Project 1920

POLAR EXCHANGE AT THE SEA SURFACE (POLES)

A report to Dr. D.A. Rothrock
University of Washington

Final Report

University of Wisconsin

Subcontract 922244

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1. Purpose of this Document

This document is a final report for the University of Wisconsin (UW[1]) portion of the project "Polar Exchange at the Sea Surface (POLES)". The subcontract number is 922244. Over the lifetime of the POLES execution phase J. Key was funded at the University of Colorado-Boulder (1991-1995), Boston University (1995-1999), and the University of Wisconsin-Madison (1999-2001). Even though progress reports have been regularly submitted to the University of Washington from 1991-2000, this report will cover major accomplishments and publications over the entire 1991-2001 period. However, detailed descriptions of the research are not included. They can be found in previous reports and journal publications.

2. Personnel

The primary contributor to the POLES project at the University of Colorado (CU), Boston University (BU), and the University of Wisconsin has been J. Key, who was funded at 30-50% FTE at CU and approximately 15% FTE at BU. As he is a federal employee in Madison, he was not funded at UW. At CU POLES funded R. Silcox as a M.A. student and partially funded A. Schweiger as a Ph.D. student. The project funded two graduate students at BU: Yong Liu from 1996-97 and Chuanyu Xu from 1998-1999. Both were Ph.D. students. Yong Liu left the program in 1997 to attend to family matters elsewhere. Chuanyu Xu continued POLES work through December 1999 but decided not to transfer to the University of Wisconsin. An undergraduate student, Alan Chan, also contributed to POLES but was unfunded. His undergraduate thesis dealt with the development of a new wave cyclone climatology. When J. Key left BU, Prof. Mark Friedl was nominated and approved to serve as PI on POLES for the September - December 1999 period. At UW one research assistant, Bill Bellon, was supported at the 50% FTE level.

3. Summary of Accomplishments

The POLES-CU/BU/UW effort addressed the energy and moisture balance of the polar atmosphere, in particular the radiation budget, cloud properties, and, most recently, heat and moisture advection. These research areas encompass the first two POLES objectives given in the January 1997 POLES report to NASA:

- Determine the heat and moisture balance of the polar atmosphere, including the surface heat balance, radiation to space, and the transport of heat and moisture into the polar atmosphere from mid-latitudes.
- Determine more accurately the amounts of polar clouds and their effect on the surface and top-of-atmosphere radiative balance.

The focus of our research since 1991 has been the development and validation of algorithms for estimating surface, cloud, and radiation properties in the polar regions from space. The instruments of choice were the Advanced Very High Resolution Radiometer (AVHRR) on-board

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1. In this report, "UW" refers to the University of Wisconsin-Madison, not the University of Washington!

NOAA polar-orbiting satellites and, in the last two years, the Moderate-resolution Imaging Spectroradiometer (MODIS) on the Terra platform. We have made considerable progress in our ability to estimate surface and cloud properties with polar-orbiting imagers. In the process we have worked with a variety of data sets and instruments, making some discoveries in the area of polar climate along the way. Our **major** accomplishments over the past ten years are briefly described in the following paragraphs. Important findings are indicated in *italics*.

Development of algorithms for the retrieval of cloud and surface properties, including surface and top-of-atmosphere radiative fluxes, using the AVHRR. Algorithms have been developed for the retrieval of: surface temperature, surface albedo, cloud amount, particle thermodynamic phase, particle effective radius, optical depth, and radiative fluxes. Examples of these parameters during the SHEBA year are given in Figures 1 and 2.

A method of estimating the cloudy sky albedo of snow based on the clear sky albedo and cloud optical depth was developed. *It was found that the mean difference between clear and cloudy sky snow albedos is approximately 5%*, with a range of 0 - 15% (Figure 3).

We modified our AVHRR ice surface temperature (IST) retrieval algorithm for use with MODIS. The MODIS Snow and Ice product (MOD29) is based in part on this algorithm.

