to more broad topics such as land-atmosphere interactions. The spatial scales of these models ranged from the small watershed, to landscape, to regional, to full Arctic Basin, to global scale models. Based on the workshop discussions, four broad model categories are currently supported.

Integrative System Models

Examples of models that actually couple general categories of processes into an integrative model include:

- *Global and Regional Climate System Models.* These models couple atmospheric general circulation models, oceanic general circulation models, sea ice models (both thermodynamic and dynamic), and land surface models into an integrated system. They can be used to study interactions within the Arctic system at several different scales and to link the Arctic to the rest of the Earth system. They are also useful tools for guidance for field programs, and data synthesis efforts.
- *Landscape or Watershed Models.* These models investigate ecosystem structure, functions, and dynamics to biogeochemical and hydrologic processes including glacial ice models. Such models are used to examine interactions within the terrestrial component of the Arctic system, and often include a combination of physical, chemical, and biological processes.

Process Models

These models tend to be disciplinary models developed to gain a better understanding of particular processes or phenomena of interest. Such models include simulations of nutrient controls over plant production, cloud-radiation interactions and atmospheric boundary layer processes, upper ocean and shelf processes and redistribution of snow over variable topography.

Models of Human/Societal Interactions with other Arctic System Components

In a sense, it is an artificial construct to separate these models into a separate category, since they may be more meaningfully considered as a type of process model. Models within the social sciences are highly varied and include policy models, economic development models, sustainable land-use models, and many more. Such models also incorporate a variety of spatio-temporal scales. As environmental changes occur within the Arctic system, it is important to model the relationships of these changes to the humans dependent on that environment. It is also vital to understand and model the impacts human populations have on the environmental system. It must be noted here that many of these potential impacts on the Arctic system are likely to originate from sources outside the Arctic; we must, therefore, promote multiple scales of investigations and the potential for nested modeling efforts.

Qualitative/Conceptual Models

Not all models are purely numeric representations of physical processes. Qualitative or conceptual models provide the vital final link in the development of ARCSS modeling. Examples of these models are present in all of the categories listed above, and include models such as the relationship between quantities measured in GISP2 ice cores and atmospheric quantities, and rule-based models of past human settlements in the Arctic. Conceptual models may be considered to be at the heart of every quantitative model, and many models are a combination of qualitative and quantitative components. In addition, conceptual models are necessary for the production of insights useful for policy making and planning.

These models are all currently supported by ARCSS initiatives and are in various stages of development and maturity. It is important that such models continue development and that they become linked to investigate concepts that cross ARCSS program boundaries. As noted in the report *Recommendations of the ARCSS ad hoc Working Group for the Arctic System Science (ARCSS) Program Advisory Committee* (14 February 1995), "The ARCSS program was initiated to gain a better understanding of interactions within the Arctic system, specifically how the Arctic system interacts with the rest of the earth's system. Integration and synthesis are the highest general priorities of ARCSS." Thus, a high priority for support over the next three-to-five years should be those modeling efforts that take an integrative approach. This is the heart of the SIMS (Synthesis, Integration and Modeling) Initiative. Integration of current and future ARCSS modeling projects can take several forms, including collaboration among modelers, and collaboration between modelers and non-modelers. The former can include the coupling of one component to another, the coupling of one scale to another (e.g., nesting), the integration of information from various regions in the Arctic, and conceptual linking, such as using climate change scenario predictions as guidance for a human/social model. The latter includes integrated approaches that use multiple forms of data in concert with specifically targeted model experiments, using models in concert with specifically targeted field programs, and conceptual linking, such as the use of historical and archeological data as verification for paleoclimatic model reconstructions. Integration must be approached with clear scientific questions in mind.

Policy for Data and Model Output Availability

Finally, the issues of data and model output availability were addressed. This is a problematic issue, as the producers of such data, whether by data collection or work with models, need to have ample time for the processing and publication of their work. Nevertheless, synthesis and integration efforts require timely exchange. It was recognized that data could be made available to particular PIs when the use of the data was going to be very different from and, in fact, outside the area of expertise of the originator of that data. In that case, the data should be made available on a PI to PI basis, with a clear agreement as to use. This issue must be addressed in each proposal to the satisfaction of reviewers and the ARCSS Program

Director. For this to be possible, it is desirable that PIs lodge a description of their data with the ARCSS Data Center, without actually providing the data itself, so that other ARCSS investigators are aware of work being done outside their area. Regular meetings such as the May 1996 ARCSS All-Investigator Workshop are also useful to this end. Further, proposals need to include a data migration plan of some sort developed by the PI. Guidelines for model output archival have been addressed since the workshop with the development of the Model Output Protocol (page 12). The responsibility of data availability remains with the investigator, however.

References

Arctic System Science: A Plan for Integration. 1993. Arctic Research Consortium of the United States, Fairbanks, Alaska.

Recommendations of the ARCSS ad hoc Working Group for the Arctic System Science (ARCSS) Program Advisory Committee. 1995. Arctic Research Consortium of the United States, Fairbanks, Alaska.

Proposed ARCSS Model Output Protocol

The NSF Arctic System Science Program (ARCSS) is moving into a new phase of its development, in which synthesis of multidisciplinary research through model development and use is becoming increasingly important. This synthesis effort necessarily relies strongly upon the availability of model information throughout the community of ARCSS investigators. In the past, model output could be considered to be covered by the ARCSS Data Protocol. It is increasingly clear, however, that there are special issues with regard to modeling that need to be addressed separately. The following protocol has been recommended.

Management Strategy

Upon receipt of an NSF ARCSS award, the Principal Investigator(s) will be contacted by the ARCSS Data Coordination Center (DCC) to establish a management plan for making their results available to other ARCSS investigators in a timely fashion. The guidelines for access are as follows.

Immediate Migration:

- A model description, including:
  - a history of model development with appropriate citations, expertise, and computing resources required for running the model, and examples of appropriate applications;
  - current model output from previous work that may be available and useful for ARCSS researchers; and
  - a statement of intent and a schedule for planned experiments (with the understanding that these may change).

Within One Year of the Model Experiment:

- Model output or a pointer to model output should be lodged with the ARCSS DCC, to be available only to other ARCSS investigators.

Within Two Years of the Model Experiment, Upon Publication, or Before the End of the Current Award:

- Model output will be available freely from the ARCSS DCC.

Exceptions to these time frames will be referred to the specific ARCSS project Science Management Office or Science Steering Committee and appropriate time period arrangements will be determined.

Special Issues

The ARCSS Data Protocol states that "all data collected in the course of ARCSS-funded research is considered to be ARCSS community property except where inappropriate due to moral, ethical or legal reasons." The same is true for modeling activities, but there are special issues to be considered. For example, models used and improved in ARCSS funded research may also have undergone development under the auspices of other programs, other agencies, or even private contracts. In addition, while a model may be community property, the use of that model by other ARCSS investigators may be unfeasible due to the cost of training, computer time and(or) computer storage space.

Further, inappropriate use of model output due to a lack of experience of users is a key issue. Whenever use of model output is planned by a non-modeler, it is the obligation of the user to contact the originator of the model output to determine if the intended use is suitable and scientifically defensible.

Finally, many models make use of the data of other ARCSS investigators, and in that sense the model output could be considered to be a "value-added data product" rather than truly independent information. In these cases, the modeler needs to work with the data collector to ensure that the availability and presentation of the model output is appropriate.

Model Output Formats and Archiving

The appropriate format for model output will be model dependent. In many cases, model output is too voluminous to be feasibly lodged at the DCC. Two options may be pursued in these cases:

- a subset of model output will be lodged at the DCC (e.g., monthly means), or
- a pointer to the PI's Web site can direct users to the model or to a contact person.

When the latter solution is chosen, the PI(s) must work with the DCC to ensure that pointers remain current and model output archives remain on-line and accessible. When space restrictions require that the PI(s) take the model output to off-line archives, a copy of the output on an appropriate medium (CD-ROM, tape, etc.) should be mailed to the DCC for long-term off-line storage. In addition to model output, format descriptions, and where appropriate, reading utilities, should be supplied. A statement regarding system requirements should be supplied, where relevant, as some models are sensitive to choice or version of platform, operating system, or compiler. It should be noted that model output often has a "shelf-life"; when new experiments supersede old ones, the PI(s) should work with the DCC to determine what output is suitable to retain.

Another option is to lodge a copy of the model itself, so that users can generate their own model output. In these cases, the same submission guidelines for model output will cover model versions developed under ARCSS funding.

Referencing

Citation will be given to the investigators responsible for both the model development and the specific model experiment in any and all papers using ARCSS model output. This reference will include citations of papers describing the model and the model experiment, or reference to the PI(s) if no papers are yet published. Acknowledgments should include the appropriate NSF Grant numbers and the model output location (e.g., ARCSS DCC; http://arcss.colorado.edu).

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1. Gordon Bonan and John E. Walsh were co-chairs at the time of the modeling workshop in 1996.

Workshop Abstracts

Testing the Accuracy of Arctic System Model for Simulation of Century-to-Millenia-Scale Variability

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Simulations with climate models show a high sensitivity of Arctic climate to increases in greenhouse gases. The simulated changes in temperature and sea-ice extent associated with CO_2 doubling far exceed the limits of interannual-to-decadal variability found in the historical records of the past century. One means of testing the accuracy of Arctic system model simulations of large changes of state is to subject these models to the large changes in external forcing known to have occurred in the past, and then compare the simulations with observations (COHMAP, 1988; Wright et al., 1993; Kutzbach and Gallimore, 1988).

Over the past ten thousand years, changes in the earth's orbital parameters have produced significant changes in high-latitude insolation. For example, at 6000 to 9000 years ago, high latitude insolation was increased, compared to present, by approximately 30 to 40 Wm^{-2} in summer and 4 to 6 Wm^{-2} in the annual average. The annual-average insolation increase, associated with increased axial tilt, is comparable in magnitude to the annual-average increase in downward IR associated with 2 x CO_2 (although the insolation increase occurs in summer-autumn only). During this same period, the atmospheric concentration of CO_2 was at the pre-industrial level of about 270 ppmv, almost 100 ppmv below present.

We propose to use Earth System Models, with special attention being given to Arctic systems, to simulate the changes in the Arctic (temperature, precipitation, runoff, snow cover, sea ice, soil moisture, permafrost, vegetation, sea-ice cover, ocean circulation) associated with orbital changes and CO_2 changes, at 9000, 6000, and 3000 years BP, and to compare the simulations with observations. The paleo observations, obtained from terrestrial and marine sediments, will be available from ongoing work of the NSF-funded TEMPO project, with which we are affiliated. These paleoclimate simulations, and comparisons with observations, may be the best method available for testing the robustness of Arctic System Models.

Our previous studies suggest that the mid-Holocene (~6000 years BP) was significantly warmer in the Arctic (~3 to 4°C), that precipitation increased by 10%, that boreal forests extended farther north, replacing tundra, and that sea ice and snow volume were reduced 40% (including changes in both thickness and fractional coverage) (Foley et al., 1994; Bonan et al., 1993). These results agree qualitatively with spotty paleoenvironmental evidence. We have learned that these results are quite sensitive to model parameterizations. Further modeling studies are needed with improved models, and quantitative data/model comparisons are required to assess model accuracy.

The period around 115,000 to 125,000 years ago also provides good opportunities for testing Arctic System Models. Around 125,000 years ago, summertime insolation extremes were almost twice as large as at 6000 years ago and there is evidence of considerable reduction in Arctic sea ice (Brigham-Grette and Hopkins, 1995) and major shifts in vegetation (Harrison et al., 1995; Gallimore and Kutzbach, 1995). At 115,000 years ago, the time of onset of glaciation, our model simulations show that the combination of orbital changes favoring cold summers, lowered CO_2, and expanded tundra may have triggered glaciation (Gallimore and Kutzbach, 1996).

Natural climate variability on time scales of decades to centuries should also be studied with models aimed at comparing simulations and observations. While excellent data sets exist (see, for example, Luckman, 1993; Mosley-Thompson et al., 1993), simulation studies with models will be difficult because changes in external forcing such as solar variability are small in magnitude and near the noise level of current climate models; and because internal variability (such as coupled atmosphere-ocean oscillations) is difficult to model accurately at present (Rind and Overpeck, 1993; Crowley and Kim, 1993).

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Modeling Human–Environmental Interactions in the North Atlantic

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Modeling has been widely used in the physical science components of ARCSS to investigate systems which, by the nature of the temporal or spatial constraints, cannot be controlled directly. Physical processes can be reduced to and represented by mathematical relationships which by scaling and appropriate application of numerical methods can be used to experiment with the system of interest. The art of modeling lies in simplifying the system sufficiently to be comprehensible while still capturing its essential dynamics. In the social sciences modeling has been comparatively limited in scope and objectives, and early attempts have been rightly critiqued as overly deterministic and unreflective of the rich diversity of the cultural and political aspects of the human landscape or the dynamics of human decision making. Social and historical data are often difficult to resolve into readily quantifiable units, and many study areas simply lack the data required to reasonably infer social rules and economic constraints. However, the development of fresh modeling approaches (such as rule-based and causal models which allow qualitative and information to be combined), and the development with fresh integrative social science theory (historical ecology, landscape archaeology, political ecology) provide an opportunity for productively modeling the interaction of humans and environment in regions where sufficient supporting data exist.

The initial objective of the NABO Models Working Group is to better understand the complex interactions of changing human land-use patterns, vulcanism, and climatic fluctuation in the evolution of the Icelandic landscape from ca. 1000 BC to ca. 1950 AD (from before human settlement to the near present). Iceland is an ideal location in which to develop integrative modeling: An island without significant human impact prior to Norse settlement (ca. AD 870), temporally marked by numerous well-studied tephra isochrones, with rich documentary, archaeological, and paleoecological data sets extant and under collection as part of ongoing PALE/NABO research. Iceland's historical sources include a series of detailed law codes (with extensive land-use regulation) providing normative social rules, a variety of sagas providing a literary inside view of how society was thought to operate by contemporaries, monastic annals and other documents (including the exceptionally detailed records of humans and stock begun in the early 18th century) indicating actual management strategies, and a wealth of letters, reports, and literature from the 17th to the 20th centuries. In combination with bioarchaeology and settlement archaeology, these written records provide an invaluable source of cultural rules that can be plausibly checked against actual practice over a 1200 year span that saw dramatic soil erosion, vulcanism, and climate change.

The most appropriate scale on which to model appears to be at the district or "hreppur" level. This medieval settlement unit typically comprised 15 to 30 farms and ca. 300 to 500 people and acted to manage common property and provide poor relief and buffering against accident or random hardship. Hreppar can be located archaeologically and historically and mapped onto localities and associated resources. At this scale the response of the physical landscape is resolvable from available geomorphological data. The constraint of modeling social and cultural structures suggests that a rule-based model is appropriate, with empirical data determining the social rules, and with parameterized physical process models coupled to these rules. The social rules are based on the various written sources and are coupled to the archaeological evidence of social structures and land-use practices operating during various time periods (periodization can be provided by a combination of documents and tephra). The critical issue concerns the premise that there exists a common currency meaningful both in social and environmental terms that can allow the model to place a value (not monetary) on elements of the physical landscape. In this northern pastoral society, grazing livestock units (expressed as cattle wealth units in the law codes) relate directly to pasture quality, which is determined by the ecological, geomorphological, and climatic factors at a particular locality. In social terms, wealth, prestige, power, and status are in important respects resolvable to this common currency and were recognized as such by medieval human actors in the system.

The success of the modeling is not contingent on the existence of detailed rules covering every aspect of society, nor on the generation of some single deterministic outcome. Rather, it aims to provide insight into the nature of the rough linkages between social land-use decision making, changing natural environment, and the resulting consequences for the landscape as a whole, allowing investigation of multiple alternate outcomes and the identification of spatial and historical nodes in decision trees evolving over time. Thus the model should not be considered a "predictive model" providing simplistic quantitative measures of the response of the Icelandic environment to narrowly defined natural and anthropogenic forcing, but as a heuristic device for providing qualitative judgements and improved insight into human–environment interactions beyond the well-constrained Icelandic case.

Atmospheric GCM Performance in Simulations of the Arctic Climate

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Introduction

Climate models produce very large high-latitude warming in winter, as a result of sea ice melt-back and(or) thinning (Houghton et al., 1990).

General circulation model (GCM) intercomparisons have shown major uncertainties in cloud feedback (Cess et al., 1989), snow feedback (Cess et al., 1991), and surface energy budget feedbacks (Randall et al., 1992). These are all key processes in the Arctic, where highly unusual cloud types occur throughout the year, where the surface is mostly covered with snow and ice and where the surface energy budget is very poorly understood.

The point is that some of the biggest predicted climate changes occur in a poorly observed region (i.e., the Arctic) and depend critically on processes that are not well modeled at present.

Problems with Large-Scale Dynamics

It might be thought that all of the problems relating to the simulation of the large-scale dynamics of the global atmospheric circulation have already been solved, and that now we only need to focus on the parameterized physics (e.g., sea ice and clouds). This is not the case.

Finite-difference global models have mostly been based on latitude-longitude coordinate systems. Such models have problems with numerical stability due to the convergence of the meridians at the poles; this is called "the pole problem." Solutions are available (Arakawa and Lamb, 1977), but these are imperfect and some problems remain.

Beginning in the early 1980's, global spectral models were proposed as "the solution" to the pole problem. It has recently become apparent that such models have serious problems with moisture advection, especially in dry regions such as the Arctic (Williamson and Rasch, 1994). Semi-Lagrangian methods have been proposed to solve this problem, but they are non-conservative, raising new concerns.

Several centers are now exploring a new finite-difference approach based on geodesic grids (Heikes and Randall, 1995). Time will tell whether these methods represent the final solution to the pole problem.

There is also a "cold pole problem," in that many climate models tend to produce excessively cold polar temperatures, particularly in winter. This leads to excessively strong zonal jets in middle latitudes. It has been suggested that this problem arises due to the neglect of gravity-wave drag associated with the major mountain ranges of the world (Palmer et al., 1986), but there is still some question as to whether additional model deficiencies contribute to the problem.

Problems with Clouds

Arctic clouds shield the ice from insolation, yet also increase the downwelling longwave. Arctic clouds appear to be promoted by breaks in the ice, particularly during winter.

Many GCMs do not produce Arctic stratus (Randall et al., 1985), and no GCM has yet been shown to do a good job with Arctic clouds. The observed clouds often have complex vertical structures and lie at least in part above the boundary layer. We do not know how much detail is needed in representing the vertical structure of Arctic clouds in climate models. If realistic simulation of the multilayer structure of Arctic clouds is needed, then very high vertical resolution (less than approximately 100 m throughout the lower troposphere) will be necessary. This would be quite expensive, and would probably require the use of higherorder closure to parameterize the turbulent fluxes in the clouds and boundary layer.

Sea Ice in Climate Models

Sea ice reflects solar radiation, preventing absorption by the ocean. It also insulates the atmosphere from the relatively warm sea water under the ice. Most GCMs still use very crude sea-ice submodels (Semtner, 1976), although there has been some progress (Flato and Hibler, 1992).

All climate models have to include sea-ice submodels, even though in many ways sea ice is poorly understood, and even though sea ice can cause all kinds of trouble. Sea ice is an example of a phenomenon that is so important that we have to put it into our models even though we are not really ready to do so.

Sea-ice simulations in coupled models are very sensitive to small changes in poorly understood parameters, e.g., the albedo of the ice-snow surface (Ingram et al., 1989). This sensitivity arises at least in part from the positive surface albedo feedback. Existing coupled atmosphere-ocean-sea ice models can produce realistic present-day, sea-ice climatologies only by arbitrarily tuning various sea-ice parameters. This is not necessarily due to problems with the sea-ice submodel itself.

Unfortunately, we currently have no way to predict the changes of these "touchy" sea-ice parameters that will accompany a climate change

Single-Column Models

Among the methods that have been devised to test physical parameterizations used in general circulation models, one of the most promising involves the use of field data together with Single-Column Models (SCMs; Randall et al., 1996). As the name suggests, an SCM can be considered to be a grid column of a climate model, considered in isolation from the rest of the model. Observations are used to specify what is going on in "neighboring columns," and observations may or may not also be used to specify tendencies due to some parameterized processes, other than those being tested. The results obtained for one observation time are used to predict new values of the prognostic variables, which are then provided as input for the next observation time. An SCM run can test a parameterization or a suite of parameterizations without complications from the rest of the global climate model, and is very inexpensive, but has demanding data requirements.

Randall et al. (1996) give examples to illustrate how SCMs can be used to investigate basic physical questions, develop cloud amount parameterizations, and evaluate the sensitivity of model results to parameter changes. SCMs are particularly valuable for testing parameterizations of cloud formation, maintenance, and dissipation, but they can also be used to test sea-ice parameterizations, for example.

Among the data needed are time varying vertical profiles of the large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. These are, of course, particularly troublesome quantities to observe, and in fact they can only be obtained by very indirect means, which have been developed to overcome problems with missing data, instrument errors, and incomplete spatial and temporal coverage. Objective analysis methods can be used to combine measurements from various sources (e.g., rawinsonde data, wind profilers, etc.) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. A second approach is to make use of products obtained through data assimilation at the operational numerical weather prediction centers. Although such products are readily available and offer high-resolution global coverage with, potentially, high time resolution as well, the physical parameterizations of the forecast model do affect the results, particularly in data-sparse regions. This is a particularly worrisome problem for vertical motion and water vapor.

Collection of datasets suitable for the application of SCMs to the Arctic is a particularly challenging problem because of the lack of data over the Arctic Ocean.

Conclusions

Existing GCMs have problems with simulating large-scale dynamics, clouds, and sea ice of the current Arctic climate. There are proposed solutions for all three problems, and some of these proposed fixes are best tested through "Single-Column Modeling." The data requirements of Single-Column Models are quite difficult to satisfy, however.

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Advanced Modeling Studies of the Arctic Ocean and Sea Ice—Toward Better Understanding of the Arctic System

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Introduction

Variability in sea ice and fresh water outflow from the Arctic Ocean into the Nordic Seas and then into the North Atlantic may change the global ocean circulation which in turn will cause significant climate change. The current global overturning cell in the ocean, the so-called conveyor-belt circulation, results in poleward heat redistribution from the equator that maintains anomalously warm winters in the northern Europe. The global thermohaline circulation is controlled in two ways by water and ice transported out of the Arctic Ocean. In the first case, a mixture of deep and intermediate waters formed on the Arctic shelves and in the open ocean, overflows the Scotland-Iceland-Greenland ridge system to begin its way around the world oceans as North Atlantic Deep Water (NADW). The flux of NADW controls the intensity of the meridional overturning cell including poleward heat fluxes. In the second case, an excess of fresh water and ice flux from the Arctic Ocean may lead to a temporary shutdown of the conveyor (or flux of NADW), resulting in the halocline catastrophe, a scenario proposed for past deglaciations (Charles and Fairbanks, 1992). The northern North Atlantic "Great Salinity Anomaly" (GSA) of the 1960s and 1970s is considered to be a small-scale analog of the halocline catastrophes. The GSA did not require dramatic increases in fresh water and ice flux nor did it depend on deglaciation but it still resulted in a capping of the deep convection in the Nordic Seas.

It is believed that the present day Arctic Seas are delicately poised with their ability to sustain convection and anomalies in fresh water/ice flux from the Arctic Ocean could be critical to the nature of the thermohaline circulation and hence global climate. Deep water formation, the most important climatic feature of the Arctic Ocean (Broecker, 1991), appears to be dominated by two important processes which do not occur in other oceans: (1) Mixing driven by shelf-slope flows and (2) open ocean convection. The details of these processes are mainly local but the effects are basin-wide.

Neither shelf-slope processes nor open ocean convection is accurately reproduced by large-scale general circulation models, what explains why so far the Arctic Ocean has been omitted in global ocean models. Different predictions of polar amplification by climate models simulating warming due to increase of CO_2 in the atmosphere, can in fact originate from those models inability to parameterize effects of high-latitude processes on the global ocean. For numerical simulations to account for the physical realism of a basin circulation, model grid size should be approaching the local radius of deformation, which for the Arctic Ocean is five to ten kilometers. A physically realistic model of the Arctic Ocean should be able to simulate processes from small to large scales, such as: (1) local distribution and dynamics of coastal sea-ice divergences, (2) cross-shelf transport mechanisms, (3) local scale chimneys, (4) open ocean plumes, (5) shelf-deep water lateral entrainments, (6) mass transport of gyre boundary currents and variability due to eddies, and (7) water exchanges in Fram Strait and through the Canadian Archipolago and overflow into the North Atlantic. These physical processes must be first quantified in order to improve our predictive understanding of decadal-to-century scale changes in the Arctic system and to narrow uncertainties in global climate model predictions of polar amplification. The dynamics of the Arctic

Ocean and sea ice need to be understood relatively well in order to address interactions among the Arctic system components and their influence on and response to the state of the global environment.

Modeling Considerations

Based on experience with global eddy-resolving models using state-of-the-art computing technology (Semtner, 1993; Dukowicz and Smith, 1994), a high resolution coupled Arctic Ocean/Sea Ice model has been developed. The model domain extends beyond the Central Arctic and includes the Nordic Sea, Canadian Archipelago, and Subarctic North Atlantic. The ocean model is a modified free-surface version of the Semtner and Chervin (1992) parallel-vector code, which allows realistic unsmoothed bathymetry. Tidal forcing can be included if desired. The ice model is a version of the thermodynamic-dynamic sea-ice model of Hibler (1979) with more efficient (Zhang and Hibler, in press) numerics.

Results from a 6-year test integration of the $^1/_6$-degree ocean model (approximately 18 km and 30 vertical levels) and the sea ice model are shown. These are compared to results from a coupled version of the two models. To allow longer-term integrations for studying deep water formation and circulation, the Parallel Ocean Model (POP) of Los Alamos has been adapted to the Arctic Ocean. Multi-decadal simulations at $^1/_6$-degree on the massively parallel Cray T3D/128 computer at the Arctic Region Supercomputing Center are presented. A case study is discussed for Pacific Water circulation in the Arctic Ocean using silica as a neutral tracer entering through the Bering Strait. This example shows the potential of the high resolution coupled Arctic Ocean/Ice model for biogeochemical studies such as carbon cycling, biological productivity, and radionuclide dispersion.

Some results from more ambitious tests of the massively parallel, eddy-resolving Arctic Ocean model with $^1/_{12}$ degree horizontal resolution and 40 vertical levels are described.

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Modeling Land-Surface Processes for Climate Models

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Land surface process models provide the surface boundary conditions required by atmospheric models. These include:

- Albedos.
- Upward longwave radiation.
- Sensible heat flux.
- Latent heat flux.
- Constituent fluxes (e.g., H_2O, CO_2).
- Surface stresses.

I will present results from a land-surface model LSM version 1 coupled to the most recent version of the NCAR Community Climate Model. This land surface model is a one-dimensional model of energy, water, momentum, and CO_2 exchanges between the atmosphere and the land accounting for: ecological differences among vegetation types; thermal and hydraulic differences among soil types; and multiple surface types, including lakes and wetlands, within a grid cell.

Processes simulated by the model include:

- Radiative transfer.
- Turbulent transfer.
- Partitioning latent heat into transpiration, canopy evaporation, and ground evaporation.
- Stomatal physiology.
- Photosynthesis, respiration, and net primary production.
- Hydrology: interception, throughfall, infiltration, runoff.
- Snow processes: albedos, accumulation, melt.
- Temperature and water for a six-layer soil column.

Special emphasis will be placed on the Arctic simulation and land-surface processes that are important in high latitudes.

A Qualitative Modeling Approach to Vegetation-Climate Interactions

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Vegetation is the key integrative landscape parameter for the Arctic system; it follows that understanding Arctic vegetation-climate interactions is the key to understanding the terrestrial system. Two of the most important interactions related to ongoing ARCSS research are: (1) vegetation is both a function of and a feedback to climate, and (2) abundance and quality of vegetation influences population size and quality of key subsistence food resources, particularly caribou. In both these examples, the transient changes in vegetation over decades to centuries are critical to modeling the future state of the Arctic system and how people can influence or prepare for these changes.

Modeling landscape parameters such as vegetation introduces difficult problems of choosing appropriate time and space scales and determining appropriate levels of resolution. We introduce a pragmatic top-down modeling approach that begins with construction of a simple, qualitative model, with minimal time and programming investment, with the aim of first testing the basic model construct and logic, and then either rejecting the model or incrementally adding detail as needed. The goal is that at any stage of the process, there is a working model that can be tested, discussed, and refined. This promotes interaction between modelers and other participants in the process, which may include scientific specialists, managers, decision makers, or community members.

We illustrate the approach with two specific examples of work in progress. The first example is a model to predict transient dynamics of northern treeline over the next 400 to 500 years. The model considers a 25 km^2 patch of upland tundra and concentrates on the key processes that are likely to cause the vegetation in the patch to switch to a conifer forest, a broad-leafed deciduous forest, or even a dry grassland. Results are obtained for various scenarios of climate change (different rates of temperature increase as well as drier or wetter conditions) and human interventions (as represented by fire frequencies, and potential densities of moose and other herbivores (Starfield and Chapin, in press). This model will eventually be input to and output from a vegetation map of Alaska, so that it can be linked to climate models being developed by other ARCSS projects and components.

The second example relates to an interdisciplinary study of the sustainability of northern communities, a newly funded ARCSS project. The primary science goal of the project is to determine the influence of policies and institutions on ecological interactions and outcomes. Here the same top-down approach is offered as a technique for building successively more detailed models to synthesize the interactions between climate, vegetation, caribou herd demography and migration routes, development, and the demography, well-being and economics of village communities. Simple, qualitative models are being developed early in the project to facilitate communication and interaction among components; this in contrast to incorporating component models in one grand system model at the end of the project.

Each subsystem (vegetation, caribou, development, institutions, and households) is developing its component models independently, but in all cases the inputs and outputs are being designed to fit into the above construct. The vegetation modeling, for example, is based on a hierarchical approach that uses history, temperature, moisture, and site nutrient status as static controls at increasingly fine spatial scales. Dynamics are controlled by life history and functional traits, with controls for traits determined by the state variables. Thus, the model will interact with the synthesis model or other component models, such as the caribou population model, at a variety of time and space scales, as appropriate.

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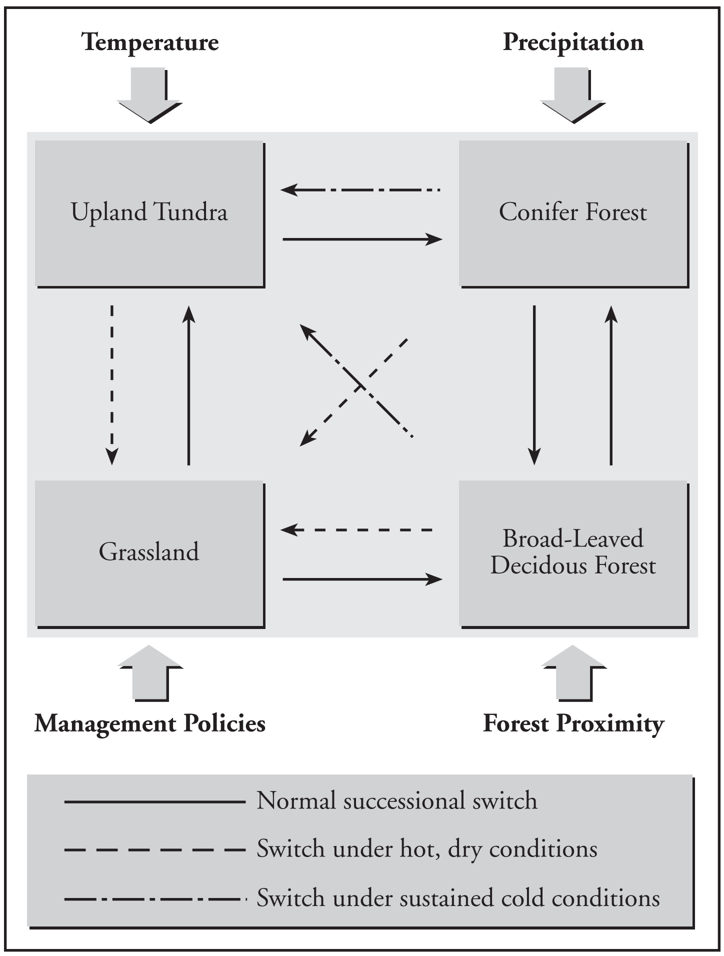

General model structure showing major ecosystem types (frames) and the switches that occur among the ecosystems under normal and abnormal climatic conditions.

The Arctic Region Climate System Model: Development and Performance over Arctic Tundra

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The Arctic Region Climate System Model (ARCSyM) has been developed for the study of ocean-ice-atmosphere and land-atmosphere interactions in the western Arctic. As part of the ARCSS LAII Flux Study, the goals of this work are:

- To provide a model for integration and interpretation of observations obtained from Arctic field programs.
- To assess the performance in the western Arctic of various land-surface/vegetation parameterizations currently available for climate modeling.
- To project climate and hydrological changes in the Arctic due to increases in atmospheric CO_2.
- To produce regional estimates of CO_2 fluxes from tundra under current and projected climate regimes.

