Status of and Outlook for Large-Scale Modeling of Atmosphere–Ice–Ocean Interactions in the Arctic

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ABSTRACT

Arctic air masses have direct impacts on the weather and climatic extremes of midlatitude areas such as central North America. Arctic physical processes pose special and very important problems for global atmospheric models used for climate simulation and numerical weather prediction. At present, the observational database is inadequate to support research aimed at overcoming these problems. Three interdependent Arctic field programs now being planned will help to remedy this situation: SHEBA, which will operate an ice camp in the Arctic for a year; ARM, which will supply instruments for use at the SHEBA ice camp and which will also conduct longer-term measurements near Barrow, Alaska; and FIRE, which will conduct one or more aircraft campaigns, in conjunction with remote-sensing investigations focused on the SHEBA ice camp. This paper provides an introductory overview of the physics of the Arctic from the perspective of large-scale modelers, outlines some of the modeling problems that arise in attempting to simulate these processes, and explains how the data to be provided by the three field programs can be used to test and improve large-scale models.

1. Introduction

The presence of sea ice alters the air–sea interaction processes relative to the open ocean. Large-scale air–sea-ice interactions influence the local and global weather and climate on timescales ranging from days to centuries and beyond. The large influence of sea ice arises in part from feedbacks introduced into the climate system by thermodynamic, radiative, and dynamic sea-ice processes.

Simulation experiments conducted with global climate models suggest that CO_2-induced warming will be amplified by the retreat and thinning of sea ice in the Arctic (e.g., Houghton et al. 1990). The simulated warming is particularly strong in the Arctic winter, when a thinning of the sea ice or a decrease in its fractional coverage tends to increase the thermal coupling between the lower troposphere and the seawater beneath the ice. Doubled-CO_2 climate simulation results presented in Houghton et al. (1990) show a 10-K range among the winter surface temperature responses simulated by major climate modeling groups, however (Fig. 1). Even the most recent IPCC assessment shows that the largest disagreement between coupled climate model simulations of present-day climate is in the polar regions (Gates et al. 1996; see their Fig. 5.1).

This degree of disagreement among the models reflects both the weakness of our current understanding of Arctic climate dynamics and the sensitivity of the Arctic climate to different formulations of various physical processes.

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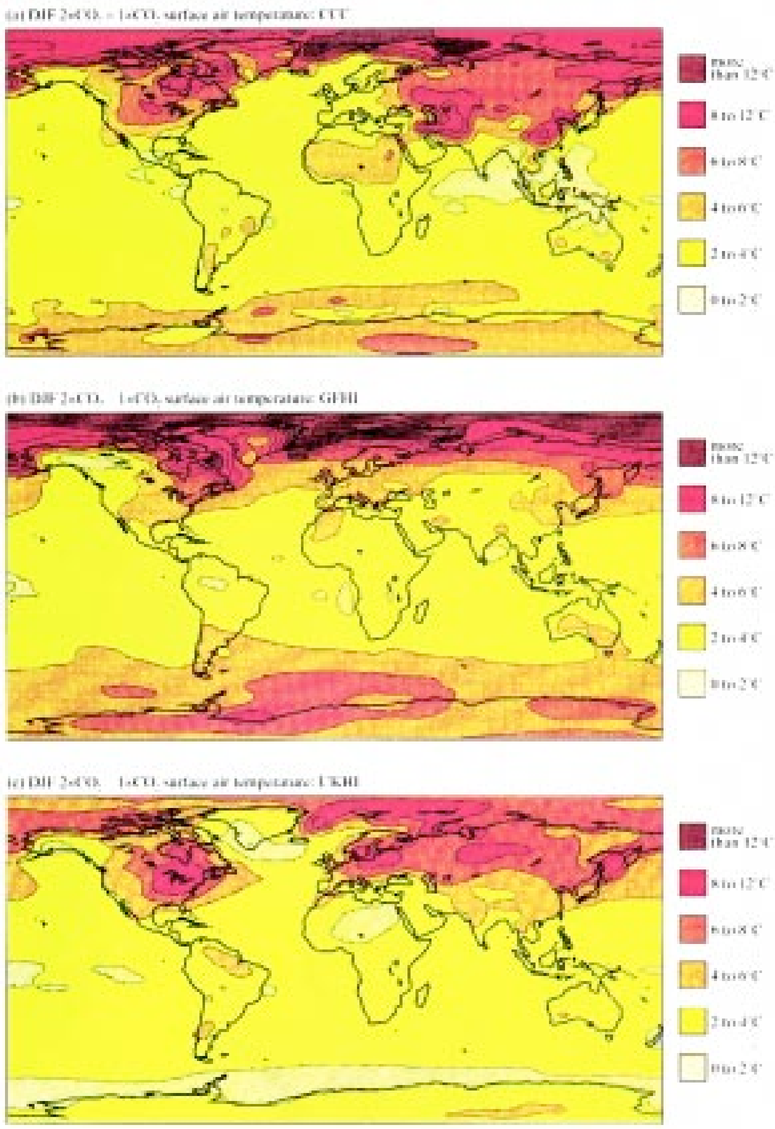

FIG. 1. Change in surface air temperature (10-yr means) due to doubling CO_2, for months December–January–February, as simulated by three high-resolution climate models: (a) CCC: Canadian Climate Centre, (b) GFHI: Geophysical Fluids Dynamics Laboratory, and (c) UKHI: United Kingdom Meteorological Office. Figure reproduced from Houghton et al. (1990), with permission of the Intergovernmental Panel on Climate Change.

Has the predicted Arctic warming been observed? The relevant climatological database over Arctic sea ice is very sparse. For example, there are no reliable, basinwide datasets for surface air temperature or sea-ice thickness for even the past 20 years, much less the past 100 years, although new data are now becoming available as a result of political realignments. Even if observations were plentiful, the CO_2 response would have to be distinguished from other temporal variations, including the forced response to variations in atmospheric aerosol concentration (volcanic, anthropogenic and biogenic), as well as natural variability. Undaunted by these difficulties, investigators have looked for climate trends in the Arctic, but with inconclusive results. Kahl et al. (1993) report no trend in Arctic Ocean surface temperatures over the past 40 years. Analysis of data from several sources during the period from 1961 to 1990 led Chapman and Walsh (1993) to conclude that summertime Arctic sea-ice extent had decreased by a small but significant amount, while there was no discernible trend in wintertime extent. They found significant warming over high-latitude land areas, but little change over the Arctic Ocean and, in fact, a significant cooling over Greenland. Johannessen et al. (1995) and Maslanik et al. (1996) have analyzed satellite passive microwave imagery and determined that the decreasing trend in summertime ice extent has continued through 1995. Bjorgo et al. (1997) have recently reported that the negative trend of Arctic sea ice for 1978–95 is apparent in the winter data as well as the summer data.

Extratropical cyclone activity has also been rising north of 60°N since at least the mid-1960s. These high-latitude increases, which are most pronounced over the central Arctic Ocean, are associated with significant reductions in sea level pressure, which do not appear to be directly related to the North Atlantic Oscillation (Walsh et al. 1996; Serreze et al. 1996). Serreze et al. (1995) and Maslanik et al. (1996) show that the downward trend in Arctic sea-ice extent (Johannesen et al. 1995) is driven primarily by late summer to early autumn ice anomalies in the Laptev and East Siberian Seas. Maslanik et al. (1996) have attributed the Eurasian sector ice reductions to a combination of thermodynamic forcings, in which warm southerly winds east of the region of increased central Arctic storm activity result in more rapid melt, and the dynamic effects of increased wind-driven ice transport away from the coast. It remains unclear, however, how the regional increases in cyclone activity associated with the ice reductions may fit into the larger context of observed changes in Northern Hemisphere climate.

In addition to warm-air advection and poleward ice transport, increased cyclone activity favors divergence and shear within the consolidated ice pack, which increases melt as the resulting open-water areas are heated through absorption of solar energy. Because a thinner ice pack is more easily disrupted by winds, this represents a potential positive feedback toward a thinner ice cover.

The maintenance of a cold halocline, separating the surface mixed layer from the deeper warm water that covers much of the basin, seems to play a critical role in the Arctic Ocean sea-ice mass balance. Recent oceanographic cruises in the Arctic (Morrison et al. 1994; Carmack et al. 1995) have documented a large increase in the area occupied by relatively warm Atlantic water immediately below this halocline. If and when such oceanic warming affects the sea-ice mass balance, the effects on the seasonally varying ice cover could be quite dramatic. The export of relatively freshwater and sea ice from the Arctic Ocean into the North Atlantic modulates the North Atlantic Ocean thermohaline circulation, which then feeds back to the Arctic climate system. Fluctuations of the thermohaline circulation are believed to be important for climate variability on timescales ranging from just a few years to millennia (e.g., Broecker 1992; Imbrie et al. 1993). For these reasons, among others, we need to understand the interactive processes by which the Arctic atmosphere–sea-ice–ocean system adjusts to external perturbations. The thermodynamic response of the Arctic climate system to such perturbations depends critically upon the mutual adjustments of the upper ocean, sea-ice thickness and concentration, and the structure and composition (vapor, clouds, etc.) of the atmosphere.

The Arctic is a region of importance for operational numerical weather prediction (NWP) because it represents a reservoir of cold air that can drastically influence midlatitude winter weather and because it represents a particularly challenging testbed for the formulations of the global NWP models. Three of the critical issues that arise in connection with evaluating and improving the capability of large-scale models to simulate the Arctic weather and climate are as follows:

- How can simulations of the present-day Arctic climate processes best be evaluated by comparison with observations?
- Which components of the models are responsible for the discrepancies between simulations and observations? Possibilities include the sea-ice submodels and the parameterized physics of clouds and boundary layer processes in the Arctic lower troposphere.
- How can observations of the present-day Arctic climate be used to improve the accuracy of simulations of future Arctic and global climate?