Validation of satellite algorithms. 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.

Radiative fluxes and cloud forcing from the ISCCP data. Polar-specific changes in the revised cloud product of the International Satellite Cloud Climatology Project (ISCCP) are in part a result of our work in polar cloud detection. We have examined the new ISCCP D2 cloud data and found it to be an improvement over the older C2 product, although comparisons with the North Pole drifting station observations (A. Schweiger) indicate that cloud amounts still have a large uncertainty. Cloud amount differences range from 10% to nearly 25%, where the largest differences are during the spring and fall in the Arctic and during the austral summer in the Antarctic. D2 cloud amounts are greater than C2 amounts in all months. Over the snow-free land and ice-free oceans differences are small.

Radiative fluxes were calculated from the ISCCP C2 (monthly) and D1 (3-hourly) data sets. The C2 flux data set, generated in 1994, has been referenced extensively by the polar science community. The newer D1 flux data set has been used to show that Arctic clouds have a cooling effect at the surface for a brief period during summer, but *clouds over the Antarctic continent warm the surface at all times of the year*, at least in the monthly, area-average mean (Figure 5). This is in contrast to the global effect of clouds, which is one of cooling.

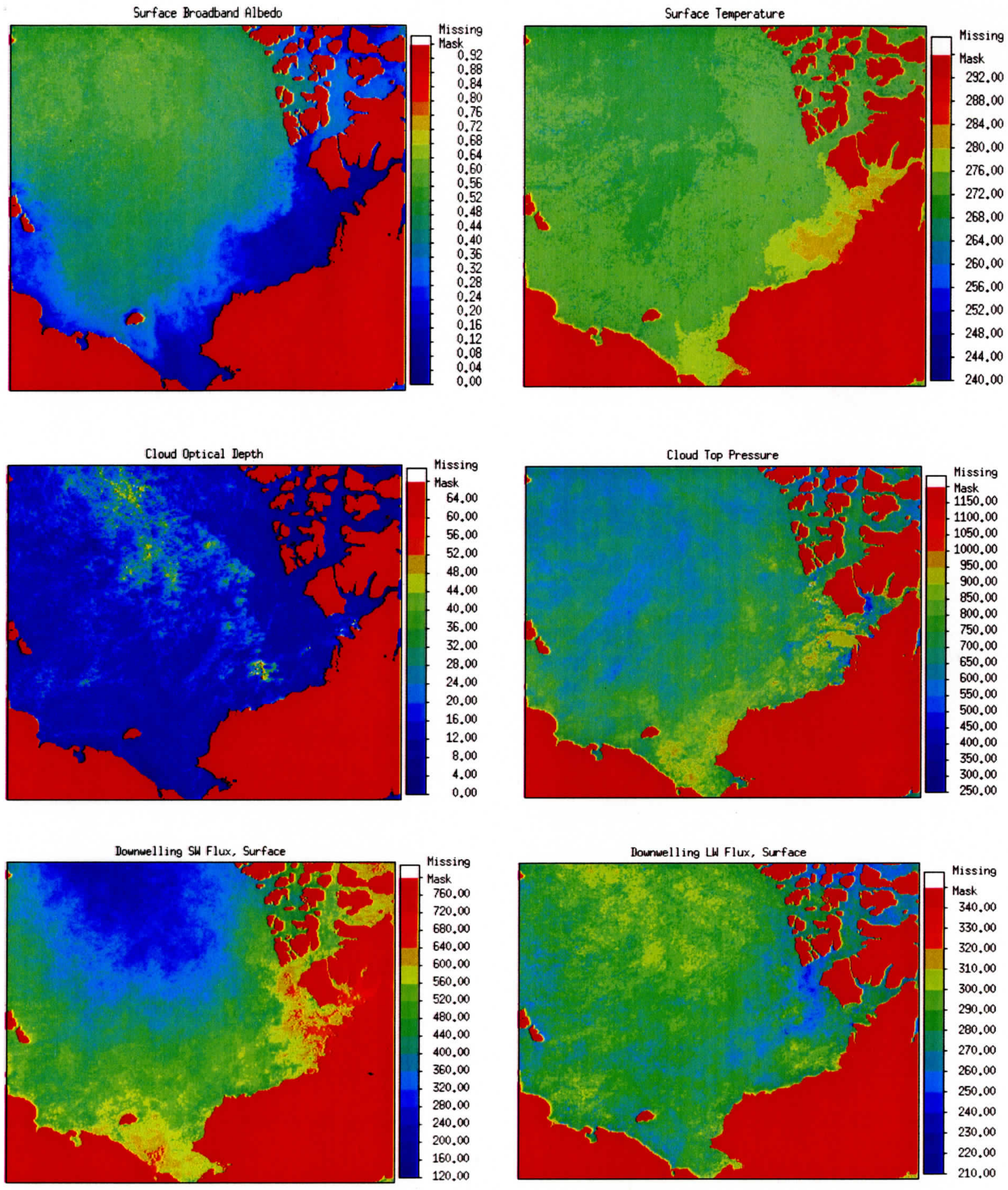

Fig. 1. Mean monthly satellite-derived surface, cloud, and radiative properties for July 1998 over the western Arctic Ocean, approximately centered on the SHEBA ship area. These and other parameters were estimated from AVHRR data. Alaska is in the lower right portion of the image.

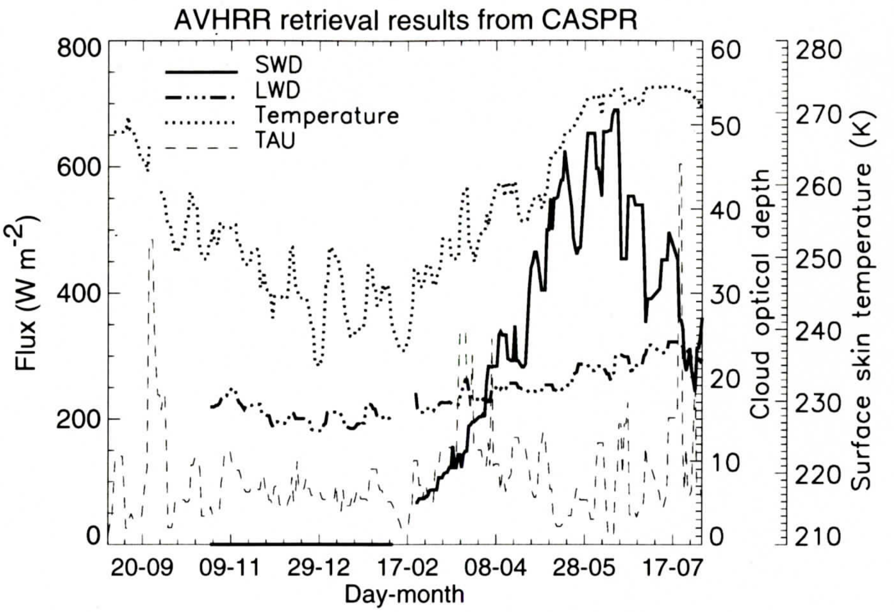

Fig. 2. Time series of surface temperature, cloud visible optical depth, downwelling shortwave (SWD) and longwave (LWD) radiation at the surface as estimated from satellite data for the SHEBA year. Results shown are averages over a 55 x 55 km area centered on the ship location.