Work is proceeding in two phases. The first is an assessment of the performance of a set of land-surface/vegetation models when forced by observed data from the Flux Study field sites (stand-alone mode). The second is the implementation of these models in ARCSyM, and an examination of their impact on the skill of the climate simulation (coupled mode). The models chosen for study are:

- Biosphere-Atmosphere Transfer Scheme (BATS Version 1E; Dickinson et al., 1993), a scheme which is used widely in global climate system models.
- Land Surface Model (LSM; Bonan, 1991), a scheme which models CO_2 exchange processes.
- Canadian Land-Atmosphere Scheme (CLASS, Verseghy, 1991; Verseghy et al., 1993), a scheme with a sophisticated treatment of snow cover and permafrost.

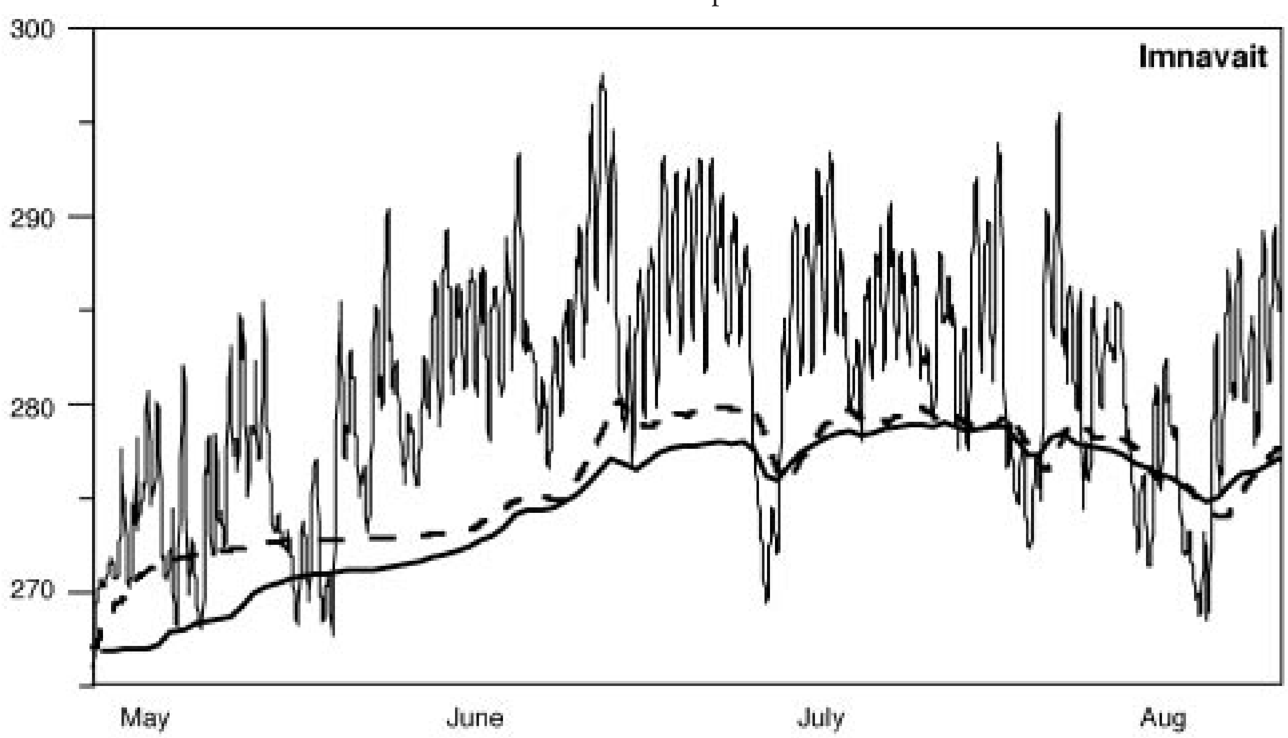

Fig. 1. LSM simulated soil temperature (30 to 70 cm average, dashed bold line) and a comparable measured soil temperature (30 to 65 cm average, solid bold line), in response to hourly atmospheric forcing (3 m air temperature, solid line).

CLASS is still being implemented, and hence only results of experiments with LSM and BATS will be presented here.

The stand-alone tests with LSM were performed using hourly Summer 1992 data from three Kane/Hinzman meteorological sites: Imnavait, Sagwon, and Deadhorse. The time period and sites were chosen for the completeness of the records, requiring minimal data interpolation, and availability of verification data. An example of the forcing data and model output is shown in Fig. 1. Following the model spin-up period (approximately one month), the LSM model response shows generally good agreement to the measured soil temperatures. Response to changes in forcing are sometimes too extreme, particularly in the early part of the summer, but by the end of the simulation period correspondence is very close.

Coupled experiments using the ARCSyM model with LSM and BATS were performed for the months of January and August 1992. In the simulations with BATS, there is a tendency for dryness, with winters too cold, and summers too warm (Lynch et al., 1995). The simulations with LSM reduce these biases considerably. An example of this behavior is given in Fig. 2, which shows the differences in January surface air temperatures between the ECMWF analyses and the ARCSyM-BATS and ARCSyM-LSM simulations respectively. The moistening effect of LSM is due to increased retention of water in the soil column, subsequently being available for evaporation. The differing temperature response is partly due to changed cloud distributions in response to this moistening effect, but clear sky albedo also has an impact. In general, the circulation produced by both model configurations showed good agreement with observations. Detailed analysis of the model results is continuing. Following the full investigation of model performance over an annual cycle, ARCSyM-LSM will be used to produce regional estimates of CO_2 net productivity over the annual cycle.

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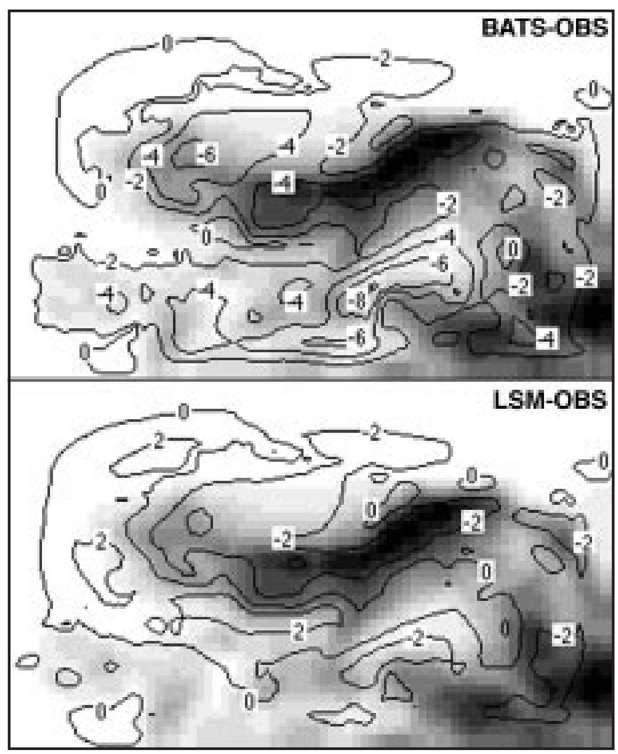

Fig. 2. Differences from EXCMWF observational analyses for mean January surface air temperature in Kelvins for the simulation using ARCSyM-BATS and that using ARCSyM-LSM.

Using Integrated Terrestrial Models to Examine Long-Term (~10^2 to 10^3 years) Variability in the Arctic Biosphere-Atmosphere System

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Changes in the state of Arctic terrestrial systems are of considerable importance to the Earth system as a whole. It is therefore necessary to develop more integrated models of terrestrial processes that will include a range of ecological, physiological, hydrological, and atmospheric processes in a single, physically consistent modeling framework. Such an integrated perspective would reconcile the disparity among existing models by including the following: land-surface processes (energy, water and momentum balance of the soil-vegetation-atmosphere system); ecosystem physiology and carbon balance; vegetation dynamics; soil biogeochemistry and nutrient cycling; and regional-scale hydrology. We are currently developing such a model—the Integrated Biosphere Simulator (IBIS).

We will discuss how such an integrated modeling approach may be used to examine the dynamic interactions between vegetation cover, land-surfaces processes and the climate system on a variety of timescales. In particular, we discuss how changes in vegetation and surface waters, induced by long-term variations in climate, may alter land-surface processes and, hence, feed back on the climate system. Preliminary work with climate and vegetation models has already demonstrated important feedback mechanisms between the Arctic climate and vegetation during the recent geologic past.

Temporal and Spatial Scaling of Carbon Storage in Arctic Tundra Using a General Ecosystem Model

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We use a general ecosystem model (MBL-GEM) to examine biogeochemical constraints on ecosystem responses to changes in CO_2 concentration, temperature, and soil moisture in Arctic moist tussock tundra. The model was calibrated to experimental data on the responses of moist tundra to fertilizer, greenhouse warming, and shading (Chapin et al., 1995) and to increased CO_2 (Oechel et al., 1987). We then use the model to reconstruct changes in ecosystem C storage over the last 160 years based on ice-core (Neftel et al., 1985) and Mauna Loa (Keeling et al., 1982) CO_2 records and tree-ring temperature records (Garfinkel and Brubaker, 1980). Our model indicates a rate of C storage of between 1 and 5 g C/m^2/yr over most of that period if soil moisture is assumed constant (Fig. 1). However, varying soil moisture has a striking effect on C storage. Because changes in soil moisture could not be reconstructed, we assumed a "worse-case scenario" in which the soil was assumed to have a 100% water-filled pore space (WFPS) at the coldest temperature in the record, and was assumed to have 60% WFPS at the warmest temperature in the record. The 60% WFPS was assumed to be the optimum soil moisture for microbial processes in the soil. Under this "worst-case scenario," our model predicts a major loss of soil C during a warming in the mid 1800s followed by a general increase in ecosystem C since about 1890 (Fig. 2). This increase in C since 1890 is not enough to recover C lost during the warming, is far more variable than in the simulation with constant soil moisture, and is characterized by large episodic C losses of as much as 190 g C/m^2/yr. Losses of C since 1987 are among the largest in our reconstruction.

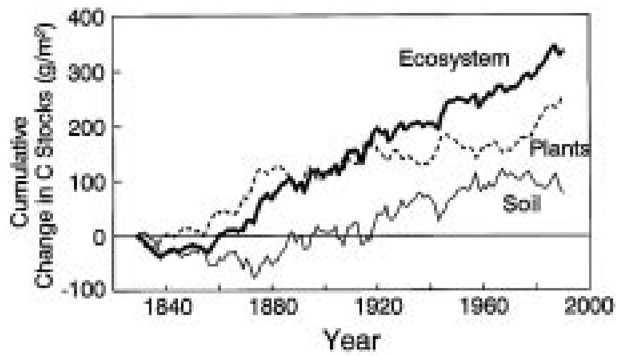

Fig. 1. Response to increased CO_2, temperature, and constant soil moisture.

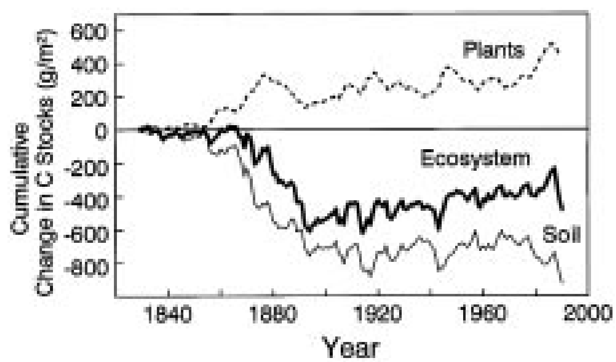

Fig. 2. Response to increased CO_2, temperature, and drier soil.

We also examine responses of tussock tundra to a doubling of CO_2, a 5°C increase in temperature, and a ±10% change in WFPS in soils. Our analysis indicates significant synergistic interactions among these factors. For example, a 5°C increase in temperature alone increased ecosystem carbon stocks by 53 g C/m^2 over 50 years. A 10% decrease in WFPS decreased carbon stocks by 189 g C/m^2 over the same period. However, in combination an increase of 5°C in temperature and a decrease of 10% in WFPS decreased carbon stocks by 967 g C/m^2 in 50 years.

In addition to the temporal scaling illustrated above, we examine the responses of tundra to the natural environmental gradient found across the whole Kuparuk Basin. We first calibrated the MBL-GEM to the responses of wet sedge tundra to the fertilizer, greenhouse warming, and shading experiments described above. We then use the model to estimate changes in ecosystem carbon storage over the entire basin based on environmental measurements. For each site we estimated net primary production based whether the ecosystem was wet sedge or moist tussock tundra and on the temperature. The productivity of wet sedge tundra is higher than tussock tundra at all sites. The temperature changes across the basin caused productivity in the foothills of both tundra types to be 1.8 times higher than the productivity on the coastal plain.

The synergistic interactions in nature among temperature, soil moisture, and CO_2, make it impossible to assess future responses to climate and CO_2 based on single-factor experiments alone. Process-based models like MBL-GEM can help improve such assessments by providing a self-consistent synthesis of the results of many experiments. The synthesis provided by these models includes the interactions among ecosystem processes that give rise to the synergistic responses to multiple factors.

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Hydrological and Biogeochemical Modeling at the GCM Scale: A Watershed Approach

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While large basin river chemistry is well-known, the processes by which materials move from the hillslope to streams and rivers are poorly understood. Therefore, there is a need for a land-surface model that can operate on the scales of whole river basins and can simulate not only the surface energy fluxes to the atmosphere, but also the flux of water, nutrients, organic matter, and trace gases to Arctic streams and rivers. The approach taken here is to start with an existing land-surface model (Stieglitz et al., subm.) which incorporates the analytic form of TOPMODEL equations and is capable of simulating basin run-off, soil moisture heterogeneity, and surface energy fluxes from both saturated and unsaturated regions of the basin without the need to resort to finite element modeling. With the support of NOAA and NFS's LTER we are now applying this to Arctic watersheds. Further, we are incorporating plant-soil and biogeochemistry models such that the flux of nutrients, organic matter, and CO_2 from the hillslope to the stream and river system can be simulated, as well as the flux of CO_2 between the atmosphere and the terrestrial biosphere.

The advent of TOPMODEL, a conceptual rainfall-runoff model (Beven and Kirkby, 1979; Beven, 1986a,b), has provided hydrologists with a powerful tool to: 1) analytically calculate the hillslope response of site-specific topography without the need to resort to finite element modeling, and 2) operate at large watershed scales by using the statistics of the topography, rather than the details of the topography itself. We incorporate the analytic form of TOPMODEL equations into a new single-column, land-surface model which tracks the mean state of the watershed. This single-column model includes six soil layers and diffusion and a modified tipping bucket model governs vertical heat and water flow, respectively. The prognostic variables, heat and water content, are updated each timestep (hourly). In turn, the fraction of ice and temperature of a layer may be determined from these variables. A three-layer snow model (Lynch-Stieglitz, 1994) and a modified BEST vegetation scheme (Pitman et al., 1991) have been incorporated into this scheme. The analytic form TOPMODEL equations and Digital Elevation Model data are used to generate baseflow which supports lowland saturated zones. Soil moisture heterogeneity represented by saturated lowlands (predicted by TOPMODEL equations) subsequently impacts watershed ET, the partitioning of surface fluxes and the development of the storm hydrograph. This approach to land-surface modeling moves away from the perspective often taken in GCMs where each grid cell represents a vertical soil column, and towards a model where the fundamental unit is the watershed. Lynch-Stieglitz (1994) and Stieglitz et al. (subm.) discuss model validation at the Sleepers River watershed.

The plant-soil system and soil biogeochemistry are modeled as follows. Carbon is sequestered from the atmosphere via plant photosynthesis. Carbon and nitrogen are then mineralized via plant/root respiration and the microbial decay of soil organic matter. The release of soil generated CO_2 is partitioned between the gaseous and dissolved phase via Henry's law and diffusion governs the transport of gaseous soil CO_2 vertically through the soil column. Plant uptake and microbial immobilization compete for the soil nitrogen pool and the net mineralized nitrogen pool is partitioned between an adsorbed and dissolved phase. DOC is calculated from the state of the soil moisture, temperature and CO_2 respiration rates. From knowledge of the dissolved concentrations of CO_2, nitrogen, and DOC at various depths, along with the depth to the water table, these dissolved pools can then be transported from the hillslope to the stream system.

While the short term goal of this work is to produce a physically based hydro-biogeochemistry land-surface model for Arctic environments, the longer term goal includes coupling to a GCM and operating at a variety of climatic regimes and spatial scales.

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Towards Improved Parameterization of Ice/Atmosphere/Ocean Interactions in Climate Models

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Accurate simulation of the Arctic Ocean sea ice is a critical challenge for regional and global climate models. Such a simulation depends on accurate parameterization of sea-ice thermodynamical and dynamical processes as well as the interactions of sea ice with the atmospheric and oceanic boundary layers. In this talk I give an overview of modeling efforts currently underway to address these topics, including recent and ongoing work at CU. A particular theme of this talk is the ice physical processes that must be included for correct coupling of the ice with the atmosphere and ocean, particularly with regards to radiation and the ocean salt balance. A perspective is given on the following issues:

- Coupling of ice dynamics and thermodynamics in the presence of an ice thickness distribution and a distribution of surface types.
- Influence of statistical heterogeneity of the ice upper and lower surfaces on ice/atmosphere and ice/ocean interfacial fluxes.
- Evolution of the cloudy boundary layer.
- Ocean mixed-layer/pycnocline interactions.
- The role of leads in the atmosphere/ocean coupling

A hierarchical modeling approach will be described in developing parameterizations that can be used for climate models, including the use of Large-Eddy Simulations of the atmospheric and oceanic boundary layers.

The role of the field data from SHEBA in improving and testing parameterizations will be discussed. A strategy will be described for using the models in setting measurement priorities and strategies for SHEBA.

Testing GCM Parameterizations of Ocean/Atmosphere/Ice Interactions with Data from Short-Term Process Studies

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The problem of treating climate change as a response to external forcing is inherently global, requiring the use of Global Climate Models (GCMs). In the long run, the value of ARCSS research will depend to a significant degree on the accuracy with which future Arctic climate can be simulated and predicted as a response to external forcing functions that are to some extent predictable. Among these are anthropogenic emissions of carbon dioxide and aerosols, and Milankovitch variations in earth's orbital parameters. Both the high sensitivity and wide variation in the simulated Arctic response of GCMs depend significantly on the model formulations of thermodynamic and hydrologic interactions occuring in a thin layer that we identify with the ocean/atmosphere/ice interface (OAI). Therefore, an important goal of ARCSS research is to develop improved models of OAI processes that reduce the uncertainty in GCM simulations of climate response in the Arctic.

To test and improve models for the OAI elements of GCMs requires data/model comparison experiments that (a) isolate the OAI processes from other model components, (b) provide links between evaluations of performance on observable time scales, and on time scales applicable to climate change, that are not observable in advance, and (c) bridge the gaps in spatial and temporal scales between the observations and the GCMs. Items (a) to (c) pose formidable challenges to any process-oriented experiment designed to improve the accuracy of models used to simulate global climate change.

A framework is presented in which two types of measurements, "local" and "survey," are available over a single annual cycle, for application to OAI model evaluation and development.

The OAI processes are isolated from other model components by distinguishing a set of internal OAI variables (e.g., ice thickness distribution, surface temperature, surface albedo, ice temperature, upper ocean temperature) from a set of external forcing variables (e.g., downward shortwave spectral irradiance, downward longwave spectral irradiance, PBL air temperature, PBL wind speed, halocline properties).

Performance of a candidate OAI model is evaluated in two parts. Given the measured state of the OAI internal variables and the measured external forcing variables: (a) Does the candidate model produce accurate lower boundary conditions for an AGCM, and accurate upper boundary conditions for an OGCM? (b) Does the candidate model produce an accurate time rate of change for the OAI internal variables? Evaluation of (a) and (b) requires that the local measurements be averaged spatially and temporally to scales compatible with the resolution of GCMs, and that the time series of observations encompass significant changes in the OAI variables that are driven by the measured forcing.

The approach is illustrated using a synthetic, internally consistent data set to drive two different models of the OAI processes. The problem of defining a spatial scale appropriate for aggregating local measurements to obtain area averages is illustrated for ice thickness and surface temperature. The fluxes of enthalpy, radiation, and water vapor are evaluated as lower boundary conditions on the atmospheric GCM and the fluxes of enthalpy, radiation, and salinity are evaluated as upper boundary conditions on the oceanic GCM.

Some implications of this procedure for SHEBA, and for the general development of an Arctic system model, are discussed.

Anticipating SHEBA Upper Ocean Modeling Issues by Revisiting the Arctic Ice Dynamics Joint Experiment (AIDJEX) Summer 1975

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In 1997-98, a major ARCSS initiative named Surface Heat Budget of the Arctic (SHEBA) will maintain a manned station for an annual cycle on perennial pack ice over the Canada Basin north of Alaska. A significant component of SHEBA is aimed at understanding the impact of heat flux from the ocean on the ice energy and mass balance. A major challenge will be synthesizing measurements made in the Lagrangian reference frame of the drifting ice station into parameterizations appropriate for both sophisticated ice/ocean/atmosphere coupled models, and for relatively coarse resolution global climate models.

In 1975-76, the Arctic Ice Dynamics Joint Experiment (AIDJEX) fielded an array of manned stations in the Arctic Ocean which drifted near the proposed SHEBA site for more than a year. In addition to surface velocity, data from the AIDJEX stations included incoming shortwave radiation, limited ice thickness measurements, plus daily profiles of upper ocean temperature and salinity. Using a heat transfer coefficient developed from measurements made in the 1980s, Maykut and McPhee (1995) examined heat flux from the ocean mixed layer to the ice during AIDJEX, and found that most of the oceanic heat flux occurred over a 100-day period beginning in mid-June. It resulted from solar heating of the mixed layer through open leads and thin ice rather than by conduction or entrainment of oceanic heat from the underlying halocline. Indeed, during AIDJEX there is some evidence that the mixed layer contributed heat to the halocline. Advection was also found to play a major role in upper ocean heat and salt budgets as the stations drifted with respect to the underlying water column. For example, at all stations the average salinity in the upper 50 m increased over the melt season, despite an estimated total ice melt of 0.75 to 1.25 m. Thus for the upper 50 m of the water column, advective flux divergence overrode a relatively large surface fresh water flux.

A numerical upper ocean model based on the mixing length formulation of McPhee (1994) is used to assess quantitatively evolution of upper ocean temperature and salinity structure observed during the AIDJEX melt season, in terms of surface momentum and buoyancy flux. To drive the model, surface stress and solar heating were prescribed following Maykut and McPhee (1995). Surface buoyancy flux, which depends almost entirely on salinity flux (melting), was estimated both from total ice melt using Maykut's kinematic ice model (Maykut and McPhee, 1995), and from consideration of the change in mixed layer salinity with respect to the 40 m level. Results reproduce reasonably well the formation of the seasonal pycnocline, yet illustrate the sensitivity of ocean heat flux to local ice divergence and the importance of advective effects on both salinity and temperature. The model results are used to discuss possible pitfalls in interpretation and modeling of anticipated SHEBA data, and to recommend design considerations for the SHEBA field experiment.

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Improving the Simulation of Sea Ice in Oceanic and Atmospheric GCMs

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A variety of research has identified polar regions as especially sensitive components of the global climate system. Paleoenvironmental evidence suggests that polar climates vary widely on time scales of decades to millions of years. Modeling experiments with GCMs involving future scenarios with doubled CO_2 (e.g., IPCC, 1990) and past climates under altered orbital configurations (e.g., Mitchell et al., 1988) have shown that high latitudes should respond most strongly to global climate changes. GCM results have attributed this strong sensitivity to the positive feedbacks associated with changes in snow and sea-ice cover, both by areal reductions in ice as well as by internal processes in multiyear pack ice. However, there are indications that the actual sensitivity is not properly known, due to inadequate representation of physical processes in models and the lack of a comprehensive observational data base to validate paleoclimatological simulations. Large-scale models have traditionally incorporated sea ice in a rather crude manner, treating it as a slab of uniform thickness—often without leads—using simple parameterizations for albedo and lateral and vertical ablation. These shortcomings may not be noticeable in simulations of the modern ice pack, because the model may be tuned to compensate for these biases. However, these shortcomings could severely hinder accurate predictions of polar climates which differ substantially from the present.

We are developing a sea ice model to be coupled with a GCM that includes more of the essential physics needed to determine the response of pack ice under altered external forcing. The ice model draws on components from several existing sea-ice models. These features include leads, melt ponds, parameterized ice dynamics, a crude ice thickness distribution, a sophisticated albedo parameterization, and a prognostic ocean-ice heat transfer (basal heat flux) which is controlled by the amount of solar radiation entering the ocean. AGCMs and OGCMs have generally neglected most of these features. OGCMs, such as the one used here, are useful for assessing the robustness of the Arctic Ocean's pycnocline under altered sea ice regimes and the extent to which sea ice changes may affect convective overturning in the North Atlantic. AGCMs may be used to estimate the net effect of multiple feedbacks induced by a perturbed climate, such as changes in Arctic cloudiness and poleward atmospheric heat convergence into the Arctic Basin.

In addition to the local effect of atmospheric and oceanic forcing within the Arctic Ocean, the ice cover may also be sensitive to conditions over adjacent land masses. For example, the terrestrial thermal regime influences properties of air masses advected over the Arctic Ocean, and the hydrologic regime affects continental runoff. Therefore, it will be important to incorporate these processes into GCMs by improving land surface packages.

The interaction between solar energy absorbed by the ice-ocean system and ablation within the pack ice constitutes a strong positive feedback mechanism which may be important for explaining past and future changes in Arctic sea ice and climate. This feedback may be especially important in the central Arctic, which experiences significant millennial-scale insolation variability due to orbital cycles. An effective way to diagnose the century-millennial scale variability of Arctic sea ice is to hindcast past responses, such as the mid-Holocene warm period, the last glacial maximum, and the previous interglacial, and then to compare the results with observational evidence for these time periods. Adequate agreement between the simulations and data would support GCM projections of extreme polar warming due to increased CO_2. Large discrepancies would lead to improved sea-ice models, by identifying which feedback mechanisms are inadequately represented, and to an improved understanding of the Arctic climate system.

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Table 1. Current state of sea ice in three GCMs.

Variable	**CCM 1**[1)]	**GENESIS 1.02**[2)]	**MOM + Ice**[3)]
Surface albedo	*f*(Sfc. temp., snow, λ)	*f*(Sfc. temp., snow, λ)	*f*(Sfc. temp., snow)
Basal heat flux	Constant	Ad hoc *f*(ocean temp.) + constant	*f*(ocean temp.) [no heat storage]
Leads	None	Ad hoc *f*(ocean temp.)	*f*(energy input & lead fraction)
Ice motion	None	Cavitating fluid approximation	Viscous-plastic rheology
Ice thickness distribution	None	Uniform distribution when melting	First year/multiyear
Melt ponds	None	None	None

[1)]Version one of the Community Climate Model (Williamson et al., 1987)

[2)]Version one of the Global Environmental and Ecological Simulation of Interactive Systems (Thompson & Pollard, 1995)

[3)]Modular Ocean Model coupled to sea ice code (Weatherly & Walsh, 1996)

Historical Evidence for Past Temperature and Sea-Ice Variations: Models for Social Impact in Iceland

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There are excellent documentary data for Iceland which give detailed evidence regarding climatic parameters such as temperature and precipitation. These exist from medieval times, but become prolific from about A.D. 1600 onwards. Main examples of these documents are: Weather diaries; annals; travel accounts; early newspapers; private and official letters; and early instrumental data (Ogilvie, 1992). These data also give information on sea ice reaching the coasts of Iceland (Ogilvie, 1992, 1996). Although the causes of sea ice are a complex mix of atmospheric and marine conditions, and the correlation between sea ice and temperature is by no means perfect, the incidence of sea ice off the coasts of Iceland is a further useful proxy indicator of climate (Bergthórsson, 1669; Ogilvie, 1992; Ogilvie 1996).

On the basis of analyses of these documentary data it has been possible to construct decadal indices which give clues regarding temperature and sea-ice changes in Iceland from 1600 onwards. It is notable that conditions vary quite markedly in different parts of Iceland. The southern part, for example, can be seen to be milder than the north (Ogilvie, 1984a). This is borne out by modern instrumental data. Noteworthy periods are, for example, the noticeably mild period which occurred around ca. 1641 to 1670, precisely in the middle of what has traditionally been regarded as the 'Little Ice Age.' The 1690s, 1740s, 1750s and 1780s were interesting decades, undoubtedly much colder than today (Ogilvie, 1984a; Ogilvie, 1992).

It is clear that to answer the question of what impacts climatic factors may have had on a given society at a certain time is inordinately complex (Wigley et al., 1985). It is helpful, however, to construct models, even simple ones, in order to facilitate the analysis. These may include the consideration of atmospheric and marine environments, social and political conditions, and economic activities, to name but a few. It can also be useful to establish exactly what form of impact climate might be expected to have on a particular aspect of society. In other words, whether climate might have had a direct (biological and physical) or an indirect (socio-economic) impact (Ogilvie, 1984b; Ogilvie, 1995). 'First-order' impacts may include such aspects as the cultivation of grain, grass growth and hay yield, sea fishing, and thermal effects on domestic animals and humans. Indirect or 'higher-order' impacts may relate, in the case of Iceland, to livestock mortality and to certain forms of social crisis which followed a failure of food sources: the desertion of farms, begging and crime, and human disease and mortality (Ogilvie, 1981).

It is not difficult to demonstrate that climate is of importance for processes that are low on the food chain, such as the growing of grass for hay. The influence of temperature on livestock mortality is also easy to demonstrate by statistical means. Further to this, in decades where there were heavy losses of livestock in five or more winters, several years of social crisis involving desertion of farms, crime, begging and human mortality followed. These latter, 'higher-order' impacts are, however, as might be expected, much more difficult to establish as being precipitated by climate than first-order impacts.

During the period 1601 to 1780 in Iceland, many years of social crisis coincided with years of severe weather. The greatest difficulties were undoubtedly experienced when a number of severe seasons followed each other as in the 1690s, 1740s and 1750s. In conclusion, however, it is important to remember that many factors other than climate were at play; not least economic and political conditions.

Acknowledgements

Funding from the LeverhulmeTrust, U.K. (Grant no. F204L) and the National Science Foundation, U.S.A. (Grant no. OPP-9418845) is gratefully acknowledged.

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Cloud-Resolving Simulations of Warm-Season Arctic Stratus Clouds: Explanatory Modeling of the Cloudy Boundary Layer

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High-latitude cloudiness plays an important role in the global climate and hydrologic cycle, yet Arctic stratus clouds and the dynamics which create and maintain them remain relatively unexplored. The importance of Arctic stratus clouds (ASC) to the Arctic climate cannot be overstated—presence of ASC increases downward longwave radiation fluxes by over 100 Wm^{-2}, whereas a CO_2 doubling directly increases the longwave flux by only four to seven Watts per square meter. Effects on the atmosphere/cryosphere moisture budget can be large as well. While the response of the atmosphere to the large variations in surface fluxes found at high latitudes is known to be significantly modulated by clouds, the three-dimensional interactions among radiation, cloud microphysics, and turbulence are poorly understood. To improve our understanding of ASC, we are running the Regional Atmospheric Modeling System (RAMS) in a high-resolution, cloud-resolving mode. Focusing on the northern coastal region of Alaska, we are using this model to explore the cloud microphysics and local atmospheric circulations which determine Arctic stratus cloud growth and maintenance.

As little previous work has been done in this relatively unexplored area of three-dimensional cloud modeling, our current effort involves a substantial component of exploration in the parameter space which supports ASC. In the warm season, this environment is typically characterized by a shallow mixed layer overlaid by a very stable air mass often containing several thin and tenuous cloud layers. The low liquid water content of these clouds can cause problems with the current cloud modeling methods. In addition, existing radiation schemes are known to be deficient at the large zenith angles typically found in the Arctic. All of these issues in turn significantly impact on our skill in predicting surface energy budgets and evolving surface processes such as evapotranspiration and the melting of snow and ice.

Our modeling efforts thus far have consisted of cloud-resolving simulations initialized from boundary-layer (tethersonde) observations taken along the coast of the North Slope of Alaska. These two- and three-dimensional simulations have met with varying degrees of success. In all cases the model was initialized with relative humidity (RH) values at or near 100% in the upper half of the boundary layer, but no cloud water was present in the initial state.

The first set of three-dimensional simulations discussed here was initialized with a profile (PBL#1) consisting of moderate, low-level shear and a modest thermal cap or inversion on the boundary layer. After two hours, a credible boundary-layer eddy structure had formed with some updrafts and down drafts exceeding 0.5 m s^{-1} in magnitude. A stratus cloud deck was present, with maximum cloud-water mixing ratio values near 0.1 grams per kilograms. While providing nearly 100% cloud cover, the stratus cloud was quite variable horizontally as would be expected from the vertical eddy structure. Just above the stratus layer in the overlying stable atmosphere, a thin band of clouds with a distinct periodic structure was noted. These clouds were found have a distinct phase relationship with the gravity waves at this level.