These issues and others will be addressed by three planned Arctic field programs Surface Heat Budget of the Arctic (SHEBA) is sponsored by the National Science Foundation and the Office of Naval Research and will collect data from a station drifting with the pack ice in the central Arctic, beginning in fall 1997 and continuing for approximately 1 yr. The Atmospheric Radiation Measurements Program (ARM), sponsored by the Department of Energy, is planning a 10-yr program of measurements at Barrow, Alaska, beginning in 1998; ARM will also provide some instruments for use at the SHEBA ice camp. The First ISCCP Regional Experiment (FIRE; ISCCP is the International Satellite Cloud Climatology Program) is sponsored primarily by the National Aeronautics and Space Administration and will collect data from aircraft and satellite platforms in the vicinity of the SHEBA ice camp, in one or two campaigns beginning in spring 1998.

For convenience, we refer to the combined field exercise as SAFIRE. Foci of SAFIRE include clouds, radiation, the atmospheric boundary layer, the surface energy balance, sea-ice mass balance, and ice–ocean heat exchange. The goals of the three individual programs are discussed in more detail later.

This article has not been written on behalf of any of the three programs, although some of the authors of this article are participating in one or more of them. We have in common an interest in large-scale modeling of the Arctic, from either a climate or a numerical weather prediction perspective. Our intention in writing this article is to provide a large-scale modeling perspective on the exciting possibilities that SAFIRE represents for progress in simulating Arctic weather and climate.

An outline of the paper is as follows. In section 2, we briefly summarize the status of global modeling of the Arctic and discuss the basic physics of the Arctic, from a global modeling point of view. This section includes a summary of important problems that arise in formulating Arctic process in global models. Section 3 summarizes the plans for SAFIRE. Section 4 relates the modeling issues to the planned observations. Section 5 gives a summary and conclusions.

2. Global modeling of Arctic physical processes

a. GCM simulations of the Arctic climate

The Arctic lower troposphere controls the flow of energy across the ice–atmosphere interface. The growth and decay of the ice thickness depends primarily on energy fluxes received from the atmosphere, ocean, and the sun, and these depend on inadequately understood, but certainly important, ways on the low-level Arctic temperature structure in the atmosphere and ocean, and cloudiness, which existing climate models cannot simulate realistically. The clouds, in turn, are affected by the upward flows of energy and moisture from the ice and ocean below. The ice-albedo feedback and the cloud-radiation feedback, and their coupling, make the energy exchanges very complex in the Arctic Ocean. The complex energy exchanges in the Arctic provide a substantial challenge to GCMs.

Atmospheric GCMs have been tested and evaluated for the midlatitudes and the Tropics, but their high-latitude performance has seldom been comprehensively evaluated. In an intercomparison of 14 GCMs, Boer et al. (1992) found that all models display anomalously cold temperatures in the upper troposphere; many models simulate near-surface temperature, which are too cold, while other simulations are too warm; all models predict too much precipitation in the Arctic; and there are large variations among models in the net surface heat flux. As noted by Walsh and Crane (1992), the simulated sea level pressure pattern in the GCM results varies widely from model to model, in some cases showing the absence of the Beaufort Sea anticyclone. Simulations of the Arctic climate by several GCMs have also been analyzed and compared with observations in considerable detail (e.g., Battisti et al. 1992; Tzeng and Bromwich 1994; Lappen 1996).

The Atmospheric Model Intercomparison Project (AMIP; Gates 1992) was organized to promote systematic evaluations and comparisons of GCMs. Approximately 30 GCMs have completed a 10-yr simulation using observed monthly averaged values of sea surface temperature and sea-ice extent. Kattsov et al. (1995) showed AMIP-modeled Arctic Ocean June net surface shortwave radiation fluxes to range from 85 to 185 W m^{-2}. Because sea surface temperature and sea-ice coverage were prescribed according to observations, the AMIP simulations did not permit assessments of the ice–ocean–atmosphere feedbacks that are the scientific drivers of SAFIRE. Nevertheless, the atmospheric model output provides potentially useful information, particularly with regard to some systematic biases that have emerged from the analysis of the output. The season in which the AGCMs show the largest temperature bias over the Arctic Ocean is spring, when there is a warm bias of 3 K in the models' ensemble mean surface air temperature (Tao et al. 1996). Not surprisingly, the bias is smaller in the models in which the prescribed albedo of sea ice is highest. Because spring is the season in which surface albedo will exert its greatest leverage on the simulated climate (Bitz et al. 1996), the AMIP results point to the importance of accurate albedo determinations over AGCM grid-cell areas in the central Arctic during the spring.

The AMIP simulations of the total cloud fraction show tremendous variability among the models in all seasons. In nearly every month, the mean cloud fraction over the Arctic Ocean varies among models from approximately 0.30 to 0.90 (Chen et al. 1995). Similar model-to-model differences occur over the subarctic land areas. Some of these differences are attributable to the methods used to evaluate the "total cloudiness" in the different models. (There are also ambiguities in definitions of "total cloudiness" from observations—surface-based or remotely sensed—resulting in considerable scatter among the observational estimates used to assess the model simulations.) Rossow et al. (1993) summarize the uncertainties associated with observations of polar clouds. Nevertheless, a discernible association between "total cloudiness" and surface air temperature emerges from the AMIP results: the cloudier models are generally colder at the surface than the other models during summer and autumn (Tao et al. 1996). The across-model comparison, however, does not show a tendency for the cloudier models to be the warmer models during the winter. This absence of a wintertime cloud-temperature association suggests a possible discrepancy with observational results from drifting ice stations (R. Colony 1996, personal communication), although the association has not been evaluated from the daily output of individual models. Such associations may indeed be present in individual models but may be overwhelmed in the model intercomparisons by the differences among the cloud formulations in the various models.

The Arctic precipitation simulated by the AMIP models also shows a large scatter among the models. The observational estimates also vary by nearly a factor of 2, partly because some of the observational estimates include gauge-corrections that raise the raw measurements by 10%–50%. While observational estimates and the model results have qualitatively similar annual cycles with maximum precipitation amounts in the late summer, the annual total precipitation over the Arctic Ocean varies by more than a factor of 2 among the models (Fig. 2). The simulated amounts are generally larger than the corresponding observational estimates; the ensemble mean of the models' bias ranges from 17% to 44%, depending on the source of the observational estimate. Associations between simulated precipitation and formulations of model cloudiness, precipitation microphysics and/or surface parameterizations have not been explored, although there is a strong across-model association between the simulated precipitation (P) and the simulated evapotranspiration (E). The correlations between regional annual means of P and E are 0.85–0.90 over subarctic land areas, and only slightly smaller over the Arctic Ocean. Thus, the models with the most evaporation over the Arctic Ocean are also those with the most precipitation over the Arctic Ocean. It may also be true, however, that existing models tend to transport too much moisture from lower latitudes into the Arctic, possibly due in part to inadequate meridional resolution.

Although we lack an adequate observational basis against which to test GCM simulations of many quantities in the Arctic, the simulated annual cycle is deficient even for quantities for which we do have reliable climatological information (e.g., surface temperature and pressure). From the studies cited above, it is clear that elements of the surface energy budget simulated by GCMs have serious errors, the errors arising from the parameterizations of sea ice, cloud characteristics and formation processes, and atmospheric radiative transfer. Because of the complex interactions and feedbacks among these elements of the GCMs, identifying the potential impact of changing a single parameterization is difficult. For example, the large discrepancies in the simulated summertime surface shortwave radiation flux may arise from deficiencies in the parameterizations of the radiation flux, cloud microphysical and optical characteristics, cloud formation processes, and/or the surface albedo.

Based upon our current understanding of the performance of GCMs in the Arctic, improved model parameterizations are needed for clouds, radiation, the atmospheric boundary layer, sea ice, and the ocean mixed layer. Additional model deficiencies related to the Arctic are associated with model numerics such as the convergence of meridians near the poles.

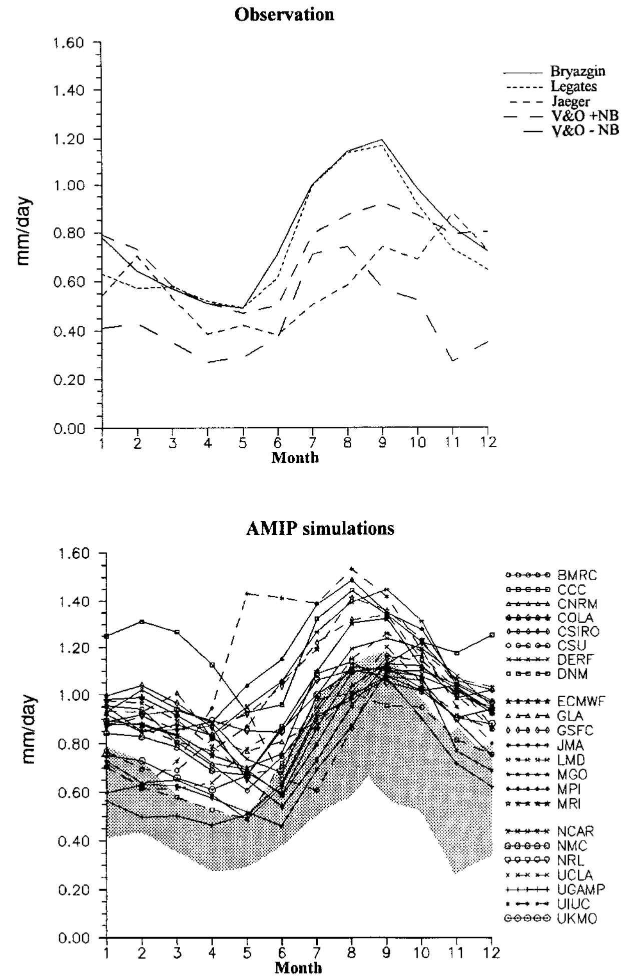

FIG. 2. Mean seasonal cycles of area-averaged precipitation (mm day^{-1}) for the ocean area poleward of 70°N; (top) observational estimates from several sources, and (bottom) AMIP model results relative to range of observational estimates (shaded area) (from Walsh et al. 1998).

b. The pole problem

Before we turn to the problems of parameterized Arctic physical processes, which are the main subject of this paper, it is useful to point out that even the large-scale dynamical aspects of the Arctic climate are not well represented in current climate models. This section and the next briefly address this point.

