Overview of North Slope of Alaska/Adjacent Arctic Ocean Science Issues

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The following material is based on presentations made during the ARM Science Team Meeting concerning the scientific issues to be addressed at the North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Atmospheric Radiation Measurement (ARM) Site and how these and complementary issues are being addressed in other national and international programs. The coordination of efforts to avoid duplication and maximize the benefit to all the parties interested and involved in the pursuit of Arctic Science is an important aspect of the planning process.

Scientific Objectives

The scientific objectives for the NSA/AAO site, which are to be achieved in cooperation with Surface Heat Budget of the Arctic Ocean (SHEBA) and the First ISCCP[(a)] Regional Experiment (FIRE) III, include the following items in order of priority:

- the radiative effects of mixed phase and ice phase clouds, aerosols, and cloud-aerosol mixtures
- description of basic cloud microphysical properties and how they are influenced by atmospheric thermodynamics and aerosol characteristics
- the relative importance of surface and advective fluxes of moisture in the formation of clouds
- the sensitivity of the boundary layer clouds to large-scale vertical motion
- interactions among turbulence, radiation, and cloud microphysical processes in the evolution of the cloudy atmospheric boundary layer
- the radiative effects of the horizontally inhomogeneous summertime stratocumulus clouds over the horizontally inhomogeneous, melting snow/sea ice surface

(a) International Satellite Cloud Climatology Project.

- response of surface albedo and ablation as a response to energy inputs
- light transmission beneath the various surface types and ice thicknesses
- relative amounts of anthropogenic versus biogenic, and local versus advected, aerosol
- physical and chemical processes affecting the conversion of sulfur-containing gases to sulfate particles
- the importance of leads in venting biogenic sulfur to the atmosphere
- disposition of shortwave radiation among surface absorption, internal absorption, and transmission in sea ice
- disposition of energy inputs between ponded and pond-free ice
- disposition of solar energy absorbed in leads
- impact of ice thickness distribution on absorbed solar radiation.

The Need for Spectrally Detailed Radiation Observations at the NSA

The identification of longwave radiative transfer problems that are unique to the NSA Cloud and Radiation Testbed (CART) site is most easily accomplished by examining the basic physics that control the radiative heating (cooling) rate. Since "cooling-to-space" dominates the tropospheric cooling, it is most appropriate to inspect the terms in the equation for the cooling to space, C_ν, written as

$$C_\nu(z) = \pi B_\nu(z)\frac{d\boldsymbol{T}_{f\nu}(z_t,z)}{dz} \qquad (1)$$

where B_ν is the Planck function at the temperature T at altitude z for the spectral interval from ν to ν+dν, and $\mathbf{T}_{f\nu}$ is the flux transmissivity. For discussion purposes $\mathbf{T}_{f\nu}$ may be written as

$$T_{f\nu} = e^{-\tau_\nu(z)} \qquad (2)$$

where $\tau_\nu(z)$ is the flux optical depth of the atmosphere above z defined as

$$\tau_\nu(z) = c\int_z^{z_t} k_\nu \rho_a dz' \qquad (3)$$

where k_ν is the monochromatic absorption coefficient

ρ_a is the density of the absorber

c is an optical depth dependent coefficient to account for the appropriate integration over zenith angle.

Thus, the most important quantities are the strength of absorption (k_ν), absorber amount (ρ_a), spectral position (ν), and temperature T. The vertical temperature gradient is also important, particularly for the strong inversions that often occur during the Arctic winter. However, those effects are not discussed herein.

For an isothermal, hydrostatic atmosphere in which the absorber density decreases exponentially with z, the altitude of maximum cooling to space occurs where the $\tau_\nu(z) = 1$ or at the surface if $\tau_\nu(0) \leq 1$. As temperature decreases, the Planck function at a given ν decreases, and the maximum of the Planck function shifts to smaller ν (Wien's displacement law).

With this brief introduction to longwave cooling, we now discuss the distribution of clear-sky radiative heating calculated by a detailed line-by-line radiative transfer model (LBLRTM; Clough 1992) using the McClatchey (1971) sub-Arctic summer and winter atmospheric profiles as input.