The second set of three-dimensional simulations was initialized with a profile (PBL#2) containing strong, low-level winds and vertical wind shear and a pronounced thermal cap. After two hours, in contrast to the PBL#1 simulations, no significant boundary-layer eddies had formed and the domain remained cloud free. Two-dimensional sensitivity simulations revealed that eddies would form in the boundary layer when the sea-surface temperature (SST) exceeded that of the lowest atmospheric level by 3.35°C. Further analysis suggests that the abrupt transition with increasing SST from a "no-eddy regime" to a more realistic eddy structure resulted from a "competition" between resolved-scale circulations and the sub-grid diffusion parameterization. Simulations with the same thermodynamic profile but weaker shear showed less sensitivity.

No precipitation was formed in either case and observations concerning precipitation are not available. Simulations of other cases (not discussed here) with observed drizzle formation have also failed to produce precipitation, suggesting that traditional bulk-microphysical approaches for conversion of cloud droplets to precipitate are not satisfactory in ASC. It may be necessary to use a much more computationally expensive explicit "bin" microphysics approach to achieve credible precipitation characteristics in ASC.

Results such as those discussed here indicate that we are at least partially successful in simulating several aspects of ASC dynamics in some environments. To be successful in more extreme environments, modifications of the model physics will likely be necessary. Work is currently underway to address several of these deficiencies. Such improvements, along with more experience in modeling ASC, will hopefully improve our skill in numerically simulating these clouds.

Investigation of Tide and Wind-Driven Motions in the Arctic Ocean

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Ice-tide interaction and wind-driven motion of ice and water have been investigated using a basic two-dimensional coupled ice-ocean model. Results of tide simulation by high-resolution numerical models demonstrated importance of tide for water and ice dynamics. Results of wind-driven motion from 48 years of atmospheric forcing demonstrate that two wind-driven circulation regimes are possible in the Arctic, a cyclonic and an anti-cyclonic circulation.

Data analysis of recent measurements obtained at various locations in the Arctic Ocean indicates a strong energy peak in the tidal frequency band, both in the water and in ice movement. The tide motion, through periodic divergence and convergence of the pack ice, generates mesoscale ice openings. The resulting residual motion sustains polynyas along the Eurasian Shelf. These periodic openings of the pack ice influence heat exchange and enhance the rate of ice production.Distribution of the main semidiurnal and diurnal tide components in the Arctic Ocean and North Atlantic have been described with a high degree of accuracy. The basic tools used to achieve this goal were computer models and ground station and satellite data on sea level, currents, and ice distribution. An interesting and important result concerns the diurnal constituents. In the diurnal band of oscillations, enhanced tidal current structures are generated by near-resonant shelf waves of tidal origin which are trapped or partially trapped over the bottom topography. Numerical computations performed in the Arctic Ocean and North Atlantic revealed about 30 regions of enhanced currents. Tide propagation that generates leads in the ice cover can be of practical significance to navigation and important for climate study.

A two-dimensional, barotropic, frictionally coupled, ocean-ice model with a space resolution of 55.5 km and driven by atmospheric forces, river run-off, and sea level slope between the Pacific and the Atlantic Oceans, has been used to simulate the vertically averaged currents and ice drift in the Arctic Ocean for the period of 1946 through 1993. Simulation results were compared with buoy data and demonstrated good agreement between observed and calculated buoy velocities. The model results show that two wind-driven circulation regimes are possible in the Arctic, a cyclonic and an anti-cyclonic circulation. One regime is characterized by prevailing of anti-cyclonic circulation during 1946 through 1952, 1957 through 1962, 1972 through 1979, and 1985 through 1988. A second regime is characterized by prevailing of cyclonic circulation as observed in the model during 1953 through 1956, 1963 through 1971, 1980 through 1984, and 1989 through 1993. These two regimes appear to alternate at five to seven year intervals (period is 10 to 15 years), and appear to be due to changes in the location of the polar lows and highs of the atmosphere. Adjustment during interaction between atmosphere, ice and ocean is realized as an oscillating process with the periods of two to three, five to seven, and 10 to 15 years.

The existence of a 10 to 15 year oscillation is supported by examining the temporal variability of dynamic heights in the Arctic Ocean, the temporal variability of the thickness of the Arctic surface water mass, temperature and salinity variations in the Faroe-Shetland Strait, and air temperature variability in the Norwegian and Greenland Seas. The regime shifts demonstrated in this paper are important to understanding the arctic's general circulation, for a long-term prediction of ice and weather conditions, and particularly important for pollution studies. It is important to climate studies to understand which circulation regime prevails at any time.

The Simulation of Lead-Induced Circulations in the Arctic ABL by ARPS

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Introduction

Leads and polynyas, which are open water in pack ice caused by divergence in ice drift and local melting, play important roles in surface heat and moisture fluxes. These, in turn, influence the atmospheric boundary layer (ABL) structures and cloudiness over the Arctic. These surface fluxes and ABL processes are omitted, oversimplified, or misrepresented in current global circulation models (GCMs) and are at least partly responsible for the large discrepancies between GCM-simulated and observed polar climates.

As part of the SHEBA (Surface Heat Budget of the Arctic Ocean) project, we are using modeling studies to understand the physical processes at work in the central Arctic, the mesoscale structures and cloudiness produced by leads and polynyas, and the relative importance of advection and local processes to the ABL structures and cloudiness; and based on those understanding, to parameterize the changes of surface fluxes and ABL structure and cloudiness as a function of the percentage of area covered by leads and polynyas for GCMs.

The Advanced Regional Prediction System (ARPS) model (1-D, 2-D, and 3-D) developed at the University of Oklahoma for the study of micro- and meso-scale phenomena is applied for the Arctic study. It will be used for both large-eddy simulations (LES) and mesoscale simulations. Physical processes that are important to the Arctic, such as radiation, ice/ocean coupling, will be added to the model in our study. Other processes such as microphysics and surface heat and moisture transfer will be evaluated for the Arctic.

Here we present some LES results from the preliminary evaluations of the model. The case simulated is from Glendening and Burk (1992), in which the turbulence and circulations are generated by a 2-D lead.

The Model

The Modifications to ARPS

The ubiquitous feature for the ABL over a lead-ice surface is the strong surface fluxes over leads and weak surface fluxes over ice. This flux contrast is crucial in driving circulations in the ABL. To simulate this feature reasonably, we need relevant formula for surface transfer coefficients, as well as a reasonable subgrid-scale turbulent transfer scheme in the layer right above the surface. The current ARPS does not fit to our needs for these processes over the lead/ice surfaces. So far we have done some modifications to the subgrid-scale turbulent diffusion.

The 1.5-order turbulent kinetic energy (TKE) closure scheme is used for the subgrid-scale turbulence closure. The dissipation coefficient used here (Moeng, 1984) is

$$C_\varepsilon = \begin{cases} 3.9 \text{ at the first level} \\ 0.19 + (0.51 l / \Delta s) \text{ otherwise} \end{cases} \quad [1]$$

instead of 0.93 above the first level as in ARPS. Here l is the mixing length, $\Delta s = (\Delta x \Delta y \Delta z)^{1/3}$, and Δx, Δy, Δz, are the grid sizes. This change of C_ε can affect the TKE dissipation under stable stratification by 20%.

For the stable surface layer, the TKE and l at the first model level above surface is forced to match the surface similarity theory. Following Glendening and Burk (1992), we have

$$TKE = (u_*/c)^2 \qquad [2]$$

where c = 0.1. Based on the transfer coefficients defined in ARPS, we obtain the length scale at the first level:

$$l = (\kappa z) / [1 + \kappa u/u_* - \ln(z/z_0)] \qquad [3]$$

where all the notations are conventional. The turbulent transfer coefficient is then

$$K_M = c(TKE)^{1/2}\, l = u_* l \qquad [4]$$

The Parameters

The parameters of the simulation follows exactly that given by Glendening and Burk (1992). The domain size is 2304 m in *x*, 200 m in *y*, and 120 m in *z*, with the 2-D lead size of 200 m in *x* and 200 m in *y*. The geostrophic wind is 2.5 m/s, and is perpendicular to the lead. The temperature is –2°C (over lead) and –29°C (over ice). The roughness length is 0.01 cm over lead and 0.1 cm over ice. The grid size is $dx = dy = 2dz$ = 8 m. The time step is 0.4 s. The lateral boundary condition (BC) is periodic, and the upper and lower BCs are rigid, with Rayleigh damping on the upper $^1/_3$ levels. The 1-D ARPS is run for 5 hours to produce the initial condition for the 2-D and 3-D simulations (Fig. 1), which are run for 750 seconds.

Results

The potential temperatures and resolvable temperature fluxes shown in Figs. 2 and 3 are the average over 550 s to 750 s. In the 3-D case the results are also averaged in the *y*-direction. Note that the lead is located at x < 200 m. The potential temperature from 3-D is in a good agreement with Glendening and Burk (1992), as well as with the 2-D simulation, although in 3-D the contours are smoother than that in 2-D due to the average in the *y*-direction for 3-D.

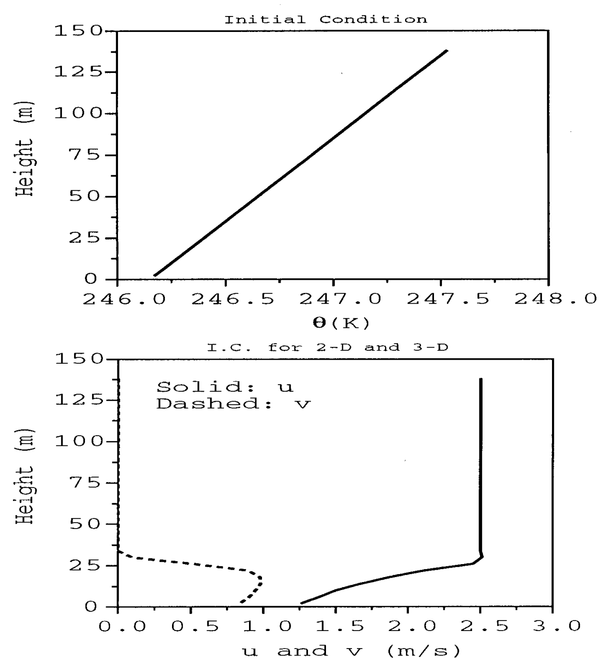

Fig. 1. Initial conditions for the 2-D and 3-D simulations.

The resolvable temperature fluxes show some differences among simulations. The vertical extent and the center of the contours are about the same in Glendening and Burk (1992), 2-D and 3-D. Horizontally, however, the contour center in 3-D does not move downstream as far as that given by GB. In 2-D this contour center moves even slower. Besides, the value at the center of 2-D is much larger than that in 3-D and by Glendening and Burk (1992). Further analysis (not shown here) shows that our model takes a longer time to reach the steady state than that required by Glendening and Burk (1992).

Conclusions

The initial results show that the model dynamics and parameterizations work fine for a LES simulation. A closer look at the surface flux para-

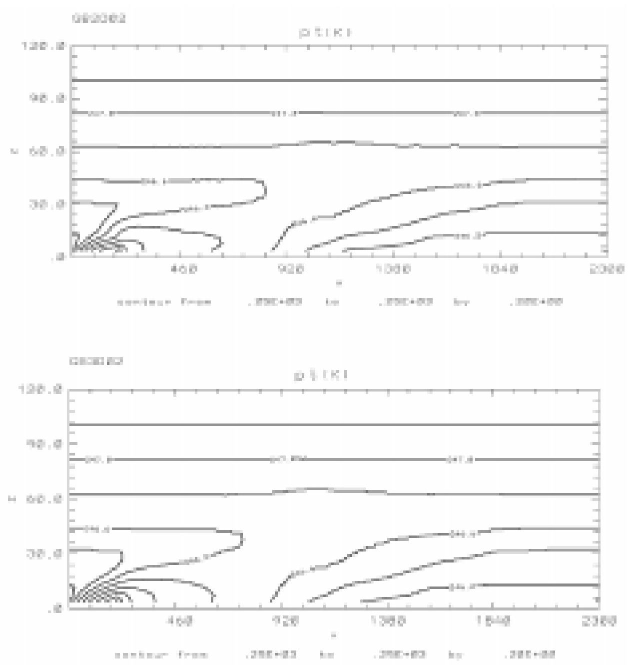

Fig. 2. The potential temperature profiles from ARPS 2-D and 3-D simulations.

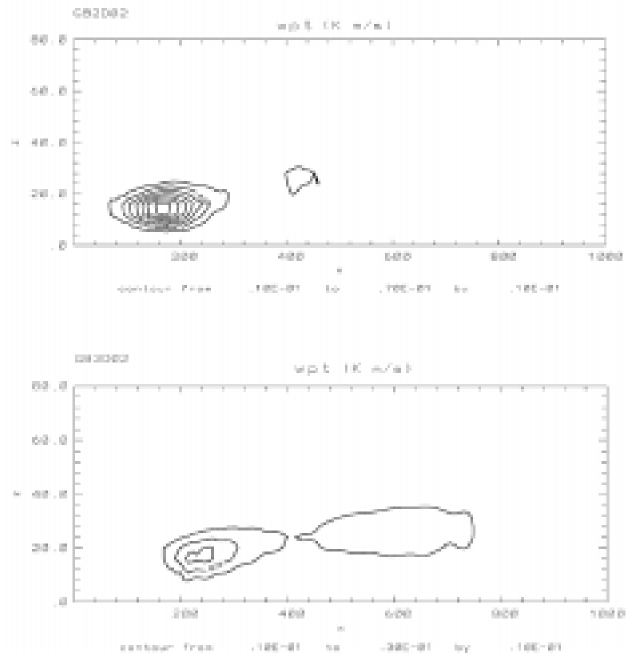

Fig. 3. Potential temperature fluxes as simulated by 2-D and 3-D ARPS.

meterization, as well as the effects of moisture and radiation on the ABL structure and surface fluxes will be further pursued in the near future.

Acknowledgments

The research is supported by the National Science Foundation ARCSS Grant OPP-9503709. The Advanced Regional Prediction System (ARPS) is developed by the Center for Analysis and Prediction of Storms (CAPS), University of Oklahoma. CAPS is supported by the National Science Foundation and the Federal Aviation Administration through combined grant ATM92-20009.

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Modeling Hydrologic and Thermal Processes in the Arctic

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A physically based, spatially distributed hydrologic and thermal model for Arctic regions is being developed and tested to aid in studies of the linkages among atmospheric, terrestrial, and aquatic systems. This model has been developed because most existing models do not adequately treat distinctive hydrologic processes in the Arctic such as snow distribution and ablation and active layer freezing and thawing. Most models also are not designed to use remotely sensed data, limiting their usefulness in the Arctic. This physically based model is composed of the essential components of the surface energy and water balances. The model calculates the balances on triangular elements which are continuous across a watershed. The modeled processes include: subsurface flow, water-table elevation, overland surface flow, channel flow, snow melt, evapotranspiration/condensation, soil-profile temperature and active layer thickness (Hinzman et al., 1995). The thermal and hydrologic models require data to calculate the entire surface energy and water balances: such as rain and snow input, air temperature, wind speed, relative humidity, and short- and long-wave radiation. Soil properties are derived from maps and data generated by other LAII investigators (D. Walker, University of Colorado and C. L. Ping, University of Alaska).

The primary products of these models are hourly or daily distributed maps of soil moisture and continuous hydrographs of channel flow at user selected locations. Other useful information includes distributed estimates of evaporation, active layer depth, and surface temperature. The hydrologic model is calibrated against measurements of soil moisture and surface runoff. It is also spatially verified by comparison to distributed maps of soil moisture generated from SAR imagery. The thermal model is verified against measurements of soil temperature and active-layer depth. The spatially distributed soil moisture levels simulated by the hydrologic model yield quite reasonable spatial and temporal levels as compared to those observed in the field (Goering et al., 1995). The thermal model can reproduce active-layer thickness, surface and sub-surface temperatures at a given site.

The elements follow the terrain surface and are configured based upon digital terrain data. During pre-processing, the direction of flow for each triangular grid element is determined (i.e., if flow is into a channel or to one or two neighboring elements). It is only necessary to determine the pathways of flow for each element once for each watershed. The direction of flow is determined using vector calculus and the gradient of each element. If flow from one element enters two others, then the proportion entering each element is algebraically determined based upon partial areas. If two elements share a common outflow side, then that boundary is a stream channel.

The surface energy balance model utilizes a new approach in determining the amount of energy transferred to the subsurface. Several previous efforts to calculate the active layer thawing or freezing based upon solution of the surface energy balance met with difficulties because the amount of energy associated with conductive heat transfer is so much smaller than the other components of the surface energy balance (Kane et al., 1990). This lead to large, often cumulative errors because in many cases the conductive heat transfer was lost in the error of the measurement of the other components. The surface energy balance in our model is simulated using a data intensive, physically based approach driven by meteorological data. Each of the equations in the surface energy balance depend strongly upon the surface temperature. The surface temperature is also the critical driving variable of the sub-surface thermal dynamics. Therefore, the equations of the surface energy balance were solved simultaneously for each time step for the effective surface temperature. This effective surface temperature is then used to drive the sub-surface thermal model. The upper boundary of the sub-surface thermal model is constrained by input surface temperature. At the lower boundary, energy flux will consist of the geothermal heat, whereas the lower boundary condition for moisture flux will be zero because of the relatively impermeable permafrost layer. A one-dimensional formulation of the soil profile was developed in order to incorporate changing thermal properties. The spatial domain of the model consists of horizontal layers of soil of varying properties. In the vertical direction, the domain extends from the surface of the soil to a depth which is sufficient to establish the lower boundary condition (23 m). At this point, the thermal model is not fully coupled with the hydrologic model nor is it a fully distributed model.

The hydrologic model is being tested in three nested watersheds on three scales: Imnavait Watershed (2.2 km^2 with 50 m elements), Upper Kuparuk River Watershed (146 km^2 with 300 m elements) and the entire Kuparuk River Watershed (8000 km^2 with 1000 m elements). The time step depends upon the spatial scale and varies for different processes within the model; for the 50 m element, subsurface flow is calculated on one-hour time increments, overland flow is calculated on one-minute time steps, and channel flow is calculated on five-second time steps. As the element size increases to 1000 m, subsurface flow is calculated on one-day time increments, overland flow is calculated on twenty-minute time steps, and channel flow is calculated on two-minute time steps. These models, when coupled with other appropriate nutrient dynamics models or mesoscale atmospheric models, produce valuable information concerning the processes which serve as linkages between the terrestrial, aquatic, oceanic, and atmospheric systems.

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Modeling the Seasonal Evolution of Non-Uniform Arctic Snow Covers in Regional Atmospheric Models

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Observations during 1994-95 winter and spring field studies in Arctic Alaska suggest that the interactions between wind, vegetation, topography, and snowfall produce snow covers of non-uniform depth and snow-water-equivalent in that region. During the winter these heterogeneous snow covers lead to spatially varying distributions of energy transfer through the snow pack, and, during the melt of the snow cover in the spring, the variation in snow depth leads to a patchy mosaic of vegetation and snow cover that evolves as the snow melts. From the perspective of a surface energy balance, the interactions between the land and atmosphere are particularly complex during this snow-melt period.

To account for these aspects of the snow cover's seasonal evolution within a regional atmospheric model, submodels are required which describe both the winter evolution of snow depth, and the surface energy partitioning during spring melt. A physically based snow transport and redistribution model is implemented to describe the winter snow-depth evolution. This mass transport model includes relevant parameters and processes such as vegetation snow-holding capacity, snow-cover shear strength, wind-induced surface shear stress, snow-transport resulting from both saltation and turbulent suspension, snow accumulation and erosion, and sublimation of the blowing and drifting snow. Running this model at resolutions finer than the regional atmospheric model produces snow-depth distributions that are at subgrid scales to the atmospheric model. During spring snow melt within the regional atmospheric model, the subgrid-scale distribution of snow produces within-grid variations of snow-covered area during melt. Simulations using an energy and mass balance model of land-atmosphere interactions and snow evolution suggest that the subgrid-scale variability of snow cover during snow melt in a regional atmospheric model significantly influences the partitioning of available energy into sensible and latent heat fluxes. A methodology to account for this subgrid-scale variability has been developed and used to simulate surface energy fluxes during snow melt over a region in the foothills of Arctic Alaska (Liston, 1995). These findings suggest that a realistic accounting for the fractional snow-covered area assists in providing a reasonable partitioning of surface fluxes under conditions of patchy snow covers. Without this accounting, regional atmospheric model simulations of evolving seasonal snow covers may significantly misrepresent the surface energy balance and associated coupling with the atmosphere.

In the current study, the Liston (1995) methodology is used to describe this period of complex land-snow-atmosphere interactions and to provide a realistic partitioning of surface energy fluxes during the melt of patchy snow covers.

A key finding of this study is the interrelationships between three curves describing: 1) the end of winter snow distribution, 2) the depletion of snow-covered area during the melt period, and 3) the available energy to melt the snow. To account for the interrelationships between these curves in a regional atmospheric model, we need to be able to: 1) describe the relationship between the exposed vegetation and the melt rate, where the exposure of the vegetation feeds back and accelerates the melt of the adjacent snow cover, and 2) know the representative shapes of the snow distribution curves for each geographic unit covered by the atmospheric model.

In addition to describing many relevant processes influencing snow in high latitudes, this regional observation, modeling, and model-validation effort represents significant improvements in the simulation of atmosphere-terrestrial interactions during the evolution of Arctic snow covers, with specific application to regional climate modeling efforts. These modeling enhancements are being developed within the context of the Colorado State University, Regional Atmospheric Modeling System (RAMS).

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Global Climate Change and the Equilibrium Responses of Carbon Storage in Arctic and Subarctic Regions

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The Terrestrial Ecosystem Model (TEM; Raich et al., 1991; McGuire et al., 1992; Melillo et al., 1993) is a process-based ecosystem simulation model that uses spatially referenced information on climate, elevation, soils, vegetation, and water availability to make monthly estimates of important carbon and nitrogen fluxes and pool sizes. Carbon enters the vegetation pool as gross primary productivity (GPP) and transfers to the soil pool as litter; it leaves the soil in the decomposition process of heterotrophic respiration. Nitrogen inputs from outside the ecosystem enter the inorganic N pool; losses leave this pool. Nitrogen in the vegetation occurs either in the structural pool or the labile pool. Structural N in vegetation is constructed from N that is derived from either the labile pool (exchange) or from soil inorganic N pool (uptake). The labile pool is replenished from N that is resorbed from senescing tissue (decay), N that is allocated for storage (exchange), or N in uptake that does not enter directly into tissue construction (uptake). Nitrogen is transferred from vegetation to the soil organic pool in litterfall. Net N mineralization accounts for N exchanged between the organic and inorganic N pools of the soil.

There are 12 input variables needed to drive TEM: PAR (photosynthetically active radiation), PET (potential evapotranspiration), rainfall, snow recharge, soil moisture, actual evapotranspiration, leaf-display duration, atmospheric CO_2 concentration, nitrogen inputs, vegetation type (18 total classes), air temperature and soil texture. The data sets are gridded at a resolution of 0.5° latitude by 0.5° longitude. The application of TEM to a grid cell requires the use of monthly data on climate, hydrology, and leaf-display duration.

We extrapolated version 4.0 of the TEM (McGuire et al., 1995) and the Marine Biological Laboratory implementation of the BIOME biogeography model (MBL-BIOME) across the globe at 0.5° resolution to estimate the equilibrium responses of carbon storage to the doubled CO_2 climates of three general circulation models (GCMs). For contemporary climate and an atmospheric CO_2 concentration of 312.5 ppmv, TEM estimates global carbon storage of 1781.4 x 10^{15} g C (Pg C). This estimate does not include the carbon content of inert soil organic matter. Arctic and Subarctic ecosystems account for 17.3% of global vegetation carbon storage and 39.8% of global soil carbon storage. The land area north of 60° N accounts for 240.1 Pg C (13.5%) of global carbon storage, with 70.3 Pg C in vegetation and 169.8 Pg C in soils. For an atmospheric concentration of 625.0 ppmv and climate changes estimated by GCMs of Oregon State University (OSU), Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS), we ran TEM to equilibrium for vegetation distributions estimated by MBL-BIOME. Among the climate scenarios, MBL-BIOME estimates that north of 60° N the area of polar desert is reduced by between 80% and 85% by the migration of tundra northward. Similarly, the area of tundra is reduced by between 45% and 55% by the migration of boreal forest northward; forested area increases between 35% and 40% north of 60° N. For 625.0 ppmv CO_2 and associated changes in climate and vegetation, the equilibrium total carbon storage of the land area north of 60° N increases between 42.1 Pg C and 48.4 Pg C. The increase in total carbon storage is primarily attributable to change in vegetation carbon storage, which increases between 39.2 Pg C and 49.2 Pg among the climate scenarios. The migration of boreal forest northward is responsible for the increases in vegetation carbon storage. Changes in soil carbon storage range between a decrease of 2.8 Pg C and an increase of 9.3 Pg C. Soil carbon storage does not substantially decrease because increases in net primary production (NPP), which cause inputs of carbon into the soil to increase, offset soil carbon losses that are caused by higher soil temperature. Increases in NPP are primarily driven by the effect of elevated temperature in enhancing the mineralization of nitrogen in northern soils, which allows plants to incorporate elevated CO_2 into production. The equilibrium responses of carbon storage to climate change in these simulations suggest that high latitudes have the potential to act as a carbon sink if the atmospheric concentration of CO_2 is stabilized. The responses also indicate that both ecosystem structure and function are important in the long-term potential for high latitudes to stabilize the atmospheric concentration of CO_2. Further progress in modeling the role of high latitudes in stabilizing/destabilizing the atmospheric concentration of CO_2 requires considering at large spatial scales the transient dynamics of functional (i.e., soil) and structural (i.e., vegetation) responses of carbon storage.

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Greenhouse Warming in an Arctic Ice-Ocean Model

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A model of the Arctic Ocean, including the dynamics and thermodynamics of sea ice, is used to simulate the ice-ocean system in the present-day climate and that of a "greenhouse" climate. The purpose of this study is to examine the response of the Arctic climate system to the warming predicted in a global atmosphere-ocean-ice general circulation model (GCM) with increasing greenhouse gases. In particular, the feedbacks between sea ice and ocean that affect the melting of sea ice can be simulated and diagnosed.

The dynamic sea ice model component is based on the Hibler (1979) dynamic model and the thermodynamic formulation of Parkinson and Washington (1979). The model accounts for the thickness and concentration of both first-year and multiyear sea ice. The surface energy balance and thermodynamic growth are computed separately for both ice types and for open water leads. The turbulent fluxes of sensible and latent heat are also computed over each ice type as a function of surface stability, air-ice temperature difference and Richardson number.

The ocean model is based on the Modular Ocean Model (MOM) of GFDL, adapted for this study as a regional model for the Arctic Ocean and adjacent seas. The model grid and ocean topography are transformed so the north pole lies on the equator of the spherical MOM grid, similar to Semtner (1987). The model resolution in 1° by 1°, or 110 km. There are 15 vertical levels, with five 5-m levels closest to the surface. This model also uses the turbulent closure scheme of Mellor and Yamada (1982) to determine the vertical mixing coefficients of heat, salt, and momentum that are dependent on vertical stability and turbulent kinetic energy. This mixing scheme has a significant impact on the simulation of the surface mixed layer and the arctic halocline.

Observed atmospheric temperatures and pressures from 1980 through 1989 are used for the present-day forcing, along with monthly mean solar radiation, precipitation, and river runoff. The greenhouse forcing is applies by adding to the present-day data the air temperature and downward longwave anomalies from an atmosphere-ocean-ice GCM in which CO_2 increases at 1% per year and the polar climate warms dramatically (Washington and Meehl, 1995). The mean annual temperature anomaly north of 70°N is 8°C, and the downward longwave anomaly is +35 Wm^{-2}. An uncertainty in this forcing is the degree to which temperatures greater than 0°C are applied over areas of fractional ice concentration.

The present-day climate experiment simulate an ice extent and ice thickness pattern that are realistically similar to observed arctic sea ice. Ice of 6 m thickness is formed by pressure ridging against the Canadian and Greenland coasts and is maintained year-round. The Beaufort Gyre and Transpolar Drift Stream are well-represented in the model. The ocean mixed layer depth varies seasonal and regionally, and the halocline acts to minimize the upward heat flux from the warmer Atlantic layer water.

In the greenhouse experiment, sea ice thickness decreases 80% in winter, but maintains an ice extent in winter only 10% less than the present-day results. The summer extent is down to 50% of the present-day, however, this is very sensitive to the application of temperatures over 0°C as mentioned above. The ocean mixed layer warms about 1.0°C, and salinities become as much as 5 ppt lower due to the melting of sea ice adding fresh water to the ocean. The halocline extends directly from the surface and is considerably stronger, leading to a more stable profile and decreases vertical mixing of Atlantic layer heat. This would indicate a negative feedback on the melting of sea ice due to the fresh water input from melting ice.

An additional greenhouse experiment was performed in which the fresh water from melting sea ice was not added to the ocean. Instead, the fresh water flux from the control case was applied. This resulted in greater melting of sea ice and ice thickness decreased to 50% of the greenhouse experiment with fresh water included. The vertical mixing of Atlantic layer heat was greater, which contributed to the melting of ice. This experiment confirms the hypothesis that the fresh water reduces the vertical ocean mixing, and provides a negative feedback on the greenhouse effect. While this is one of the few negative feedbacks in the polar regions, it is not sufficient to counteract the positive ice albedo-temperature feedback. It may, however, play a significant role in maintaining the stability of the arctic climate.

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Reconstruction of Paleo-Atmospheric Circulation at Sub-Decadal to Centennial Time Scales Based on GISP2 Chemistry Time Series: A Progress Report

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High-resolution, continuously sampled, multivariate glaciochemical records are among the most recent contributions to paleoclimatology. The chemical constituents of the atmosphere deposited in glacial ice are due to both biological, physical, and chemical processes in source areas and the patterns of atmospheric circulation which selectively transport them to the ice sheets. Since source and transport processes each respond to and influence climate, chemical records recovered from ice cores provide rich summaries of climate change which, in temporal resolution and duration, are generally unmatched by other paleoclimate records. Because of their high temporal resolution, the term "rapid climate change" has assumed a new and pressing importance. Ice cores recently recovered from central Greenland show that major alterations in atmospheric circulation can occur in less than a decade. Because of their rapidity, describing and understanding the circulatory details and forcing mechanism(s) associated with such massive atmospheric reorganizations is of great importance to paleoclimatology. Clearly, understanding decadal scale "reorganization" requires knowledge of background circulation patterns at the sub-decadal detail made feasible by ice-core glaciochemistry.

The detailed history of atmospheric circulation recorded by the chemistry of glacial ice is, however, not easily read. Each chemical constituent enters the atmosphere in a particular molecular form where it joins and is transported to the ice in an air mass having a chemical signature reflecting its own origin and circulation pathway. The climate signal from this air mass is deposited in the ice as many different compounds but extracted from the ice as the concentrations of eight individual ions Ca^{2+}, K^+, Mg^{2+}, Na^+, Cl^-, SO_4^{2-}, NO_3^-, and NH_4^+ which together represent over 95% of the soluble ionic components of the atmosphere.

The task of analyzing such multivariate time series is difficult. However, statistical and mathematical techniques are being developed and progress is being made in reconstructing air mass characteristics and broad atmospheric circulation pathways for the past 110,000 years based on the glaciochemical record from the 3,053m GISP2 ice core from Summit, Greenland. In particular, proxy records of polar circulation intensity, sea ice extent, and mid-to-high latitude biological production and atmospheric circulation have been developed and described in the literature. In addition, preliminary associations with the instrumental record of the past 100 years (e.g., the North Atlantic Oscillation and hemispheric sea level pressure and temperature fields) have been identified and are under further investigation.

An overview of analytical techniques, results, and preliminary interpretations based on the GISP2 chemistry series will be presented.

Pleistocene/Holocene Paleoclimate and Boundary Conditions Useful for Arctic Climate Model Testing: Examples from Beringia

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Paleoclimate simulations to test the accuracy of global and regional climate models require accurate paleogeographic information as baseline input data. As field scientists we are acutely aware of the large gaps that need filling in order for us to evaluate the robust nature of these simulations. At the same time it is important that the modeling community be aware of the types of data sets already available for comparing simulations. In the Beringian portion of the Arctic, an area encompassing nearly $^1/_3$ of the Arctic rim, changes in sea level and changes in seasonal sea ice have played a major role in controlling regional aridity and the size of past ice sheets and valley glaciers. During the Last Glacial Maximum (LGM), valley glaciers in mountain ranges across northern and western Alaska, as well as northeastern Russia were limited in size by the lack of available moisture (Hamilton, 1994; Brigham-Grette et al., 1994; in press). This aridity is also seen in the pervasive cover of eolian dunes and the occurrence of sand wedges across some regions of Alaska and the extremely dry nature of the vegetation (Carter, 1981; Carter, 1983). Marine workers have shown that with sea level well below –110 m exposing a dry, emergent plain, the remaining portions of the southern Bering Sea were covered with sea ice nine months of the year (Sancetta and Robinson, 1983). Yet at the same time, in parts of Beringia, the landscape experienced a brief warming, the so-called Hanging Lake Thermal Event (Matthews et al., 1989), that may be consistent with increased advection of warm air from the south as the Laurentide ice sheet grew in size. These conditions 18 to 20 ka ago are radically different from a glimpse of this region during the earliest Holocene when Beringia experienced warm conditions that were unprecedented during the insolation maximum (Hopkins, 1982). This Milankovitch-driven climate shift operated across a landscape that was undergoing radical geographic change as rising sea level swept across the Bering and Chukchi shelf, treeline advanced, organic matter began to accumulate once again in northern areas and thermokarst activity resumed.