When the computational grid of a numerical model is defined using spherical coordinates, that is, longitude and latitude, the convergence of the meridians near the poles leads to at least two major computational problems. The first is that, because the longitudinal distance between grid points becomes small near the poles, a short time step is needed to prevent computational instability. This difficulty can be overcome by the use of polar filtering (e.g., Arakawa and Lamb

1977), but the filters have side effects, and in any case they become prohibitively expensive at high resolution (Wehner and Covey 1995), especially on modern parallel computers. The second problem is that the close zonal spacing of grid points near the poles can be considered as "excessive" spatial resolution, which demands increased and not necessarily useful computational resources.

The advent of spectral atmospheric models in the 1980s partially eliminated the pole problem by implementing the computation of large-scale atmospheric dynamical process in terms of spherical harmonics (e.g., Machenhauer and Rasmussen 1972). It has now become apparent, however, that spectral methods raise new problems of their own, notably including poor representation of the advection of water vapor and cloud water (e.g., Williamson and Rasch 1994). In some models, the zonally averaged and monthly averaged water vapor mixing ratio in high latitudes was negative! This problem has led many modeling groups to abandon spectral methods for advection; semi-Lagrangian methods (e.g., Bates et al. 1993) have now found favor in many quarters. The semi-Lagrangian advection schemes do not produce spurious negative water vapor mixing ratios and also allow large time steps despite the convergence of the meridians (e.g., Williamson and Rasch 1994). At the same time, however, they do not permit exact conservation of advected quantities; the importance of this shortcoming is currently being debated.

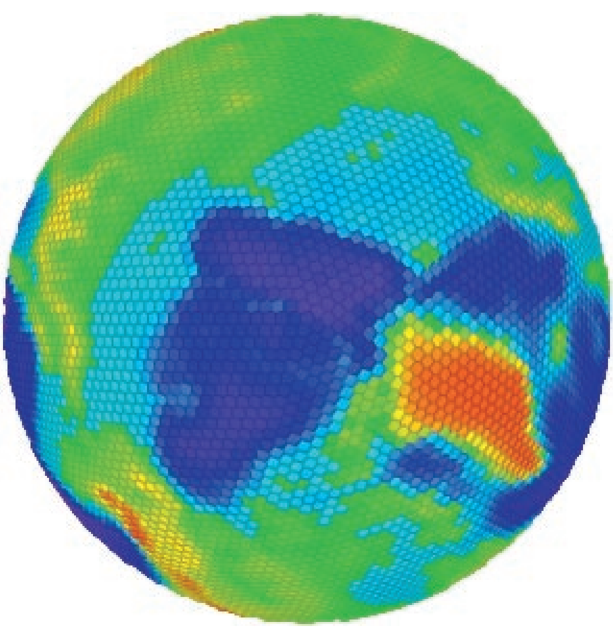

FIG. 3. View of the Arctic basin as represented on a geodesic grid, with approximately 100-km resolution. The color scale indicates topographic height or ocean depth. Greenland is represented by the orange shape at lower right, and the northern Rocky Mountains are visible near the bottom left. The figure was provided by Ross Heikes of Colorado State University.

Moisture advection is made even more problematic by the strong meridional gradients, which separate tiny mixing ratios over the winter pole from much larger values in the midlatitudes and Tropics. Accurate simulation of advection across such gradients is a challenge for any numerical scheme, although of course it can be addressed in part through the use of high meridional resolution. The errors of numerical schemes can in some cases lead to spurious down-gradient diffusion of moisture toward the pole, thus driving excessive precipitation there (Walsh et al. 1997).

Another approach to elimination of the pole problem is to use Eulerian finite-difference methods with a spherical geodesic grid, which gives an approximately uniform discretization of the sphere (Fig. 3). This idea originated in the 1960s (e.g., Williamson 1968; Sadourny et al. 1968), and has recently generated new interest (e.g., Heikes and Randall 1995a,b; Baumgartner and Frederickson 1985; Thuburn 1997; Rancic et al. 1996; Purser and Rancic 1997). It remains to be seen whether geodesic grids will prove to be useful in the climate modeling and NWP arenas, but certainly they hold promise for improved simulations of the polar regions, not only for atmosphere models but also for ocean and sea ice models.

The pole problem matters not only for the atmosphere, but also for the ocean and for sea ice. Flato and Hibler (1992) proposed two methods for avoiding this problem in an ice dynamics model. One was to insert an artificial island at the North Pole (as is often done in global ocean models); the other was to formulate the model with a special circular grid cell at the pole. Cheng and Preller (1992) addressed the pole problem in a regional model by rotating the pole in such a way that the "equator" of the grid passed through the pole associated with the Earth's rotation axis. Analytic dipole grids, which reduce to the standard polar grid as a special case, can be designed so that the poles are located over land. For example, Smith et al. (1997) have designed a global grid with the south pole located at 90°S and the north pole located over North America at 95°W, 50°N. Smith et al. constructed such a global grid with poles located in Canada and Asia and performed several successful global simulations.

The main point of this section is that problems in the simulation of polar processes are not confined to the exotic physics of sea ice and polar clouds; they extend even to the methods for representation of large-scale dynamical processes, which many researchers tend to regard as adequately modeled nonissues.

c. The cold-pole problem

Atmospheric GCMs typically produce excessively cold temperatures in the polar upper troposphere and lower stratosphere (e.g., Palmer et al. 1986; Boer et al. 1992). Because of the thermal wind balance, these cold polar temperatures imply an excessively strong westerly jet.

The introduction of parameterizations of topographic gravity-wave drag into GCMs has mitigated the cold pole problem, particularly in the Northern Hemisphere (e.g., Boer et al. 1984; Palmer et al. 1986; McFarlane 1987; Lott and Miller 1997). In this process, vertically propagating internal gravity waves, excited by flow over topography, connect the surface with the flow aloft. The drag that results from the dissipation of these waves decreases the westerly wind shear so that, as implied by the thermal wind balance, the polar regions warm relative to lower latitudes (e.g., Tao et al. 1996). Although gravity-wave parameterizations reduce the cold-pole problem, they are based on simplified theory for topographically induced waves and depend on parameters whose values are not well known. The effects of internally generated gravity waves (from convection, instabilities, and other processes) on the flow is very likely also important for the cold-pole problem, but the parameterization of these effects is less advanced.

An additional factor of possible relevance to the cold-pole problem is the rate at which energy is transported into the Arctic by the simulated atmospheric general circulation. To the extent that this rate is underestimated, the simulated Arctic climate will tend to be colder than observed.

d. Radiation

GCM simulations produce large errors in the surface radiation fluxes over the Arctic Ocean. The summertime errors in shortwave radiation flux may arise from a combination of incorrect prediction of the occurrence of clouds, incorrect determination of cloud microphysical and optical properties, incorrectly specified surface albedo, and incorrect treatment of the radiative transfer of inhomogeneous cloud over an inhomogeneous highly reflecting surface. The problems in the longwave are particularly severe for winter and arise from incorrect cloud properties and problems with treating clear-sky radiative transfer at low temperatures and low water vapor amounts.

The highly reflecting snow/ice surface strongly affects the transfer of shortwave radiation. The surface albedo is modified by snow thickness and age, as well as meltpond area and depth, lead area, ice thickness, and age.

Clouds influence the broadband surface albedo by selectively absorbing solar radiation at wavelengths greater than about 0.7 μm. Because the spectral reflectivities of snow and ice are greater in the visible region than in the near-infrared, this additional near-infrared absorption by clouds ensures that the broadband surface albedo under clouds exceeds the clear-sky value (Grenfell and Perovich 1984; Curry et al. 1996). In addition, clouds alter the distribution of the solar flux between direct and diffuse components. This can be important for surface types whose reflection characteristics are not Lambertian (e.g., snow and open water). Downwelling shortwave radiation over a highly reflecting surface will increase in the presence of clouds (e.g., Wiscombe 1975) and will increase as the surface albedo increases (e.g., Shine 1984), owing to the multiple reflections between clouds and the highly reflecting snow/ice surface. Horizontal inhomogeneities in cloud characteristics complicate significantly the radiative transfer. Given the complicated cloud types in the Arctic (discussed later), and the fact that surface conditions change rapidly over short space and timescales, shortwave radiative transfer over the Arctic Ocean is arguably more complex than anywhere else on earth, particularly during the summer melt season. The radiative interactions between the clouds and sea ice are particularly complex when the solar zenith angle exceeds 70° during the spring and fall seasons. The radiative transfer models currently used in GCMs do not perform well for large solar zenith angles.

Because the central Arctic spends a large portion of the year with little or no solar illuminations, longwave radiation plays a particularly important role in the surface energy balance. Longwave radiative transfer in the Arctic atmosphere is conditioned by the low temperature and specific humidity and the frequent occurrence of temperature inversions, particularly during the polar night. The Arctic winter atmosphere is so dry that the so-called dirty window between approximately 18- and 25-μm wavelength is largely unobscured, so that the surface and the atmosphere near the surface can lose energy to space in this wavelength region. Downward surface longwave flux calculations require accurate modeling of water vapor absorption at the low mixing ratios typical of polar conditions. Additionally, the Planck function is shifted toward longer wavelengths at the cold Arctic temperatures, so that radiative energy exchange in the dirty window is of increased importance. For these reasons, radiative transfer parameterizations that perform well at lower latitudes may fail in the Arctic (e.g., Pinto and Curry 1997). Arctic clouds are generally thin enough that their longwave emissivities are significantly less than unity, which alters their effect on the radiation balance. Moreover, Arctic stratus often form in an inversion layer and are thus warmer than the surface, so that the downward longwave flux could, at times, be larger than the upward flux emitted from the sea ice. Because these inversions are often associated with vertical temperature increases of more than 10 K over several hundred meters, deficiencies in simulations employing coarse vertical resolution are not surprising.

