Documenting, Understanding, and Predicting the Aggregate Surface Radiation Fluxes for SHEBA

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(formerly NAG5-4903)

Final Report
University of Wisconsin

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1. Purpose

This document serves as a final report for NASA grant NAG5-8625 to the University of Wisconsin-Madison (UW). The report covers work done at Boston University for the first two years of the project (as NAG5-4903) and the third and final year of the project at the University of Wisconsin (NAG5-8625). In 1999 the third year's funding and tasks were transferred to UW where the Principal Investigator (J. Key) is now stationed. A no-cost extension period of the grant ended on June 15, 2001.

This is a group project with the University of Colorado (CU) as the lead institution, where Judith Curry is the Principal Investigator. The overall project is jointly funded by NASA and NSF. The progress reported herein is specific to Boston University and the University of Wisconsin.

2. Objectives

The overall project addresses issues related to the cloud-radiation feedback and the ice-albedo feedback through a coordinated effort that utilizes aircraft and satellite observations in conjunction with surface-based observations from SHEBA. The plan was for field measurements to be used to develop an empirical and theoretical understanding of radiative transfer in the Arctic, and to develop improved models for surface radiation properties and surface radiation fluxes.

Our specific objectives were to:

1. document the variations of surface characteristics, surface radiation fluxes and cloud characteristics on a horizontal scale of approximately $(60 \text{ km})^2$ using research aircraft

2. use observations and models to develop an understanding of how the surface radiation flux components vary with surface and cloud characteristics

3. develop an empirical and theoretical understanding of 3-D radiative transfer in the Arctic and use this understanding to develop an improved parameterization of surface radiative characteristics and a 1-D radiative transfer model for the Arctic that can be used to determine surface radiative fluxes and the radiation feedbacks in climate models.

4. devise and test strategies to determine the aggregate-scale surface radiative flux components for each surface type during periods when aircraft data is unavailable, using only surface and satellite observations in conjunction with models

5. create an integrated dataset of the aggregate-scale surface characteristics, surface flux components, and cloud characteristics for use by the SHEBA community in Phase III investigations

At Boston University and the University of Wisconsin, J. Key and two graduate students (one funded by NASA and one by NSF) addressed all of these to some degree, but are focussed on #2, #4, and #5. Accomplishments are described in the next section.

3. SUMMARY OF ACCOMPLISHMENTS

Our major accomplishments are:

1. Methods for estimating cloud, surface, and radiation characteristics from satellite have been developed, refined, and applied to the SHEBA period resulting in a year-long data set that can be used for meteorological analysis and modeling studies.
2. Theoretical and empirical studies regarding the effects of clouds on surface temperature and albedo provided for the development of methods to estimate these parameters from satellite.
3. The effects of horizontal variability of cloud and surface properties on aggregate-area surface radiative fluxes were quantified and methods to correct for biases in climate models were developed.

These are summarized below. More detailed information and additional accomplishments are given in the journal publications listed in the section 4.

3.1. Estimating Cloud and Surface Properties from AVHRR Data

Considerable effort has been devoted to satellite retrievals of surface, cloud, and radiation characteristics. Existing algorithms for cloud detection, cloud properties, and radiative fluxes have been revised (at least once) as a result of validation data from the SHEBA field experiment. New algorithms for estimating cloudy sky surface temperature and albedo were developed, as described in the next section. Using these algorithms, cloud and surface properties have been estimated from AVHRR data for the SHEBA year and for the area shown in Figure 1. Five kilometer data from the AVHRR Polar Pathfinder project were used in the analyses. The retrieval algorithms of the Cloud and Surface Parameter Retrieval system were applied (CASPR). CASPR is available for general use at http://stratus.ssec.wisc.edu/caspr/caspr.html.

Sample results are shown in Figure 2. The area covered by the AVHRR subsets extends from central Alaska to the North Pole, and from Banks Island to the Laptev Sea. Figure 3 shows a time series of some of the parameters averaged over a 55 x 55 km region centered on the SHEBA ship. Results shown in these figures are only a sample of all that are computed, which includes:

- Surface temperature, clear and all-sky
- Broadband albedo, clear and all-sky
- Cloud particle effective radius
- Cloud optical depth
- Cloud particle phase
- Cloud mask
- Cloud top temperature
- Cloud top pressure
- Precipitable water
- Downwelling shortwave radiation at the surface
- Downwelling longwave radiation at the surface
- Upwelling shortwave radiation at the surface
- Upwelling longwave radiation at the surface

- Downwelling shortwave radiation at the top of the atmosphere
- Upwelling shortwave radiation at the top of the atmosphere
- Upwelling longwave radiation at the top of the atmosphere
- Cloud fraction

Once-daily and mean monthly results are available for the SHEBA period. The data set has been made available to the scientific community, as described in the *Data Products* section.