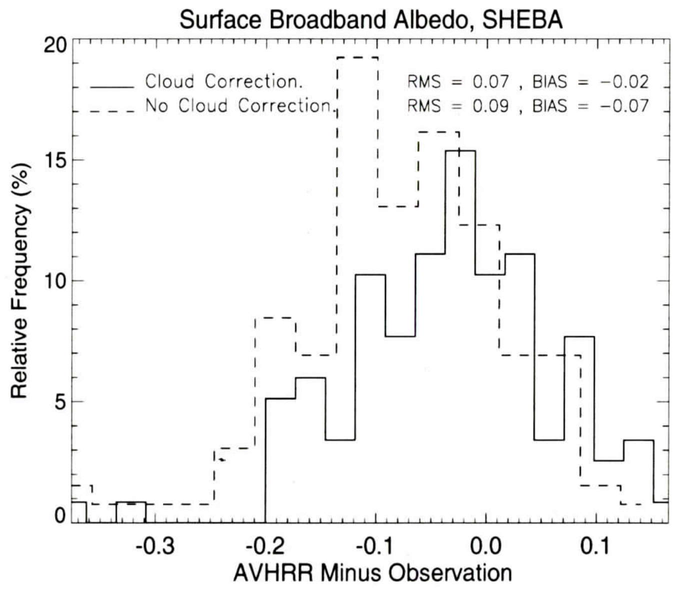

Fig. 3. Relative frequency of differences between the AVHRR retrievals of surface albedo and the SHEBA ship measurements with (solid) and without (dashed) the cloudy sky adjustment to the clear sky albedo. The bias and root-mean-square errors are also given.

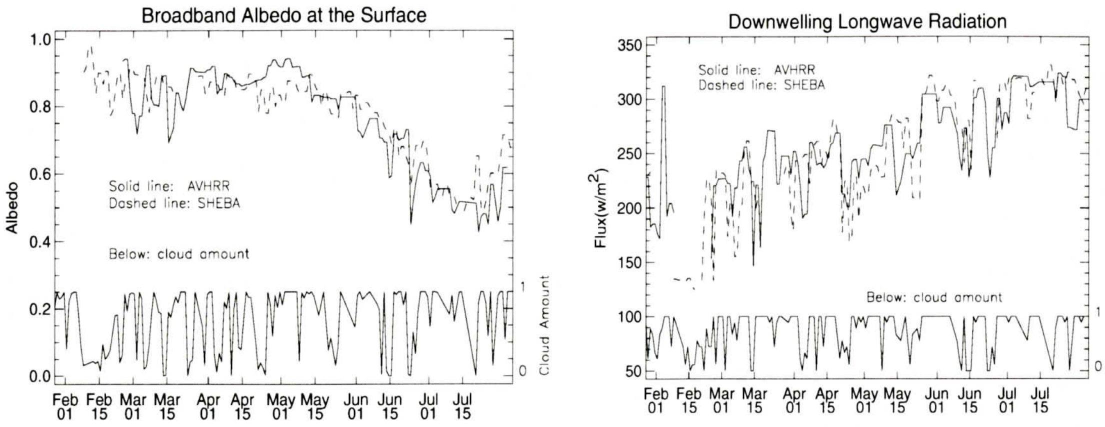

Fig. 4. Comparison satellite-derived and surface observations of all-sky surface albedo (left) and downwelling longwave radiation at the surface (right) during SHEBA. Results shown are averages over a 55 x 55 km area centered on the ship location.