Radiative transfer parameterizations in GCMs must be able to deal with these complexities, and they must recognize the intrinsic radiative coupling between the atmosphere and the underlying surface. In particular, they must account for both the vertical and the horizontal inhomogeneity of this complex system in a self-consistent manner.

e. Clouds

Clouds are the dominant modulators of radiation in the Arctic. The influence of clouds on the radiation fluxes are determined by the amount of condensed water and its vertical and horizontal distribution, the size and shape of the cloud particles, and the phase of the particles (liquid or ice).

At least four unusual cloudy boundary layer types occur over the Arctic Ocean: (i) summertime boundary layer with multiple layers of cloud; (ii) mixed-phase boundary layer clouds that occur in the transition seasons; (iii) low-level ice crystal clouds and "clear-sky" ice crystal precipitation in stable wintertime boundary layers; and (iv) wintertime ice crystal plumes emanating from leads, or cracks, in the sea ice. These cloud types provide a substantial challenge to atmospheric models. Low-level Arctic clouds are particularly difficult to parameterize because of the complex radiative and turbulent interactions with the underlying surface.

Satellite estimates of wintertime cloud cover are somewhat greater than values determined from surface observations (e.g., Curry et al. 1996) because low-level ice crystal clouds are not included in surface cloud observations. These low-level ice crystal clouds lead to radiative fluxes to be 10–40 W m^{-2} greater than expected for clear-sky conditions.

Mixed-phase low-level clouds are common in spring and autumn and represent a transition between the wintertime ice crystal and summertime liquid phase clouds. The temperature of the phase transition appears to vary with cloud age and atmospheric aerosol composition and concentration. An asymmetry between the spring and autumn phase transition has been hypothesized (Curry 1995) to arise from differences in aerosol composition and concentration arising from the springtime "Arctic haze" pollution aerosol.

Arctic summertime stratus are often observed to form in multiple layers in the lowest kilometer of the atmosphere (Herman and Goody 1976). The temperature and moisture soundings are similarly layered, and the temperature of the cloud bases can affect the surface energy balance. In summer, a shallow stably stratified layer with cloud is often observed beneath an upper cloud-capped mixed layer, with little or no turbulent mixing between the layers. The upper cloud layers appear to persist without any turbulent mixing of moisture up from the surface. The models that have been proposed to explain the observed layering have been heavily simplified, especially in their treatment of turbulence. Large-eddy simulations of Arctic stratus may soon provide more complete understanding.

During the winter, the Arctic boundary layer is extremely stable for the most part, but is penetrated here and there by vigorous, buoyancy-driven plumes above leads and other breaks in the ice. Under these conditions, the area-averaged sensible and latent heat fluxes are mainly due to the exchanges that occur over the open water, even if the areal coverage of open water is just a few percent. Over leads fluxes of order 100 W m^{-2} are typical, while over the ice the fluxes are typically less than 10 W m^{-2}. The net radiative balance can be severely perturbed by clouds and fog near a lead. Leads are sources of buoyancy, which generates turbulence, gravity waves, and mixing. A lead creates a plume of warm, moist, turbulent air that evolves as it is advected over the ice surface and interacts with the overlying boundary layer. The plume returns heat to the ice, probably increases cloudiness, and affects the boundary layer's radiative properties.

Key scientific issues relating to Arctic clouds are as follows:

- What is the influence of leads and other open water on cloud properties when there is a large surface temperature contrast with the ice?

- What is the mechanism that leads to the spectacular multiple layering of Arctic Ocean summer cloud systems?
- How does the transition of low clouds from liquid to crystalline depend on temperature and aerosol characteristics, and how does the springtime transition differ from the autumnal transition?
- Does the formation of "diamond dust" differ in polluted versus unpolluted atmospheres?

These various issues can be tied, in straightforward ways, to the design of GCM physical parameterizations, and to analyses of GCM results.

f. Sea ice

Sea-ice processes have historically been treated rather crudely in global models. In NWP models, sea-ice extent is generally specified from current observations and persisted (i.e., sea ice is not a forecast quantity). In global climate models there is a recent trend toward improving the treatment of sea ice, for example, by including some representation of ice dynamics (i.e., advection and deformation). Even in the most recent IPCC summary, only 6 of the 16 coupled climate models discussed included ice dynamics; and of these only 3 used a scheme that involved solving the sea-ice momentum equation (Gates et al. 1996). The other 10 models used parameterizations that consider only thermodynamic evolution of the ice cover (e.g., Semtner 1976); a broad survey of the ice models used in large-scale coupled models is given by Mellor and Häkkinen (1994).

The sea-ice models used in GCMs are rapidly improving, however, prompted largely by the high-latitude sensitivity exhibited by global climate models and the worry that this sensitivity may be exaggerated by the highly simplified treatment of sea ice. Recent studies show that feedbacks associated with sea ice account for roughly one-third of the climate change simulated by one GCM (Rind et al. 1995), and that, including sea-ice dynamics, has a significant effect on simulated warming, particularly in the Southern Ocean (Pollard and Thompson 1994).

Dynamical sea-ice processes affect climate in two main ways. First, advection of ice out of the Arctic into the Greenland Sea and northern North Atlantic provides the largest source of freshwater to these deep convection regions (Aagaard and Carmack 1989). Variations in this freshwater source may be a source of variability in deep ocean ventilation and thermohaline circulation. Second, ice motion and deformation are largely responsible for the spatial pattern of Arctic sea-ice thickness and for the transient formation and destruction of leads. Transport of ice within the Arctic causes climatological imbalances in the oceanic surface salt flux; for example, regions like the Kara Sea experience a net export of ice, resulting in a net source of salt expelled from growing ice. Furthermore, the accumulation of thick ice, in regions such as the north coast of Greenland and the Canadian Archipelago, alters the air–sea heat exchange by increasing the effective "insulation." This gives rise to a negative feedback, which may oppose the enhanced heat flux through thinning ice under warming conditions (Hibler 1984). On the other hand, deformation of the ice cover can also act to increase heat exchange in certain regions. Leads are formed by differential ice motion, exposing open water to the cold atmosphere in winter. Rapid heat loss in leads causes growth of thin ice in these leads, much of which is crushed into ridges by subsequent deformation. The ridges formed by this process may be tens of meters thick and therefore may survive many years, contributing to the multiyear timescale associated with ice volume anomalies. Both ice advection and deformation are strongly influenced by the large-scale mechanical behavior of sea ice. As a rather rigid material, convergent and shearing deformation is resisted, and the motion of sea ice is constrained by the presence of coastal boundaries, impeding motion toward a coast and through narrow passages. Representing these effects in a model requires a specification of the ice mechanical properties, generally in the form of a plastic yield curve (e.g., Hibler 1979). Although the effect of yield curve shape and ice strength on ice motion and thickness have been studied using models (e.g., Ip et al. 1991; Flato and Hibler 1992, 1995), their role in climate feedbacks is not yet well understood, and direct observations of appropriate large-scale ice mechanical properties are not yet possible. However, recent advances in observing ice deformation at high spatial resolution with synthetic aperture radar satellites is providing data to test various ice mechanics assumptions (Stern et al. 1995), and work is currently underway to more systematically compare the results of various ice mechanics parameterizations with a range of observations (Lemke et al. 1998).

Thermodynamic processes provide the direct connection between the atmosphere and ice cover. In particular, conduction through the ice is a source of heat at the bottom of the atmospheric boundary layer, formation of new ice in leads moderates the loss of heat from open water, while change in the surface characteristics (temperature, snow coverage, melt ponding, etc.) dramatically alter the emission and reflection of long- and shortwave radiation. Although relatively sophisticated treatments of these processes have been implemented in one-dimensional models (e.g., Ebert and Curry 1993), considerable uncertainty remains, largely due to the lack of comprehensive and contemporaneous measurements of the various items in the surface energy budget. The SAFIRE suite of experiments is aimed specifically at improving this situation. A. Arbetter et al. (1998, manuscript submitted to *J. Phys. Oceanogr.*) have recently conducted an intercomparison of different rheologies in thermodynamic/dynamic sea-ice models by examining the response of the different models to a perturbation in surface momentum flux. It was found that both the elastic–viscous–plastic rheology (Hunke and Dukowicz 1997) and viscous–plastic rheology (Hibler 1979) give realistic solutions, provided that a sufficient of iterations are done in the viscous plastic model, and thus are suitable for use in coupled GCMs.

The sensitivity of the polar ice cover to heat flux perturbations is a key issue in the context of global climate change because of the possible role of sea ice in polar amplification of a warming, although this is of course coupled to the question of cloud feedbacks (e.g., Tselioudis et al. 1993). This question has received considerable attention in the ice modeling community, with studies by Hibler (1984), Holland et al. (1993), Fischer and Lemke (1994), Curry et al. (1995), and A. Arbetter et al. (1997, manuscript submitted to *J. Phys. Oceanogr.*), among others. One of the main findings is that "slab" thermodynamic models tend to be far more sensitive to thermal perturbations than are models that include ice dynamics. Even rather subtle changes in the treatment of ice thermodynamics can have a large effect. This was demonstrated in a column model experiment by Bitz et al. (1996), wherein changes only in vertical resolution of the temperature profile changed the amount and timescale of interannual ice thickness variability by more than a factor of 2. While targeted field experiments will reduce our uncertainty regarding process parameterizations, the extent to which models reproduce variability and respond to external forcing requires long-term observations. In particular, the time series of ice concentration data from the ESMR, SMMR, and SSM/I passive microwave satellite instruments provides a source of model evaluation for decadal simulations.

g. The upper ocean

The role of the upper ocean in the ocean–atmosphere–ice system is not particularly clear for the modern Arctic because the pathways by which the heat is received in the surface waters, and their storage and later release, are still subject to some controversy, particularly because they involve a variety of spatial and temporal scales. For example, it is not clear if the canonical 2 W m^{-2} attributed to the ocean (e.g., Maykut and Untersteiner 1971) actually originates from the deep water or is in part supplied by the uptake of solar radiation through leads in the spring and summer and later released in the fall and winter (Maykut and McPhee 1995). Observations show that the ocean heat flux varies considerably on diurnal and longer timescales. Fortunately, the largest scale circulation need not be treated in order to address these problems because a careful study of the storage and fluxes of heat within a vertical column of the water suffices for an attack on this problem given observations over an entire year.