Evidence relevant to questions concerning the effects of future Arctic warming might be best addressed by looking at the Beringian region during the last interglaciation, 125 ka. Warm marine currents bathed the western coast of Alaska pushing winter sea ice some 800 km north of its modern position (Brigham-Grette and Hopkins, 1995). There is debatable evidence that the Arctic Basin may have been briefly ice free during this time. Treeline advanced northward, especially across parts of western Beringia where larix-dahurica forests advanced north some 600 km (Lozhkin and Anderson, 1995). At the same time permafrost thinned and probably thawed in southern areas.

Glacial ice extent, sea-ice extent, and sea-level change are among a variety of proxies that should be used for understanding the oceanic/atmospheric system. The PALE working groups have clearly emphasized the heterogeneous nature of climate change across the Arctic over the last 20,000 years. It is important that modelers recognize this heterogeneity and work with community-based boundary conditions developed by working groups such as PALE, LIGA, etc., across the Arctic.

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Four-Dimensional Data Assimilation Experiments over the Western Arctic using MM5

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Motivation, Objectives, and Approach

Recent research has suggested that an improved understanding of feedbacks between system components (atmosphere, ocean, sea ice, and land) is necessary before the role of the Arctic in global change can be understood. One limitation towards this goal has been the relative lack of Arctic data on which to base hypotheses and study processes. While field campaigns (LAII Flux Study, SHEBA, ARM, FIRE-III) are invaluable, to make progress such data must be integrated into a larger scale context.

Four-dimensional data assimilation (FDDA) is one approach which can be used to achieve such integration. It has the advantage of using a physically based model to incorporate the data in a dynamically consistent fashion. In the Arctic, the best approach for FDDA is to use a regional model that can be run at relatively high resolution and can incorporate satellite information from microwave and infrared sensors (e.g., SSM/I, TOVS, AVHRR, and SSM/T2).

The development of such an FDDA system for the Arctic is the goal of our research. We have chosen to use the Penn State/NCAR Modeling system (MM5; Grell et al., 1994), as it currently possesses some FDDA capabilities and can be implemented in a multiscale movable nest framework, which is appropriate for examining feedback mechanisms in the Arctic. The standard MM5 FDDA package, however, does not employ satellite information. Thus, a major thrust of our work is on developing such a capability in addition to studying the utility of including field observations over a small region such as the SHEBA ice camp.

Our approach in this work is to implement procedures for assimilating state variables from a given data source (satellite or field data). Simulations are performed with and without the FDDA procedures as are baseline simulations without FDDA. The simulations are compared with each other and with observations to assess the strengths and weaknesses of the respective approaches and to determine what changes are needed to develop an optimum FDDA package.

Model and FDDA Description

Most of the characteristics of the MM5 model are described adequately in Grell et al. (1994). Here we only note the addition of a static sea-ice package (Tilley and Curry, 1994) which uses SSM/I information and an estimated interior ice temperature to describe the ice coverage, concentration, and thermodynamic state, which is currently assumed constant throughout the period of the simulation.

Two approaches to FDDA are possible within MM5: Newtonian relaxation (or "nudging") and one-dimensional variational data assimilation. The "nudging" approach is a continuous assimilation method in which the model state is relaxed towards the observed state via the addition of artificial tendency terms based on the difference between the two states. The following equation is an example of the relation for nudging using a gridded analysis

$$\mathrm{da}/\mathrm{d}t = F + G_{\mathrm{a}} \bullet W(x, y, \mathrm{s}, t) \bullet \mathrm{e}_{\mathrm{a}} \bullet (\mathrm{a}_{0} - \mathrm{a})$$

where for variable α, F represents the forcing terms, G is a nudging coefficient with order of the Coriolis parameter, ε is an analysis confidence factor and the subscript '0' reflects the gridded analysis value. Thus, at each time step the model solution is "nudged" slightly towards the observational state in a dynamically consistent fashion.

We employ the variational approach for moisture variables such as the precipitable water which can be obtained from satellite data sources. Then the problem becomes one of minimizing, for mixing ratio q

$$\sum_{\sigma} \left(q_{\sigma}^{a} - q_{\sigma}^{p}\right)^{2}$$

subject to

$$\left(\sum_{\sigma} \frac{q_{\sigma}^{p}}{PW^{p}}\right) q_{\sigma}^{a} = PW^{obs}$$

where superscripts *p* and *a* denote the model simulation and assimilated variables, respectively and superscript *obs* denotes the observations; PW denotes the precipitable water field, which in our work is obtained from TOVS satellite retrievals. There are three possible implementations of the approach: a) simply replace the model mixing ratio with the assimilated value without changing the model temperature field; b) employ an iterative procedure to adjust the mixing ratios to saturated values when the observed precipitable water (and thus assimilated *q*'s) is greater than the saturation values for the model temperature profile; c) employ an iterative adjustment procedure based on the moist thermodynamic equation to adjust the model temperature field at locations where the assimilated *q* is greater than the saturation value.

Case A: 12 to 25 June 1995

This case corresponds to a period of research flights for the LAII Flux Study conducted by W. Oechel and collaborators over the Kuparuk watershed on Alaska's North Slope. To date, FDDA simulations on nested grids of 63, 21, and 7 km have been conducted, testing: a) the viability of a one-way nesting versus a two-way nesting approach, and b) the effectiveness of including ground field data from the Kuparuk watershed.

Figure 1 shows a difference field, at t = 48 hours, of the sea-level pressure (SLP) field between experiments that do and do not incorporate Flux Study surface data over the Kuparuk watershed. The difference pattern shows a clear dipolar pattern which is centered over the Kuparuk watershed, with some impact of the observations also visible downstream. This pattern suggests that even surface level data over a small area can have a significant impact on the assimilated fields.

However, the choice of grid hierarchy must be made with great care. Difference maps (not shown) of simulations done with a one-way nesting approach versus the two-way nesting used for the simulations in Fig. 1 show patterns that are not localized and are one to two orders of magnitude greater than those seen in Fig. 1, suggesting that any benefit obtained by adding the field data could be mitigated by the choice of approach.

Case B: 25 September to 1 October 1994

This case corresponds to one of the more cyclonically active periods during the BASE experiment

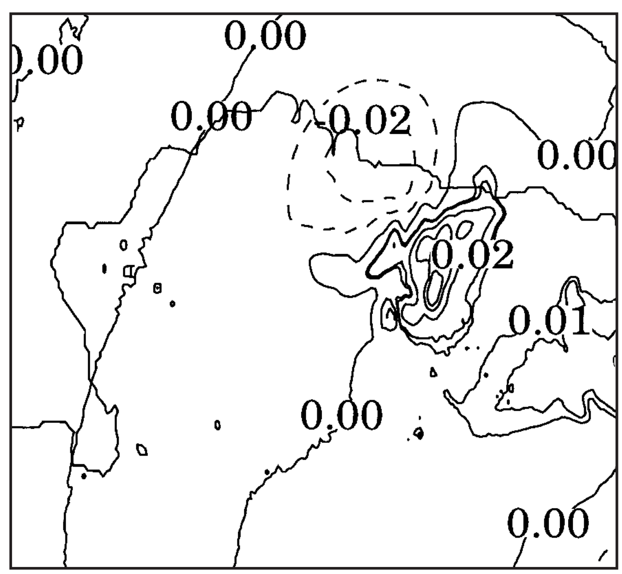

Fig. 1. Difference map of sea-level pressure field between simulations with and without LAII Flux Study surface data; results are at t = 48 h for a 7 km domain covering the Alaska North Slope.

which was focused on the Beaufort Sea area. To date, FDDA simulations on nested grids of 63 and 21 km, employing TOVS precipitable water data using the one-dimensional variational approach have beenconducted. Several difficulties have emerged as a result of these experiments. First, some smoothing of the raw TOVS PW data is required regardless of the implementation of the variational approach taken. Second, the TOVS retrievals appear to exhibit a dependency on the assumed background state used in the retrieval algorithm. Third, general rules to account for the impacts of Arctic cloud cover on TOVS retrievals are not available and thus incorrect specification of clouds with respect to the assumed background state may adversely affect the data to be assimilated, and thus the FDDA simulation as well.

Future Directions

Work is continuing to evaluate the effectiveness of FDDA for providing regional contexts of LAII Flux Study data, with simulations for longer periods now in progress. Evaluation of the initial simulations suggests that a two-way approach will likely be optimal.

While assimilation of other TOVS quantities (such as temperature profiles) simultaneously partially ameliorate the problems related to inconsistencies with the retrieval background, it may be necessary to perform satellite retrievals using the MM5 background state as part of the assimilation process. If so, such a procedure may preclude the effective use of such an FDDA system for real time applications. Future work will focus on this question.

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Sea Ice Properties

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Sea-ice research is diverse and includes a number of areas that are imperative in understanding the climate system and how sea ice impacts environmental change, both naturally and anthropogenically induced. Having a basic knowledge of both the large- and small-scale properties and processes are necessary for successful modeling of the Arctic climate particularly since GCMs predict amplification of warming in the polar regions with a continued increase of greenhouse gases.

Ice properties and processes range from microscale to macroscale. Large-scale properties and processes include ice concentration and extent, ice thickness, ice motion, sources and sinks, ice mechanical, electromagnetic, optical and thermal properties. Smaller scale properties and processes include ice formation and structure, chemical, biological, and physical properties, brine and chemical migration, sediment incorporation mechanisms. Needless to say, there is considerable overlap between the scales in that properties at one scale depend upon those at another scale.

Ice concentration and extent can be quite reliably determined remotely by satellite microwave observations—SSM/I, AVHRR, and SAR. Additionally, visual observations are made via aircraft overflights and from shipboard operations. Ice thickness is typically obtained from submarine data, drill-hole measurements, and(or) moored upward looking sonar, although detailed knowledge of the ice thickness distribution in the Arctic is lacking. Ice motion is obtained from drifting buoys, ice stations and satellite SAR. Currently, some models exist that predict back-ice trajectories.

The Arctic ice mass balance is maintained by dynamic and thermodynamic forcing. Dynamic forcing requires consideration of wind and water stress, internal ice stress, sea-surface tilt, and the Coriolis force. Thermodynamic forcing is controlled by radiative fluxes, latent and sensible heat fluxes, and ocean heat flux. Numerical dynamic-thermodynamic ice ocean models which account for the heat, mass, and momentum balances appear to do a reasonable job of predicting thickness, concentration and motion, but verification is hampered by a lack of data. Further understanding of the mass balance requires knowledge of the spatial and temporal variations of the thickness distribution, source and sink areas, and ice transport. Our greatest needs in this regard include ice-thickness distribution and ice motion for the entire Arctic Basin. Additionally, the models require improved parameterizations of the ice rheology which is currently determined indirectly by comparing model results of ice motion to ice-buoy velocities. Improved rheologies could be obtained by coupling direct measurements of in situ ice stress and mesoscale strain.

In climate models, sea ice is typically modeled as a thin, uniform slab covering the ocean responding only to thermodynamic processes. As the above paragraph points out, momentum forcing from the atmosphere and ocean cause the ice cover to be densely fractured and ridged. Thus, variations in thickness and ice type exist within very small areas. The effect of including actual thickness distribution on GCM simulations is not known, but the true ice processes are presently unresolved in these models.

One of the most important effects resulting from climate model simulations is the ice-albedo feedback mechanism. The essence of this hypothesis is that when the climate changes significant variations also occur in the snow and ice cover leading to modifications in the absorption of solar radiation at the ocean surface. The effects of melt ponds and lateral melting of floes are known to be significant but have not been studied in sufficient detail to include in models. Of particular interest are the temporal evolution of the melt pond distribution during the critical summer period and the quantification of lateral melting. Likewise, the evolution of the ice throughout the year has a large effect on the albedo. Future investigations should include the snow cover, and the distributions of brine and air pockets within the ice. It is known that sediment on the ice dramatically reduces the surface albedo, but the occurrence and distribution of ice-borne sediment are not well characterized, thus its effect on overall albedo, while thought to be minimal, is unknown.

The chemical properties of the ice including the salinity, major ions and nutrients, biological properties and contaminants are also important. The chemical properties vary depending on location of ice formation, ice type (crystal structure), age of the ice and the thermal history. Ice has proven to be an important mechanism in the transport of contaminants, both within the ice itself and via ice-borne sediment.

We currently have some understanding of:

- Ice velocities in a regional sense.
- Seasonal and interannual variations of ice extent.
- Mean ice thickness (± 1 m), some geographic variation.
- Typical thickness distribution over some of the Arctic Basin.
- Typical distributions of ridging, some geographic variation (± 50%).
- Flux of ice through Fram Strait.
- Ice production areas in a general sense.
- Evolution of chemical properties beyond first-year ice.
- Theoretical ice rheology, some short-term stress measurements.
- Albedo of some ice features.

Nonlinear Multivariate Modeling in Tundra CO_2 Flux Studies

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Experimental field studies of carbon flux in terrestrial ecosystems currently include chamber, tower, and aircraft measurements. While the chamber methods provide data on gross photosynthesis P, total ecosystem respiration R, and net ecosystem flux F at the patch-ecosystem level, the later two techniques produce only the flux data (F) representing the landscape and regional levels respectively. All these methods generate long time series of measurements (e.g., $\{F(t), t = t_1, t_2, t_3, ..., t_n\}$), which may be many megabytes in size. The natural step in their analysis is to construct predictive models to calculate the carbon flux components using the more easily measurable factors (e.g., meteorological and remote sensing data). If Y stands for P or R or F, the models may be formulated as:

$$Y = f(x_1, x_2, ..., x_m, a_1, a_2, ..., a_p) + e_y,$$

where x_i denote the environmental factors-predictors (e.g., radiation [PAR], air or soil surface temperature, NDVI, etc.), a_k are parameters describing the function f(...), and e_y is the error term.

The time series of flux component measurements $\{Y(t), t = t_1, t_2, t_3, ..., t_n\}$ coupled with records of relevant factors-predictors $\{(x_1(t), ..., x_m(t)), t = t_1, t_2, t_3, ..., t_n\}$ were used to estimate parameters of the model(s) for different ecosystem types of the circumpolar Tundra Biome.

A computer program, *CO_2 Exchange* (Fig. 1), was constructed, which estimates the parameters of nonlinear multivariate models for gross photosynthesis, total respiration, and(or) net ecosystem exchange using field measurements. Coupling of the algorithm of adaptive nonlinear optimization with the graphical interface of the Macintosh Operating System implemented in the program

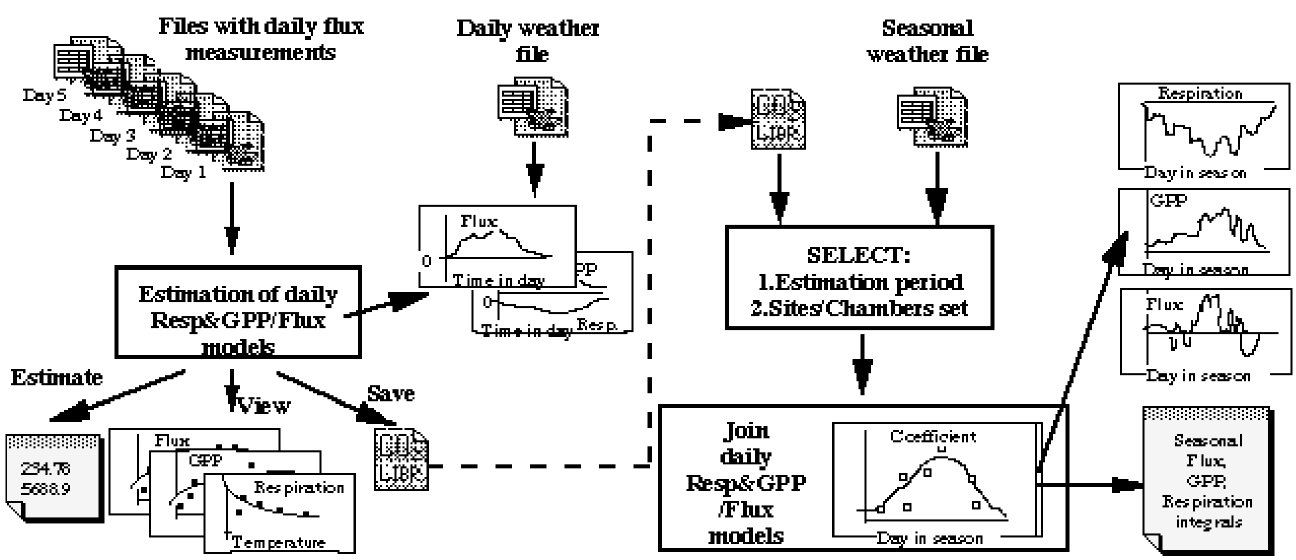

Fig. 1. General structure of the *CO_2 Exchange* program.

results in the fast and flexible estimation of parameters. The resulting models calculate the seasonal dynamics of gas exchange using meteorological and remote sensing information (Gilmanov et al., in prep.). Currently, data on PAR, air and(or) soil surface temperature, and NDVI (cf. Hope et al., 1993) serve as predictors, but the program easily allows addition of other factors (e.g., soil moisture, thaw depth). Outputs of the main model, operating on the plot scale and the minute to hour time step, are spatially aggregated to patch-ecosystem level and daily time step models to predict daily integrals of P, R, and(or) F as functions of daily PAR, temperature and NDVI (Fig. 2). The aggregated models are used in the GIS to describe geographical distribution and seasonal dynamics of the carbon flux at the landscape to regional scales (e.g., Kuparuk River Watershed).

The program was tested on data sets of chamber, tower, and aircraft CO_2 flux measurements in 1990 through 1995 on the North Slope of Alaska, and of chamber measurements on Seward Peninsula (Alaska), in Russia (Taimyr, Kolyma), and Iceland. It proved to be an efficient tool for analysis and prediction of carbon flux in tundra ecosystems. Preliminary results demonstrate agreement of flux estimates provided by chamber, tower, and aircraft techniques.

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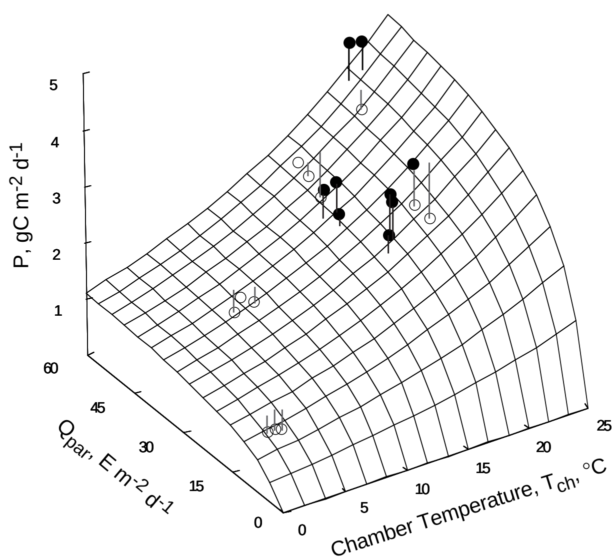

Fig. 2. Response surface of gross primary production of the shrub tussock tundra of Happy Valley site to radiation (Q_{par}), chamber temperature (T_{ch}) and NDVI. Data of field measurements are shown as points, solid points lying above the approximating surface, open points below it, and bars showing the deviation of data from the model. Mean standard deviation of the data points from the surface is 0.54 g C m^{-2} d^{-1}.

High Arctic Field Data in Support of Modeling Climate, Hydrological Processes, and the Paleoclimatic Significance of Lake Sediments

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Within three High Arctic basins (75° to 83°N), we have conducted comprehensive meteorological and hydrological field measurements. The objectives of this work are: 1) to examine the climate-sensitivity of basin hydrological outputs, in a 1.3 million km^2 region devoid of regularly gauged basins, and 2) to develop a model linking proxy hydrological data (laminated lake sediment thickness) to paleoclimate. The monitored basins ranged considerably in size (21 to 460 km^2), relief (200 to 1900 m), and extent of glacierization (0 to 88%). Each of the three basins drains into a meromictic lake, in which laminated sediments have been deposited for up to 2700 years. Weather stations were operated at two elevations in each basin, measuring barometric pressure, wind speed and direction, air temperature, humidity, and radiation (short- and long-wave). The extent and frequency of hydrological measurements varied between basins, but included discharge, water temperature, isotopic composition, electrical conductivity and total dissolved solid concentration, and suspended sediment concentration.

Analysis of data from the northernmost basin has indicated that the daily discharge of snowmelt runoff and sediment was strongly associated with air temperature at the median elevation of the basin (e.g., $r = 0.92$, 1992 suspended sediment discharge). These basin temperatures were well correlated with 600 m free air temperatures, as measured by rawinsonde above Canadian weather station Alert (250 km east). The sounding temperatures were then used in a simple statistical model to predict daily sediment transfer from the basin, over the 40-year period of record. The predicted daily loads were summed for each year, and used to slightly adjust a varve chronology for the lake. At this site, the annual sediment thickness was best correlated with the July mean temperature at 600 m ($r = 0.54$; $P < 0.01$), which indicates that sediments can provide a reliable, high-resolution paleoclimate proxy.

Further work planned with these data include partitioning the atmospheric energy inputs to the snow surface (using an energy balance model), and adapting a hydrologic-transport model (e.g., RIVER4) to predict output from each of the basins. In the latter case, the model will use either basin meteorological data or GCM output as input, to predict river basin output, in a region where gauged data are not available.

Land-Surface Process Modeling of Tundra for Microwave Remote Sensing Applications

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The development of our Land-Surface Process/ Radiobrightness (LSP/R) model for tundra areas is based on our existing one-dimensional Hydrology/ Radiobrightness (1dH/R) model for prairie soil and our microwave emission model for grass canopies. The 1dH/R model uses a finite-difference approach to coupled vertical heat and moisture transport and permits the freezing and thawing of moisture in the soil. Typical products of the 1dH/R model include surface temperature and moisture as well as liquid water and ice volume fractions as a function of time over diurnal and seasonal periods. The top layer thickness is currently 5 mm, and layer thicknesses increase exponentially with depth. This vertical resolution yields temperature and moisture profiles of sufficient fidelity to predict radiobrightness. The temporal interval is adjustable. We typically use ten minutes.

The upper layers of the current 1dH/R model will be modified to represent the organic upper portion of the active layer. Field data from our year-long Radiobrightness Energy Balance Experiment 3 (REBEX-3) on the Alaskan North Slope will be used to guide the development of an acidic tussock tundra model. Other types of vegetation cover such as non-acidic tussock tundra and coastal tundra will be accommodated by adjusting the constitutive properties of the layers. Models adjusted for one or more of these vegetation categories will be aggregated with a model for open water to represent the net behavior of any particular grid cell within the North Slope. Approaches for handling evapotranspiration and vertical water movement within the organic layers are being explored.

Feedback to the atmosphere (our “outputs”) will be compared with those from the ARCSyM LSP model (e.g., LSM or CLASS). After any significant differences are reconciled, the ARCSyM LSP model will be replaced with our LSP/R model and used in retrospective studies of stored water, soil temperature, and thickness of the active layer. The difference between predicted and observed radiobrightness will become a measure of accumulated error in the models. This difference is a significant indicator of error because radiobrightness is primarily sensitive to surface temperature and moisture.

Figure 1 is an example of model output (isotherms) over 24 hours in unfrozen soil. The surface is at the top and the solar heating pulse is clearly evident. An example of REBEX-3 microwave radiobrightness signatures for September 1994 to September 1995 are shown in Fig. 2 for 19.35 GHz H- and V-polarizations and 37 GHz H-polarization.

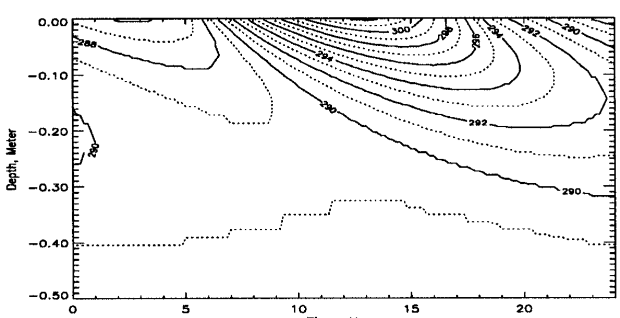

Fig. 1. An example of model output (isotherms) over 24 hours in unfrozen soil (see text).

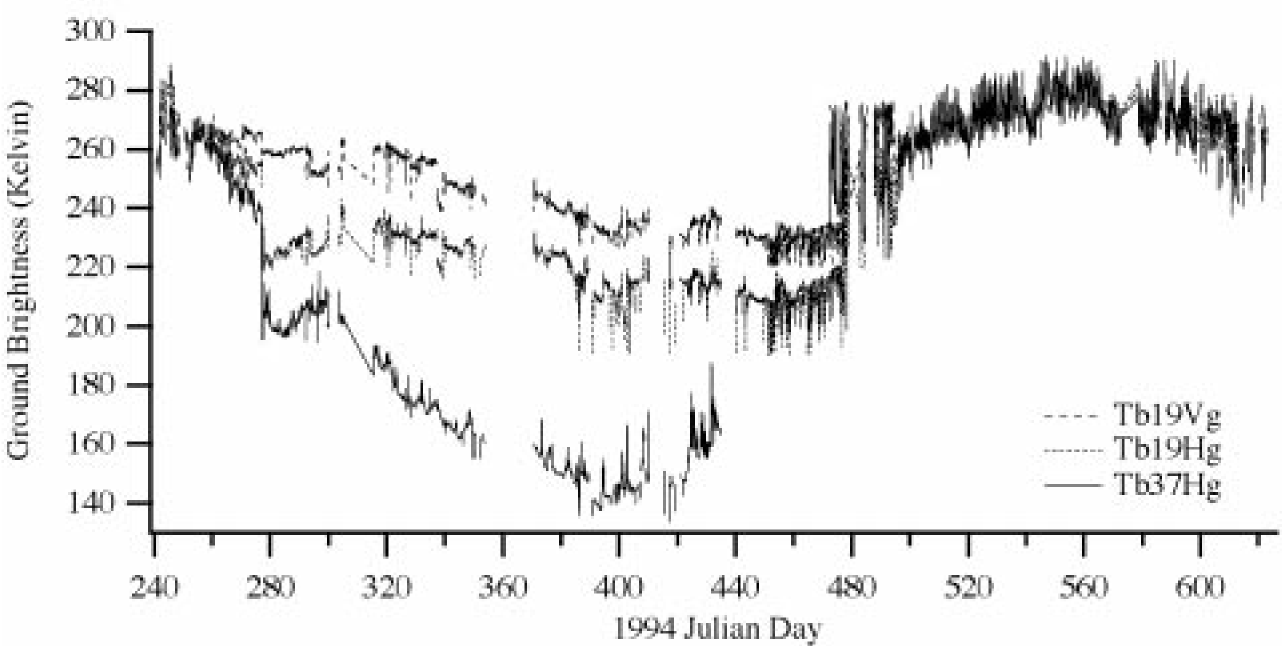

Fig. 2. An example of REBEX-3 microwave radiobrightness signatures.

An Assessment of GENESIS V. 2.0 GCM Performance for the Arctic

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Introduction

The latest version of NCAR's GENESIS (Global Environmental and Ecological Simulation of Interactive Systems) global climate model includes enhancements that address some of the problem areas present in typical GCM simulations of polar regions. Among the enhancements are a dynamic-thermodynamic ice model, greater vertical resolution in the planetary boundary layer, increased spatial resolution, and improved treatment of clouds and orographic effects. To investigate whether these enhancements yield an overall improvement for Arctic simulations, GENESIS Version 2.01 results are analyzed with emphasis on factors affecting sea-ice growth and transport.

Results from a present-day equilibrium climate simulation using an interactive ice cover and a slab mixed-layer ocean model are compared to a companion simulation using prescribed ice cover and ocean temperatures. AGCM resolution is T31 (3.75° latitude and longitude) with 18 vertical levels, including 3 levels in the planetary boundary layer to better resolve low-level temperature inversions. The surface grid resolution used by the vegetation, soil, snow, sea-ice and ocean models is 2 by 2°. Atmospheric convection uses an explicit sub-grid plume model. A three-layer thermodynamic model predicts the local melting and freezing of sea ice. Ice dynamics are simulated using a cavitating-fluid rheology, with prescribed ocean currents. The ocean is represented by a thermodynamic 50 m slab. Poleward oceanic heat transport is prescribed as a zonally symmetric function of latitude based on present-day observations. A simulation option includes the use of prescribed ice thickness, ice fraction, and SST with ice thickness and fraction specified as a function of latitude.

Two GENESIS simulations are considered here: (1) results using the prescribed ice cover and sea surface temperature (referred to here as the "prescribed" run); and (2) results using the interactive dynamic-thermodynamic ice model with the slab mixed-layer model (the "interactive" run). Means from ten-year simulations following equilibrium periods are analyzed. GENESIS outputs considered are sea-level pressure, surface-air temperature, total cloud fraction, net radiation, sea-ice fraction and thickness, and snow thickness over sea ice. Validation data sets used include monthly mean NMC sea-level pressures, climatological air temperatures, a cloud climatology based on surface observations, cloud fraction and radiative fluxes estimated from ISCCP-C2 data for 1984 through 1990, and SSM/I-derived sea-ice concentrations. Comparisons are made for the northern hemisphere from 50° to 90° latitude, depending on the coverage of the individual validation sets.

Results

Distributions of sea-level pressure show a marked improvement over results from previous GENESIS V.1 and most other GCMs included in the AMIP comparisons. At least some of this improvement is likely due to increased model resolution. Reproduction of spatial patterns is quite good in all seasons (Table 1). The basic circulation patterns that drive the Transpolar Drift Stream and Beaufort Gyre are apparent, as are other dominant circulation features of the northern hemisphere. The greatest pattern differences occur in summer, when pressures are uniformly overestimated. The model consistently underestimates pressure gradients. Inclusion of the ice and ocean models in the interactive run affect SLP noticeably, increasing the overall error but improving the match of patterns substantially in some months.

Pattern correlations, root mean square error (RMSE) values (Table 1), and means for surface air temperatures suggest good agreement between the simulations and climatology. The prescribed run tends to overestimate air temperatures over sea ice and underestimate temperatures over the continents. Errors are generally greater in the prescribed model than in the interactive run. The interactive ice model affects Arctic temperatures substantially by decreasing temperatures over ice to within 2° of the observations. A cold bias over land is present in all seasons.

Comparison of the GENESIS cloud fractions to observations yields quite different results depending on the validation data set used. Mean Arctic-averaged total cloud amounts (sum of fractional coverages of all cloud layers) are most similar to the climatology derived from surface observations, but spatial correlations with the ISCCP climatology are considerably greater (Table 1). Inclusion of modeled ice/SST increases the correlations by about 30% in spring, summer, and autumn and by 100% in winter compared to the prescribed run. Poorest correlations occur in summer in both simulations. Correlations and means for net solar radiation and total (short-and long-wave) net radiation are generally consistent with the other parameters studied and with the ISCCP validation data set, but with some large differences in particular seasons (Table 1) and locations. Meridional patterns fit well, with offsets that are within the range of uncertainty in the ISCCP-derived fluxes.

The dynamic-thermodynamic ice model yields realistic distributions of ice thickness and advection, with the characteristic thickening near the Canadian Archipelago and thinner ice in the eastern Arctic. However, ice extent is overestimated in winter and underestimated in summer. The gradients of ice concentration from the ice margins to the interior pack are too diffuse—due in part to the resolution of the surface model, and perhaps to insufficient detail in SSTs and ocean currents. Snow depths over sea ice follow a realistic annual cycle, reaching a maximum depth of about 0.2 m in spring in the central Arctic.

Summary

Compared to the characteristics of Arctic simulations in typical GCMs, GENESIS Version 2.01 yields a general improvement in all parameters examined. Sea-level pressure patterns are simulated quite well, although gradients are too weak and summer pressures are overestimated. Good correlations are found with surface air temperatures, and

Table 1. *Pattern correlations and root mean square error values (in parentheses) for the modeled ice/ocean ("interactive") run. Columns are sea-level pressure, surface-air temperature, observation-based cloud fractions, satellite-derived (ISCCP) cloud fractions, net solar radiation and total net radiation at the surface, and ice fraction. RMSE units are K for T_s and Wm^{-2} for net solar radiation and net total radiation.*

Season	Sea-level Pressure	Surface-Air Temperature	Cloud Fraction (C)	Cloud Fraction (I)	Net Solar Radiation	Net Total Radiation	Ice Fraction
Winter	.91	.96 (3.7)	-.01 (.17)	.79 (.11)	–	.09 (9.9)	.64 (.36)
Spring	.83	.94 (3.3)	-.12 (.18)	.88 (.07)	.93 (9.8)	.90 (15.8)	.55 (.43)
Summer	.81	.92 (2.3)	.13 (.22)	.24 (.21)	.54 (28.9)	.67 (21.1)	.58 (.35)
Autumn	.82	.96 (2.9)	.22 (.17)	.80 (.12)	.93 (3.1)	.74 (11.2)	.70 (.28)

surprisingly good agreement with cloud amounts and net radiation, particularly when satellite-derived and surface-based cloud climatologies are considered together. The basic patterns of sea ice distribution are reproduced, but some substantial errors in ice extent and concentration remain. The dynamic-thermodynamic ice model and slab ocean model have a noticeable effect on the simulations, and tend to improve the agreement with the validation data. Within these areas of general agreement, problems remain that lend themselves to closer examination. Overall, the simulations suggest that GCMs such as GENESIS have reached the point where the basic processes of the model are reasonably correct, so that focused observational comparisons and process studies can be used to further refine the model. Some of the inaccuracies in SLP patterns might be improved through higher spatial resolution capable of resolving relatively localized surface-atmosphere processes. The remaining uncertainties in cloud cover and surface energy balance terms require additional sensitivity studies and validation data sets to prioritize enhancements to the AGCM and surface models.