Note that there is little cooling in the troposphere below about 3 km between 0 and 400 cm^{-1} (strong H_2O absorption), 600 to 750 cm^{-1} (strong CO_2 absorption) and for $\nu \geq$ 1500 cm^{-1} (strong H_2O absorption and/or small B_ν). The maximum spectral cooling in the troposphere occurs in the pure rotational portion of the spectrum for $\nu <$ 400 cm^{-1} where as little as 0.1 cm precipitable water or less makes the atmosphere completely opaque. The spectral heating from 1000 to 1100 cm^{-1} in the upper troposphere and lower stratosphere is governed by the distribution of ozone and the temperature profile (this cannot be explained in terms of cooling to space). The spectral cooling from 600 to 750 cm^{-1} in the upper troposphere and lower stratosphere is governed by the spectral properties of CO_2.

Since the Southern Great Plains (SGP) and NSA CART sites will be primarily concerned with surface observations, it is important to examine the near-surface cooling in some detail. Summer cooling in the troposphere below about 3 km is controlled primarily by the atmospheric window region between about 750 and 1250 cm^{-1} because the optical depths in this region are small and the Planck function is relatively large. The magnitude of the cooling in this portion of the spectrum decreases between summer and winter because of the temperature decrease and the accompanying decrease in the water vapor burden. Note that the sub-Arctic cooling rates in this spectral region are typically lower than those for mid-latitudes because of the decreased water vapor burden (summer and winter) and decreased temperature (winter).

The maximum spectral cooling during the summer and winter occurs in the strong pure rotational spectrum of water vapor between about 600 and 250 cm^{-1}. As the water vapor burden decreases between summer and winter, the altitude of maximum cooling for a given wavelength decreases.

Note, however, that the spectral location of the maximum cooling for the near-surface region has shifted from the 750-1250 cm^{-1} region to the 400-600 cm^{-1} region. The altitude shift has occurred because the drying process has effectively opened the so-called dirty 25µm window to the surface. Furthermore, the maximum of the Planck function has shifted to longer wavelengths as well.

The opening of the window and the spectral shift of the Planck function are easily seen in the model spectral distribution of the vertically downwelling radiance at the surface shown in Figure 1. Regions of low radiance correspond to low spectral opacity (i.e., one sees partially to space) or to a small Planck function. The smooth, continuous portions of the curve show the envelope of the Planck function for local temperatures. It is easy to visually extrapolate these across the transparent portions of the spectrum and locate the window regions.

Conditions at the planned CART site at Barrow, Alaska, differ on occasions from the sub-Arctic atmosphere, as is illustrated in Figure 2. For the Barrow sounding of 28 February 1986 used in the calculations, the 400-600 cm^{-1} window has opened substantially, thereby allowing the identification of spectral features to $\nu < 400$ cm^{-1}. Such conditions are extremely rare for mid-latitude sites.

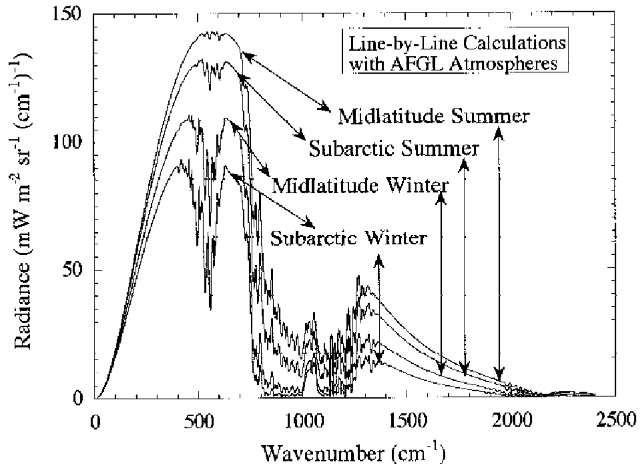

Figure 1. Model calculated clear-sky downwelling radiance at the surface for different model atmospheres. Note that the calculations have been smoothed to 20 cm^{-1} resolution for presentation purposes.