There are several other problems that are particularly difficult to deal with in current ocean–ice models. Of particular interest and difficulty, are the interactions and feedbacks between ocean heat fluxes (thermodynamics) and ice divergence/convergence (dynamics), which controls the lead area within the ice fields. Because leads are the major avenue by which heat escapes from the ocean to the atmosphere, understanding of this relationship is critical. The problem lies in our poor understanding of how the ocean heat (much of which is received through the low-albedo leads via solar radiation) is partitioned between basal melting of the ice and lateral melting of the ice in leads (Maykut and Perovich 1987). Conversely, during the growth period, it is not clear whether the ice accumulates laterally, tending to close leads and reduce further cooling and ice growth, or whether it goes toward increasing ice thickness via frazil accumulation (which has not yet been documented to the extent often predicted). Central to addressing these problems is an understanding of the lead width distribution. In present sea-ice models, only the lead fractional coverage is simulated.

Recent sensitivity studies of the impact of sea-ice on GCM response to doubled atmospheric CO_2 have underscored how the magnitude and disposition of oceanic heat storage in sea-ice-containing GCM grid cells can lead to substantial variations in simulated climate sensitivity. Rind et al. (1995) identify three different modes by which the models treat ocean-to-ice heat transfer: (a) heat conduction from below, in which energy is deposited into the water under the ice, warming it, and leading to energy transfer from the water-to-ice underside via conductive processes; (b) heat input directly to the ice underside, leaving the mixed layer at freezing; (c) heat input to the ice through leads, from the sides, which tends to increase lead area by lateral melting. Their sensitivity studies show that the partitioning of energy among these various modes has significant impact on simulated Northern Hemisphere ice extent in CO_2-doubling experiments.

At present, the surface waters of the Arctic show relatively little interaction with the underlying deep Atlantic Pacific waters. If the gyre-scale conditions in the Arctic were to change toward increased surface divergence, this would tend to open up more leads, venting more heat, and it would also tend to bring the deep water closer to the surface, promoting erosion of the thermocline. It is important to understand the controls on the heat fluxes across the pycnocline into the surface layer.

It is difficult to scale up our detailed, local-scale observations and parameterizations to the larger GCM-grid-size scales. This problem is compounded by the great heterogeneity of the overlying ice conditions, which drive comparable smaller-scale lateral changes in the surface ocean, which in turn controls and influences the surface fluxes, heat storage, and redistribution. Learning how to integrate or properly weigh these disparate processes that coexist within a single GCM cell is of considerable importance for climate simulation. Issues that must be addressed related to ice–ocean interaction include

- How is heat from solar radiation stored in the upper ocean and subsequently returned to heat the ice from below?
- How does the freshwater associated with the summertime melting modulate the exchange of heat between the ocean and the ice?
- How does the ice-thickness distribution influence the exchange of heat and salt between the ice and ocean?
- How do nonlocal effects of pressure keels modulate the exchange of heat and salt between the ice and ocean?
- What is the relative importance of heat transfer from the pycnocline into the ocean mixed layer and solar radiation stored in the mixed layer in determining the ice–ocean interfacial heat flux?
- What controls exchange of properties between the well-mixed layer and the underlying, stably stratified pycnocline?
- What controls the relative importance of lateral and vertical growth/decay of sea ice?

h. *Operational prediction of the Arctic atmosphere, ocean, and sea ice*

The conventional approach to sea ice in weather prediction models is to specify sea-ice extent (rather than concentration) from observations (which may be up to a week old); the ice extent is typically held fixed throughout the forecast integration. Several forecast centers in the United States and Europe are using numerical models to predict the atmosphere, the sea ice, and the upper ocean in the polar regions. Some centers have experimented to determine the sensitivity of their atmospheric forecasts to sea-ice prescriptions (e.g., Meleshko et al. 1990; Grumbine 1994; Watkins and Simmonds 1995). At present, such forecast systems generally consist of ice–ocean models, which are driven by output from global atmospheric GCMs, but are not coupled to them.

Both the National Centers for Environmental Prediction (NCEP) and the U.S. Navy are using the Hibler ice model (Hibler 1979, 1980) as a forecast tool for the prediction of the three-dimensional structure and movement of sea ice. NCEP is presently testing a version of the model for both the Arctic and the Antarctic using 127-km grid resolution. The planned range of operational forecasts of ice conditions, along with mixed-layer temperature and depth, is 7 days. The NCEP ice model, as well as the NCEP Medium Range Forecast Model, use ice concentration information from the daily, automated high-resolution (0.5° and 25.4 km) Special Scanning Microwave/Imager (SSM/I) passive microwave data to initial the models. Testing of these techniques has produced satisfactory results to date.

Since 1987, the U.S. Navy has been using the Hibler (1979, 1980) ice model as part of a real time, operational sea-ice forecast system, driven by surface stresses and heat fluxes from the Navy Operational Global Atmospheric Prediction System (NOGAPS). The first such forecast systems were developed for the central Arctic, Barents, and Greenland Seas with resolutions ranging from 127 to 20 km. The ocean forcing used by these models was in the form of monthly mean heat fluxes and geostrophic ocean currents. Although these monthly values were the best available at the time, they did not provide the temporal variability required for daily or weekly forecasts. In addition, as the area of interest associated with these forecasts was expanded to include all sea-ice-covered regions in the

Northern Hemisphere, a coupled ice–ocean model (Riedlinger and Preller 1991; Cheng and Preller 1992; Cheng and Preller 1997) was required. Coupling these systems provided the necessary temporal and spatial variability to the ice–ocean forecasts.

At present, these coupled ice–ocean forecast systems use atmospheric forcing from the global models but remain "decoupled" from them. Years of experience running these models in a forecast mode, and comparison of the results with observations has provided ample evidence that, not surprisingly, accurate simulation of the ice cover requires an accurate parameterization of the exchange of energy fluxes between atmosphere, ice, and ocean. Errors in these energy fluxes quickly become evident in the simulated ice cover, particularly near the ice edge. When run in a decoupled mode, the atmospheric model is provided with some estimate of the ice cover as a bottom boundary condition. If this estimated bottom boundary condition is inaccurate, it can distort both the heat flux exchange as well as surface stress interaction. The U.S. Navy's atmospheric model has recently upgraded its sea-ice boundary from a coarsely resolved "climatic" ice edge to a weekly varying ice edge derived from the National Ice Center's ice concentration analysis. Although this has provided better agreement between the ice edge derived by the ice–ocean model and the atmospheric model's lower-boundary condition, the frequency of updates (once per week) is still an issue. The ice-edge location can change substantially over the course of a week, particularly in the spring melt and fall growth seasons. One solution to this problem would be daily initialization of the atmospheric model, as well as the ice–ocean model from observations, such as the daily SSM/I ice-concentration data. Another solution would be a true two-way coupling of the atmosphere and ice–ocean models.

Another problem, which becomes apparent when the ice–ocean and atmospheric models are run in a decoupled mode, is that it is difficult to evaluate the weather forecasts for high latitudes. Regular, statistical verification of atmospheric models is routinely performed for the midlatitudes and the Tropics, but rarely for the high latitudes. Problems with the forecasts for high latitudes may go unnoticed until the forecasts are used to drive the ice–ocean models.

Coupling of the atmosphere, upper ocean, and ice forecast models has the potential to improve the forecast accuracy of each of them, and this is a realistic goal for the near future.

3. SHEBA/ARM/FIRE

a. Background

Routine, conventional observations of the atmosphere, ice, and ocean in the Arctic have been sparse. With the demise of the Russian drifting ice camps (e.g., Kahl et al. 1993), there have been no routine Arctic meteorological observations since 1991. The Arctic surface pressure buoy array (Untersteiner and Thorndike 1992) provides accurate measurements of the surface pressure field and an estimate of ice motion. Additional observations have been obtained by using submarines and ocean moorings. For example, sea-ice thickness distributions have been measured over large regions by submarine (e.g., McLaren 1989; Wadhams 1992). Satellite-based radar observations of the ice surface have become increasingly reliable, but satellite-based observations of Arctic cloudiness are still very uncertain (e.g., Rossow et al. 1993). Additional data are now becoming available.

There is a long history of productive Arctic drift experiments beginning over a century ago with the drift of the research vessel *Fram* (1893–96) and including the Arctic Ice Dynamics Joint Experiment, the Arctic Internal Wave Experiment, the Lead Experiment (LEADEX), and the Sea Ice Mechanics Initiative. During the last two decades, several aircraft datasets of relevance to clouds and radiation have been obtained over the Arctic Ocean, including the Arctic Radiation Measurement in Column Atmosphere–surface System/Cloud, Aerosol, and Radiation Arctic Field Experiment, conducted in June 1995; the Beaufort Arctic Storms Experiment, conducted in autumn 1994 (Curry et al. 1996); and the Arctic Stratus Experiment, conducted in summer 1980 (Herman and Curry 1984; Tsay and Jayaweera 1984). Many useful data have been obtained from previous field experiments, and useful technology has been developed and tested. A comprehensive dataset with simultaneous and contiguous observations of the atmosphere, ice, and ocean has not been collected, however.

