North Slope of Alaska and Adjacent Arctic Ocean Cloud and Radiation Testbed: Science and Siting Strategies

B. D. Zak
Sandia National Laboratories
Albuquerque, New Mexico

K. Stamnes
University of Alaska
Fairbanks, Alaska

Introduction

This paper serves as a summary of the current thinking regarding the development of the Atmospheric Radiation Measurement (ARM) Program's North Slope of Alaska and adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) site. Ellingson et al. (this volume) delve more deeply into the relevant high latitude science.

Rationale for a High Latitude CART Site

The broad rationale for a high latitude (HL) CART site can be summarized as follows:

- Fundamentally different atmospheric and surface physics are important at high latitudes.

If conditions did not differ too much over the entire earth, one could conceive of a situation in which one CART site at some convenient location would be adequate to achieve ARM objectives. However, such is not the case. At high latitudes, it is sufficiently cold that ice is the predominant form of condensed water much of the year both in the air (ice clouds, diamond dust, and snow) and on the surface. Ice and snow scatter transmit and absorb visible and IR radiation much differently than does liquid water.

In addition, at high latitudes, the annual average radiative energy input is negative—that is, more energy is radiated to space than is received from the sun. The difference is made up by energy transported from lower latitudes by the atmosphere and the oceans. Thus, high latitudes serve as the "heat sink" for the global climate engine.

Furthermore, because it is so cold, there is little water vapor in the atmosphere during much of the year, and that fact changes the nature of radiant heat flows (see Ellingson et al., this volume). More specifically, the so-called dirty window in the 16-28 micrometer wavelength region plays a strong role in surface and near-surface radiative cooling at high latitudes, but not at mid and low latitudes, where the window is essentially closed. The lower temperatures at high latitudes also shift more of the radiant energy distribution (Planck function) into the spectral region of the dirty window.

The surface energy balance is affected in other ways by the fact that the dirty window is largely open at high latitudes. A calculation for an actual winter case at Barrow showed that, as the sky became overcast, 45% of the increased energy received by the surface came from the dirty window region.

In addition, during the part of the year that sunlight is scarce or absent, very strong, persistent surface temperature inversions form, which further modify atmospheric processes, especially cloud formation, evolution and dissipation.

- High latitudes strongly influence global climate in a number of ways.

Major pumps for the global ocean currents are located at high latitudes (thermohaline circulation). Results from coupled ocean-atmosphere general circulation models (GCM) suggest that the operation of these pumps, which depend upon HL radiative and other processes, will be seriously affected by the ongoing changes in the composition of the atmosphere (Manabe et al. 1993). Ocean currents are known to have profound climatic influence. The influence of the “Atlantic Conveyor” on the habitability of Northern Europe is a case in point. Changes in the strength and distribution of ocean currents are a mechanism for global propagation of the influence of high latitude climate change. Although the ocean currents themselves are not within the charter of ARM, the changes in radiative transfer phenomena, which may cause the ocean current changes through effects on the HL current pumps, definitely are.

Snow/ice albedo feedback influences regional and even global radiant energy flows. Snow and ice have high reflectivity (albedo) in the visible portion of the electromagnetic spectrum, that portion where most of the energy emitted by the sun resides. When the snow and/or ice melts, the albedo falls precipitously. As a result, much more of the incident energy from the sun is absorbed at the surface, and a smaller fraction is reflected back into space. The surface tends to heat further, causing faster melting and the absorption of yet more energy. Thus, there is positive feedback. The secondary aspects of this feedback, however, which influence its net effect are, at best, poorly understood. Earlier melting, for instance, probably results in increased cloud formation, which may mitigate to some extent the snow/ice albedo feedback because clouds have high albedo as well.

Large quantities of carbon are tied up in the Arctic tundra, which covers a deep layer of permafrost. Regional warming is believed to be causing both a warming of the surface and a deepening of the surface (active) layer which melts and re-freezes annually. It is hypothesized that these physical effects will cause the net release of carbon in the form of greenhouse gases (methane and carbon dioxide) from the tundra. In fact, there is evidence that over the last few decades, the Arctic tundra has changed from a net sink to a net source of atmospheric carbon(a) This phenomenon, too, represents a positive feedback.