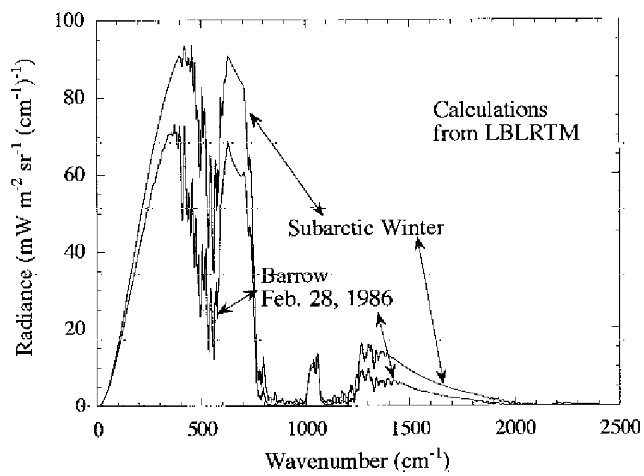

Figure 2. As in Figure 1, but for extreme Barrow winter conditions relative to those for the Sub-arctic winter model atmosphere.

Those interested in the surface energy budget should note that the portion of the spectrum for 400-600 cm^{-1} which is not filled in Figure 2 represents about 45% of the unfilled portion of the spectrum from 800 to 1200 cm^{-1}. Thus, as the sky becomes overcast, about 45% of the increased energy that the surface receives will come from the dirty window.

Therefore, the absorption parameterizations in this region are important for both heating rate and surface energy budget considerations.

Absorption and emission in the 400 to 600 cm^{-1} portion of the spectrum is dominated by strong water vapor lines. The parameterization of the absorption of this portion of the spectrum requires not only the specification of the strengths of the local lines, but also the shapes of the lines away from the line centers. Clough et al. (1989) have devoted a considerable effort at defining the parameterization of the effects of water vapor line wings—the so-called water vapor continuum—across the entire spectrum from the laboratory measurements of Burch (1981). The data reported by Clough et al. include temperatures only as low as 296K for both the self- and foreign-broadened portions of the continuum. Furthermore, the continuum coefficients in this region are large and are in a region with a substantial spectral gradient. Laboratory measurement errors in this portion of the spectrum translate directly to errors in the magnitude and altitude of the cooling rate.

The observations being taken at the SGP CART site with the Atmospherically Emitted Radiance Interferometer (AERI) cover the portion of the spectrum from about 550 to 3000 cm^{-1}. Thus, this device cannot see the entire 400-600 cm^{-1} dirty window. Furthermore, comparisons of AERI observations with line-by-line calculations for cool, dry conditions at the SGP and for conditions during the Spectral Radiance Experiment (SPECTRE; Ellingson et al. 1993) show the poorest agreement in the region from 550 to 600 cm^{-1} of any portion sensed by the AERI. This result does not give us great confidence in our ability to calculate fluxes and cooling rates in this portion of the spectrum.

In summary, the lower temperatures and water vapor burdens typical of sub-Arctic and Arctic conditions open the 400-600 cm^{-1} window region of the spectrum to study that is infrequently available in mid-latitudes. This portion of the spectrum contributes strongly to the cooling of the middle-troposphere at middle and tropical latitudes, and it is a significant contributor to the near-surface cooling and surface radiation budget of the Arctic. Results from SPECTRE and ARM indicate that models have significant deficiencies in this portion of the spectrum. Furthermore, the current design of the AERI instrument being used at the SGP CART site prohibits this instrument from seeing the entire dirty window.

In view of the fact that spectrally detailed observations at $\nu < 500\ cm^{-1}$ are required to validate and improve models of water vapor absorption, it appears that ARM can make a substantial contribution to improving the situation by extending the range of sensitivity of instrumentation planned for the NSA site to about 350 cm^{-1}. It should be noted, however, that along with such spectral observations must come *accurate* observations of the vertical profile of water vapor. Such observations appear to be possible only with precision frost-point hygrometers or with Raman lidar.

