The surface energy budget in the antarctic summer sea-ice pack

Joseph Sheedy

October 15, 1999

Abstract

Radiation and heat balance measurements were carried out during a cruise of the U.S. Coast Guard Cutter *Polar Sea* from Hobart, Tasmania to McMurdo Station, Antarctica during December 1998- January 1999. The net energy balance varied most strongly with sea-ice extent, cloudiness, and meteorlogical conditions. Radiation measurements in the UV were also carried out continuously.

Introduction

The antarctic region plays an important role in the global climate system. The well popularized ice-albedo feedback mechanism has been proposed as the primary impetus behind the historically observed rapid changes in climate, forcing the system between semi-stable attractor basins. The total sea-ice extent in the Antarctic varies annually by over 500% (Gloerson et al, 1992). Besides the radiative fluxes, changes in ice extent affect the transfer of sensible and latent heat, since ice acts as an insulator between the ocean and atmosphere. Conversely, changes in the energy balance affect the formation and ablation of the ice. The net results of these forcings are not well represented in today's climate models, and few direct measurements of the energy budget have been carried out. Attempts to correlate UV intensity with the total ozone column were unsuccessful due to technical difficulties with the TOMS-satellite during the time of the cruise.

Energy Balance

The simplest expression for the energy balance at an ideal, planar surface considers only the principle of conservation of energy:

$$R_N = S + L + H_S \tag{1}$$

where R_N is the net radiation, S is the sensible heat, L is the latent heat, and H_S is the heat from the subsurface. The net radiation at the surface consists of two seperate components, the long- and shortwave radiation:

$$R_N = (SW_{in} - SW_{out}) + (LW_{in} - LW_{out}) \tag{2}$$

where SW_{in} is the incoming shortwave radiation, SW_{out} is the reflected shortwave radiation, LW_{in} is the incoming IR radiation, and LW_{out} is the outgoing IR radiation. These four fluxes were measured directly for this study. Incoming and outgoing values are defined as the hemispherically integrated fluxes in the positive and negative normal directions to the surface. The albedo α, or surface reflectivity, is calculated by taking the ratio of the reflected to the incoming shortwave radiation.

The sensible and latent heat fluxes are determined with more difficulty. If the atmosphere were completely motionless, all sensible heat transfer would be through conduction, and easily calculated given the temperature profile between the surface and the air. However, the real atmosphere is fluid, and so the magnitudes of energy and momentum transfer vary with the turbulent motions present in the system. Since we are concerned with air motions across the vertical gradients of temperature and humidity, the fluxes can be calculated from the net transport of particles, given the average vertical wind speed. Instrumentation for directly measuring the vertical wind speed with sufficient accuracy and time resolution was unavailable for this study. Alternatively, bulk aerodynamic formulas were used to calculate estimated vertical wind speeds. With this method the sensible and latent heat fluxes are given by

$$S = \rho C_D c_p u (T_a - T_s) \tag{3}$$

$$L = \rho C_D L_E u (q_a - q_s) \tag{4}$$

where T_a, q_a (T_s, q_s) are the air temperature and water vapor mixing ratio at the reference height and the surface, respectively, ρ =average air density of the layer, c_p =specific heat of air at constant pressure, L_E =latent of vaporization for water, u =wind speed, and C_D =transfer coefficient of momentum. u, q_a, and T_a were measured directly, and the other parameters were provided by indirect measurements or theoretical calculations.

For this study, a homogeneous ocean temperature was assumed, and accordingly, the heat from the subsurface is zero.

Measurements and Instrumentation

All of the measurements used in this study were taken from instruments mounted on the fly bridge of the *Polar Sea*, 32m above seaboard. Radiation measurements were taken from six separate radiometers to allow simultaneous readings of incoming UVA and UVB radiation, and both incoming and reflected radiation in the visible and infrared regions of the spectrum. The shortwave instruments were Eppley PSP pyranometers. They are temperature compenstated and have a cosine response error or $\pm1\%$ for solar elevations greater than $20°$ and $\pm3\%$ for elevations of $10°$-$20°$. For the incoming and outgoing infrared radiation, Epply model PIR pyrgeometers were used. The two instuments measuring the upward radiation were mounted on a rigid aluminum boom from the fly bridge of the ship, giving them a view of the surface. The ship's hull was thus in the field of view of the instruments, and its effect is not negligible. The hull is a dark red color, and under the total cloud coverage and diffuse light conditions which were common, the effect of the hull in the visible range was relatively constant. Wendler et al [1994], made spot measurements using a similar setup that showed errors in the range of 0-6%. Also, the longwave measurements were adversely affected. No corrections were carried out. Incoming UVA and UVB radiation were measured with an Eppley Ultra-Violet radiometer and a Yankee Environmental Systems UVB radiometer, respectively.