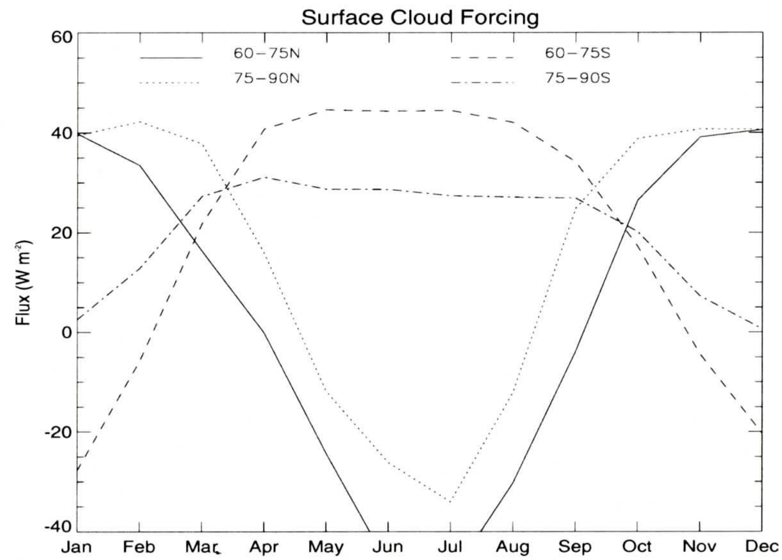

Fig. 5. Monthly mean cloud radiative effect ("forcing") at the surface for two latitudinal zones in the Arctic and two in the Antarctic. Values are derived from the ISCCP D1 cloud data and the TOVS Path-P temperature and humidity profiles.

A global climatology of wave cyclones. The 40-year NCEP Reanalysis pressure data was used to identify and track cyclones worldwide. The cyclone data set was used to show that statistically significant *trends in cyclone frequencies exist at 1000 mb and 500 mb in certain seasons for all regions and latitude zones, and in some cases the trends at the two levels are of opposite sign.* This was particularly true in the Arctic (Figure 6).

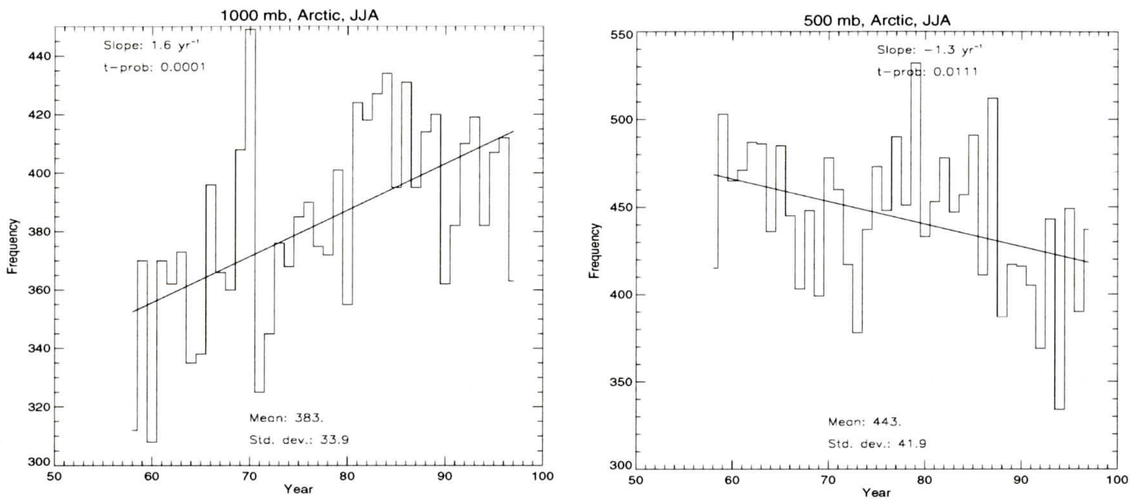

Fig. 6. Trends in cyclone frequencies in the Arctic summer at 1000 mb (left) and 500 mb (right). Both trends are statistically significant. The opposite sign of the trends implies a change in large scale circulation and tropospheric temperatures.

Comparison of observed and modeled clouds. We have used the regional climate model ARCSyM to simulate the total cloud amount over the Arctic area poleward of 60N at a 100 km horizontal resolution. Figure 7 shows a comparison of January 1990 cloud amounts produced by the model and that given in the ISCCP D2 data. There is a large discrepancy between the modeled and satellite-derived clouds. On the average, the modeled cloud amount is significantly less than the satellite-derived quantity, especially over the Arctic ocean. In contrast, cloud amount over north Greenland is overestimated by the model.