Cloud-Radiation Feedback in the Arctic Ocean

The cloud-radiation feedback mechanism may be described for the Arctic Ocean as follows. A perturbation to the Arctic Ocean radiation balance may arise from increased greenhouse gas concentrations and/or increasing amounts of aerosol. A perturbation in the surface radiation balance of the sea ice results in a change in sea ice characteristics (i.e., ice thickness and areal distribution, surface temperature, and surface albedo). These changes in sea ice characteristics, particularly the surface temperature and fraction of open water, will modify fluxes of radiation and surface sensible and latent heat, which will modify the atmospheric temperature, humidity, and dynamics. Modifications to the atmospheric thermodynamic and dynamic structure will modify cloud properties (e.g., cloud fraction, cloud optical depth), which will in turn modify the radiative fluxes.

The cloud-radiation feedbacks over the Arctic Ocean have been explored by conducting a series of modeling experiments using a one-dimensional coupled sea ice-atmosphere model (Curry and Ebert 1992). Three cloud feedbacks (cloud distribution, cloud water content, and cloud dropsize) are examined individually. The individual cloud-radiation feedbacks in the Arctic are determined to be of opposite sign to those generally determined globally; i.e., the surface is warmed by increasing cloud fraction, increasing condensed water content, and decreasing particle size. This reversal of the sign of the cloud-radiation feedbacks in the Arctic arises from the presence of the highly reflecting sea ice, the absence of solar radiation for a large portion of the year, low temperatures and water vapor amounts, low cloud water contents, and the presence of temperature inversions. A multivariate sensitivity analysis is done for the cloud feedbacks in combination. For an atmospheric warming perturbation of +1°C and the associated water vapor and cloud water content feedbacks (positive), a decrease in total cloud fraction of 10% would be sufficient to counter the warming at the surface and give a net zero surface temperature change.

Arctic Cloud Properties Determined from Broadband Radiometric Measurements

At Barrow, Alaska, completely overcast skies exist frequently throughout the year. The most usual cloud types under such conditions (as determined from surface observations precluding observations of upper layer clouds) are low stratus and fog. The National Oceanic and Atmospheric/Administration (NOAA/CMDL) station in Barrow is equipped with Eppley pyranometers that measure downwelling solar irradiance (broadband) as well as shortwave albedo. These measurements can be used in conjunction with a radiative transfer model to estimate cloud optical depth by varying the optical depth in the model until computed downward irradiance agrees with the measured value (Leontieva and Stamnes 1994a). For the period from April through August 1988 at Barrow, 68 cases of complete overcast conditions were identified when hourly averaged solar irradiances at the surface (downward and upward), as well as cloud observations and sounding data, were available. From these data, the seasonal behavior of the cloud optical depth was determined.

The Potential for Determining Cloud Properties from the MFRSR Instrument

A new instrument deployed in the ARM program is the Multi-Filter Rotating Shadowband Radiometer (MFRSR). This instrument provides spectrally resolved diffuse and direct irradiances at six wavelengths: 415, 500, 610, 665, 862, and 940 nm with nominal 10-nm bandwidth.

A simulation of the atmospheric transmission behavior of these channels reveals that the 862-nm channel would be particularly useful for determining cloud optical depth (by a procedure similar to that described for the broadband measurements above) because this channel is less affected by atmospheric aerosols than the channels at shorter wavelengths. As in the case of broadband measurements, knowledge of the surface albedo is required to accurately estimate the optical depth (especially for high surface albedo), but the narrowband channel at 862 nm is expected to give more accurate optical depth estimates because, unlike the broadband measurements, it is not affected by water vapor absorption.

Determination of cloud droplet effective radius is difficult from transmission measurements using only one channel because a change in droplet size leads to changes in absorption and forward scattering characteristics that tend to compensate each other so that the transmission is left almost unchanged. However, simulations show that cloud droplet equivalent radius could be inferred from bispectral transmittance measurements (using one channel without liquid water absorption: 862 nm, and one with: 2.2 microns).

Thus, an additional MFRSR channel at 2.2 microns could, in combination with the existing 862-nm channel, yield valuable information on droplet size. This suggests that it would be useful to explore the feasibility of including such a channel in the MFRSR instrument (Leontieva and Stamnes[a]).