Meteorological measurments necessary for simple energy budget calculations were taken. Wind speeds taken from a Met One model 014A anemometer and a Met One wind direction sensor model 024A. They were corrected for the movement of the ship using GPS measurements from a Magellen Nav5000A. Sea surface temperature was taken with an Omega OS43L1MV infrared thermometer. Since the upwelling longwave radiation is a function of surface skin temperature, this instrument was used as a check against the temperature given by the Eppley instrument using the Stefan-Boltzmann law,

$$T_s = \sqrt[4]{\frac{LW_{out}}{\epsilon\sigma}} \tag{5}$$

. The air temperature and relative humidity was measured with a Vaisala HMP-45A probe. Atmospheric pressure was measured with a Parascientific Digiquartz pressure transducer model 216B-101.

Following Wendler and Quakenbush (1994), we measured the standard deviation of the pitch and roll of the ship. Under the relatively calm conditions of the open seas, and the characteristic slow travel of the ship through the ice, no errors due to pitch and roll could be found in the data.

Each of the instruments was sampled every two seconds by a Campbell 21X data logger. The point measurements were buffered and averaged every five minutes, then stored onto a laptop computer For a more complete description of the instruments, see Wendler [1997].

Visual observations were carried out by the ship's crew. We used ice concentration, cloud amount, and wind speed when we did not carry out our own measurements. This was done in hourly intervals. Seperate readings of the same parameters, with the addition of sea-surface temperature taken from a bucket sample, were recorded at three hour intervals. Detailed observations of sea-ice characteristics were taken at hourly intervals in accordance with the ASPeCt program [Allison et al., 1993; Allison and Worby 1994].

Results

A data set was obtained between December 20, 1998 and January 18, 1999. The ship's track can be seen in figure 1. The meteorological measurements are represented in figure 2.

After reaching the sea ice edge, the air temperature remained fairly steady, around the freezing point of sea water for the first half of the journey, as the boat tended to stay out of the ice pack. On June 6, 1999, we entered the fast ice of McMurdo sound, where reduced heat transfer between the surface and the air due to the insulative effects of ice allowed the near-surface air temperature to fluctuate more strongly with the weather systems. Two major synoptic weather events occurred, which showed up as characteristic dips in the pressure field (972mb and 976mb). Strong winds and high seas accompanied the first event.

In figure 3, the mean diurnal variation of the global and reflected radiation is presented for hourly averaged values, and plotted with a least-squares fitted sine curve. Given the wide range of latitudes traveled (57°S - 78°S), changing ice and weather conditions, and orientation of the instruments, these averaged measurements must be viewed with a measured amount of suspect.

The net radiation balance as given by equation 2 is plotted in figure 3. The shortwave flux dominates the balance, as expected during the summer season. The

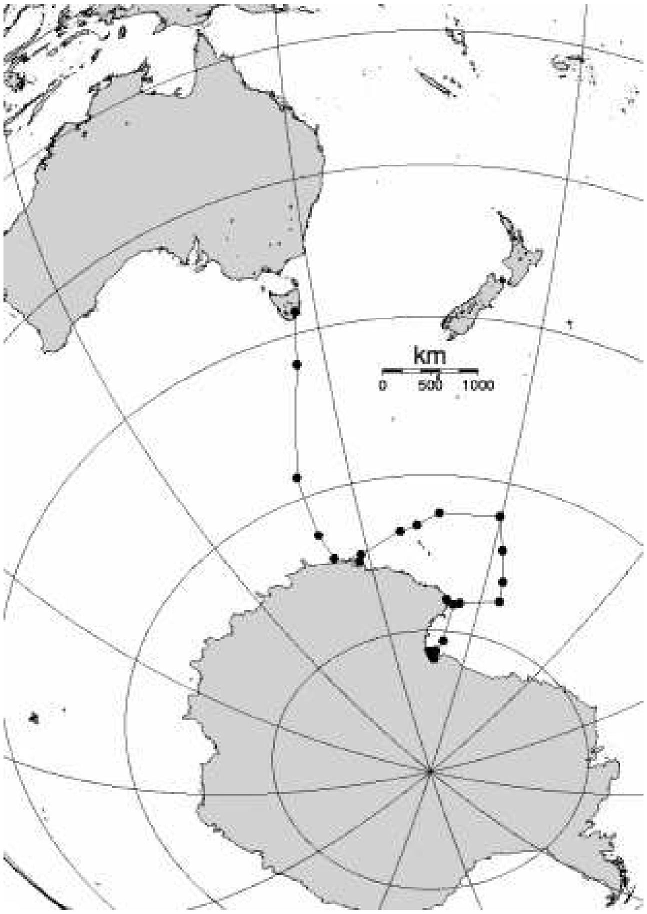

Figure 1: The location of the ship each day at noon.