Available observations are inadequate to understand and improve deficiencies in the representation of Arctic physical processes in GCMs that are related to clouds, atmospheric radiation, and the surface energy balance, and the influences of these processes on the sea-ice mass balance. SHEBA, ARM, and FIRE have been designed to fill this knowledge gap by providing a comprehensive, high-quality dataset that documents the processes, which determine the characteristics of radiation, clouds, the surface energy balance, and the sea-ice mass balance over a complete annual cycle.

b. SHEBA

SHEBA (Moritz et al. 1993) is a research program designed to address clouds, atmospheric radiation and the surface energy balance, and their interactions with physical processes that determine the sea-ice mass balance of the Arctic Ocean. The central motivation behind SHEBA is the large discrepancies among global circulation model simulations of present and future climate in the Arctic and uncertainty about the impact of the Arctic on climate change. These difficulties are due, in large part, to incomplete understanding of the physics of vertical energy exchange within the ocean–ice–atmosphere system. The central theme of SHEBA emerges from issues related to the surface energy balance, especially the ice-albedo and cloud-radiation climate feedback mechanisms. The SHEBA program is based on the premise that improved understanding of the physical processes involved in the surface energy budget and air–sea-ice interactions is needed to address the issues of climate feedback in the Arctic and to improve our ability to model the Arctic climate.

SHEBA is a multidisciplinary research program designed to determine the ice–ocean–atmosphere processes that control the surface albedo and cloud-radiation feedback mechanisms over an annual cycle, in order to bring about the improvement of large-scale models of Arctic ocean–atmosphere–ice processes. The essence of SHEBA as a project is to conduct a year-long field experiment (starting autumn 1997) at a drifting station on the pack ice of the Arctic Ocean, in combination with remote sensing and modeling analyses of the entire Arctic Basin. The observational program at the drifting ice station emphasizes a coordinated and comprehensive measurement effort examining the physical processes associated with interactions among the radiation balance, mass changes of the sea ice, storage and retrieval of heat in the mixed layer of the ocean, and the influence of clouds on the surface energy balance. The large-scale context for the SHEBA field site will be provided by geophysical data products derived from satellite-borne sensors and analyses derived from large-scale models.

There are three main parts to the conceptual design of the SHEBA program:

1) Documenting the ice-mass balance and the surface energy balance. This portion of the experiment consists of measurements conducted at the ice camp that define these quantities on a spatial scale of approximately 10 km.
2) Understanding of physical processes that determine the mass balance and the surface fluxes. To understand the processes that determine the evolution of the surface fluxes requires that measurements be made in the atmospheric and oceanic boundary layers. In particular, processes that determine the characteristics of boundary layer clouds are required to understand the disposition of shortwave radiation through the atmosphere–ice–ocean system. In addition to measurements at the ice camp, mesoscale observations are required to interpret processes involved in determining the characteristics of boundary layer clouds. This implies that measurements are needed not only at the ice camp, but throughout the surrounding region, in order to quantify the time-dependent state of the system on the aggregate scale.
3) Predicting the ice-mass balance and surface fluxes on scales that are relevant for climate modeling. Once improved parameterizations of physical processes are determined using observations obtained at the ice camp and from aircraft and submarines, these parameterizations must be evaluated against observations in a systematic way in the context of models of the coupled atmosphere and ocean. Two different strategies will accomplish this: the single-column analogue to a coupled general circulation climate model (SCM), and a coupled regional climate model. These strategies require extension of the observational base to a scale of 100 km (for the SCM experiments) and to the scale of the Arctic Basin (for the regional climate model experiments).

The strategy adopted by SHEBA will improve key parameterizations needed for use in climate models. The performance of the model parameterizations must be evaluated by comparison with observations. SHEBA proposes to focus on model performance over timescales ranging from approximately 1 h to 1 yr, with special emphasis on changes over the annual cycle.

GCMs, including the higher-resolution versions of the foreseeable future, cannot resolve the local-scale variations of individual features at the ice–ocean surface. Such features include leads, meltponds, ridges, snow drifts, and ice and snow of varying thickness. These features have a large impact on the surface energy balance and surface mass balance associated with variations in surface albedo, surface temperature, and other properties. A single GCM grid cell extends horizontally over an area containing many small-scale features of the atmosphere and the ice–ocean surface. SHEBA proposes to address this mismatch in scales by making measurements on two different scales. Local-scale measurements will be made by sensors deployed from fixed locations on the ice surface, and area-aggregated measurements will be made by (a) spatial surveys above, on, and under the ice and (b) synthesis of satellite and point-surface observations with models. The area-aggregated measurements are designed to document the thermodynamic state and fluxes of the atmosphere–ice–ocean system on a horizontal scale that may be compared to a single GCM grid cell.

c. ARM

The programmatic focus of ARM is on the development and testing of parameterizations of cloud and radiative processes, for use in GCMs (DOE 1996). The primary scientific issues being addressed by ARM are:

- What are the direct effects of temperature and atmospheric constituents, particularly clouds, water vapor, and aerosols on the radiative flow of energy through the atmosphere and across the Earth's surface?
- What is the nature of the variability of radiation and the radiative properties of the atmosphere on climatically relevant space and timescales?
- How can we quantify the relative importance of and interactions among the various dynamic, thermodynamic, and radiative processes that determine the radiative properties of an atmospheric column and the underlying surface?
- How do radiative processes interact with dynamical and hydrologic processes to produce cloud feedbacks that regulate climate change?

In order to achieve these goals, ARM has undertaken a program of multiyear measurements of atmospheric radiation and closely related parameters at three locales (Stokes and Schwartz 1994): the southern Great Plains of North America, the tropical Western Pacific, and the north slope of Alaska and adjacent Arctic Ocean (NSA–AAO). It is this third locale, which will be the last of the three to be occupied, that relates to SAFIRE.

The NSA–AAO was chosen as a locale because the atmospheric and surface conditions in this region are markedly different from those at the other ARM sites and are representative of high latitudes: low temperatures, sustained high surface albedo over most of the year, continuous low sun during summer, and polar night during most of the winter. The NSA–AAO site will be centered at Barrow, Alaska. ARM has entered into a cooperative agreement with SHEBA, to make use of the SHEBA ice camp as a supplementary site, in order to allow study of how radiative transfer differs from the central Arctic ice pack, to coastal environments, to more continental areas inland.

d. FIRE

The overall scientific objectives of FIRE are to

- expand our basic knowledge of how clouds and cloud systems interact with their environment and the climate;
- identify, quantify, and simulate the processes instrumental in the evolution of large-scale cloud systems;
- quantify the capabilities of current models for simulating large-scale cloud systems and the radiative properties of these systems, and improve cloud physics and radiation parameterizations used in general circulation models;
- assess and improve the reliability of currently used cloud/radiation monitoring systems from space and from the ground; and
- assess the capability of future cloud/radiation monitoring systems, such as the Earth Observing System (EOS).

An overview of the FIRE program to date is given by Randall et al. (1995). FIRE Phase I was designed to address fundamental questions concerning the maintenance of cirrus and marine stratocumulus cloud systems. FIRE research over those years has led to major improvements in our understanding of the role of these clouds in the global climate system. FIRE Phase II (1989–94) focused on more detailed questions concerning the formation, maintenance, and dissipation of these cloud systems. FIRE Phase III will continue with the above, and in addition it will undertake an investigation of Arctic cloud systems (Randall et al. 1996b).

FIRE is now preparing to go to the Arctic in order to study a variety of Arctic cloud systems under spring and summer conditions. The primary motivations for the Arctic phase of FIRE are:

1) The physical processes at work in the Arctic cloudy boundary layer are poorly understood.
2) Arctic boundary-layer clouds are poorly simulated by current climate models.
3) Satellite remote sensing algorithms currently cannot accurately retrieve Arctic surface and cloud characteristics.

The objective of the FIRE III Arctic program is to document and understand the Arctic cloud-radiation feedbacks, including changes in cloud fraction and vertical distribution, water vapor and cloud water content, and cloud particle concentration, size, and phase, as atmospheric temperature and chemical composition change. A major aircraft campaign is planned for spring 1998 in conjunction with the SHEBA ice camp. In addition, FIRE III has key research objectives related to evaluating aircraft and satellite remote sensing technologies.

The aim of the FIRE Phase III Arctic field experiment is to produce an integrated dataset that

- supports the analysis and interpretation of physical processes that couple clouds, radiation, chemistry, and the atmospheric boundary layer;
- provides in situ data for testing of satellite and ground-based remote sensing analyses; and
- provides initial data, boundary conditions, forcing functions, and test data to support Arctic FIRE modeling efforts.

FIRE's strategy is to collect in situ and remote measurements of the Arctic cloud and surface characteristics. These data, to be collected using aircraft, will be supplemented by surface measurements provided by SHEBA and ARM.

Aircraft observations are needed to describe accurately the statistical characteristics of the surface ice features on a horizontal scale of 100 km. A long-range research aircraft will be used that is equipped with scanning radiometers that measure at visible, near-infrared, thermal, and microwave wavelengths. Such an aircraft will be available during the SCM IOPs (Intensive Operations Periods). When flown at low altitudes below clouds, the aircraft remote sensing instruments can resolve ice surface characteristics occurring on horizontal scales of a few meters to a few tens of meters (depending on sensor and wavelength). The high-resolution aircraft scanning radiometers will be used to determine the fractional coverage of open water, thin ice, first-year ice, second-year ice, and multiyear ice, and the associated distribution of surface temperatures and albedoes. Lead width and pond size distributions along the flight track can be determined by examining the small-scale spatial structure of leads encountered by the scanning radiometers.

