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Introduction to special section: FIRE Arctic Clouds Experiment

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1. Introduction

The sensitivity of climate models seems to be particularly dependent on their treatment of radiation feedback processes in the Arctic. However, there are substantial uncertainties in the cloud, sea ice, and radiation properties of the Arctic, which is an environment where almost all measurement systems and analyses are working at their limit of capability. Motivated by these sensitivities and uncertainties, an intense effort was jointly sponsored by the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the Department of Energy (DOE), and the Office of Naval Research (ONR) to design a research program to address these issues. This planning culminated in three closely coordinated projects: the Surface Heat Budget of the Arctic Ocean (SHEBA) (sponsored primarily by NSF and. ONR), the FIRE Arctic Clouds Experiment (sponsored primarily by NASA), and the Atmospheric Radiation Measurement (ARM) Program (sponsored by DOE). To guide the articulation of science issues for these projects related to Arctic clouds and radiation, *Curry et al.* [1996] prepared an extensive review of research on this topic prior to 1995.

This special section of the *Journal of Geophysical Research–Atmospheres* focuses on one of these coordinated programs: the FIRE (First International Satellite Cloud Climatology Project) (ISCCP) Regional Experiment) Arctic Clouds Experiment, which was conducted during April-July 1998. The main goal of the experiment was to examine the effects of clouds on radiation exchange among the surface, atmosphere, and space and to study how the cold underlying surface influences the evolution of boundary layer clouds. The strategy of the FIRE Arctic Clouds Experiment was to use research aircraft to obtain remote and in situ measurements of the properties of clouds, aerosols and the sea ice/ocean surface. The aircraft observations were made over surface-based observational sites in the Arctic Ocean by the SHEBA project [*Perovich et al.*, 1999] and at Barrow, Alaska, by the ARM Program [*Stamnes et al.*, 1999]. Observations collected during the field phase of the FIRE Arctic Clouds Experiment are being used to evaluate and improve climate model parameterizations of Arctic cloud and radiation processes, satellite remote sensing of cloud and surface characteristics, and understanding of cloud-radiation feedback processes. To facilitate collaboration and coordination among the three programs, the data sets are being archived in a form that will make them readily accessible worldwide. Further information on the FIRE Arctic Clouds Experiment and data archival can be found at http://eosweb.larc.nasa.gov/ACEDOCS/ ace_intro.html.

A complete overview of the FIRE Arctic Clouds Experiment was given by *Curry et al.* [2000], along with some preliminary research results. Some further results of this research are presented in this special section of *the Journal of Geophysical Research–Atmospheres*. A special section on the SHEBA project is scheduled to be published in the *Journal of Geophysical Research–Oceans* in 2001.

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2. Scientific Highlights of the Special Section

Consistent with the scientific objectives of the project, this description of the special section is grouped according to the following major research themes: cloud processes, aerosol processes, radiation processes, and remote sensing.

2.1. Clouds

The FIRE Arctic Clouds Experiment addressed substantial uncertainties that exist in our present understanding of Arctic clouds. These uncertainties arise from difficulties in observing these clouds and from the unusual cloud types that form in the polar regions. *Lawson et al.* [this issue] analyzed observations of clouds in the Arctic boundary layer using the cloud particle imager. *Pinto et al.* [this issue] described the preponderance of mixed phase clouds in the Arctic. *Rangno and Hobbs* [this issue] described airborne observations of ice crystals including an assessment of processes responsible for high ice particle concentrations. *Shupe et al.* [this issue] retrieved cloud water contents and hydrometeor sizes using a 35 GHz cloud radar. A comparison of the surface-based cloud observations (from cloud radar and lidar, and microwave and infrared radiometers) with in situ aircraft measurements is described by *Hobbs et al.* [this issue]. Observed interactions of boundary layer clouds with turbulence are analyzed by Q. Wang and S. Wang (unpublished data, 2001).

The observations of Arctic cloud properties are used in several modeling studies. *Girard and Curry* [this issue] and *Lohmann et al.* [this issue] conducted single-column model simulations of clouds, focusing on mixed phase clouds and cloud-aerosol interactions. Single-column simulations using explicit microphysics [*Khvorostyanov et al.*, this issue] and bulk microphysics [*Lohmann et al.*, this issue] highlighted the importance of and uncertainty in assumptions about ice nucleation processes. *Jiang et al.* [this issue] used large-eddy simulation with explicit microphysics to address the influence of entrainment of cloud condensation nuclei at cloud top on cloud microphysical and dynamical structure, radiative properties, and cloud evolution.

2.2. Radiation

The radiation environment of the Arctic is complicated considerably by the highly reflective and inhomogeneous snow/ice surface; temperature and humidity inversions, low temperatures and humidity, and high solar zenith angles. The unprecedented radiation measurements during this experiment are being used to advance our understanding of radiative transfer in this complex environment. *Benner et al.* [this issue] conducted radiative closure experiments for a variety of cases observed during late spring and summer. *Garrett et al.* [this issue] described for the first time direct observations of the asymmetry parameter in ice clouds.

The snow/ice surface is highly reflective, inhomogeneous, and with low thermal conductivity (when covered with snow). *Tschudi et al.* [this issue] analyzed airborne remote sensing of surface features, and the influence of variations in these surface features on sea ice albedo. *Brooks et al.* [this issue] analyzed surface radiation fluxes and albedo over the land surface near Barrow. *Curry et al.* [this issue] compared a variety of different snow/ice surface albedo parameterizations against SHEBA observations. *Wang et al.* [this issue (b)] simulated the radiative interactions between boundary layer clouds and the snow surface and examine the influence of this interaction on cloud and boundary layer development and evolution of snow surface temperature.