Acknowledgements

This work is supported by NSF grants OPP-9423506 and OPP-9321547.

Contemporary Water and Constituent Balances for the Pan-Arctic Drainage System: Continent to Coastal Ocean Fluxes

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This project will model the pan-Arctic water balance with particular emphasis on spatially explicit estimation of freshwater export via rivers to the Arctic coastal seas. Water balances will be quantified for the contemporary situation and annual variability from 1975 through 1990 determined. Water balance and river routing models will be combined with river constituent monitoring data to develop models of the fluxes of sediment, organic carbon, and nutrients from continents to the Arctic Ocean. The product will be a spatially explicit baseline of contemporary water and constituent fluxes from land to water for the pan-Arctic drainage. This baseline is needed to judge the likely impacts of predicted climate and land-use changes on pan-Arctic water and nutrient balances. Societal impacts of changes in runoff and constituent fluxes include not only feedback to global climate change but also impacts on the biotic resources of Arctic wetlands, lakes, rivers, and coastal seas.

The research is interdisciplinary and international in scope. Areas of expertise and contributing U. S. scientists include Arctic river biogeochemistry (B. Peterson, Marine Biological Lab, Woods Hole), water balance modeling (C. J. Vorosmarty, University of New Hampshire), permafrost modeling (S. Frolking, University of Delaware), precipitation distribution estimation (C. J. Willmott, University of Delaware), and aerological water vapor convergence/divergence fields (M. Serreze, University of Colorado). International contributions and collaborators include controls of riverine biogeochemical fluxes (M. Meybeck, University of Paris), river discharge and hydro-meteorological data sets (I. Shiklomanov, Russian State Hydrological Institute, St. Petersburg, Russia), pan-Arctic monitoring of water and constituent fluxes: AMAP program (V. Kimstach, Arctic Monitoring and Assessment Programme, Oslo, Norway), and Russian riverine nutrient fluxes (V. Gordeev Shirshov, Institute of Oceanology, Moscow, Russia).

The goal of the project is to secure a quantitative understanding of how runoff and associated biogeochemical fluxes are linked between the pan-Arctic land mass and the Arctic coastal zone. We will employ a data-rich approach linking several models and their associated biophysical data sets within a GIS-based analysis system for the entire Arctic Ocean watershed. Our emphasis is on the contemporary setting for the period 1975 through 1990. The scope of the modeling work suggests a spatial resolution of approximately 50 km and weekly-to-monthly time steps. This choice of model resolution is based on our ongoing work at continental and global scales analyzing carbon, nitrogen, and water-cycle dynamics. Below is a brief description of two of the models to be used in our synthesis study of the pan-Arctic water cycle.

Water-Balance Model (WBM)

This model is currently used in global research and will be modified by incorporating a simplified version of a physically based permafrost model. Required inputs include data on vegetation, soils, and climatic forcings. Time series of meteorological inputs (e.g., precipitation, temperature) will be developed from interpolation techniques with explicit error estimates. Outputs are time-varying fields of evapotranspiration, changes in soil water and active-layer depth, and runoff across the pan-Arctic land mass. Calibration/validation will employ site-specific data available from independent sources.

Water-Transport Model (WTM)

Runoff from WBM is routed using the WTM through simulated river networks to generate discharge hydrographs at any point within the pan-Arctic watershed system. Hydrographs are conditioned upon contributing area, flow velocities, and associated wetland storage. Water-transport estimates will be validated against measured discharges maintained within several monitoring archives to which we have direct access.

The project will concentrate in years 1996 and 1997 on improving the continental scale water balance, river routing, and water-transport models of the Arctic watershed. Concurrently, we will be securing or developing data sets on precipitation, discharge, and constituent concentrations in Arctic rivers. During 1998 and 1999 the emphasis will shift to the estimation and modeling of constituent fluxes (predominantly sediment, C, N, and P) from continents to the coastal seas off the Arctic Ocean.

Global Atmospheric Model Simulations of Arctic Climate

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Simulations of present-day Arctic climate by approximately thirty general circulation models have been examined in a diagnostic subproject of the Atmospheric Model Intercomparison Project (AMIP). The forcing of all the models by observed sea-surface temperatures and sea ice from a 10-year period (1979 through 1988) permits comparative evaluations of the model biases as well as the models' simulations of the interannual variations contained in the observational data. The models capture the latitudinal and seasonal variability of surface air temperatures in the Arctic, although a cold bias of –3.3°C is apparent over northern Eurasia during spring, especially in the models that do not include vegetative masking of the high-albedo snow. The ensemble mean of the model bias over North America is less than 2°C in all seasons. Over the Arctic Ocean, the spring temperatures generally have a warm bias that averages 3.0°C, but the bias is smaller in the models in which the prescribed albedo of sea ice is highest. Although most models do not reproduce the seasonal cycle of Arctic cloudiness, the correlations (across models) between simulated cloudiness and surface-air temperature are negative and statistically significant in the summer months. The corresponding correlations for the winter months are small and statistically insignificant. The models without gravity-wave drag are generally colder than the other models at the Arctic surface, especially during autumn.

The simulations of Arctic sea-level pressure vary widely from model to model. Several of the higher-resolution models are very successful in reproducing the seasonality and spatial distribution of sea-level pressures over the Arctic Ocean.

The models show a strong tendency to over-simulate Arctic precipitation. Over the Arctic Ocean, the ratio between the annual mean simulated precipitation and the corresponding observational estimates is typically 1.2 to 1.8. The ratios for Greenland and the major Subarctic drainage basins of Eurasia and North America are even larger. To the extent that the data on evaporation permit observational estimates, it appears that the models also over-simulate evaporation in the Arctic, at least during the winter half of the year. For the Arctic Ocean, the net precipitation-minus-evaporation as simulated by the models is considerably larger than the moisture flux convergence computed from rawinsonde data. Since these biases exceed the observational uncertainties, they will need to be addressed by the modeling community before simulations of the Arctic hydrologic cycle can be viewed with confidence.

Arctic Sea-Ice Variability in a High-Resolution Model

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Variation of Arctic sea ice is simulated by a high-resolution (18 km) sea ice model based on the Hibler (1979) dynamic/thermodynamic model with more efficient numerics (Zhang and Hibler, 1997). The model is driven by three-day averaged ECMWF atmospheric forcing and three-day oceanic forcing derived from the same resolution Arctic Ocean model, based on the Semtner and Chervin (1992) free surface model. The model is integrated for 11 years with repeated 1992 forcing for the first six years; and with 1990-94 atmospheric forcing and repeated 1992 oceanic forcing for the last five years. Only the last five years of results are analyzed.

Video animation (one frame every 3 days, with a total of 607 frames) illustrates that the model realistically simulates opening and closing of Northeast Water polynyas (off the extreme northeastern Greenland) and smaller coastal polynyas farther south along the eastern Greenland coast. In addition, North Water polynyas (in Baffin Bay and Smith Sound), and polynyas in the vicinities of Novaya Zemlya, Severnaya Zemlya, and Franz Josef Land, and in the Canadian Archipelago are also well simulated. The surface heat budget indicates that polynyas are the source of intense heat flux to the atmosphere.

With the high-resolution model, eddies in ice motion in the Greenland Sea, the Baffin Bay, and the Beaufort Sea are resolved. Ice feels not only the large-scale ocean currents but also ocean eddies. Effects of ocean eddies leave signatures in ice motion, ice thickness, and ice concentration. The ice vortex at the edge of the east Greenland Current has a striking resemblance to the one in the observational study by Wadhams and Squire (1983). The Odden (eastward extension of sea ice in the Greenland Sea south of 75°N) and Nordbukta (embayment of sea ice to the north of Odden) phenomena studied by Carsey and Roach (1994) using satellite and in-situ data are reproduced by the model. Low ice concentration within the Arctic pack ice of the Canada Basin (see front cover of this volume) reported by Barry and Maslanik (1989) using SMMR data and drifting buoys is also present in the model output. In summary, the model is able to simulate the variation of Arctic sea ice with detail never before achieved.

To quantify the spatial distribution of the ice extent and its seasonal and interannual variability, time series of the ice extent, the ice area, and open water within ice pack over various regions are calculated (Fig. 1). Comparison with SMMR observation (Gloersen et al., 1992) indicates that this model realistically simulates the seasonal trends in regional ice growth and decay. The volume transport of ice through Fram Strait (Fig. 1) shows a lower ice transport in 1990 and a larger ice transport in 1991 and 1992, and there are events of northward ice transport, which agrees with Andrew T. Roach's estimation (pers. com.). The magnitude of ice volume transport is comparable to calculations by Vinje and Finnekåsa (1986). The monthly mean of ice concentration from the model output very much resembles that from the DMSP-F8/F-11 SSM/I data (downloaded from the National Snow and Ice Data Center's anonymous FTP site).

Along with the stand-alone, sea-ice model results, preliminary results from the coupled ice-ocean model are also presented in the video animation. Due to the limitation in submitting color figures, we invite you to visit our Web page where all of results mentioned above can be found (http://vislab-www.nps.navy.mil/~braccio/maslowski/vector.html).

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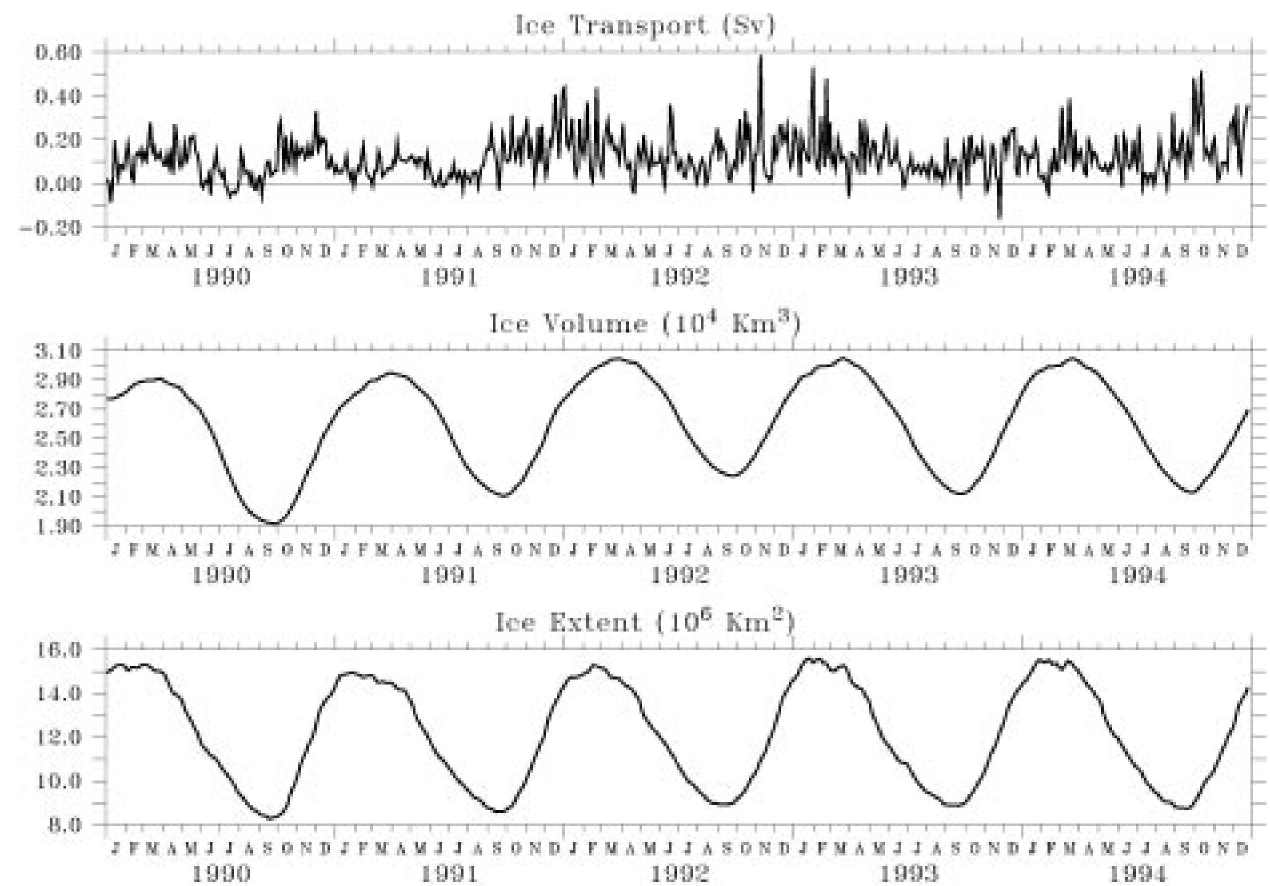

Fig. 1. Time series of ice transport through Fram Strait (upper), ice volume (middle), and ice area (lower) over the full model domain.

Modeling Activities Within ARCSS Components

Paleoenvironmental Studies Component

Greenland Ice Sheet Project Two
– GISP2 –

GISP2 Modeling Efforts

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Overview

Modeling efforts from the GISP2 project encompass a wide range of topics. Depth/age modeling cover predicted time scales, ice divide location and ice thickness changes. Flow modeling of the ice sheet include boudinage formation, flow law hypotheses, and fracture analysis of firn. Accumulation modeling at GISP2 looks at the effect of ice sheet thickness changes on accumulation history, uses remote satellite sensing to look at the relationships between accumulation and temperature and the control of atmospheric circulation on snow accumulation. Paleoclimatic modeling at GISP2 encompasses a wide variety of topics including paleotemperatures, chemical signal characteristics, atmospheric circulation, ocean ice cover, Arctic control on climate change, complexity of Holocene climate and new approaches to glaciochemical time series analysis. Air/snow exchange modeling, which is still currently being investigated at the GISP2 site, include modeling of transfer functions for hydrogen peroxide and aerosol chemical species. Below are abstracts of papers which comprise some of the modeling efforts of the GISP2 project. For a complete abstract collection of GISP2 please refer to the Contribution Series produced by the GISP2 Science Management Office (Phone 603/862-1991; Fax 603/862-2124; E-mail smo@unh.edu).

Abstracts

Depth/Age Modeling

Predicted Time Scales for GISP2 and GRIP Boreholes at Summit, Greenland
C. Schott, E. D. Waddington, and C. F. Raymond
1992. Journal of Glaciology 38(128). 162 – 168.

Two deep-drilling projects (GISP2 and GRIP) in central Greenland will provide ice cores for paleoclimate studies. Drilling decisions and preliminary interpretations require age-depth curves (time-scales). Using a finite-element momentum-balance model, we calculate the modern ice-flow pattern on the flowline through the two drill sites. Our model appears to require relatively soft ice either throughout the ice sheet or below the Wisconsinan-Holocene transition in order to match the modern geometry and mass balance. By scaling the ice velocity to an assumed mass-balance history throughout the past 200,000 years, we estimate the time-scales at both sites. At GISP2, a flank site, we place the 10,000 years BP isochrone (representing the Wisconsinan-Holocene transition) at 1535 m ice-equivalent depth. At GRIP, on the ice divide, the corresponding depth is 1377 m. Our calculations show ice older that 200,000 years at 100 m above the bed at both coring sites. The time-scale calculation can be used for drilling decisions and preliminary interpretations. It should be refined as more regional-survey and ice-core data become available.

Sensitivity of the Ice-Divide Position in Greenland to Climate Change
S. Anandakrishnan, R. B. Alley, and E. D. Waddington
1994. Geophysical Research Letters 21. 441 – 444.

Model calculations of depth-age relations for deep ice cores in central Greenland are sensitive to stability of the ice-divide position. In addition, the folding of layers observed in the deep ice could be instigated by divide migration changing the velocity and particle path of ice flow. We use simple steady-state calculations to show that lateral divide migration of between 10 km and 50 km and elevation change of approximately 100 m is likely on glacial-interglacial time scales, enough to affect model dating. The ice-divide location appears to be most sensitive to the position of the ice-sheet margins. By contrast, the ice-divide elevation is most sensitive to the accumulation rate, the temperature profile, and the ice-stiffness profile.

Constraints on Holocene Ice-Thickness Changes in Central Greenland from the GISP2 Ice-Core Data
J. F. Bolzan, E. D. Waddington, R. B. Alley, and D. A. Meese
1995. Annals of Glaciology 21. 33 – 39.

The depth-age relation observed in the GISP2 ice core is the result of the integrated effects of ice-sheet changes over time, as well as the accumulation-rate history. Here we construct a forward model to compute ages at various depths in the core. In the model, the ages are functions of parameters that describe the thickness as a function of time. Using the maximum likelihood inverse method, these parameters are iteratively adjusted until measured and computed ages agree satisfactorily. The results suggest that the thickness along the flowline connecting the GISP2 and GRIP drill sites has not changed significantly since the onset of the Holocene. We also derive bounds on the likely thickness changes. Because these bounds are independent of assumptions concerning the processes driving the ice-sheet evolution, they can provide useful constraints for other ice-sheet modeling efforts.

Flow Modeling

Boudinage: A Source of Stratigraphic Disturbance in Glacial Ice in Central Greenland
J. Cunningham and E. D. Waddington
1990. Journal of Glaciology 36(123). 269 – 272.

A hydrodynamic model of interface stability in a stratified fluid is reviewed. The model predicts that irregularities on the boundaries of a stiff layer, embedded in a soft matrix, are unstable in pure shearing flow, when compression is normal to the layer. Perturbations on such a layer can grow to form symmetric pinch-and-swell structures called boudins. The model predicts initial perturbation growth rates on the boundaries of an interglacial period ice layer. We find that, beneath an ice divide, irregularititeson the Sangamon layer boundaries will not kinematically decay, as the layer thins. Finite-element modeling is used to determine the strain history of Sangamon ice beneath the divide at Summit, Greenland. That history suggests boundary irregularities have grown, relative to layer thickness, at least 26 fold over the past 90,000 years. The result may be sever distortion or severing of the layer. Core holes penetrating the layer may recover anomalously thick or thin columns of ice resulting in erroneous environmental and climatic interpretations. Radio echo-sounding may be useful in searching for zones of boudinage, which should be avoided when coring. Initial perturbations might arise from mass-balance spatial variations or from transient flow fields.

Flow-Law Hypotheses for Ice-Sheet Modeling
R. B. Alley
1992. Journal of Glaciolog 38(129). 245 – 256.

Ice-flow modeling requires a flow law relating strain rates to stresses in situ, but a flow law cannot be measured directly in ice sheets. Microscopic processes such as dislocation glide and boundary diffusion control both the flow law for ice and the development of physical properties such as grain size and c-axis fabric. These microscopic processes can be inferred from observations of the physical properties, and the flow law then can be estimated from the microscopic processes. A review of available literature shows that this approach can be imperfectly successful. Interior regions of large ice sheets probably have depth-varying flow-law "constants," with the stress exponent, n, for power-law creep less than 3 in upper regions and equal to 3 only in deep ice; n probably equals 3 through most of the thickness of ice shelves and ice streams.

Finite Element Analysis of the Modified Ring Test for Determining Mode I Fracture Toughness
M. P. Fischer, D. Elsworth, R. B. Alley, and T. Engelder
International Journal of Rock Mechanics 33(1). 1 – 15.

Plane strain fracture toughness (KIc) values are determined for the modified ring (MR) test through numerical simulation of crack growth to highlight the sensitivity of MR KIc values on applied displacement or force boundary conditions, slip conditions at the specimen-platen interface, and the Poisson ration (v) of the test material. Numerical calculation of fracture toughness in the MR test is traditionally conducted assuming a uniform force along the specimen loading surfaces and no slip between the specimen and the loading platens. Under these conditions KIc increases by 30 to 40% as v decreases from 0.4 to 0.1. When slip is allowed at the specimen-platen interface under a uniform force, KIc values are independent of v, and for any given v, are 5 to 25% less than those determined under a no-slip boundary condition. Under a uniform displacement of the specimen loading surfaces, KIc is essentially independent of v, regardless of specimen-platen interaction. Moreover, although KIc values determined under uniform displacement and no-slip boundary conditions are always higher than those determined under uniform displacement and slip-allowed boundary conditions, the average difference in KIc for these two methods is less than 5% for the two specimen geometries examined. This suggests that under uniform displacement conditions, KIc is essentially independent of specimen-platen interaction. Because KIc values determined from MR testing are strongly dependent on the modeling procedure, future reports of KIc determined from this test should be accompanied by detailed reports of the modeling procedure. Until further testing reveals the most accurate simulation technique, we advocate use of a uniform displacement formulation for KIc determination from MR testing because results from this method are insensitive to most modeling parameters. Numerical results from models conducted under uniform force, no-slip boundary conditions should be viewed as an upper bound to KIc.

Accumulation Modeling

Spatial and Temporal Characterization of Hoar Formation in Central Greenland using SSM/I Brightness Temperatures
C. A. Shuman and R. B. Alley
1993. Geophysical Research Letters 20(23). 2643 – 2646.

The summertime formation and burial of low-density, coarse-grained, hoar layers in the snow of central Greenland can be mapped using satellite passive-microwave data. Variations in a signal derived from Special Sensor Microwave/Imager (SSM/I) brightness temperature trends correlate temporally and spatially with hoar complex formation over approximately 120,000 km^2 of the Greenland ice sheet's dry firn facies. Observations at the Greenland Ice Sheet Project II (GISP2) site indicate that changes in surface conditions and microwave data correspond to four hoar events over two summers, as expected from theory. Following a snowfall, the smooth, high-density surface reflects some emitted, 37 GHz, horizontally-polarized (H) radiation but little vertically-polarized (V) radiation. Progressive surface roughness increase and density decrease during hoar formation causes a gradual decrease in H reflection. Formation and burial of a hoar layer thus causes a slow decrease followed by an abrupt increase in the V/H ratio. Hoar layers have been used to date the GISP2 ice core through the entire Holocene; archived microwave data now can be studied to assess the timing and frequency of the formation of these extensive stratigraphic markers in central Greenland.

Characterization of a Hoar-Development Episode using SSM/I Brightness Temperatures in the Vicinity of the GISP2 site, Greenland
C. A. Shuman, R. B. Alley, and S. Anandakrishnan
1993. Annals of Glaciology 17. 183 – 188.

Formation of a surface-hoar/depth-hoar complex at the GISP2 site in central Greenland was correlated with large changes in Special Sensor Microwave/Imager (SSM/I) brightness-temperature data. Pass-averaged SSM/I brightness-temperature data over a $^1/_2$ degree latitude by 1 degree longitude cell for the 19 and 37 GHz, vertically (V) and horizontally (H) polarized bands were manipulated to yield differential (V-H) trends which clearly show a gradual decline as the hoar formation caused a progressively rougher surface with progressively lower density. The hoar episode ended as snowfall and high winds buried and destroyed the surface-hoar layer and caused rapid V-H increases in approximately 1 day. Comparison of the differential trends to changes in the field-monitored variables and theoretical values suggests that the V-H trends are sensitive primarily to changes in surface roughness, and secondarily to near-surface density changes. Consistent expression of trends in microwave brightness temperature over 35 adjacent study cells indicates that this technique may provide a remote-sensing signature capable of defining the timing and spatial extent of surface- and depth-hoar formation in central Greenland.

An Empirical Technique for Estimating Near-Surface Air Temperatures in Central Greenland from SSM/I Brightness Temperatures
C. A. Shuman, R. B. Alley, S. Anandakrishnan, and C. R. Stearns,
1995. Remote Sensing of Environment 51. 245 – 252.

Near-surface air temperatures in central Greenland can be estimated from satellite passive microwave brightness temperatures supported by limited air-temperature data from automatic weather stations. In this region, brightness temperature depends on snow emissivity, which varies slowly over time, and on snow temperature, which varies more rapidly and is controlled by air temperature. The air temperature and brightness temperature data define an emissivity trend which can be modeled as an annual sinusoid. Estimated air temperatures represent an integrated near-surface value that defines the overall temperature trend at the Greenland summit. The modeled emissivity trend allows daily-average air temperatures to be estimated across significant gaps in weather station records, as well as quality control of their temperature data. The technique also generates annual trends of emissivity which can be used to calibrate or test radiative transfer models of microwave emissivity from dry firn.

Temperature and Accumulation at the Greenland Summit: Comparison of High-Resolution Isotope Profiles and Passive Microwave Brightness Temperature Trends
C. A. Shuman, R. B. Alley, S. Anandakrishnan, J. W. C. White, P. M. Grootes, and C. R. Stearns
1995. Journal of Geophysical Research 100(D5). 9165 – 9177.

Long-term passive microwave brightness temperature trends, supported by short-term automatic weather station (AWS) temperature data, show that the Greenland Summit area experiences secondary warm periods in the late fall and(or) winter as well as primary midsummer warmth. High-resolution isotope profiles from snow pits dug in 1989, 1990, and 1991 near the Greenland Ice Sheet

Project II (GISP2) site reveal that stable isotope ratios ($d^{18}O$ and dD) preserve this distinctive temperature cycle. This indicates that snow accumulation occurs frequently through the year at the Summit and that the isotope record initially contains temperature information from many times of the year. Comparisons of the records have allowed amounts, rates, and seasonal distribution of accumulation to be estimated as well as the weighting function for isotope thermometry and isotopic diffusion to be evaluated. Through an empirically-derived emissivity model using AWS air temperature data and brightness temperatures, our technique allows isotope values preserved in the snow to be related to estimated near-surface air temperatures. Density-corrected, water-equivalent profiles allow the amounts and timing of accumulation to be determined. Our results indicate that stable isotope ratios from the near-surface snow at the Greenland Summit are a reliable, high-resolution temperature proxy. This gives confidence to the paleoclimatic interpretation of isotope signal variations in the GISP2 core.

The Effect of Ice Sheet Thickness Changes on the Accumulation History Inferred from GISP2 Layer Thicknesses

N. A. Cutler, C. F. Raymond, E. D. Waddington, D. A. Meese, and R. B. Alley

1995. Annals of Glaciology 21. 26 – 32.

In order to infer past net accumulation rates at the Greenland summit using layer thickness data from the GISP2 ice core, we have developed a nonlinear, one-dimensional flow model of an ice sheet that allows for thickness change in response to mass balance variations. The model is used to investigate how net accumulation rate changes affect the time evolution of: (1) The ice sheet thickness, (2) the vertical strain rate pattern, and (3) the corresponding internal annual layer structure. The model is parameterized to fit the present net accumulation rate and thickness of the Greenland ice sheet summit. This parameterization results in a characteristic time constant for adjustment to accumulation changes of about 6000 years and yields an ice sheet about 400 meters thinner than its present thickness during the last glacial period.

Accumulation rate histories inferred from GISP2 layer thickness data using both a constant and variable thickness model are compared. In general, the variable thickness model predicts lower accumulation rates for the last glacial maximum to the present. However, sensitivity analyses indicate that the inferred accumulation history cannot be precisely determined by this model. Our analysis defines an envelope of likely accumulation histories bounded above by the accumulation history inferred by the constant thickness model and bounded below by a calculation from this new model where the ice sheet thickness is most sensitive to mass balance changes. General features of this envelope include: (1) Minimum accumulation rates during the last glacial period range from about $^1/_3$ to $^1/_4$ the present rate (0.24 m/yr ice equivalent),(2) the maximum accumulation rate during the Bølling-Allerød warm period (13-15 ky BP) ranges from 0.16 to 0.20 m/yr ice equivalent, and (3) the lower bound predicts a more gradual increase in accumulation since the end of the Younger Dryas than the constant thickness model upper bound.

Dominant Control of Atmospheric Circulation on Snow Accumulation in Central Greenland

W. R. Kapsner, R. B. Alley, C. A. Shuman, S. Anandakrishnan, and P. M. Grootes

1995. Nature 373. 52 – 54.

Atmospheric circulation and not temperature is the primary control on snow accumulation in central Greenland over the last 17,000 years, based on correlation of accumulation to temperature calculated from the isotopic composition of a deep ice core. Within both warm (Holocene) and cold (Younger Dryas, glacial maximum) climate states, the sensitivity of accumulation to temperature is less than expected if accumulation is controlled primarily by the ability of warmer air to deliver more moisture. During transitions between warm and cold climate states, accumulation varies more than can be explained thermodynamically, probably because of storm-track shifts. In a greenhouse-warmed world, any circulation changes may be more important than the direct effects of temperature change in controlling accumulation in Greenland and its contribution to sea-level change.

Paleoclimatic Modeling

Toward using Borehole Temperatures to Calibrate an Isotopic Paleothermometer in Central Greenland

K. M. Cuffey, R. B. Alley, P. M. Grootes, and S. Anandakrishnan

1992. Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section) 98. 265 – 268.

Analysis of borehole temperatures in ice sheets can improve the accuracy of isotopic paleothermometry by making possible independent calibrations of isotope-temperature relations. Here we present a preliminary calibration of the delta ^{18}O paleothermometer for central Greenland. A numerical thermal model converts isotope-derived surface-temperature histories to temperature-depth profiles. Comparison with measured borehole temperatures allows calibration of the paleothermometer using formal inverse techniques.

Greenland Ice Core "Signal" Characteristics: An Expanded View of Climate Change

P. A. Mayewski, L. D. Meeker, M. C. Morrison, M. S. Twickler, S. I. Whitlow, K. K. Ferland, D. A. Meese, M. R. Legrand, and J. P. Steffensen

1993. Journal of Geophysical Research 98(D7). 12,839 – 12,847.

While there are several rich proxy records covering much of the last millennium, little is know about the composition of the soluble constituents of the atmosphere at this time. However, it is within the framework of the last millennium that the complexities of natural variability and the effects of anthropogenic forcing of the environment are interwoven. Inherent in this natural variability are properties of non-linearity, stationarity and non-stationarity all of which can be assessed by an innovative form of signal analysis that has been applied to glaciochemical time-series recently recovered from central Greenland.

Complexity of Holocene Climate as Reconstructed from a Greenland Ice Core

S. R. O'Brien, P. A. Mayewski, L. D. Meeker, D. A. Meese, M. S. Twickler, and S. I. Whitlow

1995. Science 270. 1962 – 1964.

Glaciochemical time series developed from Summit, Greenland, indicate that the chemical composition of the atmosphere was dynamic during the Holocene epoch. Concentrations of sea salt and terrestrial dusts increased in Summit snow during the periods 0 to 700, 2400 to 3100, 5000 to 6100, 7800 to 8800, and more than 11,300 years ago. The most recent increase, and also the most abrupt, coincides with the Little Ice Age. These changes imply that either the north polar vortex expanded or the meridional air flow intensified during these periods, and that temperatures in the mid to high northern latitudes were potentially the coldest since the Youngest Dryas event.

Calibration of the Delta ^{18}O Isotopic Paleothermometer for Central Greenland, using Borehole Temperatures: Results and Sensitivity

K. Cuffey, R. Alley, P. Grootes, J. Bolzan, and S. Anandakrishnan

1994. Journal of Glaciology 40. 341 – 349.

We calibrate the delta ^{18}O paleothermometer for central Greenland using borehole temperatures, a thermal model forced by a measured delta ^{18}O record, and formal inverse techniques. The calibration is determined largely by temperature fluctuations of the last several centuries, including the little ice age. Results are generally insensitive to model variables. Results of this borehole calibration also seem to be in good agreement with modern spatial gradients of delta and temperature. We suggest that calibrations of isotopic paleothermometers using borehole temperatures are a useful paleoclimate tool because they are independent of spatial gradients and include the effects of prehistoric temperatures over ice sheets.

A New Approach to Glaciochemical Time Series Analysis

L. D. Meeker, P. A. Mayewski, and P. Bloomfield

In: R. Delmas (ed.). 1995. Ice Core Studies of Global Biogeochemical Cycles, Annecy, France. NATO advanced Sciences Institutes Series 1, Vol. 30. 383 – 400.

Time series obtained from glacier ice cores present special difficulties to the scientist and time series analyst. These series generally represent multivariate non-stationary and non-linear processes sampled non-uniformly in time. As a consequence, few of the traditional methods of time series analysis are immediately applicable in their usual formulation. Here we discuss the analytical problems presented by glaciochemical time series and review some of the procedures available or under development to explore the paleoclimatological information they contain.