FIRE will undertake studies based on satellite remote sensing and will also use in situ data to evaluate these remote sensing techniques. An important goal of FIRE is to gather "ground truth" data for use with products from EOS (Dozier 1994), SCARAB (Stubenrauch et al. 1996), and other satellite platforms. The first launch in the NASA EOS series is anticipated in June 1998 (Arrhenius, the platform formerly known as EOS-AM); at this time, the NSA–AAO site will be in its "mature" operational stage. In addition, the EOS program has an international component (IEOS) coordinated with the National Space Development Agency of Japan and the European Space Agency. Such coordination gives us an opportunity to receive data from space-borne instruments, that in many aspects are similar to those to be flown on the EOS satellites. Active instruments such as those flown on RADARSAT (Mullane et al. 1994) and ADEOS (Haruyama 1994) also provide valuable data on sea ice.

e. SAFIRE: Data integration to support model evaluation and improvement

To meet the individual programmatic objectives of the SHEBA, ARM, and FIRE programs, and to achieve the common goal of improving GCM simulation of clouds, radiation, and the surface energy balance in the Arctic, close cooperation among the programs is required, especially to ensure that all necessary observations are obtained without costly duplication. The major collaborative field experiment is planned in the Arctic Ocean during 1997 and 1998. This experiment includes measurements to be made from a year-long ice camp.

A major goal of the three programs is to produce integrated datasets for use by the modeling and remote sensing communities. The following integrated datasets for modeling will be prepared.

- *Integrated radiative flux dataset*. This dataset will include vertical profiles of temperature and trace gas concentrations and profiles of cloud and aerosol characteristics that can be used as input for a radiative transfer model. Observed spectral radiation fluxes at the surface, top of atmosphere, and within the atmosphere will be included in the dataset to evaluate the modeled fluxes. Horizontal variability of clouds, surface characteristics, and surface radiation fluxes will be measured periodically with research aircraft.

- *Atmospheric boundary layer LES dataset.* A complete dataset will be assembled for each of several different cloudy boundary layer situations for use in the GEWEX GCSS (Global Cloud System Study) Boundary Layer Cloud model intercomparisons (Browning 1993). This dataset will include cloud properties, mean and turbulent profiles, and advective fluxes.
- *Single-column coupled air–sea-ice model dataset.* Time series of area-averaged vertical profiles of atmospheric, sea ice and oceanic quantities, snow distribution, lateral boundary forcing, horizontal variability of sea ice and cloud characteristics, surface albedo, and interfacial fluxes will be assembled into a dataset that can be used to initialize, force, and test parameterizations of radiation, clouds, atmospheric boundary layer, sea-ice processes, and ocean mixed layer against the field observations.
- *Regional model dataset.* Numerical weather prediction analyses, satellite products, and conventional meteorological observations on the scale of the Arctic Ocean basin will be provided to initialize, force, and evaluate regional models.

4. Connecting the observations to global modeling research

a. Interactions with operational NWP systems

Data collected at the SHEBA ice camp will be put onto the Global Telecommunications System, in order to make it possible for operational numerical weather predictions such as NCEP and ECMWF to assimilate data through their analysis systems. As the ice camp drifts during the year-long field exercise, the position of the camp will be updated so that the data will always be appropriately "navigated" at the time of assimilation. These assimilated field data will make it possible for the operational centers to construct the best possible representation of the evolving weather over the Arctic basin, and particularly in the vicinity of the SHEBA ice camp. In addition, it will improve the quality of the NWP products that will be used by SAFIRE investigators after the field experiment is concluded. We hope that the intensive effort made to improve Arctic data assimilation for SAFIRE will provide the foundation for routinely producing improved analyses of the Arctic atmosphere.

SAFIRE modelers will use two types of operational NWP products in order to perform their research. The first consists of operational synoptic products, such as maps of low-level winds, which can be used in a forecasting mode to plan aircraft missions or ice camp activities. The second consists of detailed depictions of the time evolution of the atmosphere over the ice camp.

The quality of the analyses obtained through data assimilation is strongly affected by the physical parameterizations of the forecast model used, especially in data-sparse regions such as the Arctic, and especially for vertical motion and water vapor. Assimilation products nevertheless offer unmatched spatial coverage and comprehensive information about the dynamical fields, and there is no question that they will play a very important role in SAFIRE research. At the same time, it is our hope that SAFIRE will provide data useful to operational prediction centers. The analyses may be redone later, making use of more complete input data and better models. As SAFIRE and other polar programs evolve, it is important that the polar community interact with global modeling and data assimilation centers in order to ensure that improved parameterizations are incorporated into global models and future data assimilations. The World Climate Research Program's Arctic Climate System Study is actively fostering such collaboration through is Working Group on Atmospheric Reanalysis.

b. Using the data to test parameterizations

Improved parameterizations of physical processes can be tested using observations collected at the ice camp and from aircraft. 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. 1996a). The SCM is a framework for testing key-process models and parameterizations in a GCM by isolating a single vertical array or "column" of cells from the global model, and operating the model in what is called single-column mode. This subset of the model retains virtually all of the parameterized physical processes that must be represented in climate models, and offers a convenient approach to testing parameterizations of the physics. 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. An SCM experiment can test a single parameterization or a suite of parameterizations without complications from the rest of the global climate model, and is very inexpensive computationally; however, it has very demanding data requirements. A problem with the SCM is that although feedbacks that work inside a single column are active in a SCM, others involving the large-scale circulation cannot be included. As a result, problems with the parameterization that involve large-scale feedbacks cannot be detected using a SCM; they are best studied with a full climate model.

To operate SCMs, it is necessary to specify the initial values of the prognostic variables within the column to provide the time-dependent boundary conditions for the column, and to supply suitable data for evaluation of the model results. Figure 4 summarizes the fluxes that must be considered in a combined single-column model of the atmosphere, ice, and upper ocean of the type discussed by Bitz et al. (1996). The vertical flux F_A, which could be measured in the atmosphere just above the surface, combines the surface measurements of upwelling and downwelling radiation, sensible and latent heat (derived from the observed low-level temperature, humidity, and wind), and precipitation. The insolation at the top of the atmosphere is accurately computable from the earth's orbital parameters. The ice–ocean and mixed-layer heat fluxes, F_O and F_{OB}, can be derived from profiles of mixed-layer temperature, salinity, and current. The horizontal fluxes, D_A, D_O, D_I, represent horizontal advection in the atmosphere (from operational NWP analyses, which have assimilated SAFIRE observations), in the ocean (from mixed-layer profiles), and the net convergence/divergence of sea ice within the SAFIRE study area, based on ice-motion studies.

Observations serve to determine the boundary and initial conditions of the prognostic variables and to document the actual temporal evolution of the prognostic and diagnostic variables simulated by the models. The following parameters are required for model initialization, testing, or forcing at the boundaries:

- vertical profiles of atmospheric temperature, humidity, wind velocity, cloud and aerosol properties, and radiative fluxes;
- vertical profiles of temperature, salinity, and currents in the upper ocean;
- vertical profiles of horizontal advection of atmospheric temperature and humidity and large-scale atmospheric divergence;
- horizontal advection of heat and salt in the upper ocean;
- statistics of the ice-thickness distribution, lead fraction, snow cover, and meltpond properties;
- areally averaged interfacial energy flux at the underside of the ice; and
- the temperature profile through the ice–snow column.

The most difficult data requirement of SCMs is the atmospheric advection into the cell, and the large-scale vertical motion. Indirect methods must be used to determine these quantities, and these methods are very sensitive to missing data and other errors of measurement. In principle, objective analysis methods can be used to combine *direct* measurements from various sources (e.g., surface-based rawinsondes, wind profilers, aircraft dropsondes) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. These can then be analyzed to infer the various quantities needed as input for the SCMs. It does not appear that there will be sufficient spatial coverage to allow this approach to work for SAFIRE, however. A second approach is to make use of operational data assimilation products, as mentioned above. This will certainly be feasible in SAFIRE.

ARM's SCM intensive observational period strategy has been used at ARM's southern Great Plains site in Oklahoma (Stokes and Schwartz 1994) and during TOGA COARE (Webster and Lukas 1992). It is a major strategy of the GEWEX Cloud Systems Study (GCSS; GEWEX is the Global Energy and Water Experiment; Chahine 1992). The difficulties in successfully closing the atmospheric heat and moisture budgets of the column are described by Randall et al. (1996a). A variant of the SCM strategy has been used by Battisti et al. (1997) to diagnose the sensitivity of the Arctic climate simulated by the Geophysical Fluid Dynamics Laboratory climate model to the parameterization of surface albedo.

We have several reasons for being optimistic about successfully conducting SCM research in SAFIRE:

- Atmospheric variability in the Arctic occurs on much larger space and timescales than in the southern Great Plains and in the tropical western Pacific Ocean.
- The vertical velocity of the Arctic atmosphere is generally weaker than 1 cm s^{-1} (e.g., Peixoto and Oort 1992; Curry and Herman 1985).