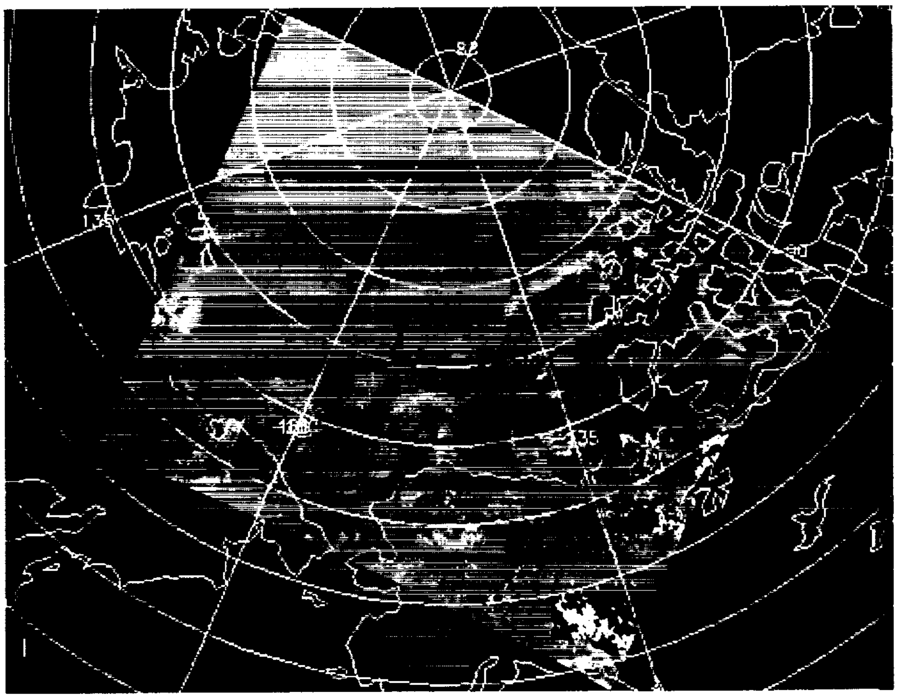


Fig. 1. The study area. The curve is the drift track of SHEBA ship during the year-long experiment. It started at (75.70°N, 144.10°W) on Oct. 2, 1997 and ended at (78.20°N, 160.70°W) on Aug. 3,1998.

Surface observations from the SHEBA ship site have proven useful in validating the satellite retrievals. Data from temperature probes, radiometers, and surface remote sensing instruments have been used to validate retrievals of surface albedo, surface temperature, and surface radiative fluxes. Figure 4 shows a comparison of all-sky surface albedo and downwelling longwave radiation as measured by instruments at the SHEBA camp and as estimated from AVHRR data. The largest differences are, in general, related to cloud cover because the satellite estimates are averages over a relatively large area and the surface observations are point measurements. Overall the agreement is good.