Radiative Transfer in Sea Ice

Arctic sea ice plays an important role in the global climate system. The mass balance of sea ice in the Arctic is controlled primarily by the absorption of solar energy, and radiative transfer plays a crucial role in the exchange of energy between atmosphere, sea ice, and ocean. Radiation absorbed within the ice may change its internal structure and thereby modify its optical properties. These changes lead to an alteration of the radiative energy transmitted into the ocean and reflected back to the atmosphere, which in

(a) Leontieva, E. N., and K. Stamnes. Remotely sensed measurements of cloud optical depth using a ground-based multi-filter rotation shadowband radiometer in the Arctic. Submitted to *Polar Record*.

turn affects the stratification and circulation of the atmosphere and ocean. To understand these interactions between the atmosphere, sea ice, and ocean, we must investigate the factors that determine the disposition of solar radiation within this coupled system, namely the fraction of solar energy absorbed by the ice, transmitted to the ocean, and reflected back to the atmosphere.

To study the radiative transfer process in the coupled atmosphere-sea ice-ocean system, a model has been developed that provides an accurate, self-consistent solution of the radiative transfer equation for the entire system satisfying appropriate boundary and layer interface conditions, including the reflection and refraction at the air-ice and air-water interface (Jin and Stamnes 1994). The input parameters required by the model are observable physical properties, such as profiles of atmospheric pressure, temperature, gaseous absorbers, cloud (liquid/ice) particle size and concentration, as well as profiles of temperature, density, and salinity in the ice.

Modeling results indicate that sea ice has a significant impact on the partitioning of solar radiation between the atmosphere, sea ice, and ocean (Jin et al., accepted). These results show that

- absorption increases with increasing ice density everywhere in the coupled system except in the atmosphere, but decreases with increasing salinity
- most of the energy absorbed by the sea ice is deposited in the top 10 cm of the ice
- for clear skies over bare ice, 50% of the total solar energy disposed of by the entire system is absorbed by the uppermost 10 cm of the ice, but clouds and snow on the ice significantly reduce this fraction
- beneath 50 cm in the ice only visible radiation is left
- as the sea ice thickness increases, the absorption increases in the ice, but decreases in the ocean and the entire system
- for sea ice thickness greater than about 70 cm, the total absorption (by the entire system) remains constant.

Finally, we note that scattering by ice inclusions, especially air bubbles, plays a crucial role in the solar energy partitioning within the entire system. Thus, the air volume fraction in the top layer of the ice seems to be an important parameter.

Arctic Regional Climate System Model

Because radiative transfer affects the distribution of diabatic heating, Arctic cloud-radiative interactions will affect the atmospheric circulation and climate regionally (i.e., in the Arctic and sub-Arctic) and quite possibly in areas equatorward of the Arctic. One-dimensional cloud-radiative formulations that are developed and validated with field measurements can be implemented in three-dimensional models in order to assess the regional and global impacts. One such vehicle for regional climate assessments is the Arctic Regional Climate System Model (ARCSYM), which has recently been implemented over an Alaskan domain. The atmospheric component of ARCSYM is a version of the NCAR RegCM2 (Regional Climate Model, Version 2). Details of the formulation are given by Giorgi et al. (1993), although recent changes include the implementation of a more efficient semi-explicit time-integration technique and, of more relevance to ARM, the radiative transfer scheme of the NCAR Community Climate Model (Version 2 CCM2). ARCSYM also includes a dynamic/thermodynamic sea ice model over the ocean and a land surface (soil/vegetation) package known as BATS.1E (Biosphere-Atmosphere Transfer Scheme, Version 1E) (Dickinson et al. 1992). Experiments are planned with alternative land surface packages, e. g., the Canadian CLASS (Cross-chain Loran Atmospheric Sounding System) formulation, designed more specifically for climates in which snow and ice play major roles.

Recent simulations of the Alaskan domain with ARCSYM (Lynch et al.[a]) span monthly periods during summer and winter. The resolution is 63 km and the domain includes Alaska, the Bering region, the Gulf of Alaska, and the southern Chucki/Beaufort Sea. An annual cycle simulation

(a) Lynch, A. H., W. L. Chapman, J. E. Walsh, and G. Weller. Development of a regional model of the western Arctic. Submitted to *J. Clim.*

of the Alaskan North Slope at 21 km resolution is now in progress. In all cases, the model is forced laterally by time-varying observational analyses from the European Center for Medium-Range Weather Forecasting.