2.3. Aerosols

As pointed out by *Pinto et al.* [this issue], *Girard and Curry* [this issue], *Khvorostyanov et al.* [this issue], *Jiang et al.* [this issue], *Lohmann et al.* [this issue], and *Benner et al.* [this issue], the microphysical and optical properties of Arctic clouds are particularly susceptible to influence by atmospheric aerosol. *Yum and Hudson* [this issue] described airborne measurements of total aerosol particles and also cloud condensation nuclei. The measurements presented a picture whereby the Arctic aerosol originated primarily from long-range transport, with considerable depletion in the boundary layer owing to cloud scavenging. *Rogers et al.* [this issue] described ice-nucleating aerosol particles using a continuous flow diffusion chamber mounted on a research aircraft. Aerosol particle concentrations in the late winter/early spring Arctic atmosphere were remarkably low, which results in the frequent observation of supercooled liquid water at temperatures below -20°C. A source of ice-nucleating particles was observed sporadically near the surface, possibly associated with biological productivity in leads.

2.4. Remote Sensing

Satellite retrievals of cloud and surface characteristics are hampered by temperature and humidity inversions; low temperatures and low water vapor amounts; little visible, thermal, and microwave contrast between the clouds and the underlying surface; heterogeneity of the underlying surface; and the presence of complex cloud types (e.g., mixed phase clouds, thin multi-layered clouds).

Minnis et al. [this issue] addressed the difficulties of sensing polar clouds from visible and infrared satellite observations over the highly reflecting cold surface. Using AVHRR observations, *Doelling et al.* [this issue] examined top-of-atmosphere cloud radiative forcing and determined net cooling, even during summer. *Dong et al.* [this issue] evaluated the AVHRR retrievals of cloud properties against surface and aircraft measurements. *Platnick et al.* [this issue] described a new retrieval algorithm for cloud optical properties using a solar reflectance method. *Maslanik et al.* [this issue] used AVHRR products (cloud fraction and optical depth, all-sky skin temperature, and broadband surface albedo, surface radiation fluxes) to examine variability in the Arctic Ocean.

The FIRE Arctic Clouds Experiment provided an opportunity to test new remote sensing instruments, some of which will be flying on NASA EOS platforms. *Marchand et al.* [2000] used the airborne multiangle imaging spectroradiometer to determine and evaluate retrievals of cloud optical properties and cloud top geometry. *Wang et al.* [this issue] compared retrievals of ice cloud properties using the following instruments onboard the NASA ER-2: millimeter imaging radiometer, cloud lidar system, and MODIS airborne simulator.

3. Conclusions

The FIRE Arctic Clouds Experiment has provided a wealth of data that are being used to improve our understanding of cloud and radiative processes in the Arctic, the ability to remotely sense from satellite the Arctic clouds and snow/ice surface, and the parameterization of cloud and radiation processes in large-scale models.

When evaluated against the *Curry et al.* [1996] review of Arctic clouds and radiation, substantial progress has been made as a result of these field observations, particularly in the context of addressing specific science questions related to physical processes associated with Arctic clouds, radiative transfer, aerosols, and the atmospheric boundary layer. Continued analysis beyond the results given in this special issue will provide further insights into these processes. The basic data sets from these projects are now being archived, and the project investigators have made the initial evaluations of data quality for their observations.

To address the more complex issues associated with improving the parameterization of Arctic cloud and radiation processes in climate models and the determination of Arctic cloud and radiation characteristics from satellites requires assessment of the data in terms of internal consistency among the different measures of a single variable and different variables that are related, and the error bars on the measurements based on this analysis. Continued analysis is required particularly of the measurements of cloud microphysical properties from airborne and ground-based sensors and the surface radiation fluxes.

Application of the field observations obtained from these projects to evaluating and improving climate model parameterizations of cloud and radiation processes is being conducted largely under the auspices of the GEWEX (Global Energy and Water Experiment) Cloud Systems Studies (GCSS) of the World Climate Research Programme (WCRP). The GCSS Working Group 5 Polar Clouds (chair J. Curry; http://paos.colorado.edu/~curryja/wg5/home.html) was formed largely to exploit the enormous potential of data sets from the FIRE Arctic Clouds Experiment, SHEBA, and ARM to parameterizations of clouds, radiation, and atmospheric boundary layer processes in the polar regions. The GCSS Working Group on Polar Clouds leverages heavily the investment made by the U.S. funding agencies, since it involves a large group of international scientists and has adopted the modeling goals and other issues related to cloud and radiation processes that are articulated by the science plans for these projects. The GCSS Working Group on Polar Clouds is coordinating formal model intercomparisons and evaluations. In collaboration with the WCRP Arctic Climate System (ACSYS) Numerical Experimentation Group, a regional model intercomparison study has been initiated for the SHEBA year. Case studies are also being prepared using the aircraft data from the FIRE Arctic Clouds Experiment to evaluate and compare radiative transfer models, microphysical parameterizations, and boundary layer simulations and parameterizations.

Evaluation of satellite retrievals of Arctic cloud properties and radiation fluxes for the SHEBA year is being conducted, but the final assessment of these retrievals awaits the refined interpretation of the aircraft in situ measurements of cloud microphyhsical characteristics and their comparison with retrievals from the ground-based cloud radar and lidar. As a consequence, the evaluation of the four available satellite Arctic cloud climatologies for the SHEBA year has not yet been completed. This evaluation will provide a foundation for improved retrievals from forthcoming NASA satellite missions, including TERRA, AQUA, CLOUDSAT, and PICASSO-CENA.

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