- Interpretation of satellite remote sensing data to obtain the distribution and character of high latitude clouds, snow and sea ice is an important, but poorly-solved problem.

Satellite data have proved invaluable for both global climate monitoring and climate process studies, but the use of satellite data to analyze high latitude processes is impeded by an array of interpretation problems (Jeffries and Dean 1994).

Primary Scientific Focus: High Latitude Phenomena

The primary objective of the NSA/AAO is to elucidate high latitude processes in such a way that their mathematical description can be accurately and cost-effectively incorporated into GCMs. Taken together, the models and model parameterizations simulate the operation of the relevant HL feedback mechanisms, and feedbacks dominate climate.

HL Atmospheric Radiative Transfer

The melting of snow and ice cover results in a sharp change in surface albedo, and this change triggers a whole family of feedback mechanisms. The initiation and rate of melting is most strongly influenced by downwelling longwave radiation (LWR), which at high latitudes is dominated by the extent and character of cloud cover and influenced to a lesser extent by the water vapor profile (see Ellingson et al., this volume). Hence, clouds play a critical role in nearly all HL feedback mechanisms as a modulator of the timing and rate of change of surface albedo.

In addition, at high latitudes, cloud cover tends to be stratified, nearly continuous, and persistent and, hence, plays an even larger role in influencing energy transfer than in most other locales. Thus, accurate modeling of radiative energy flows with clouds present is critical.

HL Cloud Formation, Evolution and Dissipation

For climate modeling purposes, modeling of cloud formation, evolution and dissipation processes is just as important as modeling radiative transport in the presence of clouds. At high latitudes, however, the problem of modeling cloud behavior is complicated considerably by the fact that ice clouds predominate for much of the year.

(a) W. Oechel, 1994, personal communication.

Cloud processes are, in general, poorly understood, a fact that is particularly true of processes relating to the formation and behavior of ice clouds.

Behavior of HL Surface Radiative Characteristics

Surface albedo has a pronounced impact on radiative transfer through the atmosphere under both clear and cloudy sky conditions (Jin et al., accepted), but high surface albedo has a striking impact on the effects of clouds. Because the albedo of snow is typically greater than the albedo of cloud, clouds over snow-covered surfaces may decrease the fraction of shortwave radiation reflected to space (Tsay et al. 1989), which is just the reverse of their effect over lower albedo surfaces. So when the snow melts, this cloud feedback may change sign. The need is to accurately model/parameterize the behavior of high latitude surface radiative characteristics for inclusion in GCMs.

HL Aerosol Direct and Indirect Radiative Effects

Contrary to intuition, the Arctic atmosphere is polluted, especially in late winter. The basic reason is that, although the total magnitude of the Arctic pollutant sources is modest, pollutant removal from the Arctic atmosphere by natural processes at this time of the year is very slow. This removal-resistant pollution leads to significant direct perturbation of the radiation budget (Shaw et al. 1993). Aerosol influences cloud condensation, evolution and evaporation, and, hence, cloud optical properties (Twomey et al. 1984).

Validation of HL Satellite Remote Sensing Algorithm

Satellite remote sensing plays a crucial role in understanding energy flows over large areas (even areas the size of CART sites) and in extending what is learned at CART sites to the earth as a whole. Furthermore, satellite remote sensing depends critically upon an accurate understanding of atmospheric radiative transfer. Hence, improvement of HL satellite remote sensing is a relevant and important scientific objective of the NSA/AAO CART site. Snow and ice-covered surfaces greatly complicate the interpretation of satellite remote sensing data. Because clouds, snow, and ice all have high albedo, it is particularly difficult to distinguish between them.

Secondary Scientific Focus: Other Accessible Relevant Phenomena

The NSA/AAO CART site offers attractive opportunities to study certain phenomena which are believed to be important to the achievement of ARM goals, but which are not specific to high latitudes. These phenomena form a secondary focus for the NSA/AAO.

Generic Marine Stratus

On average, marine stratus covers 18% of the earth’s surface (DOE 1991). Since it occurs mostly over open water, it greatly increases the albedo of most of the regions of the earth it covers. The Locale Recommendation Team (LRT) recognized the importance of this fact in recommending that an eastern ocean margin (marine stratus) locale be developed as one of five primary CART sites.