Changes in Continental and Sea-Salt Atmospheric Loadings in Central Greenland during the Most Recent Deglaciation

R. B. Alley, R. C. Finkel, K. Nishiizumi, S. Anandakrishnan, C. A. Shuman, G. R. Mershon, G. A. Zielinski and P. A. Mayewski

1995. Journal of Glaciology 41(139). 503 – 514.

By fitting a very simple atmospheric-impurity model to high-resolution data on ice accumulation and contaminant fluxes in the GISP2 ice core, we have estimated changes in the atmospheric concentrations of soluble major ions, insoluble particulates and 10Be during the transition from glacial to Holocene conditions. For many species, changes in concentration in the ice typically overestimate atmospheric changes, and changes in flux to the ice typically underestimate atmospheric changes, because times of increased atmospheric contaminant loading also are times of reduced snowfall. The model interpolates between the flux and concentration records by explicitly allowing for wet- and dry-deposition processes. Compared to the warm Preboreal that followed, we estimate that the atmosphere over Greenland sampled by snow accumulated during the Younger Dryas cold event contained on average four to seven times the insoluble particulates and nearly seven times the soluble calcium derived from continental sources, and about three times the sea salt, but only slightly more cosmogenic 10Be.

Changes in Atmospheric Circulation and Ocean Ice Cover over the North Atlantic During the Last 41,000 Years

P. A. Mayewski, L. D. Meeker, S. I. Whitlow, M. S. Twickler, M. C. Morrison, P. Bloomfield, G. C. Bond, R. B. Alley, A. J. Gow, P. M. Grootes, D. A. Meese, M. Ram, K. C. Taylor, and W. Wumkes

1994. Science 263. 1747 – 1751.

High-resolution, continuous multivariate chemical records from a central Greenland ice core provide a sensitive measure of climate change and chemical composition of the atmosphere over the last 41,000 years. These chemical series reveal a record of change in the relative size and intensity of the circulation system that transported air masses to Greenland (defined here as the polar circulation index [PCI]) and in the extent of ocean ice cover. Massive iceberg discharge events previously defined from the marine record are correlated with notable expansions of ocean ice cover and increases in PCI. During stadials without discharge events, ocean ice cover appears to reach some common maximum level. The massive aerosol loadings and dramatic variations in ocean ice cover documented in ice cores should be included in climate modeling.

Resolved: The Arctic Controls Global Climate Change
R. B. Alley
In: W. O. Smith, Jr., and J. M. Grebmeier (eds.). 1995. Arctic Oceanography: Marginal ice zone and continental shelves. American Geophysical Union Coastal and Estuarine Studies 49. 263 – 283

Paleoclimatic records of the most recent million years show strong variability in the Arctic, and nearly synchronous variability of similar or smaller magnitude elsewhere. The timing of climate variability relative to changes in the seasonality and strength of sunlight reaching the Earth (Milankovitch forcing) shows that much of the global response is controlled by conditions at high northern latitudes. Physical modeling of this system requires some important climatic element with a slow time constant, and Arctic or Subarctic continental ice sheets are the only viable candidates at the present time. Shorter-period (Heinrich/Bond and Dansgaard/Oeschger) oscillations are strongest in the North Atlantic region but appear elsewhere. Internal oscillations of ice sheets and of the North Atlantic ocean are the leading hypotheses for controlling mechanisms. The global climate system is probably linked to Arctic forcing and oscillations through the deepwater formation in the North Atlantic, and its effects on global atmospheric circulation, sea ice, carbon dioxide, methane and dust.

Large Arctic Temperature Change at the Wisconsin-Holocene Glacial Transition
K. M. Cuffey, G. D. Clow, R. B. Alley, M. Stuiver, E. D. Waddington, and R. W. Saltus
1995. Science 270. 455 – 458.

Analysis of borehole temperature and GISP2 ice-core isotopic composition reveals that the warming from average glacial conditions to the Holocene in central Greenland was large, approximately 15°C. This is at least a three-fold amplification of the coincident temperature change in the Tropics and mid-latitudes. The coldest periods of the last glacial were probably 21°C colder than the present over the Greenland ice sheet.

Air/Snow Transfer Modeling

Overview of Field Data on the Deposition of Aerosol-Associated Species to the Surface Snow of Polar Glaciers, Particularly Recent Work in Greenland
J. E. Dibb
1996. NATO ARW on Processes of Chemical Exchange between the Atmosphere and Polar Snow 1(42). 249 – 274.

This contribution presents a review of recent field experiments investigating the relationship between the composition of snow falling onto polar glaciers and the composition of aerosols in the overlying atmosphere. The limited data existing prior to the late 1980's indicated that aerosol removal processes should cause fractionation between the composition of aerosols and snow. Uncertainties regarding the relative importance of ice-nucleation scavenging, in-cloud riming of snow flakes and dry deposition over polar ice sheets precluded assessment of the impact the likely fractionation would have on efforts to reconstruct temporal variations in aerosol chemistry from ice core chemistry records. Two large international experiments on the Greenland ice sheet after 1988 focused on these, and other, issues central to understanding air-snow exchange processes. These experiments confirmed that ice-nucleation scavenging is the major process incorporating aerosol-associated species into polar snow. This process enriches snow in large aerosols relative to the aerosol population aloft. Dry deposition was found to be of minor importance at the present time, but also enriches the snow in large aerosols and the species associated with them. Since the large aerosols over Greenland are predominantly derived from sea-salt and dust, while SO_4^{2-}, NH_4^+, and several pollutant trace metals are concentrated in submicron aerosols, snow chemistry presents a biased view of aerosol composition. However, it would appear to be possible to incorporate such a bias into efforts to reconstruct aerosol chemistry records from ice cores, were it not for several complicating factors. Spatial variability in snow chemistry will likely impose an inherent limit on the temporal resolution that will be possible in such reconstructions. Variations in the seasonal pattern of snow accumulation over time have the potential to greatly complicate interpretation of ice core chemistry records. Unfortunately, it is not clear if seasonal changes in snow accumulation could be recognized and quantified from ice core records, if they have occurred. Deposition of aerosols and associated species by fog droplets was found to be of greater importance than expected. This mechanism does not fractionate the atmospheric aerosol population to the same extent as snowfall and dry deposition. Variations in the relative contributions of fog versus snow over time (on seasonal to millennial scales) would thus alter the relationship between the composition of aerosols and the snowpack. Here again, it is uncertain whether such changes could be recognized in an ice core and accounted for in the reconstruction of past aerosol composition and loading.

Atmosphere-Snow Transfer Function for H_2O_2: Microphysical Considerations

M. A. Conklin, A. Sigg, A. Neftel, and R. C. Bales
1993. Journal of Geophysical Research 98(D10). 18,367 – 18,376.

H_2O_2 analyses of polar ice cores show an increase in concentration from 200 years to the present. In order to quantitatively relate the observed trend in the ice to atmospheric levels, the atmosphere-snow transfer behavior and post-depositional changes must be known. Atmosphere-snow transfer was studied by investigating uptake and release of H_2O_2 in a series of laboratory column experiments in the temperature range –3 to –45°C. Experiments consisted of passing H_2O_2-containing air through a column packed with 200-μm diameter ice spheres, and measuring the change in gas-phase H_2O_2 concentration with time. The uptake of H_2O_2 was a slow process requiring several hours to reach equilibrium. Uptake involved incorporation of H_2O_2 into the bulk ice as well as surface accumulation. The amount of H_2O_2 taken up by the ice was greater at the lower temperatures. The sticking coefficient for H_2O_2 on ice in the same experiments was estimated to be on the order of 0.02 to 0.5. Release of H_2O_2 from the ice occurred upon passing H_2O_2-free air through the packed columns, with the time scale for degassing similar to that for uptake. These results suggest that systematic losses of H_2O_2 from polar snow could occur under similar conditions, when atmospheric concentrations of H_2O_2 are low, i.e., in the winter.

A Simple Model to Estimate Atmospheric Concentrations of Aerosol Chemical Species Based on Snow Core Chemistry at Summit, Greenland

M. H. Bergin, C. I. Davidson, J. E. Dibb, J.-L. Jaffrezo, H. D. Kuhns, and S. N. Pandis
1995. Geophysical Research Letters 22(24). 3517 – 3520.

A simple model is presented to estimate atmospheric concentrations of chemical species that exist primarily as aerosols based on snow core/ice core chemistry at Summit, Greenland. The model considers the processes of snow, fog, and dry deposition. The deposition parameters for each of the processes are estimated for SO_4^{2-} and Ca^{2+}, and are based on experiments conducted during the 1993 and 1994 summer field seasons. The seasonal mean atmospheric concentrations are estimated based on the deposition parameters and snow cores obtained during the field seasons. The ratios of the estimated seasonal mean airborne concentration divided by the measured mean concentration for SO_4^{2-} over the 1993 and 1994 field seasons are 0.85 and 0.95, respectively. The ratios for Ca^{2+} are 0.45 and 0.90 for the 1993 and 1994 field seasons. The uncertainties in the estimated atmospheric concentrations range from 30 to 40% and are due to variability in the input parameters. The model estimates the seasonal mean atmospheric SO_4^{2-} and Ca^{2+} concentrations to within 15 and 55%, respectively. Although the model is not directly applied to ice cores, the application of the model to ice core chemical signals is briefly discussed.

The Diel Variations of H_2O_2 in Greenland: A Discussion of the Cause and Effect Relationship
R. C. Bales, J. R. McConnell, M. V. Losleben, M. H. Conklin, K. Fuhrer, A. Neftel, J. E. Dibb, J. D. W. Kahl, and C. R. Stearns
1995. Journal of Geophysical Research 100(D9). 18,661 – 18,668.

Atmospheric hydrogen peroxide (H_2O_2) measurements at Summit, Greenland in May through June, 1993 exhibited a diel variation, with afternoon highs typically 1 to 2 ppbv and nighttime lows about 0.5 ppbv lower. This variation closely followed that for temperature; specific humidity exhibited the same general trend. During a 17-day snowfall-free period, surface snow was accumulating H_2O_2, apparently from nighttime co-condensation of H_2O and H_2O_2. Previous photochemical modeling suggests that daytime H_2O_2 should be about 1 ppbv, significantly lower than our measured values. Previous equilibrium partitioning measurements between ice and gas phase suggest that air in equilibrium with H_2O_2 concentrations measured in surface snow (15 to 18 μM) should have an H_2O_2 concentration 2 to 3 times what we measured 0.2 to 3.5 m above the snow surface. Using a simple eddy diffusion model, with vertical eddy diffusion coefficients calculated from balloon soundings, suggested that atmospheric H_2O_2 concentrations should be significantly affected by any H_2O_2 degassed from surface snow. Field measurements showed the absence of either high concentrations of H_2O_2 or a measurable concentration gradient between inlets 0.2 and 3 m above the snow, however. A surface resistance to degassing (i.e., slow release of H_2O_2 from the ice matrix) is a plausible explanation for the differences between observations and modeled atmospheric profiles. Degassing of H_2O_2 at a rate below our detection limit would still influence measured atmospheric concentrations and help explain the difference between measurements and photochemical modeling. The cumulative evidence suggests that surface snow adjusts slowly to drops in atmospheric H_2O_2 concentration, over time scales of at least weeks. The H_2O_2 losses previously observed in pits sampled over more than one year are thought to occur later in the summer or fall.

Processes of Chemical Exchange Between the Atmosphere and Polar Snow: Key to Interpreting Natural Climate Signals in Ice Cores
R. C. Bales and E. W. Wolff
1995. EOS 76(47).

(No abstract available.)

Paleoenvironmental Studies Component

Paleoclimates of Arctic Lakes and Estuaries
– PALE –

PALE Modeling Efforts

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Overview

PALE, whose main focus is the collection and integration of paleo-data from the Arctic, contributes to both ARCSS and other global modeling efforts by providing information for evaluating model results and for defining boundary conditions used in modeling experiments. The current modeling activity in PALE emphasizes approaches using both conceptual (e.g., Bartlein et al., 1991) and atmospheric general circulation models (AGCMs). Analyses within the latter class of models include either or both:

- The direct comparison of paleoclimatic trends inferred from the proxy data to the AGCM results (Fig. 1, Approach 2); and
- the use of the AGCM results to simulate a particular proxy (e.g., pollen abundances) with subsequent comparison to the paleoclimatic data (Fig. 1, Approach 1; see also Webb et al., 1993).

These types of analyses are key components of ongoing projects of the National Center for Atmospheric Research (NCAR) and the Paleoclimatic Mapping Intercomparison Project (PMIP). PALE

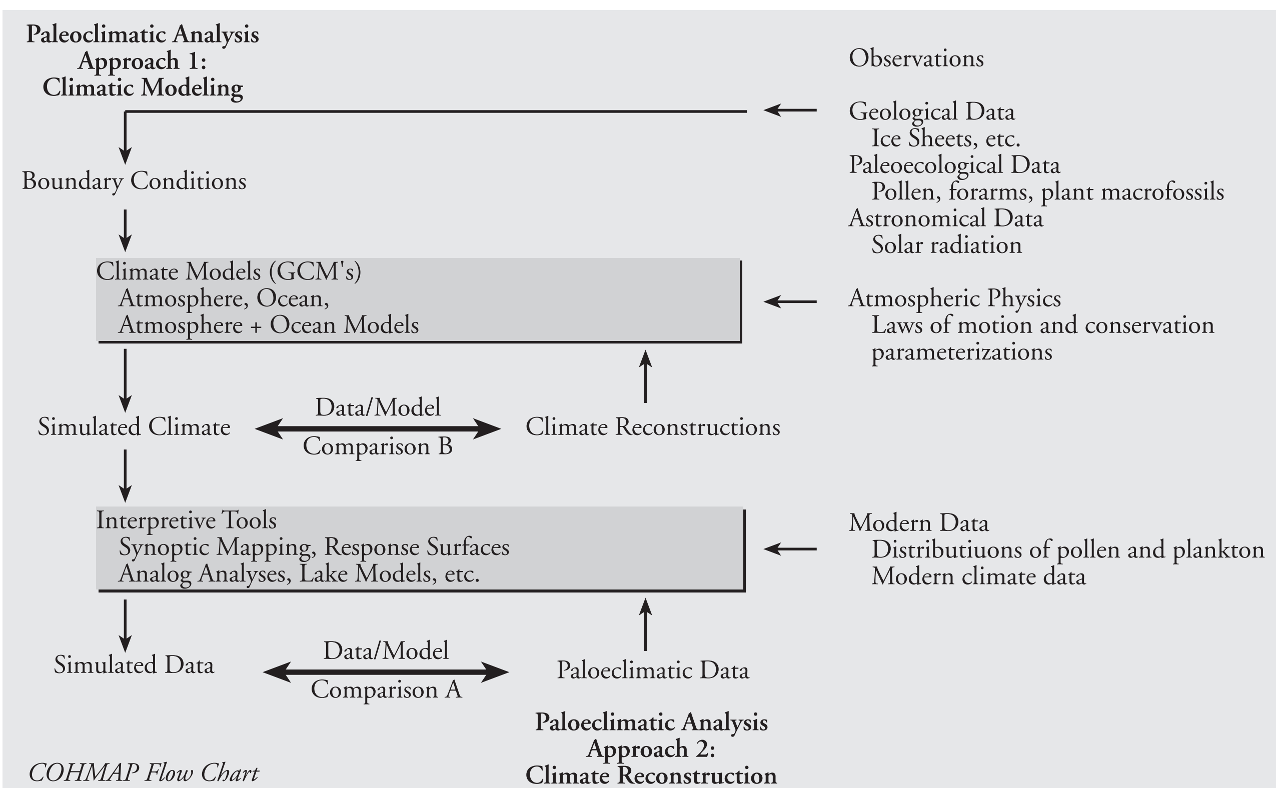

Fig. 1. Interactive scheme for comparison of paleo-data and AGCM results. From Bartlein et al. (in prep.).

also is working with modelers applying vegetation or biome models (e.g., Prentice et al., 1992; Harrison et al., 1995; Prentice et al., 1992; Bergengren and Thompson, in prep.) as a means to examine terrestrial responses to changing climates. In addition to such global-scale efforts, PALE is developing regional paleoclimatic models for the northwestern North Atlantic sector and Beringia.

Currently, the main climatic modeling emphasis in PALE revolves around applications of the GENESIS global climate model (Thompson and Pollard, 1995a,b) and collaboration with NCAR modelers. Vegetation modeling efforts include cooperative work with the NCAR researchers and with the BIOME 6000 project (Prentice and Webb, 1994). The following is a brief summary of model activities related to PALE:

Ice Sheet Initiation Research

Simulations address the rate at which snow/ice is predicted to accumulate on Baffin Island in response to 116-114 ka insulation forcing. Further work will investigate the role that a large Baffin Island ice cap might play in initiating glaciation in other regions.

Ice Sheet-Mass Balance Research

This work includes improvements to the model simulation of mass balance of the Greenland ice sheet with the goal of having a credible tool for application to experiments under conditions of the last glacial maximum. Simulations for the 21 ka world will investigate the role of sea-surface temperatures, atmospheric greenhouse gas concentrations, and altered vegetation patterns on the mass balance of the Laurentide ice sheet (Fig. 2). An inability to simulate the Laurentide mass balance with an otherwise credible model may call into question ice sheet reconstructions or assumptions about the equilibrium nature of the last glacial maximum.

PMIP Simulations

The goal of PMIP is to establish a framework for evaluating state-of-the-art AGCMs by comparing the performance of thirteen major models in simulating paleoclimate conditions significantly different from today. Each modeling group is making two standard (identical boundary conditions) paleoclimate simulations at 21 ka (glacial maximum) and 6 ka (interglacial conditions although with a seasonal insulation anomaly). Paleoclimatic interpretations based on fossil data are being used as an independent means to evaluate the quality of AGCM results. NCAR is participating in PMIP by performing simulations for 6 ka using standard PMIP protocols. NCAR will also perform additional 6 ka simulations to investigate the effects of interactive sea-surface temperatures and vegetation on simulated 6 ka climate. Mapped 6 ka PALE vegetation reconstructions will be used as a boundary condition in at least one experiment. As well as the 6 ka experiments, 21 ka simulations will be performed in collaboration with John Kutzbach and colleagues at the University of Wisconsin.

Global Simulation for 10 ka

In addition to the standard PMIP runs, an 10 ka experiment will be conducted using GENESIS 2.0 with a slab ocean and interactive vegetation. Although much of the North American Arctic remained ice-covered at this time, Alaska and most areas of northeastern Asia were ice-free, thereby providing information about possible responses to deglaciation at northern high latitudes.

Investigation of the Potential for Limited Area Modeling in the Arctic

Higher resolution nested climate models over limited-area regions have been under development recently. NCAR has one such regional modeling system and will investigate the feasibility and utility of performing regional climate simulations for the North Atlantic sector of the Arctic and for Beringia.

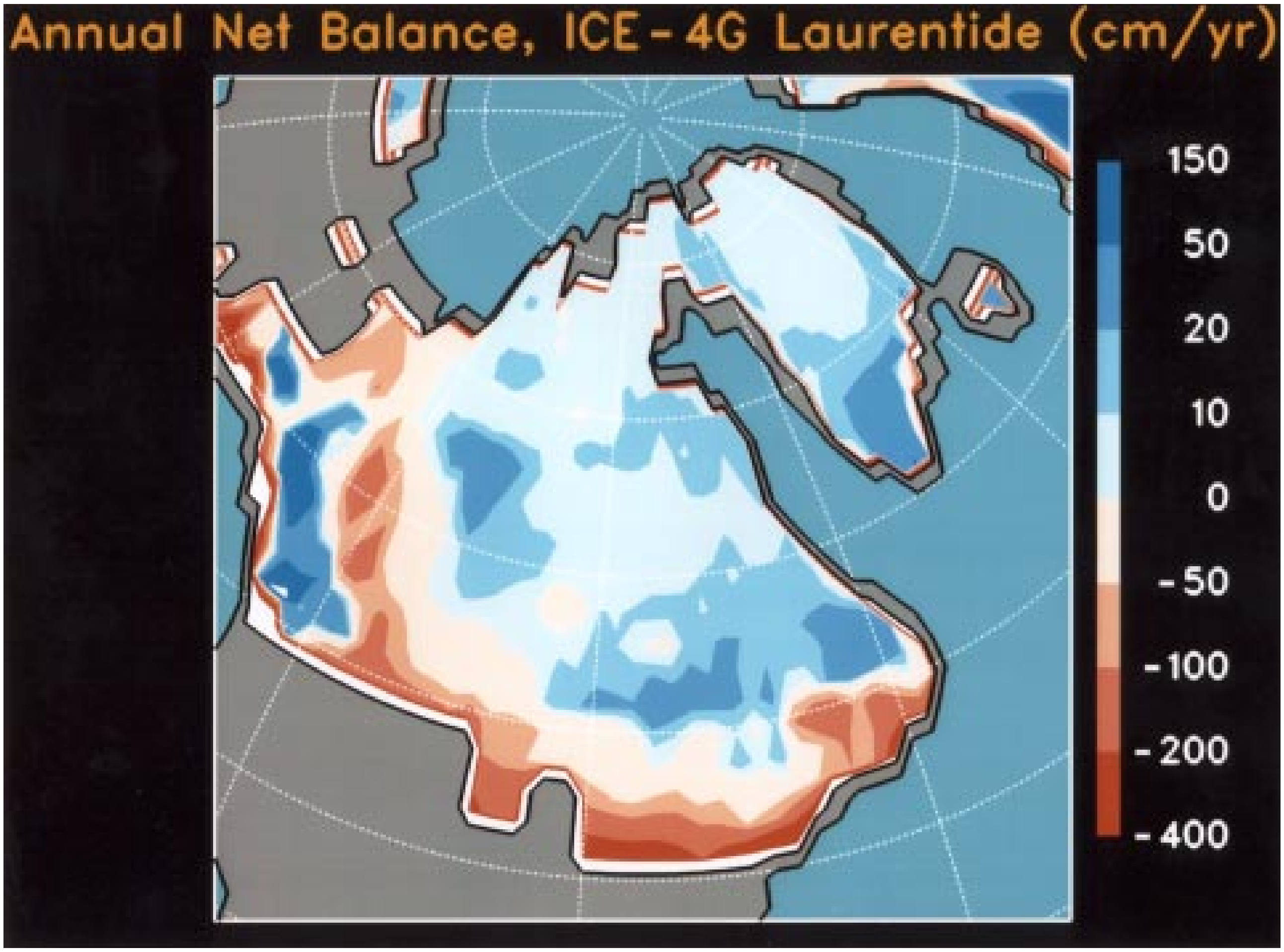

Fig. 2. The annual net mass balance over the Laurentide ice sheet at 21 ka as simulated by the GENESIS version 2.1a global climate model. The ice reconstruction is from Peltier (Science. v. 265, p. 195). The net balance averaged over the entire ice sheet is strongly negative, due mostly to strong ablation near the southern boundaries. The GENESIS model does a good job of simulating the net balance on the present-day Greenland and Antarctic ice sheets; thus the imbalance simulated for the last glacial maximum is paradoxical for now.

Global Vegetation Models

Global vegetation models are being used to improve the understanding of possible responses of vegetation to future climatic changes. Like the climatic models, they rely on model evaluation through comparison with paleobotanical records. PALE is involved with two such efforts using the BIOME (Prentice et al., 1992) and EVE (Equilibrium Vegetation Ecology) models (Bergengren and Thompson, in prep.). The role of PALE researchers is to help evaluate and, when possible improve, the capabilities of the vegetation models. The BIOME model is based on 14 plant functional types applied with an environmental sieve (including such factors as cold tolerance, heat and moisture requirements) and a dominance hierarchy. Predictions of the distribution of these plant functional types, subsequently divided into biomes based on combinations of dominant types, are driven by various climatic and soil factors. The EVE is also a phytogeographical model. It predicts the equilibrium fractional cover of 110 vegetation plant forms as a function of monthly climatic variables and also includes the effects of light competition and fire disturbance. EVE does not predict biomes directly but derives biome properties from the continuous distribution of component plant forms.

Both quantitative and conceptual models of climatic change will remain central elements of the PALE program. The use of such models are key for improving knowledge of the various controls and feedbacks that influence circumpolar and/or smaller regions within the Arctic. Although the primary focus of PALE is on climatic history and the role of the Arctic in the global climate system, the potential exists for further model development to increase understanding of landscape-scale responses to global environmental changes. This work would likely include the development and application of a hierarchy of models that encompass global- to regional-scale climatic models and landscape-scale process models of different environmental subsystems.

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NCAR Climate Modeling in Support of PALE

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The PALE modeling effort has thus far concentrated on the issues of ice sheet mass balance and initiation, using the Global Environmental and Ecological Simulation of Interactive Systems model, GENESIS 2.0 (Thompson and Pollard 1995a,b). A present-day and Last Glacial Maximum (LGM) simulation (Paleoclimate Model Intercomparison Project [PMIP] run) have been used to determine the mass balance over the ice sheets. A 116 ka simulation has been used to determine the likelihood of ice sheet initiation during the last interglacial-glacial transition. A simulation of the climate at 6 ka BP has been completed using the interactive Equilibrium Vegetation Ecology (EVE) vegetation model (Bergengren, pers. com.), in addition to the PMIP-specified 6 ka simulation. We are in the process of applying both the modern climatology and 6 ka BP GENESIS climatology (with EVE) to a regional model simulation of the north Atlantic, to provide a more accurate representation of the climate within this region, during a time of maximum Holocene warmth. We are also in the process of running a global simulation of the climate at 11 ka (calendar years), one of the warmest recent periods in Beringia.

We have studied ice sheet mass balance with a modern and LGM simulation in order to assess ice sheet mass balance during geologically real time slices. We have developed a new method of predicting ice sheet mass balance, applicable to any general circulation model (GCM), involving a pre-, during, and post-processing correction to the ice sheet regions. These corrections account for both the grid and spectral smoothing of the ice sheet topography, and for refreezing of surface snow melt. A comparison of the present surface mass balance over Greenland and Antarctica to the observed surface mass balances shows that GENESIS 2.0 does a good job at predicting the accumulation over both Greenland and Antarctica without the corrections. However, the ablation rates are too large without the corrections, since the ice sheets as "seen" by the model are too low. The mass balance rates, with the corrections applied, are close to the observed mass balance rates (19 cm/year over Greenland compared to 15 cm/year observed, and 22 cm/year over Antarctica compared to 18 cm/year observed). The mass balance over the Laurentide ice sheet during the LGM, with either the ICE-4G (Peltier, 1991) or CLIMAP (1981) ice sheet reconstructions and prescribed CLIMAP sea surface temperatures (SSTs), are strongly negative. These negative values imply errors either in the model itself or in the prescribed LGM boundary conditions. The assumption of zero or positive mass balance at 21 ka may also be in error (Clark 1992; 1994).

We have approached the question of ice sheet initiation by calculating the mass balance rates in the regions of suspected ice sheet initiation during 116 ka, the last interglacial-glacial transition. Orbital insulation was much lower than present during summer in high northern latitudes. These lower insulation conditions are thought to be responsible for the initiation of the LGM ice sheets. We have used modern boundary conditions (including no northern hemisphere ice sheets other than Greenland and Antarctica) except for the 116 ka orbital insulation. The entire region of Keewatin, Labrador, and Baffin Island is snow covered during winter. However, by August, all the snow cover has decreased except on Baffin Island. In order for ice sheets to grow to their full extent, snow cover must continue unabated throughout the year in at least a single location. This result supports the contention that Baffin Island is the most likely location for the initiation of the ice sheets.

The 6 ka BP time period has been chosen as an important time slice for PALE because of the maximum terrestrial warmth in the North Atlantic region (Williams et al., 1995). PMIP has also chosen this time slice as important for modeling studies because the only major boundary condition that differs from the present is orbital insulation (Jette, 1995). In order to compare the geologic data with modeling results, we require a higher resolution model of the north Atlantic than GCMs are able to provide. We are therefore performing simulations with a regional model to predict sub-GCM grid scale climate processes, such as precipitation and storm patterns that depend upon the detailed topography and coastlines of the region. A regional model incorporates the same fundamental physics as a GCM, but applied to only a small region of the globe. Regional models require one-way nesting of global scale data at the boundaries provided by either a GCM or global analysis. We are using the ARCSyM mesoscale model (Lynch et al., 1995), a revised version of RegCM2 (Giorgi et al., 1993a,b), which was developed to account for Arctic climatic processes such as sea ice and ice-phase clouds.

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Studies of the Contemporary Environment Component

Ocean/Atmosphere/Ice Interactions
– OAII –

Modeling Activities Within OAII

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Overview

The marine environment of the Arctic is an interactive system, comprising the water, ice, air, biota, dissolved chemicals, and sediments of the Arctic Ocean and its adjacent seas. Through the operation of processes that are only partially understood, this system strongly affects the steady and time-varying climatic state of the earth and responds sensitively to climate perturbations that originate outside the Arctic. In addition, this system can change significantly as a consequence of anthropogenic factors, including resource development, fish and wildlife management practices, and the direct input of anthropogenic substances to the components of the system. System changes that have been observed over the last several decades, and changes that may be anticipated in response to future forcing (e.g., future increases of atmospheric greenhouse gas concentrations), have important consequences for the ecology, economy, society and culture of the Arctic (Weller et al., 1991).

The ARCSS Ocean/Atmosphere/Ice Interactions (OAII) component seeks to document, understand and predict the state of the evolving arctic marine environment. OAII has identified six science priorities for research emphasis:

- Surface energy budget, atmospheric radiation and clouds;
- circulation of the Arctic Ocean;
- hydrologic cycle of the Arctic Ocean;
- productivity and biogeochemical cycling;
- coupled OAII modeling; and
- paleoceanography of the Arctic

Coupled modeling of the Ocean/Atmosphere/Ice (OAI) system addresses problems within each of the remaining five priority areas, and constitutes the aspect of OAII most relevant to this report. Also, significant model-related research is performed within each of the priority areas, to address specific processes in isolation, or in a partially-coupled mode.

The overall goal of the OAII modeling efforts is to contribute towards more accurate simulations, assessments and predictions of the arctic marine system, on time scales relevant to global change (e.g., the next 10 to 100 years). Specific objectives of the OAII modeling efforts include:

- Achieve demonstrable improvements in the simulation of the Arctic OAI system in global, coupled, ocean-atmosphere climate models. Implement these improved models to simulate and predict the future state of the arctic system.
- Develop models of the circulation of the Arctic Ocean, including its currents, sea ice cover, stratification, shelf-basin exchanges, and freshwater transports, given appropriate atmospheric forcing functions and lateral boundary conditions. These models must be sufficiently realistic to warrant application to assessment and sensitivity studies, in which the atmospheric components of change are prescribed.
- Develop models that provide a realistic account of the contribution of the arctic OAI system to the present global budgets of carbon and nutrients.
- Develop models to simulate the response of the arctic marine ecosystem to perturbations in the environmental controls, including atmospheric climate, nutrient supply, harvesting and pollutants.

The importance of arctic OAI processes to global climate is illustrated by global climate model simulations that portray an arctic marine environment in which global greenhouse warming is amplified (Houghton et al., 1990; Houghton et al., 1996), due to a combination of effects including the retreat and thinning of the sea ice cover, the confinement of surface air temperature changes by the highly stratified atmospheric boundary layer, and changes in the poleward transport of heat by the atmosphere. This potential polar amplification of global change singles out the Arctic as a sensitive and vulnerable region. The importance of arctic OAI hydrological processes to global ocean circulation is indicated by the fact that the Arctic Ocean provides inputs of relatively low-salinity sea ice and seawater at the northern boundary of the Atlantic Ocean. This freshwater source makes a vital contribution to the oceanic stratification in this region. Estimates of the freshwater budget by Aagaard and Carmack (1989) suggest that rather small variations in this source may be sufficient to control the ventilation of the deep North Atlantic, and may be responsible for the "great salinity anomaly" which moved through the subpolar gyre of the North Atlantic during the 1960s and 1970s (Dickson et al., 1988). The modeling activities conducted within the OAII component of ARCSS are discussed below in the context of the four objectives listed previously.

Summary of Studies and Results

The low-frequency (10 to 100 year time scale) variability of the arctic upper ocean-sea ice-atmosphere system was simulated using a one-dimensional thermodynamic model by Bitz et al. (1996) and Battisti et al. (1997). In these studies, the thermodynamic processes that couple the atmosphere to the sea ice and upper ocean are represented using a single column analogous to a single horizontal grid-cell in a global climate model (Moritz et al., 1992). The representations of the vertical coupling processes, such as surface fluxes, ice growth/melt, heat conduction and atmospheric radiation can be varied easily in this framework, to evaluate the potential impact on variability. Bitz et al. (1996) find that the high frequency forcing associated with variability in poleward atmospheric heat transport produces a significant (circa 1 m standard deviation) low frequency response in the sea ice thickness (time scale 10 to 15 years) due to heat storage within the ice, and surface albedo feedbacks associated with the onset of melting. The existence of such low frequency variability would greatly complicate efforts to detect a trend in ice thickness that may be attributed uniquely to global greenhouse warming.

Battisti et al. (1997) found that the simplified arctic physics employed in a leading global climate model (the Geophysical Fluid Dynamics Laboratory [GFDL] model) produce only about one-fourth as much low frequency variability in ice thickness as produced by the standard column model of Bitz et al. (1996). The main differences are the representation of the snow cover and the resolution of the vertical sea ice temperature profile in the column model. Diagnostic analyses of the arctic atmospheric climate simulated by the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) suggest that the model over-represents the heat conduction through sea ice in regions where the real sea ice is relatively thick. This enhanced heat conduction appears to affect the distribution of surface air pressure over the arctic, which is not well simulated by the CCM2 (Battisti et al., 1992).