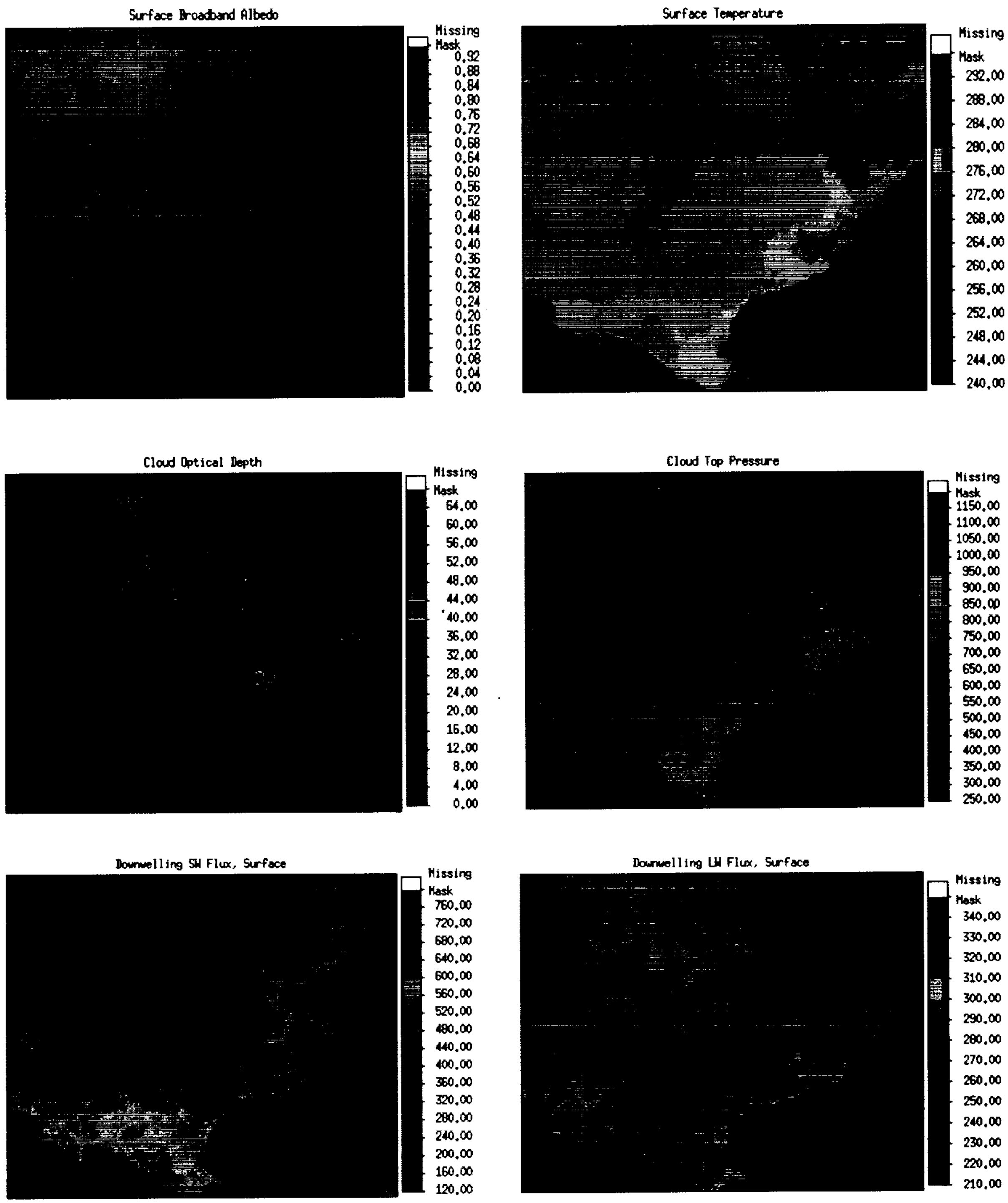


Fig. 2. Mean monthly satellite-derived surface, cloud, and radiative properties for July 1998 over the western Arctic Ocean, approximately centered on the SHEBA ship area. These and other parameters were estimated from AVHRR data.

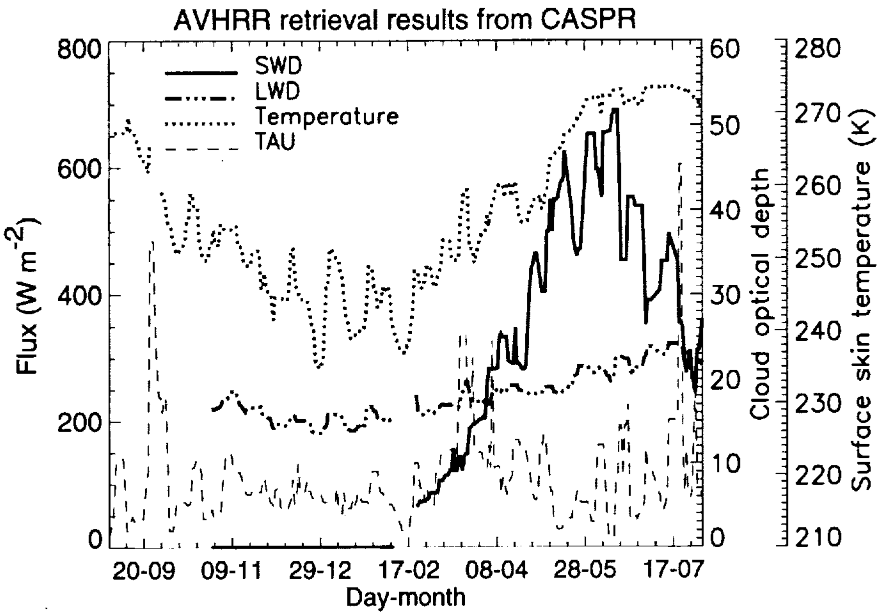
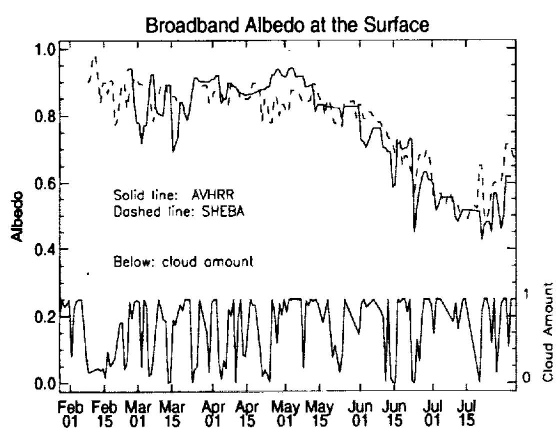