Now that anticipated resource constraints have limited ARM to three primary CART sites, it would be helpful to the achievement of ARM objectives if the issues associated with marine stratus were addressed to the extent possible at the NSA/AAO. Because stratus is common over the NSA/AAO throughout the year, it is well positioned to address these issues.

Ice Phase Clouds

Ice phase clouds are important globally, not just regionally. However, at lower latitudes, ice phase clouds occur almost exclusively at high altitudes, where they are much less accessible to researchers. The frequency with which winter Arctic stratus clouds occur in the NSA/AAO locale makes ice clouds both climatologically important and relatively easy to study.

High Heat and Water Vapor Fluxes

The LRT felt that the high latent and sensible heat fluxes and their resulting effects in the Gulf Stream merited special study. The Gulf Stream was the fifth recommended primary CART site. The NSA/AAO does not exhibit such high latent and sensible heat fluxes over the entire region; however, in winter, leads and polynyas locally do exhibit extraordinarily high fluxes. Thus, especially in connection with lee polynyas, which occur conveniently close to shore, the NSA/AAO offers an attractive opportunity for studying these phenomena.

Transition Zones

Sharp transitions offer special challenges to all models, especially spectral model[a]. The LRT had suggested that a secondary CART site be selected to address these challenges (DOE 1991). Because it encompasses the Arctic coast, the NSA/AAO is appropriate for this task.

Critical Questions

The above primary and secondary issues both directly and indirectly relate to our ability to answer the following critical questions (as well as most other important questions that concern Arctic climate).

- Will the perennial Arctic ice pack survive the ongoing changes in atmospheric composition?

The magnitude of the predicted surface temperature changes in the Arctic raises a real question as to whether the perennial Arctic ice pack would remain perennial if the predicted changes were in fact realized. Disappearance of the ice pack for even part of the year would have a major secondary impact on the climate, at least of the northern hemisphere.

- What will be the net effect of atmospheric changes on the strength of the high latitude global ocean circulation pumps?

Any significant impact on the ice pack would likely have major resulting influence on the global thermohaline circulation, and hence, on global climate.

- Why do current GCMs fail to get observed temperature trends over the Arctic Ocean right?

Current GCMs predict that the greenhouse warming will be greatest over the Arctic Ocean and smaller over the Arctic land. Just the reverse has been observed over the last few decades. One explanation may be simply that GCM vertical resolution near the surface is inadequate, but that is by no means certain. What is certain is that HL processes are poorly simulated in the present generation of GCMs.

Siting Strategy: Phased Implementation

Because of currently anticipated resource constraints, the NSA/AAO CART site needs to be implemented in a phased manner. The phasing described here seeks to take maximum advantage of opportunities for interagency synergism, as well as to make optimum use of work already done or in progress for earlier CART sites. The strategy is designed so that each phase is a building block for successive phases, but also so that each phase produces results of independent value.

Phase I: Radiative Transfer - the Perennial Arctic Ice Pack versus Coastal Environments

We propose to focus initially on radiative transfer rather than cloud behavior experiments because the instrumentation requirements are more modest. By focusing initially on radiative transfer experiments, one can begin acquiring one class of needed data at a lesser cost while building towards the capability of acquiring the more expensive class of data as well. The other element of the strategy recognizes the need to accurately model and measure HL radiative processes over both HL land and HL sea, as well as the transition region in between.

The proposal is to simultaneously acquire radiative transfer experiment data (in which both radiative energy flows and the surface and atmospheric characteristics which influence

---

(a) W. Budd. 1994. Personal communication. Comments on the Gibbs phenomenon made at the High Latitude Ocean Atmosphere-ICE Interactions Workshop, 26-30 July, University of Alaska, Fairbanks.

them are measured) within the perennial Arctic ice pack as part of the SHEBA (Surface Heat Budget of the Arctic Ocean) experiment and in the coastal environment of Barrow. An interagency effort led by the National Science Foundation and the Office of Naval Research, SHEBA is focusing on climate-relevant processes in the perennial Arctic ice pack over a full annual cycle, beginning in spring 1997.

Phase II: Radiative Transfer, HL Coastal versus HL Inland Environments

Once SHEBA ends, the ARM instrumentation used in SHEBA would be moved to a site approximately 100 km inland from Barrow in the vicinity of the village of Atqasuk (Figure 1). This inland site is expected to have a significantly more continental character than Barrow (colder and dryer in winter, warmer in summer). Between phases I and II, a transect of radiometric experimental data will have been acquired which, taken together, should contribute significantly to the needed understanding of radiative transfer in the Arctic as a whole.