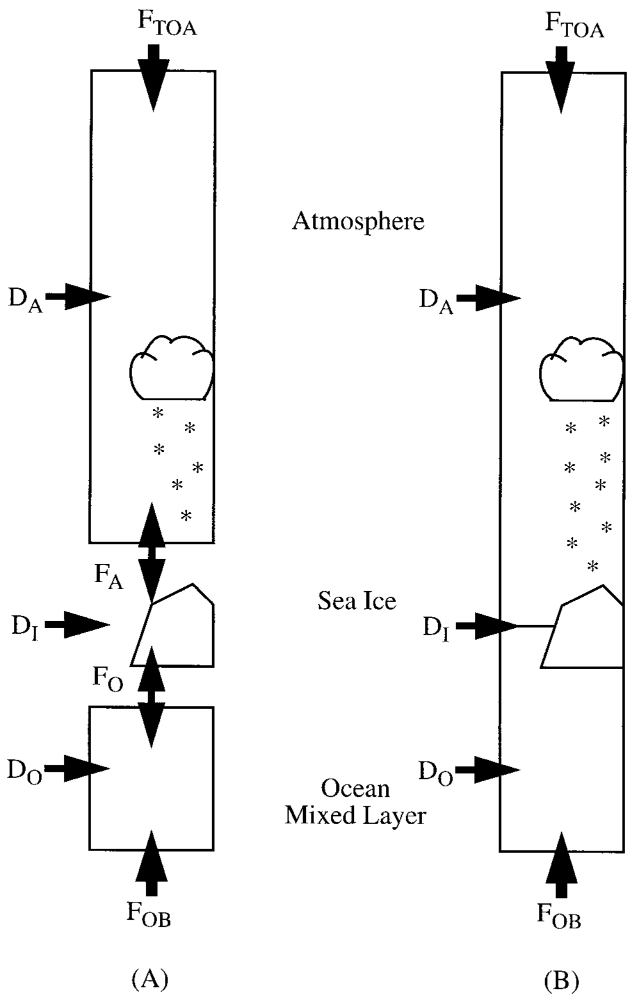

FIG. 4. Testing models of atmosphere, sea ice, and ocean mixed layer separately (in A), and in a coupled column model (in B). Vertical fluxes, F, are forcings at the top-of-atmosphere, atmosphere–ice interface, ice–ocean interface, and bottom-of-ocean mixed layer. Horizontal fluxes, D, are net flux convergences into each component.

- Horizontal exchange of water masses in the upper Arctic Ocean occurs relatively slowly and infrequently. Ocean fronts are relatively few and far between in the region, so that they should not cause major difficulties.
- Except for ice divergence (which is reliably measured from drifting surface pressure buoys and also satellite-derived ice-motion vectors), changes in the coupled atmosphere–ice–ocean system are dominated by vertical exchange processes.

c. *Use of SAFIRE data to evaluate and improve sea ice and upper-ocean models*

A variety of sea-ice/upper-ocean models can be evaluated and compared using the SAFIRE data, in the "single-cell" framework shown in Fig. 4a (e.g., Bettge et al. 1996). The SAFIRE observations required as initial conditions, and forcing data for these models are listed in Table 1. The model-predicted variables such as ice thickness, open-water fraction, ice-growth rate, snow cover, and surface temperature, can be validated against SAFIRE observations of these variables for different ice types. Within this framework of SAFIRE forcing and validation, it will be possible to test revisions of sea-ice models (such as including multiple ice thicknesses) in a way that reproduces the observed surface energy balance. Similarly, atmosphere and ocean models can be tested and improved using this same framework of forcing and validation.

The major challenge in improving sea-ice models is to synthesize the different physical processes included in the 1D thermodynamic and ice-thickness distribution models into the 2D models that include ice dynamics. Climate modelers have been reluctant to incorporate significantly more complex sea-ice parameterizations into their models until the elements of the parameterizations are adequately tested against observations. SHEBA plans to provide a dataset that can be used to evaluate many aspects of sea-ice thermodynamic processes that are candidates for incorporation into climate models.

Specific sea-ice thermodynamic parameterizations that can be evaluated against the SAFIRE observations include

- surface albedo as a function of surface characteristics;
- radiative transfer in sea ice, leads, and the upper ocean;
- formation of new ice in leads in the presence of redistribution by winds and ocean currents;
- life cycle of meltponds, runoff from ponds, and pond optical properties;
- life cycle of a newly-formed ridge and local ridge heat exchanges with the atmosphere and ocean;
- rate of frazil ice formation;
- snow distribution and wind redistribution of snow;
- changes in ice mass; and
- influence of the ice-thickness distribution on turbulent exchanges at the upper- and lower-ice interfaces.

The observations required to develop and evaluate the aforementioned parameterizations include

- time series of ice thickness, ablation/accumulation at upper surface and ice bottom and side walls;

- time series of the reflection, absorption, and transmission of solar radiation;
- optical properties and vertical radiance distribution of the snow and major ice types;
- snow-depth surveys;
- surveys of meltpond areal extent, depth, volume, and runoff to the ocean;
- vertical profiles of salinity, temperature, density, and air volume in snow and ice;
- optical transmissivity in leads and the upper 30 m of the ocean;
- spectral irradiances (shortwave and longwave) at the surface;
- radiometric "skin" surface temperature;
- spectral and wavelength-integrated albedo;
- bidirectional reflectances of the snow/ice surface;
- rainfall and snowfall rates;
- covariances of heat, moisture, and velocity components in the atmospheric and oceanic boundary layers;
- surface roughness lengths over and under different ice types; and
- surface-layer wind speeds, air temperature, and water vapor mixing ratios.

TABLE 1. Data needed to drive and/or evaluate the results of single-column sea ice and upper-ocean models.

Observation	How the observation will be used
Time series of temperature and humidity profiles and cloud characteristics (or alternatively the downward surface radiative fluxes, including spectral and diffuse/direct information)	Input
Time series of snowfall and rainfall	Input
Initial ice-thickness distribution and snow-thickness distribution, other surface characteristics	Input
Initial temperature profiles in ice of different thicknesses	Input
Initial lead fraction and lead width distribution	Input
Initial profile in the ocean mixed layer	Input
Time series of advection of temperature and salinity in the mixed layer	Input
Time series of cell boundary divergence	Input
Time series of ice-thickness distribution in neighboring cells	Input
Time series of surface wind stress	Input
Time series of ice–ocean interfacial flux	Evaluation of the model results
Time series of surface albedo and surface energy flux components.	Evaluation of the model results
Time series of ice, snow, and meltpond thickness distributions and areal coverages	Evaluation of the model results
Time series of ocean mixed layer temperature and humidity profiles.	Evaluation of the model results

Plans call for SHEBA to construct a dataset for the study of sea ice for the entire annual cycle. A dataset for the ocean mixed layer will be constructed for periods when the mesoscale ocean array is providing suitable advection data. The dataset will be constructed for a "single-cell" of approximately 100 km^2 area, following the drift of the ice camp.

d. Regional modeling

A regional model of the Arctic coupled climate system can be used for exploration of coupled model sensitivities and feedbacks and testing of parameterizations prior to incorporation into global coupled models. Toward addressing deficiencies in Arctic climate simulations, the Arctic Region Climate System Model (ARCSyM) has been developed (Walsh et al. 1993; Lynch et al. 1995). The ARCSyM is based upon the NCAR regional climate model but includes a full 3D ocean as well as a 2D dynamic thermodynamic sea-ice model. An additional application of regional models for SAFIRE is the utilization of a mesoscale model to do high-resolution analyses over the Arctic Ocean, assimilating nontraditional satellite and in situ measurements. The model of Thompson and Burk (1992) was used for this purpose during LEADEX. Data assimilation techniques are also being used increasingly with sea-ice models (e.g. Kwok et al. 1995).

Observations on the scale of the Arctic Ocean basin are required to: 1) initialize, force, and evaluate 3D regional models; and 2) provide a detailed analysis of surface fluxes to force 3D sea-ice models. The planned or ongoing large-scale arrays of in situ measurements listed in section 3e will be crucial for the success of this research.

Once satellite retrieval schemes have been improved using the combination of base camp and aircraft observations, satellites can provide observations on the scale of the Arctic Ocean basin of cloud properties (e.g., Rossow 1995), top-of-the atmosphere and surface radiation fluxes (e.g., Schweiger and Key 1994), ice characteristics (e.g., Kwok et al. 1995), surface temperature and albedo (e.g., Key and Haefliger 1992), atmospheric temperature and humidity profiles (e.g., Francis 1994), and ozone abundance. We expect that the NASA Radarsat Geophysical Processing System Working Group will provide high spatial resolution sea-ice deformation data throughout the SHEBA experiment, with a time resolution of 3–8 days.

e. Summary

At the smallest scale (< 10 km), observations obtained at the SHEBA ice camp will be used to test detailed process models and to test satellite retrieval algorithms. Improved process models that have undergone rigorous sensitivity testing will be used as the foundation for developing parameterizations suitable for GCMs. At the intermediate scale (10–100 km), observations from the field experiment and from other data sources will be combined into unified analyses, using 4D data assimilation schemes. These analyses will be used with single-column models, as discussed above. At the scale of the Arctic basin, assimilation-based analyses will be used to drive and evaluate a coupled regional model with improved parameterizations. The problem of relating these various scales is in itself an important area for research, of course.

5. Summary and conclusions

Sea ice in all its complexity, extremely stable stratification in the lower troposphere, low water vapor amounts, multilayer clouds, and the storage, redistribution, and release of energy from the ocean are among the physical phenomena that challenge large-scale modelers as they attempt to simulate the large-scale circulation of the atmosphere in the Arctic. Additional problems arise from such modeling "technologies" as latitude–longitude grids, which were not designed with the Arctic in mind.

Tropical processes, such as cumulus convection, have long been a key focus of large-scale model development efforts, and this is well and good. The Arctic is also critically important, however, for both climate simulation and global numerical weather prediction. One of the messages of this paper is that large-scale modelers are increasingly recognizing the importance of the Arctic when they set their model development priorities.

Existing climate models give wildly different answers for present Arctic climate, and this is due, in part, to deficiencies in at least some of the parameterizations and numerical methods used and to gaps in our current knowledge. With this in mind, NSF, DOE, and NASA have spawned three field programs: SHEBA, ARM, and FIRE. In this paper, we have briefly summarized the problems and tried to show how these interdependent Arctic field programs will produce data suitable for evaluation and development of parameterizations of Arctic processes for use in large-scale models. The data collected by SHEBA, ARM, and FIRE, over the next several years, will provide unprecedented opportunities to learn more about the role of the Arctic in the global circulations of the atmosphere and ocean. We fully intend to take advantage of this opportunity and hope that the entire large-scale modeling community will join us in this effort.

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