Fig. 3. Time series of surface temperature, cloud visible optical depth, downwelling shortwave (SWD) and longwave (LWD) radiation at the surface as estimated from satellite data for the SHEBA year. Results shown are averages over a 55 x 55 km area centered on the ship location.



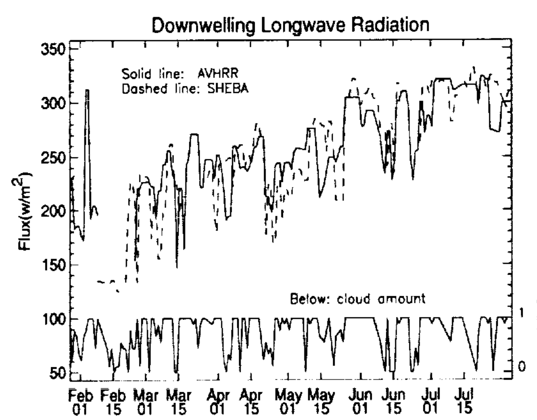


Fig. 4. Comparison satellite-derived and surface observations of all-sky surface albedo (left) and downwelling longwave radiation at the surface (right) during SHEBA. Results shown are averages over a 55 x 55 km area centered on the ship location.

3.2. The Influence of Clouds on Surface Temperature and Albedo

In the Arctic cloud cover is extensive at all times of the year, with monthly means ranging from 50-80%. Retrievals of the clear sky surface albedo temperature are therefore of limited utility for climate studies.

3.2.1. Cloudy Sky Surface Temperature

Is it possible to estimate the surface temperature under cloud cover from thermal satellite data? Previous studies have used nighttime data to examine the relationship between clouds and surface temperature. Here a thermodynamic model is used to extend the analyses to daytime conditions. The thermodynamic model includes radiative transfer, sea ice/snow energy balance, and atmospheric turbulence components.

Figure 5 illustrates the effect of clouds on the surface temperature of sea ice. The results shown were determined with SCCM, a single column version of NCAR's CCM3 climate model. All other surface and atmospheric properties were held constant while cloud optical depth was varied. While the effect of clouds shown in the figure is significant, the observed effect is actually larger than that modeled with SCCM.

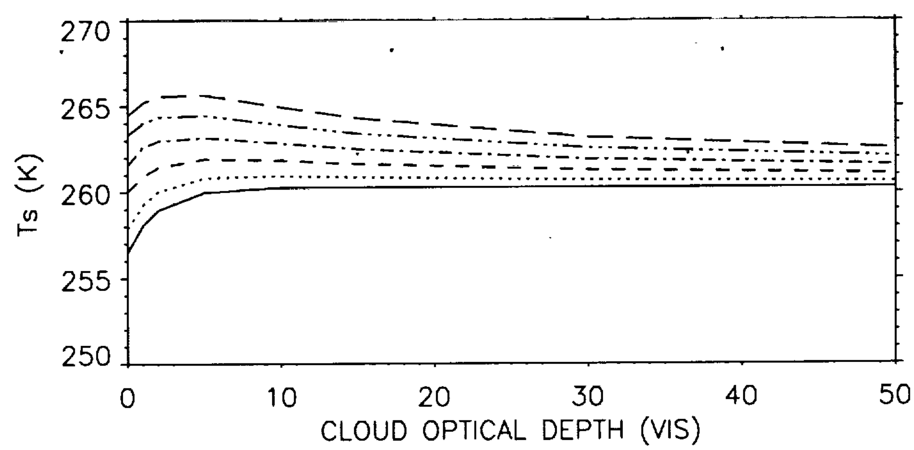


Fig. 5. Modeled (SCCM) surface temperature of sea ice as a function of visible cloud optical depth. Lines correspond to different solar zenith angles from 90 degrees (bottom, solid line) to 40 degrees (top) in increments of 10 degrees. For this simulation the ice thickness is 2 m, snow depth is 20 cm, and the wind speed is 3 m/s.