Phase III: Cloud Formation, Evolution and Dissipation

In phase III, the focus of the NSA/AAO CART site would be broadened to include HL cloud behavior. Cloud behavior experiments must take into account the fact that clouds move. To understand how clouds evolve in time, it is necessary to have multiple instrumentation sets spread over a large area. Such a strategy will involve the extended CART site: additional boundary facilities on the west near Wainwright, and perhaps on the east somewhere between Cape Simpson and Nuiqsut; augmented automated weather stations over the enclosed area; and very likely, some number of data buoys deployed offshore.

Candidate observations and instrumentation for the NSA/AAO are listed in Table 1.

Status and Plans

In order to begin Phase I in concert with SHEBA during spring 1997, preliminary instrumentation must be deployed before the onset of the 1996-97 winter. Otherwise, the instrumentation deployed to SHEBA will have no Arctic experience. That would be highly imprudent in light of the difficulties of implementing any necessary “fixes” out in the ice pack. Working backwards, to meet the schedule, one needs to do the basic (non-Arctic) instrumentation testing during spring to summer 1996. One also finds that overall site planning, environmental assessment, permit-supporting studies, and preliminary engineering must be well underway now. They are.

References

Chapman, W. L., and J. E. Walsh. 1993. Recent Variations of Sea Ice and Air Temperature in High Latitudes. *Bull. Am. Met. Soc.* **74**:33.

Jeffries, M. O., and K. G. Dean. 1994. *3rd Circumpolar Symposium on Remote Sensing of Arctic Environments, Programs and Abstracts*. University of Alaska, Fairbanks.

Jin, Z., W. F. Weeks, S.-C. Tsay, and K. Stamnes. The effect of sea ice on the solar energy budget in the atmosphere-sea ice-ocean system: A model study. Accepted for publication in *J. Geophys. Res.*

Kahl, J. D., et al. 1993. “Absence of Evidence for Greenhouse Warming over the Arctic Ocean during the Past Forty Years.” *Nature* **361**:335.

Manabe, S., T. Delworth, and R. J. Stouffer. 1993. Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. *J. Clim.* **6**.

Shaw, G. E., K. Stamnes, and Y.-X. Hu. 1993. Arctic Haze: Perturbation to the radiation field. *Meteorol. Atmos. Phys.* **51**:227.

Twomey, S. A., M. Piepgrass, and T. L. Wolfe. 1984. An assessment of the impact of pollution on global cloud albedo. *Tellus* **36B**:356.

Tsay, S.-C., K. Stamnes, and K. Jayaweera. 1989. Radiative Energy Budget in the Cloudy and Hazy Arctic. *J. Atmos. Sci.* **46**:1002.

U.S. Department of Energy (DOE). 1991. *Locale Analysis Report*. Washington, D.C.

Walsh, J. E. 1993. The Elusive Arctic Warming. *Nature* **361**:300.

Table 1. NSA/AAO Candidate Observations and Instrumentation.

Observations	Instrumentation
surface radiative fluxes: broad-band spectral direct diffuse	solar and IR radiometers IR thermometer(s) rotating shadowband radiometer total, diffuse, direct radiometers sun tracking photometer extended spectral range AERI
cloud properties: location, structure, phase, sky coverage, optical depth, emissivity	elastic scatter lidar millimeter radar whole sky imager rotating shadowband radiometer 10 micron zenith radiometer
whole atmosphere: water vapor, liquid water, temperature, wind speed and direction profiles, column densities	microwave radiometer rawinsonde extended spectral range AERI 915- and/or 449-MHz wind profiler with RASS
aerosols: optical depth, vertical profiles, near-surface character	sun tracking photometer rotating shadowband radiometer elastic scatter lidar aerosol collection and sizing multi-wavelength nephelometer aethelometer
boundary layer structure: temperature, wind, humidity and turbulence profiles	915- and/or 449-MHz wind profiler with RASS rawinsonde multi-level instrumented tower
surface meteorology: wind speed and direction, temperature, pressure, humidity, precip rate and integrated precip	surface met station w/tower
surface characterization: surface temperature, moisture, snow depth, albedo (BDRF), heat and water vapor fluxes, snow cover, sea ice cover	IR thermometer(s) thermistor array moisture sensors snow depth gauge array albedo/BDRF sensor set eddy correlation system marine radar