Analysis of scale issues in remote sensing. The importance of satellite sensor field-of-view in remote sensing studies of surface and cloud features was quantified theoretically and empirically. Not surprisingly, the accuracy with which the area fraction of clouds or sea ice leads can be estimated depends on the true area fraction, the spatial structure, and the thresholding operation used to label each pixel. Taking the analysis one step further, it was shown that *pixel size has a substantial effect on estimates of turbulent heat transfer from leads to the atmosphere.*

Measurement of Mt. Pinatubo aerosols. Sun photometer measurements made (by J. Key) in Alaska and over the western Arctic Ocean in 1992 and 1993 were used to determine aerosol optical depth and, roughly, particle size. *Bi-modal size distributions and visible optical depths greater than 0.2 were observed above the tropopause.* These results were important for satellite retrievals of surface and cloud properties.

Software tools. These software products were developed under POLES. They are available to the public (http://stratus.ssec.wisc.edu):

- **Streamer**, a radiative transfer model for general meteorological and satellite applications. Streamer is used by well over 100 scientists in 33 countries.

- The Cloud and Surface Parameter Retrieval (**CASPR**) system toolkit for educational and research applications. The AVHRR algorithms developed with POLES funding are part of CASPR.

- **FluxNet**, a neural network implementation of Streamer. While more limited in function than Streamer, FluxNet is up to 10,000 times faster and is therefore ideal for processing large satellite data sets.

Data sets. The following data sets were developed and made available to the public (http://stratus.ssec.wisc.edu):

- **Cloud and surface properties from AVHRR** during the SHEBA year. See Figure 1 for an example.

- The **AVHRR Polar Pathfinder** (APP). This 20-year data set is comprised of twice daily, 5 km gridded AVHRR radiance data, three cloud masks, and clear sky surface temperature and albedo. The funding for data set production did not come from POLES, but the APP products are based on the algorithms developed under POLES.

- **Extended APP products**. A 20-year, twice daily 25 km data set based on the APP product is currently being generated. The data set will include cloud properties and radiative fluxes.

- **Radiative fluxes based on the ISCCP** monthly C2 and three-hourly D1 cloud data sets for seven and nine years, respectively.

- A 40-year global **climatology of wave cyclones**.