Using a more comprehensive, higher-resolution column model based on the NCAR CCM2, Beesley and Moritz (subm.) investigate possible explanations for the observed annual cycle of low cloudiness over the Arctic Ocean. They find that the annual cycles of atmospheric moisture flux convergence and surface evaporation do not account for the winter/summer difference in low cloudiness. The critical factor appears to be the smaller residence time of ice-phase cloud particles in winter, associated with the fact that ice nuclei are much less abundant than droplet nuclei. They note that in the Atmospheric Model Intercomparison Project (AMIP; Tao et al., 1996) the atmospheric GCMs that represented ice-phase precipitation processes did a better job of simulating the annual cycle of arctic cloudiness than the models that do not represent this process.

Taken together the studies cited above indicate that to accurately simulate the variability of arctic climate (and thus define accurately the signal/noise problem of detecting arctic climate change) GCM's need to: (i) resolve the temperature profile through sea ice; (ii) represent the surface albedo accurately as a function of the state of the sea ice; and (iii) represent ice-phase cloud and precipitation processes.

McInnes and Curry (1995), studied the formation of summertime arctic stratus clouds, revisiting the Herman and Goody (1976) problem of multi-layered clouds with a more advanced radiation and turbulence closure model. They report that radiative transfer is important to the maintenance of multiple cloud layers, and the broad qualitative features can be simulated reasonably well with a vertical resolution of only 200 m, giving hope that the physics can be adapted to global climate models.

Curry et al. (1996) survey the literature on clouds and atmospheric radiation in the Arctic. They conclude that the arctic ice pack should be a sensitive indicator of climate change. Based on their survey, the authors call for a major increase in the observational data base on arctic clouds and radiation.

Maykut and McPhee (1995) combine models for the turbulent transfer of heat in the upper ocean and the evolution of the sea ice thickness distribution, with observations of ice growth, short-wave radiation, ocean temperature, and sea ice strain rate to estimate the heat budget, ice mass budget and salinity budget for an area of pack ice on the order of a GCM grid cell. The results indicate that the flux of sensible heat from the ocean to the ice is strongly time dependent, ranging from near zero in winter up to 60 W/m^2 in summer. The source of energy that drives this variable flux is almost certainly the short-wave radiation absorbed in leads and areas of thin ice. It follows that the deeper ocean in this region (Arctic Ice Dynamics Joint Experiment [AIDJEX] southern Beaufort Sea) is nearly isolated thermodynamically from the mixed layer above. Analysis of the salinity budget shows that the temporal changes in the upper ocean are poorly understood and need closer attention.

In connection with the Northeast Water Polynya Project (NEWP; Deming et al., 1993), Yager et al. (1995) describe a conceptual model for arctic polynyas as sinks for atmospheric carbon dioxide, and suggest that these features could provide a small, negative feedback tending to reduce the atmospheric CO_2 buildup from anthropogenic emissions. During summer, biological processes deplete the total inorganic carbon in the surface waters of the polynya, promoting a CO_2 flux from the atmosphere to the surface water. During winter, the ice cover limits the flux in the reverse direction, providing time for the CO_2-enriched water to circulate to greater depth, and to lose suspended matter to the sediments.

Several OAII investigators study individual processes that need special attention in coupled models, and that appear to play important roles in the real OAI system. Gawarkiewicz and Chapman (1995) and Chapman and Gawarkiewicz (1995) analyze the formation of dense (salty) water in a coastal polynya and its subsequent offshore transport over a sloping continental shelf. The resulting density front at the polynya edge exhibits an instability, generating eddies which transport the dense water away from the coast, and thus limit the maximum water density that can be formed. Chapman and Gawarkiewicz (1997) develop simple formulas which predict properties of the dense water in terms of atmospheric forcing and polynya geometry. Such eddying, topographically influenced shelf flows are thought to be important mechanisms in the exchange of water masses between the continental shelf seas and the central Arctic Ocean and, in particular, the maintenance of the upper halocline in the deep arctic basins.

The importance of deep convective plumes for climate and ocean general circulation is discussed in Paluszkiewicz et al. (1994). Garwood et al. (1994) employ buoyancy-driven ocean models to estimate the range of forcing parameters that produces deep convective eddies in the marginal seas. Jiang and Garwood (1996) model the overflow of dense water onto a continental slope, and find instabilities growing as topographic Rossby waves on the dense plume. They suggest that the resulting surface cyclonic eddies may provide a signature for indirectly observing deep overflows through the Denmark Strait.

Kowalik and Proshutinsky (1993) use a model to study the diurnal tidal constituents K1 and O1 in the Arctic Ocean. In more than 30 local regions along the continental slope, topographic waves are generated by the tidal forcing and enhanced currents are simulated. Using a similar model in a regional application, Kowalik (1994) finds that a resonance between topographic waves and tidal forcing explains the observed enhancement of tidal currents on the Yermak Plateau. Enhanced tidal currents and residual currents are also simulated in the Barents Sea (Kowalik and Proshutinsky, 1995). Arctic Ocean tidal data and modeling are reviewed and summarized by Kowalik and Proshutinsky (1994).

Glendening (1995) uses a large-eddy atmospheric simulation (LES) model to study the vertical and horizontal structure of the turbulent heat flux over a lead in the pack ice during winter. He finds that the sensible heat flux, integrated horizontally over the domain, decreases exponentially with height; that the height of maximum heat flux is approximately one-fourth the height of the top of the plume; and that a significant fraction of the energy transferred to the air over the lead is re-transferred to the (ice) surface downwind of the lead. From the LES results, he derives a parameterization for large scale climate modeling applications, in which the average flux varies in proportion to the $^1/_3$ power of the air-water temperature difference, and the $^2/_3$ power of the lead size.

Walsh and Dieterle (1994) model the carbon and nitrogen budgets for a continental shelf water column, using a quasi-two dimensional physical, biological and chemical model. They find that approximately half the seasonal resupply of nitrate stocks to their initial winter conditions in the southeastern Bering Sea derives from in situ nitrification, with the rest obtained from deep-sea influx. The model portrays this system as a sink for atmospheric CO_2 under present climate conditions. It is possible that the system served as a source for atmospheric CO_2 prior to the industrial revolution. The model indicates an order of magnitude of one gigatons carbon per year sequestered by temperate and polar shelf ecosystems combined.

Walsh et al. (1997) employ a similar lagrangian model to simulate the transit of a water parcel along a 2850 km trajectory from the southeastern Bering Sea to the northwestern Chukchi. The model replicates the major seasonal features of nitrogen and carbon cycling on these shelves. The model further suggests:

- The residence time of Pacific shelf waters in the Arctic ocean halocline is about 10 years;
- production of particulate organic carbon (POC) within the adjacent ice-covered Arctic Ocean slope waters may be ten-fold larger than early estimates for the Polar Basin;
- four-fifths of all dissolved organic carbon (DOC) within Bering Strait is of marine origin from the southeastern Bering Sea; and
- over half the satellite-sensed color signal from these waters represents DOC rather than phytoplankton pigments.

There is significant interest and activity in research on improved representations of sea ice in climate models (see abstracts by Maslowski et al.; Curry; Vavrus and Liu; Shao and Dickinson; Maslanik et al.; and Zhang et al; this volume).

Current Activities

Two important community-wide modeling activities are now underway in connection with ARCSS-OAII. First, the SHEBA Project (Surface Heat Budget of the Arctic Ocean) is about to enter Phase 2, which entails the acquisition of a comprehensive, ocean-ice-atmosphere data set over the course of a full annual cycle, from within the perennial pack ice of the Arctic Ocean. The data set will document the time evolution of this system on local scales, associated with individual features (e.g., leads, ridges, multiyear ice, snow drifts, melt ponds, cloud elements), and aggregate scales relevant to the behavior of a GCM grid cell. The data set will also document the key processes that are thought to determine this time evolution, and in this way will facilitate comparisons between both prognostic and diagnostic model results and observations. Phase 3 of SHEBA (2000 to 2002) will be devoted to the application of the data set to the development and implementation of improved climate models of the arctic OAI system.

Second, a polar climate working group has been established for the global, coupled Climate System Model (CSM) of NCAR. SHEBA, ARCSS-OAII and, in general, all of ARCSS, are seen as valuable partners in the CSM efforts to improve the simulation of global and arctic climate. R. Moritz (University of Washington) and J. Weatherly (NCAR) are co-chairing the Polar Climate Working Group. The group has agreed to establish an information page on the web, accessed through the NCAR CSM Home Page <http://www.cgd.ucar.edu/csm/index.html>, to assemble and make available certain common data sets for use in arctic climate modeling, to develop and apply modeling tools, such as a stand alone arctic OAI column version of CSM and a stand alone sea ice model, and to perform and analyze key modeling experiments to address questions about the arctic climate system, and to assess and improve model performance.

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Studies of the Contemporary Environment Component

Land/Atmosphere/Ice Interactions
– LAII –

LAII Modeling Studies

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Overview

Projects within the LAII program use mathematical modeling as either the primary research method or as means of synthesizing understanding of various parts of the arctic system and of extending the understanding to a large scale or to a long time period. All are designed to predict the results temporally or spatially or both. While the long-term goal is modeling of the entire Arctic, only a few models are working at this level. Instead, most of the Flux Study models are organized to simulate the whole Kuparuk River basin, some 8000 km^2. Others are models of processes and interactions at the ecosystem or landscape level that apply widely in the Arctic but are not tied to a specific location.

Fluxes of Water and Energy as Factors Coupling Terrestrial Processes with Regional Climate

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Climatic warming is expected to be most pronounced at high latitudes and to cause a northward movement of boreal forest into areas formerly occupied by arctic tundra. This forest development would likely increase terrestrial carbon storage and create a positive feedback to regional warming through increased absorption of solar radiation. We present the first simulations of future rates of change from arctic to boreal vegetation in response to different rates of climatic warming. Our model suggests that future time lags and directions of ecosystem change from tundra to boreal forest are highly sensitive to the rate of warming, climatic variability, and changes in precipitation and fire regime. We estimate a 150 to 250 years time lag in forestation of tundra following climatic warming and suggest that, with rapid warming under dry conditions, there would be significant development in Alaska of boreal grassland-steppe, a novel ecosystem type that was common during the late Pleistocene but today is regionally rare. Together, the time lag in forestation and grassland-steppe development would delay the positive feedback of vegetation change to climatic warming, providing a window of opportunity to control fossil fuel emissions, the primary cause of climatic warming.

Nonlinear Multivariate Modeling in Tundra CO_2 Flux Studies

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Experimental field studies of carbon flux in terrestrial ecosystems currently include chamber, tower, and aircraft measurements. While the chamber methods provide data on gross photosynthesis P, total ecosystem respiration R, and net ecosystem flux F at the patch-ecosystem level, the later two techniques produce only the flux data (F) representing the landscape and regional levels respectively. All these methods generate long time series of measurements (e.g., $\{F(t), t = t_1, t_2, t_3, ..., t_n\}$), which may be many megabytes in size. The natural step in their analysis is to construct predictive models to calculate the carbon flux components using the more easily measurable factors (e.g., meteorological and remote sensing data). If Y stands for P or R or F, the models may be formulated as:

$$Y = f(x_1, x_2, ..., x_m, a_1, a_2, ..., a_p) + e_y,$$

where x_i denote the environmental factors-predictors (e.g., radiation [PAR], air or soil surface temperature, NDVI, etc.), a_k are parameters describing the function f(...), and e_y is the error term.

The time series of flux component measurements $\{ Y(t), t = t_1, t_2, t_3, ..., t_n\}$ coupled with records of relevant factors-predictors $\{(x_1(t), ..., x_m(t)), t = t_1, t_2, t_3, ..., t_n\}$ were used to estimate parameters of the model(s) for different ecosystem types of the circumpolar Tundra Biome.

A computer program, *CO_2 Exchange* (Fig. 1), was constructed, which estimates the parameters of nonlinear multivariate models for gross photosynthesis, total respiration, and(or) net ecosystem exchange using field measurements. Coupling of the algorithm of adaptive nonlinear optimization with the graphical interface of the Macintosh Operating System implemented in the program

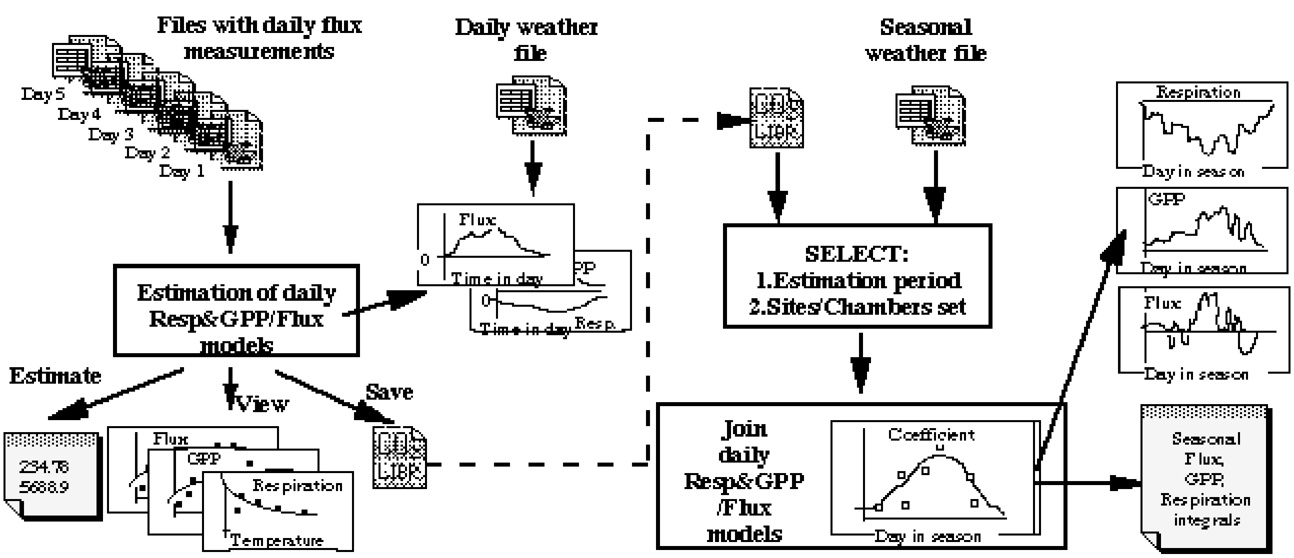

Fig. 1. General structure of the *CO_2 Exchange* program.

results in the fast and flexible estimation of parameters. The resulting models calculate the seasonal dynamics of gas exchange using meteorological and remote sensing information (Gilmanov et al., in prep.). Currently, data on PAR, air and(or) soil surface temperature, and NDVI (cf. Hope et al., 1993) serve as predictors, but the program easily allows addition of other factors (e.g., soil moisture, thaw depth). Outputs of the main model, operating on the plot scale and the minute to hour time step, are spatially aggregated to patch-ecosystem level and daily time step models to predict daily integrals of P, R, and(or) F as functions of daily PAR, temperature and NDVI (Fig. 2). The aggregated models are used in the GIS to describe geographical distribution and seasonal dynamics of the carbon flux at the landscape to regional scales (e.g., Kuparuk River Watershed).

The program was tested on data sets of chamber, tower, and aircraft CO_2 flux measurements in 1990 through 1995 on the North Slope of Alaska, and of chamber measurements on Seward Peninsula (Alaska), in Russia (Taimyr, Kolyma), and Iceland. It proved to be an efficient tool for analysis and prediction of carbon flux in tundra ecosystems. Preliminary results demonstrate agreement of flux estimates provided by chamber, tower, and aircraft techniques.

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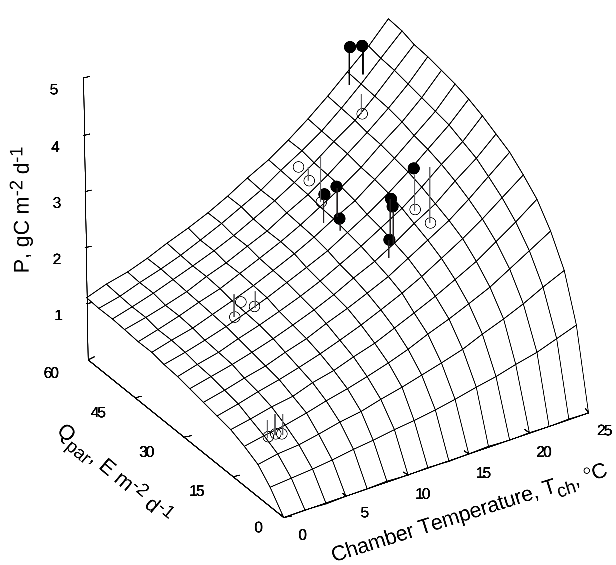

Fig. 2. Response surface of gross primary production of the shrub tussock tundra of Happy Valley site to radiation (Q_{par}), chamber temperature (T_{ch}) and NDVI. Data of field measurements are shown as points, solid points lying above the approximating surface, open points below it, and bars showing the deviation of data from the model. Mean standard deviation of the data points from the surface is 0.54 g C m^{-2} d^{-1}.

Arctic Hydrologic and Thermal Model

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A physically based, spatially distributed hydrologic and thermal model for arctic regions is being developed and tested to aid in studies of the linkages among atmospheric, terrestrial and aquatic systems. This physically based model is composed of the essential components of the surface energy and water balances. The model calculates the balances on triangular elements which are continuous across a watershed. The modeled processes include: subsurface flow, water table elevation, overland surface flow, channel flow, snowmelt, evapotranspiration/condensation, soil profile temperature and active layer thickness.

Inputs

This model requires data to calculate the entire surface energy and water balances: Such as rain and snow input, air temperature, wind speed, relative humidity, short and longwave radiation. Elements are configured based upon digital terrain data. Soil properties are derived from maps and data generated by other LAII investigators (Walker, Ping).

Outputs

The primary products of this model are hourly or daily distributed maps of soil moisture and continuous hydrographs of channel flow at user selected locations. Other useful information include distributed estimates of evaporation, active layer depth, and surface temperature.

Verification

This model is calibrated against measurements of soil moisture and surface runoff. It is also verified by comparison to distributed maps of soil moisture generated from SAR imagery.

Scales

This model is being tested in three nested watersheds on three scales: Imnavait Watershed (2.2 km^2 with 50 m elements), Upper Kuparuk River Watershed (146 km^2 with 300 m elements) and the entire Kuparuk River Watershed (8000 km^2 with 1000 m elements). The time step depends upon the spatial scale and varies for different processes within the model; for the 50 m element, subsurface flow is calculated on one hour time increments, overland flow is calculated on one minute time steps and channel flow is calculated on five second time steps. As the element size increases to 1000 m, subsurface flow is calculated on one day time increments, overland flow is calculated on twenty minute time steps and channel flow is calculated on five minute time steps.

Spectral Vegetation Index Models for Carbon Fluxes

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Description

A set of regression models have been developed to estimate daily gross primary production (GPP) as a fraction of incident photosynthetically active radiation (PAR) and daily ecosystem respiration (R) on the North Slope of Alaska. These models were developed using carbon flux data collected using small chambers (0.5 m^2) at sites in the foothills and coastal plain of the North Slope. The normalized difference vegetation index (NDVI) was a significant independent variable in each regression model and was calculated from red and near infrared reflectances measured over the chambers using a hand-held radiometer. All data were collected during the summer of 1994.

Separate models were developed for the foothills and coastal plain regions. The NDVI alone was a good predictor of GPP/PAR while the product of NDVI and daily mean air temperature was the most suitable model for predicting R at both locations.

Inputs

The NDVI, daily PAR and daily mean air temperature.

Outputs

Daily GPP expressed as a fraction of daily PAR and daily ecosystem respiration.

Scales

Data from 10 to 12 chambers distributed within an area of approximately 90 m^2 at each site were averaged for use in the regression analyses. Consequently, these models are expected to be suitable for data collected at the scale of eddy correlation towers and flux aircraft. Additional scaling strategies may be necessary as similar approaches are attempted with NDVI values derived from satellite data.

A Land Surface Process/Radiobrightness Model for Arctic Tundra

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We are developing an LSP/R model for arctic tundra that is a one-dimensional, physically based model of energy and moisture fluxes within tundra and between tundra and the atmosphere. It has the ARCSyM LSP model interface (i.e., that of LSM or CLASS), so that it will run with ARCSyM. While the LSP/R model is too computationally intensive to be an operational LSP model for ARCSyM, it can be run retrospectively for selected regions to obtain much higher fidelity estimates of temperature and moisture profiles within tundra than would be available from any operational LSP model.

We anticipate that the predicted flux exchanges between the tundra and the atmosphere will be similar between the LSP/R model and the chosen operational LSP model. To the extent that the fluxes agree, the predicted radiobrightness will permit a comparison with satellite observation and a correction of the LSP/R or LSP model estimates of temperature and moisture within the tundra. To the extent that the predicted fluxes differ, the corresponding differences between the LSP/R and LSP models will have to be resolved during LSP model validation.

The first version of the LSP/R model is being developed for wet acidic tundra—a major landscape unit of the Alaskan Arctic. Model development is supported by data from our one-year field experiment, Radiobrightness Energy Balance Experiment 3 (REBEX-3), that was conducted adjacent to the Sag River DOT Camp on the North Slope. The model for coupled temperature and moisture in freezing and thawing soils is complete. We are in the process of adding a biophysical representation of the vegetation to the model.

Comparisons between radiobrightnesses observed by REBEX-3 and radiobrightnesses observed by satellite will guide our management of the scaling issue. Our basic approach to scaling up to a grid cell shall be to use a weighted aggregate of the LSP/R model for wet acidic tundra and versions for wet non-acidic tundra and coastal tundra. Special Sensor Microwave/Imager (SSM/I) satellite data have been obtained for the September 1994 to September 1995 REBEX-3 period. These will be resampled to the 20 km ARCSyM grid for the North Slope and archived for ARCSS investigators.

Although not currently a part of our ARCSS work, we also have developed a physically-based one-dimensional model of snowpack evolution, SNOWFLO, for use in predicting snowpack microwave emission signatures.

Inputs

Surface weather, solar insulation. Initial state is derived from our separate annual model.

Outputs

Latent and sensible heat, surface moisture and temperature plus radiobrightness at the SSM/I frequencies and polarizations.

Spatial Scale

The basic model will apply to a sub-grid cell area with one of three types of tundra. Scaling up to a grid cell or SSM/I pixel will be accomplished by aggregating these model versions.

Temporal Scale

Sub-hourly; current time step is 10 minutes.

Sustainability of Arctic Communities: Interactions Between Global Changes, Public Policies, and Ecological Processes

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An interdisciplinary group will focus on relationships between global changes in climate and development and changes in vegetation, caribou populations and movements, human use of caribou, wage employment, and perceived local control. A principal goal of the project will be to develop a synthesis model allowing policy choices. The policy and synthesis modeling integrates subsystem models (i.e., caribou, household production, and development) to produce information that will help policy makers understand relationships between policies, forces of change, and the sustainability of Arctic communities.

We will design the synthesis model using a top down approach where one starts with a very simple model that reflects gross dynamic changes and then successively refines this model down to the appropriate level of detail, defined in terms of the goals or objectives of the model, to address the policy questions that have been posited. A preliminary set of key linkages among the subsystem models are identified in Table 1.

Table 1. Key linkages among the subsystem models.

Input from:	**Output to:**				
	Policy and Synthesis	*Vegetation*	*Caribou*	*Development*	*Households, Institutions*
Global Climate (Exogenous)		Snow cover; green up	Snow depth; temperature	Sea ice; thaw season; permafrost	
Policy and Synthesis		Design and use of roads and facilities	Design and use of roads and facilities	Local, state, and national environment and tax policies	Policies on local government autonomy
Vegetation			Forage availability and quality		
Caribou	Status of herds (healthy or declining)	Grazing pressure			Caribou number, location, quality
Development		Facilities location	Facilities location; human activity		Tax base; demand for labor
Households, Institutions	Wage, employment, subsistence, local control		Caribou hunting effort	Labor supply	

Arctic Snow Transport Model

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Description

This physically-based model simulates the time evolution of the 3-dimensional snow depth distribution in arctic environments. It includes an accounting of the relevant snow transport mechanisms such as saltation and turbulent suspension, the surface shear stress is modified in the presence of saltation, sublimation of the blowing and drifting snow is included, the wind field is interpolated from the observations and adjusted for topography, and snow-vegetation interactions are included through the vegetation snow-holding capacity.

When driven with observed atmospheric forcing, this model describes how the winter snow cover accumulates on the tundra and is redistributed by the interactions of wind and topography. In addition, it provides an accounting of the snow-pack losses due to the sublimation of the wind-transported snow. A key output of this model is the end-of-winter snow depth and water-equivalent distributions which are crucial inputs for snow hydrology and regional atmospheric model simulations during the spring snow-melt period.

Inputs

Observations of daily atmospheric forcing: Air temperature, wind speed, wind direction, relative humidity (or some other moisture variable), and precipitation. High-resolution (10 to 300 m) vegetation distribution and topographic data sets for the domain of interest.

Outputs

Daily snow depth and snow-water-equivalent depth over the domain throughout the winter season. Integrated winter quantities include end-of-winter snow depth, total winter snow depth change due to (1) precipitation, (2) saltation and suspension transport, and (3) sublimation.

Scales

The model performs integrations covering the arctic snow season while running at a daily time step, and with a grid resolution of 10 to 300 meters. The total domain coverage is variable and the model is able to include regions ranging from 1 to 300 km on a side depending on the availability of the input data sets.

Mesoscale Climate Modeling

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The strong sensitivity of polar climate to the simulated surface fluxes of heat, moisture and momentum is undoubtedly responsible for many of the deficiencies in the simulations of the Arctic by global climate models. However, rigorous explanations of these deficiencies have been lacking because of the complexity of the interactions between the atmosphere (including clouds), ocean, land, snow and sea ice.

The approach we have taken to reach an understanding of the role of the Arctic in climate is a high-resolution limited area model system approach. This approach, while expensive and difficult, is physically based and has yielded promising preliminary results, hence offering a wide range of applications.

The Arctic Region Climate System Model (ARCSyM) has been under development since 1992, and is now recognized as a leading regional model of the Arctic. ARCSyM has been developed to simulate coupled interactions among the atmosphere, sea ice, ocean and land surface of the western Arctic. The atmospheric formulation is based upon the NCAR regional climate model RegCM2, and includes the CCM2 radiation scheme and the Biosphere-Atmosphere Transfer Scheme (BATS). The dynamic-thermodynamic sea-ice model includes the Hibler-Flato cavitating fluid formulation and the Parkinson-Washington thermodynamic scheme linked to a mixed-layer ocean.

Simulations have been performed at a range of horizontal resolutions, from 7 to 63 km, in order to assess the performance of the model and to guide the development of new, high-latitude specific physical parameterizations. Experiments at the coarser resolutions have addressed the model sensitivity to sea ice dynamics (rarely done in global climate models), the subgrid-scale moisture treatment, to ice phase physics in the explicit moisture parameterization, to changes in the relative humidity threshold for the autoconversion of cloud water to rainwater, and to changes in cloud parameters affecting cloud-radiative interactions.

Work is proceeding in three phases. The first phase is concerned with assessment of the land surface-vegetation models. An appraisal of the existing BATS package using up-to-date vegetation data is currently underway, with a year-long experiment being run to compare with the 1992 field data from the LAII-Flux Study Alaska North Slope Data Sampler. The Canadian Land Surface Scheme (CLASS) has been successfully coded, and will be linked to the ARCSyM for appraisal following the BATS assessment. Further, colleagues at NCAR are developing a simplified version of the Land Surface Exchange (LSM) package which also will be assessed as soon as it is available.

The second phase is the examination of the role of the cloud-radiation interactions. Sensitivity studies involving mixed phase moist processes, shallow convection, cloud-radiative parameters and more efficient radiative transfer schemes are underway.

The third phase involves the coupling of a regional ocean circulation model and a high-resolution, mixed-layer model, to complete the basic suite of component models in the climate system model. This work is currently being undertaken in conjunction with researchers at Rutgers University.

The ultimate goals of the research are as follows:

- To provide a prioritization of the problems and issues confronting modelers of the Arctic system;
- to create a climate system model that is appropriate for long-term simulations of high-latitude climate; and

- to create a coupled model for studying individual phenomena such as polynya formation and land surface run-off, which require such an approach.

Acknowledgments

This research was funded by NASA Grant NAGW 2829, and NSF Grant DPP 9214810.

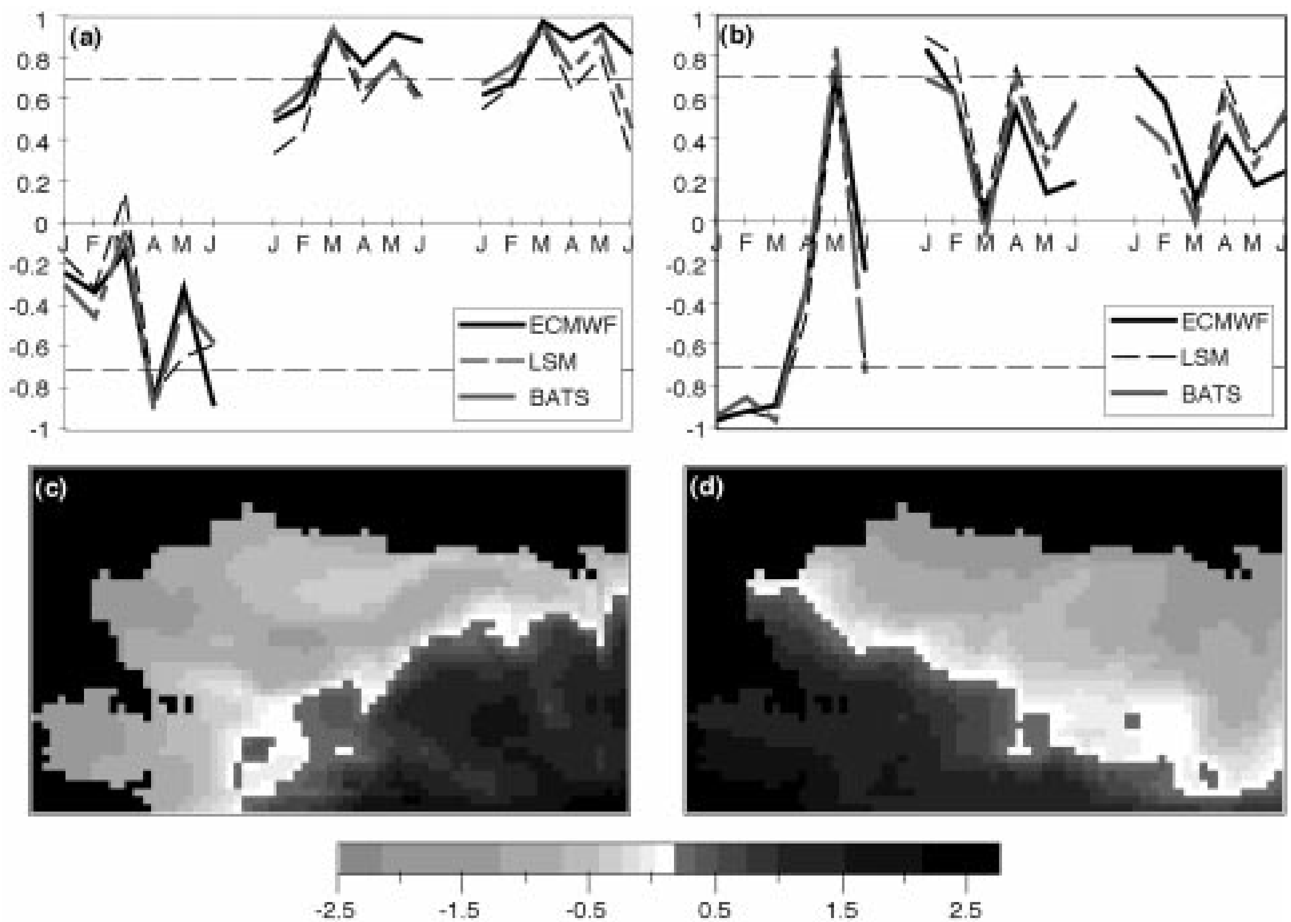

Fig. 1. Using a multivariate principal component analysis, we investigate the relationships between two land surface models (BATS, LSM) implemented in ARCSyM and analyzed climate parameters (ECMWF) over the North Slope of Alaska. Annual cycle simulations were performed for the year 1992, with results from the first six months of the simulations (the spring transition) shown here. Component loading patterns for (a) eigenvector 1 and (b) eigenvector 2; from left to right, the patterns represent sea level pressure (SLP), surface air temperature (SFT) and surface moisture mixing ratio (SFQ). Of the two retained eigenvectors, the first eigenvector loadings show a summer/continental pattern, primarily in temperature and moisture. The higher ECMWF loadings indicate a greater coherence of structure due to the lower resolution of the analyses. The LSM and BATS loadings do not change through the spring transition as strongly or monotonically as the observational analyses, although BATS transitions more rapidly than LSM. The scores associated with these loadings (representing the spatial variance) are shown in (c) and (d) for the LSM simulation. The first eigenvector indeed represents a summer/continental pattern, with a thermal low centred over the south-eastern part of the domain, associated with high temperatures and moisture in the boundary layer. The second eigenvector loadings demonstrate a winter/maritime pattern, primarily in SLP. Characteristic of this winter/maritime pattern are strong Aleutian and Bering Sea cyclonic activity, with a zonal temperature and moisture structure (not shown).