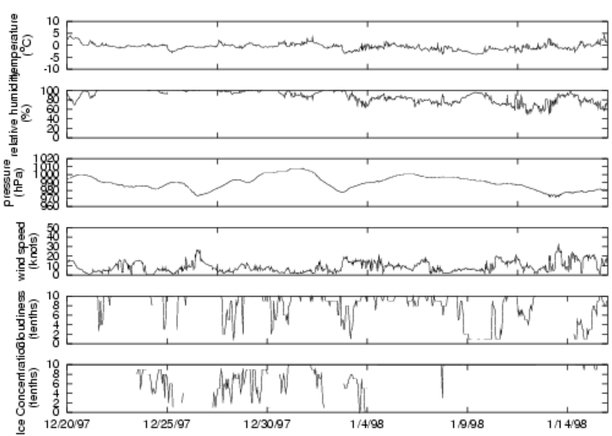

Figure 2: Meteorological measurement beginning shortly before reaching the ice edge.

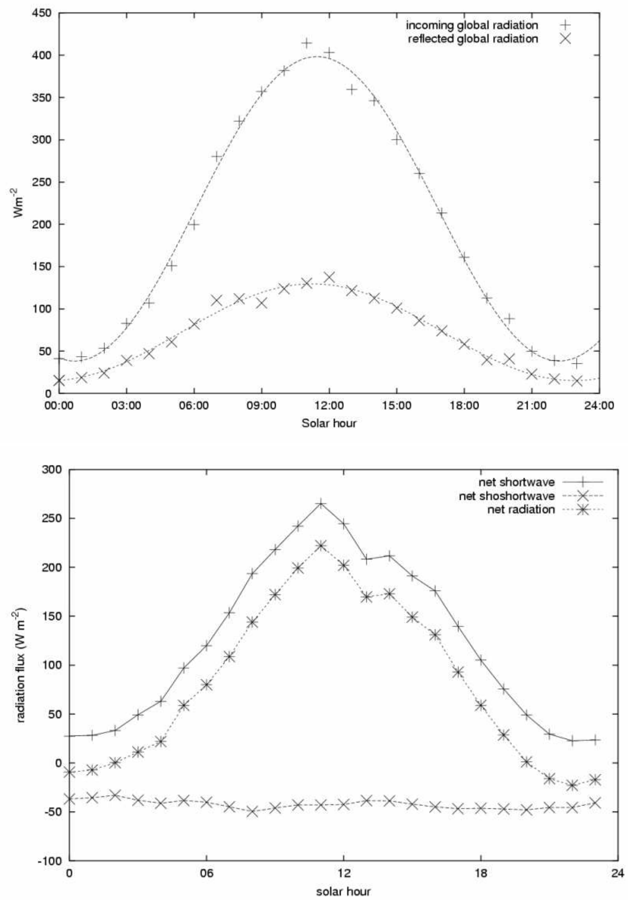

Figure 3: a) Hourly values of incoming and reflected shortwave radiation, averaged over a twenty day period. b) Net radiation balance.

ice/ocean surface remained at a relatively contstant temperature throughout the daily cycle, and thus the outgoing longwave radiation was steady. The absolute maximum incoming solar radiation was 906 Wm^{-2}, recorded at 1200 local time of December 30, 1998. The maximum hourly mean value over the data set was 421 Wm^{-2} incoming, and 138 Wm^{-2} outgoing shortwave radiation. The hourly albedo values had minima at 0900 and 1600, solar time.

This diurnal variation in the albedo is based primarily on the change in the surface reflectance with solar elevation. The solar elevation was calculated at each data point. Using the time of day, and latitude and longtitude from the GPS the solar elevation was calculated with a few terms of a fourier series as given by Hartmann [1994]. The exponential nature of the dependence of albedo on solar elevation is shown by in figure 4. Since the reflected radiation must go to zero with the incoming, there can not be a one to one correspondance between albedo and solar elevation.