Data from SHEBA demonstrated that transitions between clear and overcast conditions in winter and at low solar elevations correspond to rapid changes in absorbed radiation, wind speed, and surface temperature, but during the melt season changes in wind speed and absorbed radiation have little effect on surface temperature. Sensitivity analyses done with SCCM showed that in the absence of lateral heat advection, surface temperature appears most sensitive to ice thickness and least sensitive to wind speed, and that the most pronounced changes in surface temperature occur when ice is thin and snow depth is shallow.

An adjustment to satellite-derived clear sky temperatures was developed with multiple regression models that also incorporate wind speed and solar zenith angle. Figure 6 illustrates the effect of the correction for SHEBA data. The adjustment varies by season, as does the cloud radiative effect. Tests with two data sets showed that the cloudy sky surface temperature can be estimated with an uncertainty of 1-3°C, depending on the time of year. Given that the difference between the clear and cloudy sky temperature is typically on the order of 6°C, employing the method in satellite retrievals will provide a more spatially complete and physically accurate assessment of the sea ice surface temperature. However, the adjustments were observed to be overestimates in some cases and underestimates in others. Over time periods of a few days to one week, these errors should have a mean near zero. We therefore recommend that the empirical models be used in the formulation of multi-day averages of surface temperature.

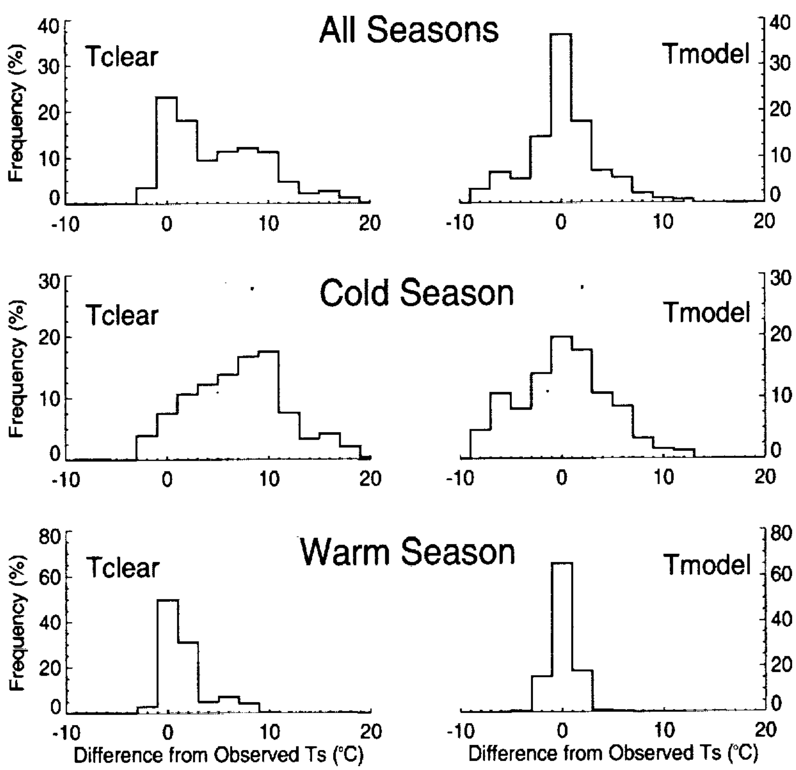


Fig. 6. Frequency distribution of differences between SHEBA ground-based measurements of surface temperatures under cloudy conditions and satellite estimates of the clear sky value (Tclear) and the adjusted clear sky value from the regression models (Tmodel).

3.2.2. Cloudy Sky Surface Albedo

The effect of clouds on the surface albedo, especially that of snow and ice, is significant and should be considered in satellite retrievals. We have shown theoretically and empirically that the snow/ice albedo is on the average 4-6% (absolute) higher under cloud cover than for clear skies, with a range of slightly less than 0 to approximately 15%. A method for retrieving the clear sky broadband albedo of snow/ice from the advanced very high resolution radiometer (AVHRR) was developed, as was an adjustment for cloud effects. The adjustment is an empirical correction to the clear sky albedo that is a function of cloud optical depth and solar zenith angle. It is independent of sensor type and can also be used with non-satellite data sets.