Global Climate Change and the Equilibrium Responses of Carbon Storage in Arctic and Subarctic Regions

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We extrapolated the terrestrial ecosystem model (TEM) and the Marine Biological Laboratory implementation of the BIOME biogeography model (MBL-BIOME) across the globe at 0.5° resolution to estimate the equilibrium responses of carbon storage to the double CO_2 climates of three general circulation models (GCM's). For contemporary climate and an atmospheric CO_2 concentration of 312.5 ppmv, TEM estimates global carbon storage of 1781.4 Pg C. This estimate does not include the carbon content of inert soil organic matter. Arctic and Subarctic ecosystems account for 17.3% of global vegetation carbon storage and 39.8% of global soil carbon storage. The land area north of 60° N accounts fro 240.1 Pg C (13.5%) of global carbon storage, with 70.3 Pg C in vegetation and 169.8 Pg C in soils. For an atmospheric concentration of 625.0 ppmv and climate changes estimated by GCM's of Oregon State University (OSU), Geophysical Fluid Dynamics Laboratory (GFDL), and the Goddard Institute for Space Studies (GISS), we ran TEM to equilibrium for vegetation distributions estimated by MBL-BIOME. Among the climate scenarios, MBL-BIOME estimates that the area of polar desert is reduced by between 80% and 85% by the migration of tundra northward. Similarly, the area of tundra is reduced by between 40% and 50% by the migration of boreal forest northward. For the changes in CO_2, climate, and vegetation, the equilibrium soil carbon storage of the land area north of 60° N increases 52.3 Pg C for the OSU climate, but decreases 1.9 Pg C for the GFDL climate and 3.0 Pg C for the GISS climate. The migration of boreal forest northward substantially increases vegetation carbon storage for all climate scenarios. Thus, the equilibrium responses of carbon storage to climate change in these simulations suggest that high latitudes have the potential to act as a carbon sink if the atmospheric concentration of CO_2 is stabilized. Further progress in modeling the role of high latitudes in stabilizing/destabilizing the atmospheric concentration of CO_2 requires considering at large spatial scales the transient dynamics of functional (i.e., soil) and structural (i.e., vegetation) responses of carbon storage.

Active-Layer/Landscape Interactions: A Retrospective and Contemporary Approach in Northern Alaska

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Modeling efforts in this project are proceeding along two lines of inquiry.

(1) Physical modeling of soil thermal and moisture regimes. A physically based model is being used to replicate the soil thermal and moisture regimes at Barrow for periods in the 1960, 1970s, and 1990s in which active-layer thickness, soil temperature, and other parameters were monitored in the vicinity. Verification of the model with these data sets allows extension to earlier decades for which climate data are available, and for the future, under various climate-change scenarios. The primary goal of the exercise is to predict the effects of future changes in climatic parameters on soil temperature and active-layer thickness.

A description of the model currently in use was published by Anisimov (1989b). The model is driven by standard climatic data information (air temperature, humidity, precipitation, solar radiation, cloudiness) and information about surface and soil properties and local geographic conditions. The model's hydrometeorological section calculates an equilibrium surface temperature and the water content of the upper layer of the soil, based on relationships between components of the energy balance and input climatic parameters. Its thermal section tracks heat transport and movement of the phase boundary within the multilayer soil system using temperature-dependent thermal properties and budgeting moisture content in the organic and mineral soil layers. The model represents evolution of the soil thermal and moisture regimes at specific locations for which subsurface properties are known in detail.

The model was developed and validated using data from northern Eurasia (Anisimov 1989a). Its performance was tested using soil-temperature data from four permafrost training sites in Russia: Yakutsk, Vorkuta, Syrdah (Lena river basin), and Solenyj (northern part of west Siberia). The sites differ substantially in climatic and soil conditions. Comparison of calculated temperature profiles at each site with measured data from four consecutive years showed good agreement. Results for Barrow indicate that the model tracks interannual variations in active-layer thickness with a high degree of accuracy. The model can also be applied to larger areal units by running it for the range of subsurface characteristics existing within the region of interest.

(2) Spatial modeling of active-layer thickness. An integrated program of field measurements and spatial modeling was initiated for the Kuparuk River basin in 1995. The strategy provides information about active-layer thickness and its variability over large areal units. Required input data are: (a) high-frequency temperature series (thawing season degree-day totals) at sites chosen to be representative of specific soil/vegetation associations (thermal data are obtained with inexpensive automatic data loggers); (b) soil texture and moisture data obtained from the same locations; (c) a digital elevation model of the region of interest; and (d) a digital map of vegetation/soil associations within the areal unit. GIS technology is used to compute seasonal thaw depth at each DEM node by means of relatively simple solutions for phase boundary position. Topoclimatic effects

are addressed through an index constructed by computing potential solar radiation at each node. Output is in the form of digital or printed maps of active-layer thickness. Because the model makes intensive use of digital topographic information, it is capable of discerning variation at high spatial frequencies. The model is currently running for the Kuparuk River basin using node spacing of 300 m, but given adequate temperature and soil information, could be used at other spatial scales.

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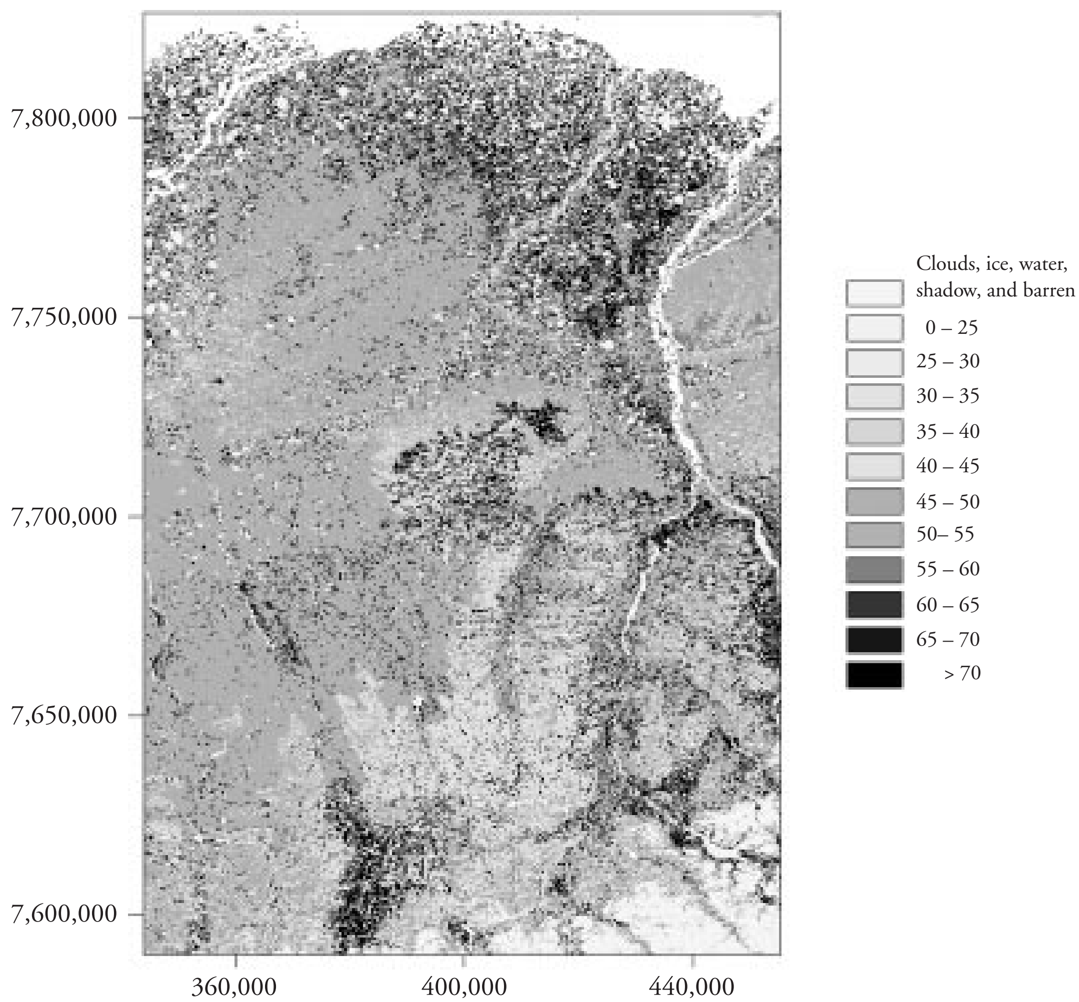

Computed active-layer thickness in the Kuparuk River basin, mid-August 1995.

Modeling Activities: Active Layer and Permafrost

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Description

Two finite difference models and a finite element model are currently being used. These heat conduction and moisture transport models are capable of handling phase change and the effects of temperature and unfrozen water (in frozen soils) on the transport parameters. Standard meteorological data (air temperature and snow cover) are used to drive the models. The models are being used to investigate heat and moisture transport processes in the active layer and permafrost and to assess the impact of changes in climate on the subsurface soils. In future ARCSS studies, we expect to use these models to determine the response of the active layer and permafrost to climatic and solar (sunspot cycle) variability in the region between the arctic coast and the Brooks Range.

We have also developed and are using several analytical models to calculate thermal offset values, determine the maximum thaw depth of the active layer, calculate thermal parameters from the data, determine the effects of snow cover on ground surface temperatures, and to calculate heat fluxes at the surface during warming and cooling of the permafrost.

Inputs

Seasonal, annual, and inter-annual changes in air temperatures and(or) ground surface temperatures, geothermal heat flow, material (snow, vegetation, soil) parameters, and appropriate initial conditions.

Outputs

Temperature fields in the active layer and permafrost over multi-year time scales, annual thaw depths and thawing rates of the active layer, thermal parameters, and heat fluxes at all levels.

Scales

One finite difference model is one-dimensional and used mostly for process studies. The other numerical models are two-dimensional so that they can be used for the interpretation of vertical profiles in transects across the study region. Spatial scales from centimeters to kilometers and time scales from days to millennia have been used in the model.

Temporal Scaling of Carbon Sequestration in Arctic Tundra Using a General Ecosystem Model

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We use a general ecosystem model (MBL-GEM) to examine biogeochemical constraints on ecosystem responses to changes in CO_2 concentration, temperature, and soil moisture in arctic moist tundra. The model was calibrated to experimental data on the responses of moist tundra to fertilizer, greenhouse warming, and shading (Chapin et al., 1995) and to increased CO_2 (Oechel et al., 1987). We then use the model to reconstruct changes in ecosystem C storage over the last 160 years based on ice-core (Neftel el al., 1985) and Mauna Loa (Keeling et al., 1982) CO_2 records and tree-ring temperature records (Garfinkel and Brubaker, 1980). Our model indicates a rate of C storage of between 1 and 5 g C/m^2/yr over most of that period if soil moisture is assumed constant. However, varying soil moisture has a striking on C storage. Because changes in soil moisture could not be reconstructed, we assumed a "worst-case scenario" in which the soil was assumed to have a 100% water-filled pore space (WFPS) at the coldest temperature in the record, and was assumed to have 60% WFPS at the warmest temperature in the record. The 60% WFPS was assumed to be the optimum soil moisture for microbial processes in the soil. Under this "worst-case scenario," our model predicts a major loss of soil C during a warming in the mid 1800's followed by a general increase in ecosystem C since about 1890. This increase in C since 1890 is not enough to recover C lost during the warming, is far more variable than in the simulation with constant soil moisture, and is characterized by large episodic C losses of as much as 190 g C/m^2/yr. Losses of C during the last decade are among the largest in our reconstruction.

We also examine responses to a doubling of CO_2, a 5°C increase in temperature, and a ±10% change in WFPS. Our analysis indicates significant synergistic interactions among these factors that make assessments of future responses to climate and CO_2 difficult. We conclude with a discussion of the vital role of models in such assessments and the problems of validating long-term responses to climate and CO_2.

References

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Modeling Component of the Effects of Climate Change and Sea Level Rise on the Tundra Ecosystem of the Yukon-Kuskokwim Delta, Alaska

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The model in this project will consist of two major components: (1) A model of goose population dynamics and (2) a model of vegetation. The vegetation model will incorporate air and soil temperature, grazing effects and tidal flooding. The vegetation model will be driven, by temperature and tidal flooding generated by a global circulation model developed for the Bering Sea area. Feedbacks from the goose component will be through trampling, fertilization and clipping associated with grazing. Spatial effects of tidal flooding will be predicted from spatial elevation maps. Field experiments on effects of temperature, tidal flooding and grazing are currently underway and the vegetation model has not yet been fully developed. We focus on the brant population model which is nearly complete, below.

The brant population model relies primarily on parameter estimates generated from the study of a marked population of brant nesting on the Yukon-Kuskwokim (Y-K) Delta. This study has produced estimates of the following parameters: Adult survival during summer, fall, winter and spring, juvenile survival from hatch to fledging, fledging to winter and winter to summer, age-specific reproductive rates (including probability of breeding and clutch size); nest success, and subsistence and sport harvest. Growth rates of goslings are a direct function of food quality and availability and gosling growth directly influences survival probability during the first year. First-year survival, in turn, has an important influence on population dynamics. The vegetation model will therefore, directly link to the goose model via the effects of plant biomass and plant composition on gosling growth.

In its current form the goose model is driven externally by harvest, nest success and feedbacks from population size, which influence gosling growth. Subsistence harvest is a simple linear function of population size, which tends to stabilize population dynamics. Similarly density dependent feedbacks on gosling growth also stabilize population dynamics. Currently we model nest success as a stochastic function, related to the uncertain nature of predation on nests. When the vegetation model is joined to the goose model we anticipate that vegetation dynamics will drive goose population dynamics to a series of pseudo-stable states. Dynamics of the goose population will in turn influence harvest by subsistence and recreational hunters.

The goose model encompasses the entire Pacific brant population, which nests from western Alaska to the Canadian Arctic. Therefore, this model is at least regional in scope. Dynamics of the brant population are governed primarily by the more than 70% of the population that nests on the Y-K Delta. Our experiments on plants are being conducted across a series of landscapes at two colony locations. approximately 70 km apart. These results should, therefore, be relevant to the coastal zone of the Y-K Delta, where we have the most confidence in our understanding of brant demography. We, therefore, anticipate that the combined model will be relevant to the Y-K Delta coast.

Hydrological and Biogeochemical Modeling at the GCM Scale: A Watershed Approach

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While large basin river chemistry is well-known, the processes by which materials move from the hillslope to streams and rivers are poorly understood. Therefore, there is a need for a land surface model that can operate on the scales of whole river basins and can simulate not only the surface energy fluxes to the atmosphere, but also the flux of water, nutrients, organic matter, and trace gases to arctic streams and rivers. The approach taken here is to start with an existing land-surface model (Lynch-Stieglitz et al., subm.) which incorporates the analytic form of TOPMODEL equations and is capable of simulating basin run-off, soil moisture heterogeneity, and surface energy fluxes from both saturated and unsaturated regions of the basin without the need to resort to finite element modeling. With the support of NOAA and NFS's LTER we are now applying this to arctic watersheds. Further, we are incorporating plant-soil and biogeochemistry models such that the flux of nutrients, organic matter, and CO_2 from the hillslope to the stream and river system can be simulated, as well as the flux of CO_2 between the atmosphere and the terrestrial biosphere.

The advent of TOPMODEL, a conceptual rainfall-runoff model (Beven and Kirkby, 1979; Beven, 1986a,b), has provided hydrologists with a powerful tool to: 1) analytically calculate the hillslope response of site specific topography without the need to resort to finite element modeling, and 2) operate at large watershed scales by using the statistics of the topography, rather than the details of the topography itself. We incorporate the analytic form of TOPMODEL equations into a new single column land surface model which tracks the mean state of the watershed. This single column model includes 6 soil layers and diffusion and a modified tipping bucket model governs vertical heat and water flow, respectively. The prognostic variables, heat and water content, are updated each timestep (hourly). In turn, the fraction of ice and temperature of a layer may be determined from these variables. A three layer snow model (Lynch-Stieglitz, 1994) and a modified BEST vegetation scheme (Pitman et al., 1991) have been incorporated into this scheme. The analytic form TOPMODEL equations and Digital Elevation Model data are used to generate baseflow which supports lowland saturated zones. Soil moisture heterogeneity represented by saturated lowlands (predicted by TOPMODEL equations) subsequently impacts watershed ET, the partitioning of surface fluxes and the development of the storm hydrograph. This approach to land-surface modeling moves away from the perspective often taken in GCM's where each grid cell represents a vertical soil column, and towards a model where the fundamental unit is the watershed. Lynch-Stieglitz (1994) and Lynch-Stieglitz et al. (subm.) discuss model validation at the Sleepers River watershed.

The plant-soil system and soil biogeochemistry are modeled as follows. Carbon is sequestered from the atmosphere via plant photosynthesis. Carbon and nitrogen are then mineralized via plant/root respiration and the microbial decay of soil organic matter. The release of soil generated CO_2 is partitioned between the gaseous and dissolved phase via Henry's law and diffusion governs the transport of gaseous soil CO_2 vertically through the soil column. Plant uptake and microbial immobilization compete for the soil nitrogen pool and the net mineralized nitrogen pool is partitioned between an adsorbed and dissolved phase. DOC is calculated from the state of the soil moisture, temperature and CO_2 respiration rates. From knowledge of the dissolved concentrations of CO_2, nitrogen, and DOC at various depths, along with the depth to the water table, these dissolved pools can then be transported from the hillslope to the stream system.

While the short term goal of this work is to produce a physically-based hydro-biogeochemistry land-surface model for arctic environments, the longer term goal includes coupling to a GCM and operating at a variety of climatic regimes and spatial scales.

Model Inputs

Air temperature, dew point temperature, precipitation, wind speed, incoming longwave radiation, incoming shortwave radiation.

Model Outputs

Ground and snowpack temperatures, saturated fraction of watershed, state of upland soil moisture (at depth), discharge (partitioned into surface runoff and baseflow), stream concentrations of DOC, dissolved CO_2, and nitrogen, and terrestrial/atmosphere fluxes of water, energy, and CO_2.

Spatial Scales

Small watershed up to the scales required by today's mesoscale models.

References

Chapin, F.S., III, G.R. Shaver, A.E. Gibblin, K.J. Nadelhoffer, and J.A. Laundre. 1995. Responses of Arctic tundra to experimental and observed changes in climate. Ecology. 76. 694 – 711.

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Contemporary Water and Constituent Balances for the Pan-Arctic Drainage System: Continent to Coastal Ocean Fluxes

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Despite the pivotal role of the coupled Arctic climate-river-coastal ocean system in the global change question, there has been virtually no synthesis of continental runoff and constituent delivery for the region as a whole. The specific objective of this project is to secure a quantitative understanding of how runoff and associated biogeohemical fluxes are linked between the pan-Arctic land mass and the Arctic coastal zone. We will employ a data-rich approach linking several models and their associated biophysical data sets within a GIS-based analysis system for the entire Arctic Ocean watershed (Figures 1 and 2). Our emphasis is on the contemporary setting for the period 1975 through 1990. The scope of the modeling work suggests a spatial resolution of approximately 50 km and weekly to monthly time steps. This choice of model resolution is based on our ongoing work at continental and global scales analyzing carbon, nitrogen and water cycle dynamics. Below is a brief description of three models to be used in our synthesis study of the pan-Arctic water cycle.

Water Balance Model (WBM)

Modification of a simulation used in concurrent global research, incorporating a simplified version of a physically-based permafrost model. Required inputs include data on vegetation, soils, climatic forcings. Time series of meteorological inputs (e.g., precipitation, temperature) to be developed from interpolation techniques with explicit error estimates. Outputs are time-varying fields of evapotranspiration, changes in soil water and active layer depth, runoff across the pan-Arctic land mass. Calibration/validation through site-specific data available from independent sources.

Water Transport Model (WTM)

Runoff from WBM routed using the WTM through simulated river networks (Fig. 2) to generate discharge hydrographs at any point within pan-Arctic watershed system. Hydrographs conditioned upon contributing area, flow velocities, and associated wetland storage. validated against measured discharges maintained within several monitoring archives to which we have direct access.

Aerological Approach

Derived from archives of rawinsonde ascents north of 50°N and re-analysis products (e.g., NMC) to determine net convergence/divergence fields from vapor flux fields. These are to be combined with station-based precipitation fields (see above) to determine basin-wide evapotranspiration and runoff, and checked for consistency against associated outputs derived from the WBM/WTM.

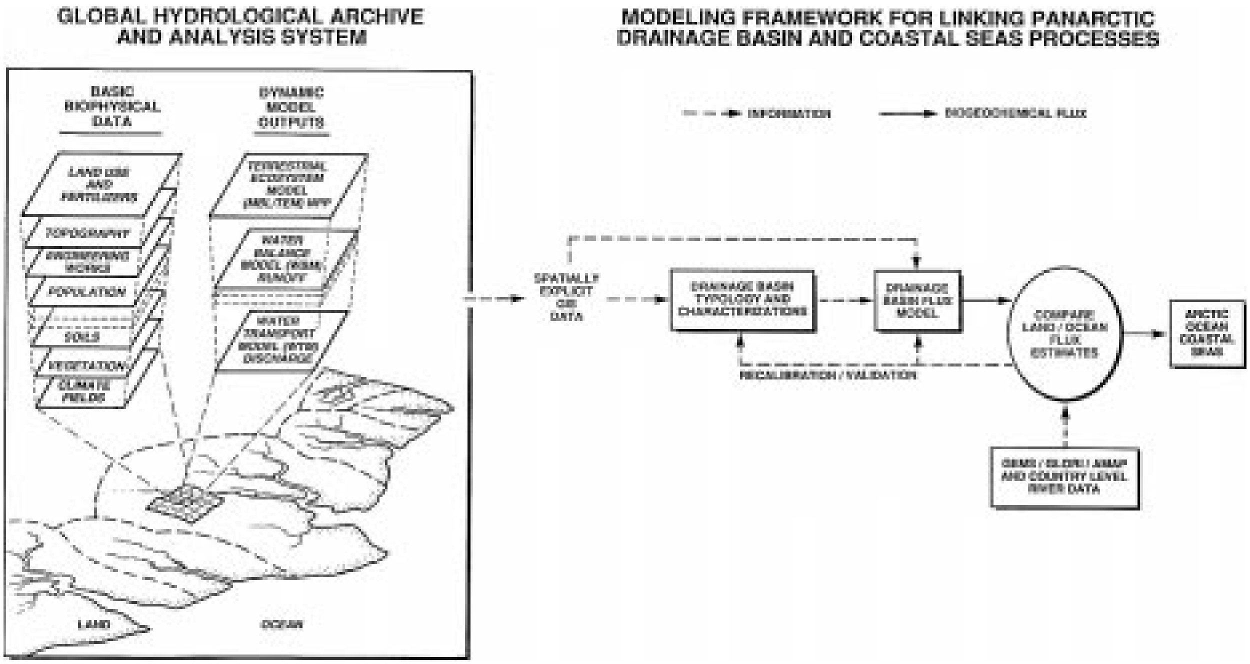

Fig. 1. Models used in the study.

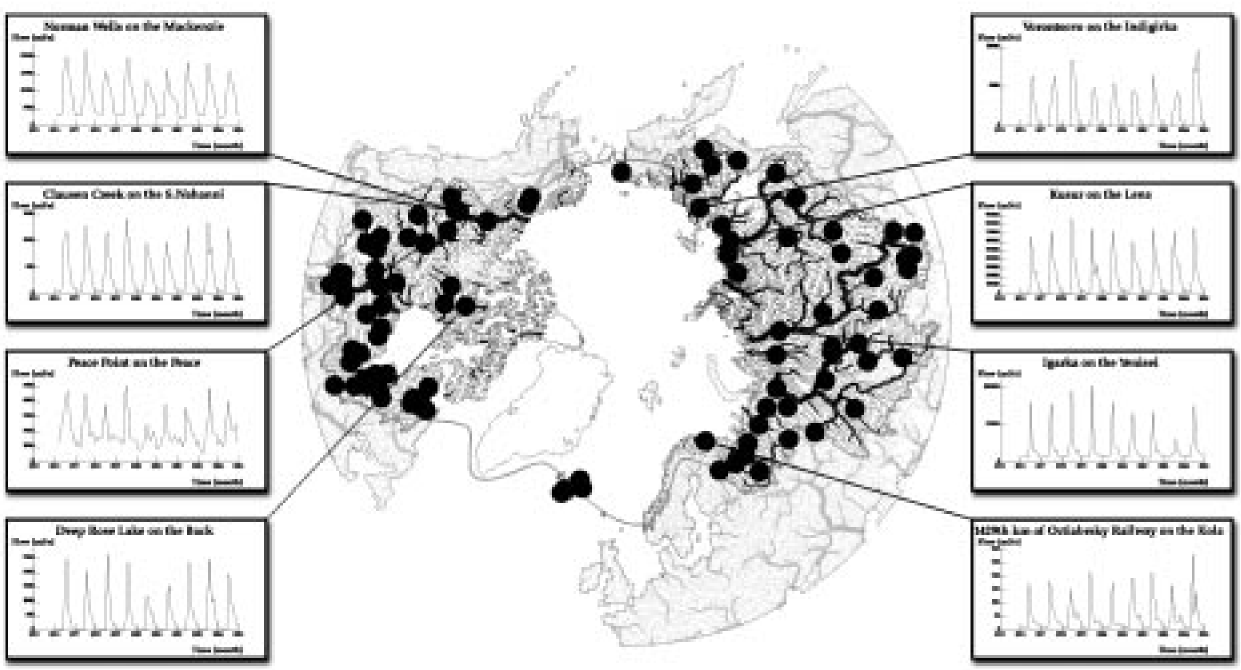

Fig. 2. Simulated Arctic river networks and UNESCO selected river discharges (30 minute resolution).
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Appendices

ARCSS Modeling Workshop
15-16 January 1996
National Snow and Ice Data Center
Boulder, Colorado

Workshop Program

Gordon Bonan, John E. Walsh—Co-Chairs

Monday, 15 January 1996 (Day 1)

8:00 a.m.	**Welcome, Introductions, Comments**	*G. Bonan, J. Walsh*
	General Information	*W. Warnick*
8:15 a.m.	**NSF ARCSS Program**	*G. Bonan, J. Walsh*
	(on behalf of Mike Ledbetter, ARCSS Program Director)	
8:30 a.m.	**ARCSS Research—Results/Plans ➤➤ an "Arctic System Model"**	
	(15 min presentations, 15 min Q&A at end of section)	
	• Greenland Ice Sheet Project Two (GISP2)	*D. Meese*
	• Paleoenvironments from Lakes and Estuaries (PALE)	*S. Thompson*
	• Ocean/Atmosphere/Ice Interactions (OAII)	*R. Moritz*
	• Land/Atmosphere/Ice Interactions (LAII)	*J. Hobbie*
	• Human Dimensions of the Arctic System (HARC)	*D. McGinnis*
10:00 a.m.	**Break**	
10:15 a.m.	**ARCSS Modeling Program**	*R. Moritz, J. Walsh*
10:30 a.m.	**Overviews of System Models**	*R. Moritz—Moderator*
	(25 min each, 10 min Q&A at the end of the section)	
	• Testing the Accuracy of Arctic System Models for Simulation of Century-to-Millennia-Scale Variability	*J. Kutzbach*
	• Modeling human-environmental interactions in the North Atlantic	*A. Kerr*
11:30 p.m.	**Components of a System Model**	*J. Walsh—Moderator*
	(20 min each, 10 min Q&A before lunch)	
	• Atmospheric GCM Performance in Simulations of the Arctic Climate	*D. Randall*
	• Advanced Modeling Studies of the Arctic Ocean and Sea Ice—Toward Better Understanding of the Arctic System	*W. Maslowski*

12:20 p.m.	**Lunch** (on your own)	
1:30 p.m.	**Components of a System Model** (20 min each, 10 min Q&A at end of section) • Modeling Land/Surface Processes for Climate Models • A Qualitative Modeling Approach to Vegetation-Climate Interactions	*J. Walsh—Moderator* *G. Bonan* *A. Starfield*
2:20 p.m.	**Broad Linkages Among Components** (20 min each, 10 min Q&A before break) • The Arctic Region Climate System Model: Development and Performance over Arctic Tundra • Using Integrated Terrestrial Models to Examine Long-Term (10^2 to 10^3 year) Variability in the Arctic Biosphere-Atmosphere System	*D. Randall—Moderator* *A. Lynch* *J. Foley*
3:10 p.m.	**Break**	
3:30 p.m.	**Broad Linkages Among Components** (20 min each, 10 min Q&A at end of section) • Temporal Scaling of C sequestration in Arctic Tundra Using a General Ecosystem Model • Hydrological and Biogeochemical Modeling at the GCM Scale: A Watershed Approach	*D. Randall—Moderator* *E. Rastetter* *M. Lynch-Stieglitz*
4:20 p.m.	**Moderated Plenary Discussion** An Arctic System Model	 *J. Kutzbach—Moderator*
5:30 p.m.	**Adjourn**	
5:30 p.m.- 6:30 p.m.	**Poster Session (Reception)**	
6:30 p.m.- 9:00 p.m.	**Modeling Working Group Meeting** (Dinner provided for MWG) Other Workshop participants – on your own	

Tuesday, 16 January 1996 (Day 2)

8:00 a.m. **Welcome and Comments** *Bonan, Walsh*

8:15 a.m. **Broad Linkages Among Components** *D. Randall—Moderator*
(20 min each, 20 min Q&A before break)

- Towards Improved Parameterization of Ice/Atmosphere/Ocean Interactions in Climate Models *J. Curry*
- Testing GCM Parameterizations of Ocean/Atmosphere/Ice Interactions with Data from Short-Term Process Studies *R. Moritz*
- Anticipating SHEBA Upper Ocean Modeling Issues by Revisiting the AIDJEX (1975) Summer *M. McPhee*
- Improving the Simulation of Sea Ice in Oceanic and Atmospheric GCM's *S. Vavrus*

10:00 a.m. **Break**

10:15 a.m. **Broad Linkages Among Components** *D. McGinnis—Moderator*
(20 min, 5 min Q&A at end of section)

- Historical Evidence for Past Temperature and Sea-Ice Variations: Models for Social Impact in Iceland *A. E. J. Ogilvie*

10:40 a.m. **Process Models**[1] *E. Rastetter—Moderator*
(12 min each, 10 min Q&A before lunch)

- Cloud-Resolving Simulations of Warm-Season Arctic Stratus Clouds: Exploratory Modeling of the Cloudy Boundary Layer *P. Olsson*
- Investigation of Tide and Wind-Driven Motions in the Arctic Ocean *A. Proshutinsky*
- The Simulation of ABL Structures as Generated by Lead/Ice Surface in the Winter Arctic by ARPS *Qingqiu Shao*

11:30 a.m. **Lunch (MWG Meeting)** Lunch provided for MWG
Other participants are on your own

1:00 p.m. **Process Models** *E. Rastetter—Moderator*
(12 min each, 10 min Q&A at end of section)

- Modeling Hydrologic and Thermal Processes in the Arctic *L. Hinzman*
- Modeling the Seasonal Evolution of Non-Uniform Arctic Snowcovers in Regional Atmospheric Models *G. Liston*
- Global Climate Change and the Equilibrium Responses of Carbon Storage in Arctic and Subarctic Regions *D. McGuire*

1:50 p.m.	**Datasets and Modeling** (12 min each, 6 min Q&A before break)	*G. Bonan—Moderator*
	• Reconstruction of Paleo-Atmospheric Circulation at Sub-Decadal to Centennial Time Scales Based on GISP2 Chemistry Time Series: A Preliminary Report	*D. Meeker*
	• Pleistocene/Holocene Paleoclimate and Boundary Conditions Useful for Arctic Climate Model Testing: Examples from Beringia	*J. Brigham-Grette*
2:20 p.m.	**Break**	
2:30 p.m.	**Datasets and Modeling** (12 min each, 6 min Q&A at end of section)	*G. Bonan—Moderator*
	• Four-Dimensional Data Assimilation Experiments over the Western Arctic Using MM5	*J. Tilley*
	• Sea-Ice Properties	*D. Meese*
3:00 p.m.	**Moderated Panel Discussion —** **Toward an Arctic System Model**	*J. Walsh—Moderator*
4:00 p.m.	**Closing Comments**	*Chairs*
4:15 p.m.	**Adjourn Workshop**	

Posters

- Nonlinear Multivariate Modeling in CO_2 Flux Studies — *T. Gilmanov*
- High Arctic Field Data in Support of Modeling Climate, Hydrological Processes, and the Paleoclimatic Significance of Lake Sediments — *D. Hardy*
- Land Surface Process Modeling of Tundra for Microwave Remote Sensing Applications — *E. Kim*
- An Assessment of GENESIS V.2 GCM Performance for the Arctic — *J. Maslanik*
- Contemporary Water and Constituent Balances for the Pan-Arctic Drainage System: Continent to Coastal Ocean Fluxes — *B. Peterson*
- Global Atmospheric Model Simulations of Arctic Climate — *J. Walsh*
- Arctic Sea-Ice Variability in a High-Resolution Model — *Y. Zhang*

1. A presentation by John Weatherly was added to the agenda during the workshop
   - Greenhouse Warming in an Arctic Ice-Ocean Model — *J. W. Weatherly*

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