Figure 4 also shows the data averaged every five min-

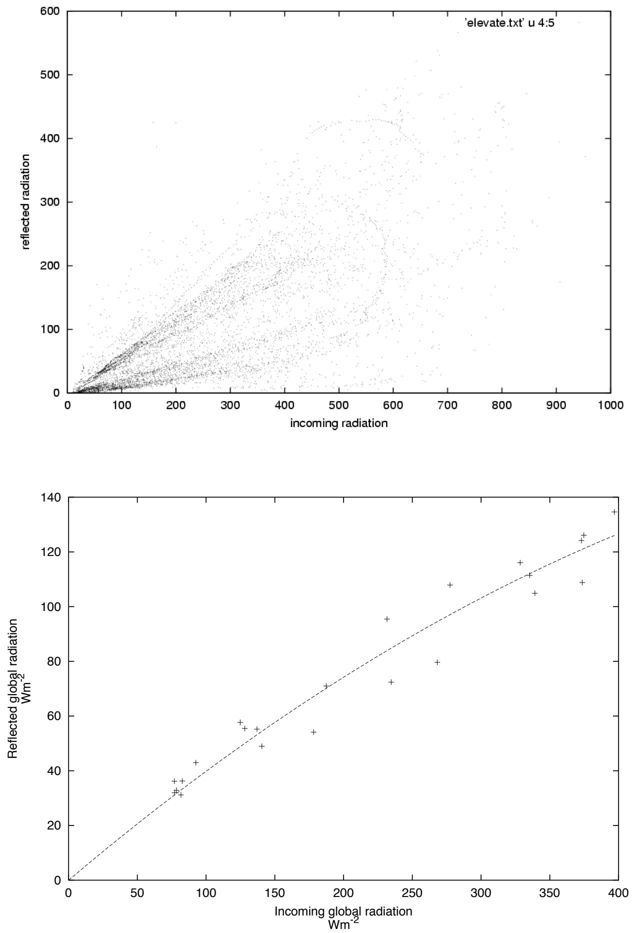

Figure 4: a) Instantaneous points of incoming and reflected radiation. b) Hourly averaged data shows has an exponential relationship.

utes. There are two distinct albedo regimes noticable in this plot, corresponding to albedos of 0.5 and 0.2. The UVB measurements showed a similar relation to solar elevation. The dependence becomes approximately linear for solar elevations above 23°.

The Omega instrument used for measuring the sea surface temperature proved unreliable. Therefore, the SST given by equation 5 was used for calculations of the turbulent heat fluxes. The sensible heat transfer was calculated with equation 3, an air density of 1.25kg m^{-3}, and $C_D = 1.5 \times 10^{-3}$ following Wendler, (1997). Latent heat transfer, equation 4, requires knowledge of the humidity at the surface, in addition to the measurements taken at the reference level. Exact saturation was assumed, and was calculated from a third order taylor series of the Clausius-Clapeyron equation expanded about 0°C, at the surface temperature. The results of these calculations are in figure 5.

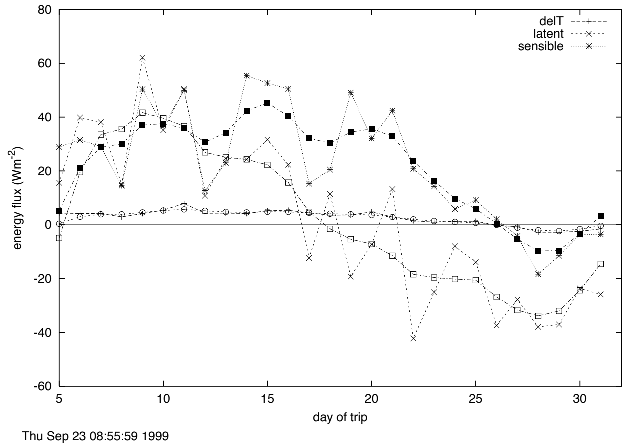

Figure 5: Daily averages of the sensible and latent heat fluxes. Smoothed curves are three point running means, filtered twice.

Conclusions

Radiation measurements were taken in the southern ocean in and near the ice pack.

References

[1] Bintanja, R., Jonsson, S., Knap, W.H., The annual cycle of the surface energy balance of Antarctic blue ice, *Journal of Geophysical Research,* 102(D2), pp. 1867-1881,1997.

[2] Hartmann, D.L., Global Physical Climatology, 411pp., Academic Press, Inc., San Diego, CA, 1994.

[3] Hauser, H., G. Wendler, U. Adolphs, M.O. Jeffries, Energy exchange in early spring over sea ice in the Pacific sector of the Southern Ocean. *Journal of Geophysical Research, 1*04(D4), pp. 3925-3935,1999.

[4] Makshtas, A.P., The heat budget of Arctic ice in the winter, 78pp., International Glaciological Society, Cambridge, U.K., 1991.

[5] Wendler, G., U. Adolphs, A. Hauser, and B. Moore, On the surface energy budget of sea ice. *Journal of Glaciology,* 43(143).

[6] Wendler, G., D. Gilmore, J. Curtis, On the formation of coastal polynyas in the area of Commonwealth Bay, Eastern Antarctica. *Atmospheric Research,* 45, .

[7] Worby, A.P., Allison, A., Ocean-atmosphere exchange over thin, variable concentration Antarctic pack ice. *Annals of Glaciology,* 15, pp. 184-190, 1991.