An application of the algorithm to data from SHEBA demonstrated that clear and cloudy sky snow surface albedo can be obtained from space with an uncertainty of approximately 7% absolute. Figure 7 shows the frequency of differences between the AVHRR retrievals and the SHEBA ship measurements with and without the cloudy sky adjustment for the entire time series. The bias (AVHRR minus surface observation) and root-mean-square errors (RMS) are also given. The bias without the adjustment for cloud cover is 0.065; with the adjustment it is 0.022. The difference between them (0.043) agrees well with theoretical and observed effects of cloud cover. While it may be sufficient to adjust a monthly clear sky surface albedo climatology for clouds by incorporating the mean cloud effect of approximately 5%, adjustments for cloud optical depth should be performed with instantaneous retrievals.

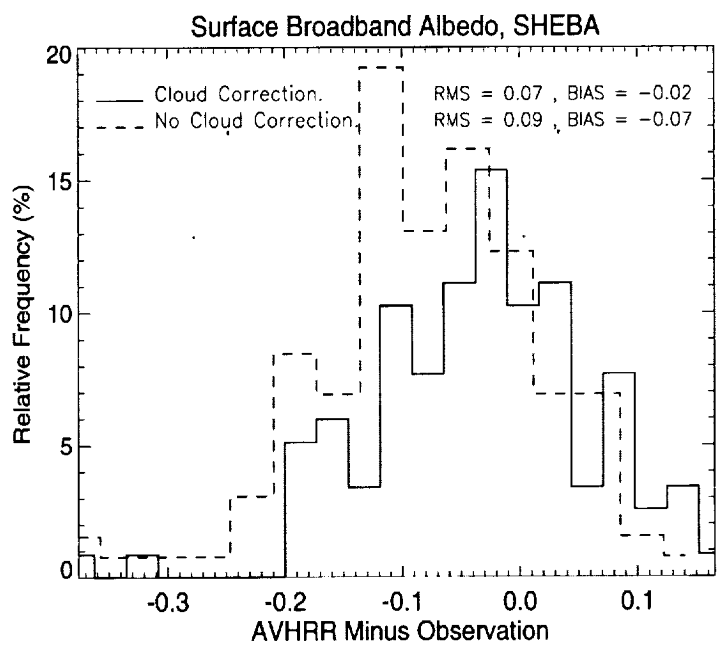


Fig. 7. Relative frequency of differences between the AVHRR retrievals of surface albedo and the SHEBA ship measurements with (solid) and without (dashed) the cloudy sky adjustment. The bias and root-mean-square errors are also given.

3.3. The Effects of Horizontal Variability on the Surface Radiation Budget

One of the primary goals of our project is to assess the effect of 3-dimensional (3D) surface and cloud structure on large-area aggregate fluxes and satellite retrievals of cloud and surface properties. Figure 8 illustrates the theoretical effect of horizontal variability in cloud optical depth on downwelling visible fluxes as a function of solar zenith angle. The simulations employ the 3D radiative transfer model SHDOM, written by F. Evans (Univ. of Colorado), a Co-PI on the project. The plot gives average optical depths over a hypothetical cell (e.g., a GCM grid cell), with varying optical depths but identical geometrical thickness at every point in the cell. Clearly the assumption of a horizontal, uniform cloud layer, as often used in GCMs, can result in significant errors in fluxes. Errors in top-of-atmosphere radiances are expected to be much larger.