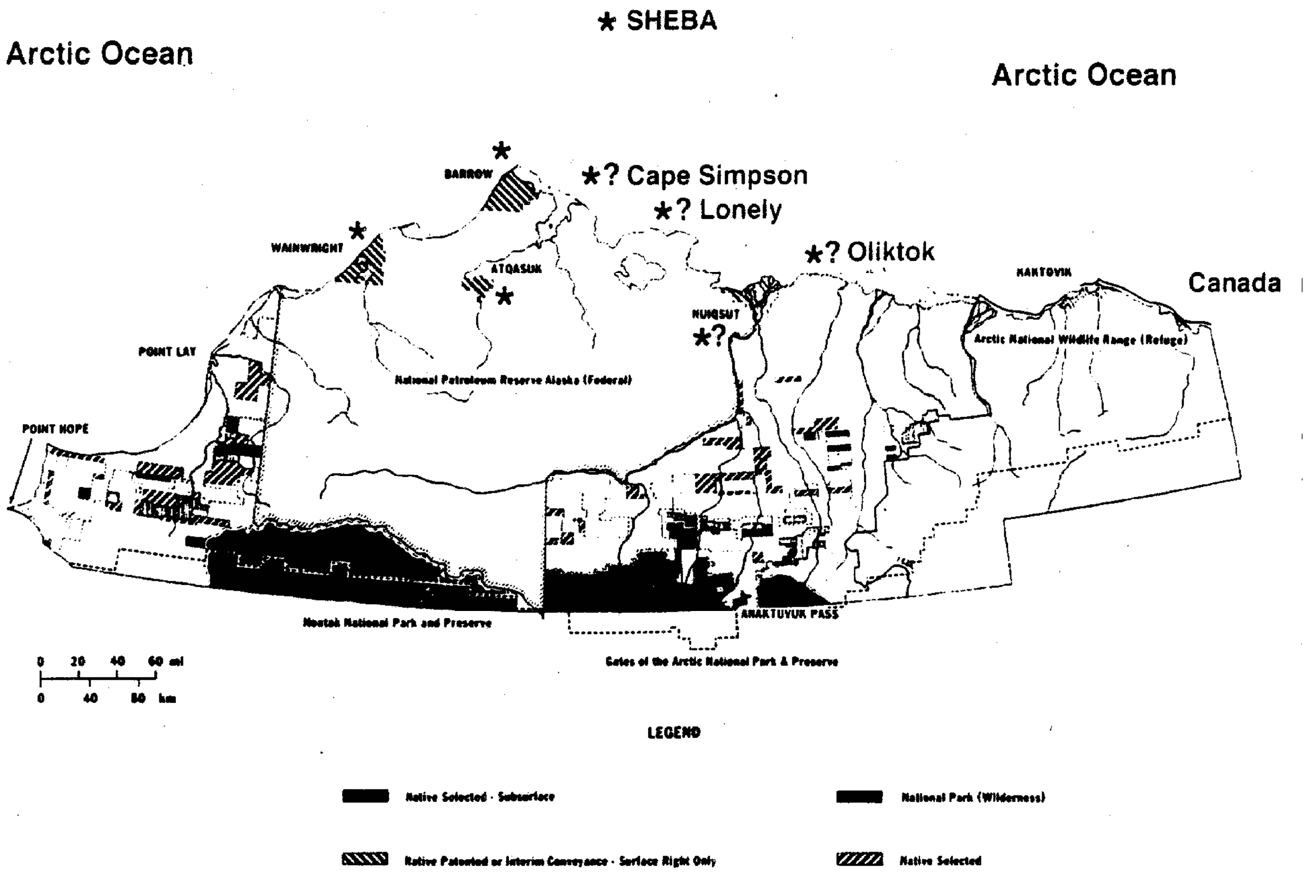

Figure 1. North slope of Alaska map. Asterisks mark proposed major NSA/AAO CART instrumentation locations. Asterisks with question marks indicate candidates for the eastern boundary location.