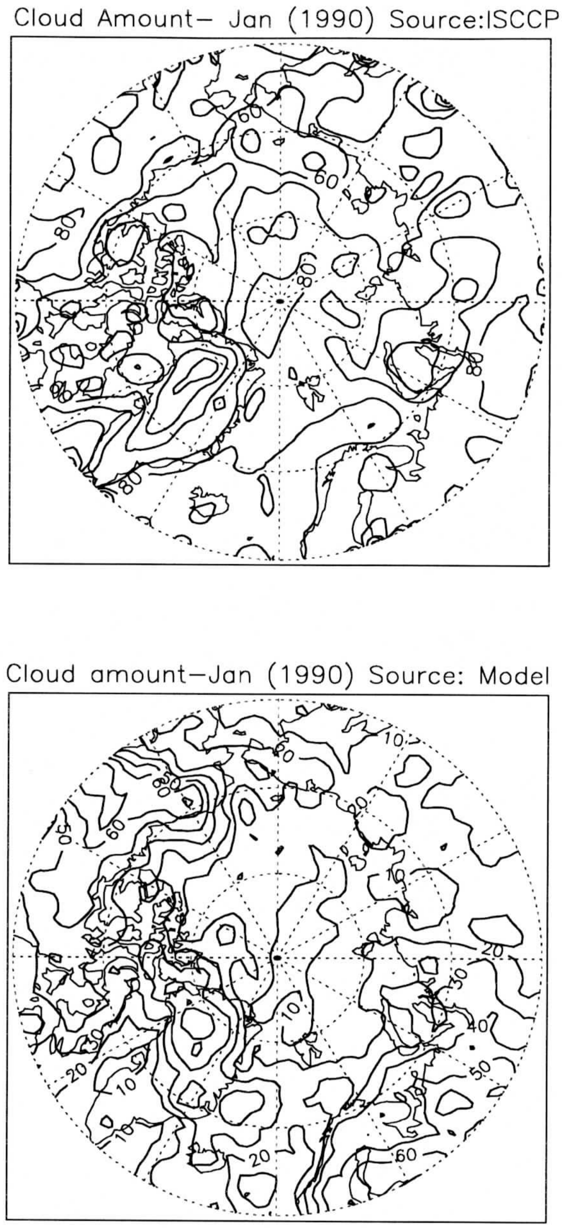

Fig. 7. ISCCP D2 and modeled (ARCSyM) cloud amounts in January 1990 over the Arctic.

4. POLES-Supported Journal (Reviewed) Publications

Summary: 32 refereed papers, one Ph.D. dissertation, one Master's thesis, and one undergraduate thesis over 11 years acknowledging POLES support in whole or in part.

4.1 Journal Papers

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.

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.

Key, J. and A. Chan, 1999. Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies, *Geophys. Res. Lett.*, 26(14), 2053-2056.

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

Key, J. and A.J. Schweiger, 1998. Tools for atmospheric radiative transfer: Streamer and FluxNet. *Computers and Geosciences*, 24(5), 443-451.

Serreze, M.C., J. Box, and J. Key, 1998. A new monthly climatology of global radiation for the Arctic and comparisons with NCEP/NCAR reanalysis and ISCCP-C2 fields. *J. Climate,* 11(2), 121-136.

Key, J., Y. Liu, and R. Stone, 1997. Development and evaluation of surface shortwave flux parameterizations for use in sea ice models. *Annals Glaciol.*, 25, 33-37.

Maslanik, J., C. Fowler, T. Scambos, J. Key, and W. Emery, 1997. AVHRR-based polar pathfinder products for modeling applications. *Annals Glaciol.,* 25, 388-392.

Meier, W., J. Maslanik, and J. Key, 1997. Multiparameter AVHRR-derived products for Arctic climate studies. *Earth Interactions*, Vol. 1., October 25.

Key, J., A.J. Schweiger, and R.S. Stone, 1997. Expected uncertainty in satellite-derived estimates of the high-latitude surface radiation budget. *J. Geophys. Res.,* 102(C7), 15837-15847.

Key, J., J. Collins, C. Fowler, and R. Stone, 1997. High-latitude surface temperature estimates from thermal satellite data. *Remote Sensing Environ.*, 61, 302-309.

Schweiger, A. and J. Key, 1997. Estimating surface radiation fluxes in the Arctic from TOVS brightness temperatures, *International J. Remote Sensing*, 18(4), 955-970.

Key, J., R.S. Silcox, and R.S. Stone, 1996. Evaluation of surface radiative flux parameterizations for use in sea ice models. *J. Geophys. Research (Oceans)*, 101(C2), 3839-3849.

Maslanik, J. and J. Key, 1995. On treatments of fetch and stability sensitivity in large-area estimates of sensible heat flux over sea ice. *J. Geophys. Res.*, 100(C3), 4573-4584.

Khalsa, S.J.S. and J. Key, 1995. Atmospheric temperature variability in the Arctic as revealed in a TOVS data record. *Polar Record*, 31(177), 199-210.

Serreze, M.C., J.A. Maslanik, J. Key, R.F. Kokaly, and D.A. Robinson, 1995. Diagnosis of the record minimum arctic sea ice extent during 1990. *Geophys. Res. Letters*, 22(16), 2183-2186.

Key, J., J.A. Maslanik, and E. Ellefsen, 1994, The effects of sensor field-of-view on the geometrical characteristics of sea ice leads and implications for large-area heat flux estimates, *Remote Sensing Environ.*, 48(3), 347-357.