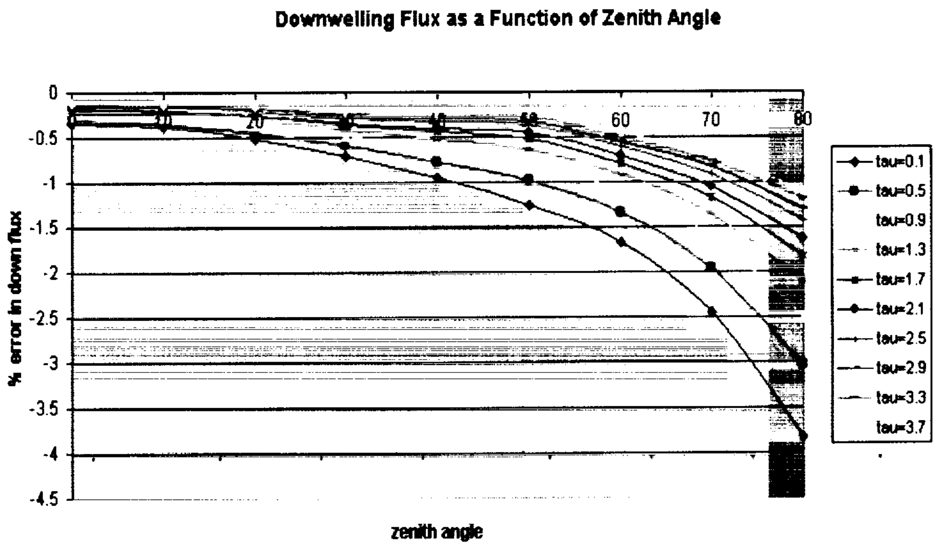


Fig. 8. Differences ("error") in downwelling visible (narrow band) flux at the surface computed using one-dimensional and three-dimensional radiative transfer models over a range of cloud optical depths (tau). The plot shows the error as a function of solar zenith angle.

A geostatistical analysis of satellite retrievals over the SHEBA region was done to assess the nature of the spatial and temporal variability of surface, cloud, and radiation characteristics. Downwelling shortwave and longwave fluxes at the surface exhibited temporal correlation over a long time period (about 180 days), but cloud optical depth and cloud fraction had nearly no correlation over the time period. In the spatial semivariogram (not shown), radiative fluxes, surface skin temperature, and surface broadband albedo showed persistence with distance. They have two ranges (the distance over which variance changes significantly) corresponding to two different scales. The first is about 150 km, the second is over 2000 km. This is reasonable because the semivariogram was calculated along a line of longitude and therefore reflects the large-scale systematic latitudinal distribution of the climate. The shorter distance scale reflects the mesoscale climatic variation. Cloud particle effective radius and optical depth have a range of about 400 km, which means that within that distance the cloud properties are correlated.

Given the spatial variability of surface and cloud parameters and, for some, their nonlinear relationship with radiative fluxes, one would expect that using mean surface and cloud properties within a climate or ice model grid cell to compute radiative fluxes could result in substantial errors. This was investigated by computing average radiative fluxes for a hypothetical model grid cell as (a) the mean of fluxes calculated for every 5 km pixel, and (b) the result of using area average mean surface and cloud properties in the flux calculation. The difference between them is termed the "flux bias". The annual average shortwave flux bias was 9.46% while the mean longwave flux bias was -7.04%. The bias can be as large as 22% for both the downwelling shortwave and longwave fluxes.

An empirical analysis of the relationship between the biases and geophysical parameters was performed, and regression equations were developed to estimate the downwelling shortwave (SWD) and longwave (LWD) flux biases under all weather conditions. The equations can be applied to fluxes calculated using area-average surface and cloud properties. Figure 9 shows the frequency of flux biases before and after the adjustment during SHEBA. The simple regression approach to correcting the fluxes for the biases that result from horizontal variability was found to reduce the average biases to nearly zero and to reduce the standard deviations by 50%. The correction can be easily implemented in numerical models.

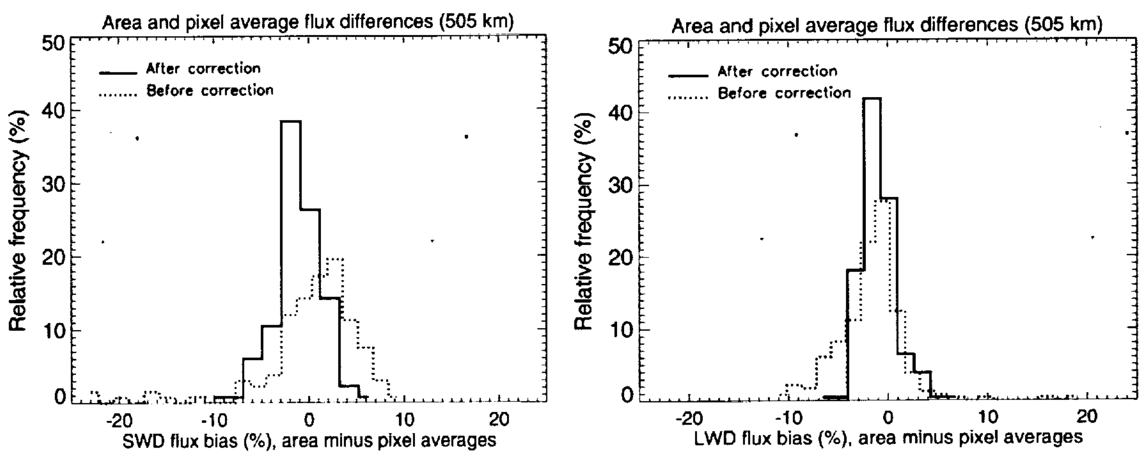


Fig. 9. Relative frequency of downwelling shortwave (SWD, left) and longwave (LWD, right) flux biases between the area- average and pixel-average fluxes before and after correction. Values shown are for the period September 1997 through August 1998.