The early results show warm biases of several °C in the simulated surface air temperatures. During the winter, the warm bias appears to be attributable to excessive downward fluxes of longwave radiation, which in turn seem to be associated with biases in the simulated cloud properties. During the summer, the simulated cloud-radiative interactions appear to bias the model toward relatively low evaporation rates.

It is clear that more accurate representations of the cloud-radiative interactions will be required if the surface temperatures are to be simulated with sufficient accuracy to permit meaningful model experiments with changes in snow cover, permafrost, and trace gas releases. A high priority is the implementation of high-latitude modifications to the model's radiative parameterizations or, alternatively, the implementation of cloud-radiative formulations developed in conjunction with the ARM NSA/AAO program.

National/International Interconnections and Synergisms

The extension of the NSA ARM effort to the AAO will occur in conjunction with SHEBA, an eighteen-month field experiment based at a manned drifting sea ice camp in the perennial pack ice of the Arctic Ocean. This $20M+ experiment is led by the National Science Foundation as part of its Arctic System Science (ARCSS) program and by the Office of Naval Research. The SHEBA field program is scheduled to begin in April 1997. The SHEBA observational effort will emphasize the relationship between radiative fluxes (especially as affected by surface- and cloud-radiative interactions), the mass balance of sea ice, and the storage and retrieval of energy and salt in the mixed layer of the ocean. As described by Zak et al. (1994), SHEBA and the ARM NSA efforts are sufficiently complementary that the scheduling and siting have been designed to maximize the synergism. In effect, SHEBA permits the extension of ARM/NSA to the ice-covered waters of the Arctic Ocean.

Another ARCSS effort that is of direct relevance to ARM/NSA is the Arctic trace gas "Flux Study" of the Land-Atmosphere-Ice-Interactions (LAII) component of ARCSS. The Flux Study consists of 1) measuring fluxes of trace gases (CO_2, methane) to the atmosphere and of water-transported materials to the ocean, 2) determining the primary controls of the fluxes, and 3) scaling and synthesizing to the regional scale (Alaskan North Slope and beyond). The primary field sites are in the Kuparuk drainage basin of the Alaskan North Slope. The ultimate goal of this study is to assess the feedbacks between climatic change and the release of greenhouse gases from Arctic terrestrial regions. The LAII Flux Study interfaces with the ARM/NSA effort both geographically (through field measurements in adjacent regions of the North Slope) and scientifically (through the link between surface radiative fluxes, soil/vegetation temperature and wetness, and rates of trace gas flux from/to terrestrial ecosystems). The "scaling and synthesis" component of the LAII Flux Study uses the ARCSYM, which is now being run over a domain that encompasses both the LAII Flux Study area and the proposed ARM/NSA CART array.

The Arctic Climate System Study (ACSYS) is a new initiative of the World Climate Research Program. ACSYS is expected to span a period of approximately ten years. ACSYS emphasizes the climate component of the arctic system through its focus on the Arctic Ocean, its sea ice cover, and its energy and water budgets. A topic of particular emphasis in ACSYS is the cloud-radiative interaction that is crucial to a quantitative description and understanding of the surface energy budget in the Arctic. Both ARM/NSA and SHEBA are potential U.S. contributions to ACSYS. The findings of ARM and SHEBA are expected to directly affect the ACSYS-coordinated ice-ocean modeling, which will likely be the key to an assessment of the stability of arctic sea ice in a changing climate.

Phase III of the First ISCCP[(a)] Regional Experiment (FIRE III) is a NASA-led effort planned to take place in the Arctic in conjunction with SHEBA and NSA/AAO. The emphasis of FIRE is to provide in situ data, currently lacking, on cloud radiative properties to validate and improve satellite retrievals and GCM performance in the Arctic. The use of instrumented aircraft is expected to play a major role in

(a) International Satellite Cloud Climatology Project.

FIRE. Coordination between the FIRE III, ARM, and SHEBA programs in the Arctic will be facilitated by the presence of several members of the FIRE III Science Team on the SHEBA Science Working Group, the ARM Science Team Executive Committee, and the ARM NSA/AAO Advisory Panel.

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