Barry, R.G. and J.R. Key, 1994, Observational studies of Arctic ocean ice-atmosphere interactions, *Polar Geography and Geology*, 8, 1-14.

Schweiger, A.J. and J. Key, 1994, Arctic Ocean radiation fluxes and cloud forcing based on the ISCCP C2 cloud data set, 1983-90, *J. Appl. Meteorol.*, 33(8), 948-963.

DeAbreu, R.A., J. Key, J.A. Maslanik, M.C. Serreze, and E.F. LeDrew, 1994, Comparison of *in situ* and AVHRR-derived surface broadband albedo over Arctic sea ice, *Arctic*, 47(3), 288-297.

Key, J., J.A. Maslanik, T. Papakyriakou, M.C. Serreze, and A.J. Schweiger, 1994, On the validation of satellite-derived sea ice surface temperature, *Arctic*, 47(3), 280-287.

Key, J, 1994, The area coverage of geophysical fields as a function of sensor field-of-view, *Remote Sensing Environ.*, 48(3), 339-346.

Key, J, 1993, Estimating the area fraction of geophysical fields from measurements along a transect, *IEEE Trans. Geosci. Remote Sensing*, 31(5), 1099-1102.

Schweiger, A.J., M.C. Serreze, and J. Key, 1993, Arctic sea ice albedo: a comparison of two satellite-derived data sets, *Geophys. Res. Letters*, 20(1), 41-44.

Maslanik, J. and J. Key, 1993, Comparison and integration of ice-pack temperatures derived from AVHRR and passive microwave imagery, *Annals Glaciol.*, 17, 372-378.

Steffen, K., R. Bindschadler, C. Casassa, J. Comiso, D. Eppler, F. Fetterer, J. Hawkins, J. Key, D. Rothrock, R. Thomas, R. Weaver, and R. Welch, 1993, Snow and ice applications of AVHRR in polar regions: report of a workshop held in Boulder, Colorado, May 20, 1992. *Annals Glaciol.*, 17, 1-16.

Stone, R. and J. Key, 1993, The detectability of winter sea ice leads in thermal satellite data under varying atmospheric conditions, *J. Geophys. Res.*, 98(C7), 12469-12482.

Stone, R.S., J. Key, and E. Dutton, 1993, Properties and decay of stratospheric aerosols in the Arctic following the 1991 eruptions of Mount Pinatubo, *Geophys. Res. Letters*, 20(21), 2359-2362.

Key, J. and M. Haefliger, 1992, Arctic ice surface temperature retrieval from AVHRR thermal channels. *J. Geophys. Res.*, 97(D5), 5885-5893.

Schweiger, A.J. and J. Key, 1992, Comparison of ISCCP-C2 and Nimbus-7 satellite-derived cloud products with a surface-based cloud climatology in the arctic, *J. Climate*, 5(12), 1514-1527.

4.2 Theses

Schweiger, A.J., 1992, Arctic radiative fluxes modeled from the ISCCP-C2 data set, 1983-1986, Ph.D. dissertation, Dept. of Geography, University of Colorado-Boulder, 218 pp.

Silcox, R.A., 1994, Downwelling radiation fluxes at the Arctic surface based on parameterizations, M.A. thesis, Dept. of Geography, University of Colorado-Boulder, 86 pp.

Chan, A.C.K., 1998, A global climatology of 500 mb cyclones, Undergraduate Work for Distinction, Dept. of Geography, Boston University, 68 pp.

5. Scientific Computing Facility

The POLES-CU/BU/UW Scientific Computing Facility (SCF) has evolved since 1991. It currently consists of two Sun workstations (Ultra 5 and Ultra 10), one PC, one printer, an 8 mm tape drive, a scanner, and approximately 100 GB of external disk storage. Two other Sun workstations, one PC, and one printer have become obsolete.

6. Inventions

There have not been any inventions.