4. PUBLICATIONS SUPPORTED IN WHOLE OR IN PART BY NAG5-4903

<u>Journal Papers</u>:

Gultepe, I., G. A. Isaac, J. Key, T. Uttal, J. Intrieri, D.O'C Starr, and K. B. Strawbridge, 2000. Dynamical and microphysical characteristics of Arctic clouds using integrated observations collected over SHEBA during the April 1998 FIRE.ACE flights of the Canadian Convair, *J. Geophys. Res.*, submitted (May 2000).

Wang, X. and J. Key, 2001, Aggregate-area radiative flux biases, *Annals Glaciol.*, 34, accepted (June 2001).

Key, J., X. Wang, J. Stroeve, C. Fowler, 2000, Estimating the cloudy sky albedo of sea ice and snow from space, *J. Geophys. Res.*, in press.

Schweiger, A., R. Lindsay, J. Francis, J. Key, J. Intrieri, and M. Shupe, 2000, Validation of TOVS Path-P data during SHEBA, *J. Geophys. Res.*, in press.

Wang, X. and J. Key, 2000, Spatial variability of the sea ice radiation budget and its effect on aggregate area fluxes, *Annals Glaciol.*, in press.

Maslanik, J., J. Key, C. Fowler, T. Nyguyen, X. Wang, 2000, Spatial and temporal variability of surface and cloud properties from satellite data during FIRE-ACE. *J. Geophys. Res.*, in press.

Stroeve, J., J. Box, C. Fowler, T. Haran, J. Key, and J. Maslanik, 2000, Intercomparison between in situ and AVHRR Polar Pathfinder-derived surface albedo over Greenland, *Rem. Sens. Environ.*, 75, 360-374.

Key, J. and J. Intrieri, 2000, Cloud particle phase determination with the AVHRR, *J. Appl. Meteorol.*, 36(10), 1797-1805.

Schweiger, A.J., R. Lindsay, J. Key, and J. Francis, 1999. On the status of arctic clouds in multiyear satellite data sets, *Geophys. Res. Lett.*, 26(13), 1845-1848.

<u>Conference Proceedings Papers</u>:

Wang, X. and J. Key, 2001, Aggregate-area Radiative Fluxes, Proceedings of the Sixth Conference on Polar Meteorology and Oceanography, American Meteorological Society, San Diego, 14-18 May 2001, 293-296.

Key, J. and A.M. Wong, 1999. Estimating the cloudy sky surface temperature of sea ice with optical satellite data. *IGARSS'99 Proceedings*, Hamburg, Germany, 28 June - 2 July.

Key, J., D. Slayback, C. Xu, and A. Schweiger, 1999. New climatologies of polar clouds and radiation based on the ISCCP "D" products. *Proceedings of the Fourth Conference on Polar Meteorology and Oceanography*, American Meteorological Society, Dallas, TX, January 10-15, 227-232.

Wong, A.M., J.R. Key, and R.S. Stone, 1999. The effect of clouds on surface temperature and implications for remote sensing at high latitudes. *Proceedings of the Fourth Conference on Polar Meteorology and Oceanography*, American Meteorological Society, Dallas, TX, January 10-15, 294-299.

Curry, J.A., J. Pinto, J. Maslanik, and J. Key, 1999, Overview of C-130 research aircraft observations obtained during SHEBA/FIRE. *Proceedings of the Fourth Conference on Polar Meteorology and Oceanography*, American Meteorological Society, Dallas, TX, January 10-15.

Theses:

Wong, A.M., 2000, Estimating the Cloudy-sky Surface Temperature of Sea Ice: Implications for Satellite Remote Sensing, Master's thesis, Department of Geography, Boston University, 57 pp.

5. Data Products

A data set consisting of satellite retrievals of cloud properties and radiative fluxes over the western Arctic Ocean - described earlier in this report - was delivered to the Joint Office for Science Support (JOSS) data system at the National Center for Atmospheric Research. JOSS manages the archive for all SHEBA data sets. Products in this data set include daily and monthly parameter images over the whole SHEBA region, and daily and monthly means of each parameter for the entire SHEBA region and a for a smaller area around the ship site. The data and read routines can be obtained from JOSS or from http://stratus.ssec.wisc.edu/products/sheba_caspr.

6. Inventions

There were no inventions.