An integrated platform for observing the radiation budget of sea ice at different spatial scales

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Abstract

An integrated instrument package for measuring and understanding the surface radiation budget of sea ice is presented, along with results from its first deployment. The setup simultaneously measures broadband fluxes of upwelling and downwelling terrestrial and solar radiation (four components separately), spectral fluxes of incident and reflected solar radiation, and supporting data such as air temperature and humidity, surface temperature, and location (GPS), in addition to photographing the sky and observed surface during each measurement. The instruments are mounted on a small sled, allowing measurements of the radiation budget to be made at many locations in the study area to see the effect of small-scale surface processes on the large-scale radiation budget. Such observations have many applications, from calibration and validation of remote sensing products to improving our understanding of surface processes that affect atmosphere-snow-ice interactions and drive feedbacks, ultimately leading to the potential to improve climate modelling of ice-covered regions of the ocean. The photographs, spectral data, and other observations allow for improved analysis of the broadband data. An example of this is shown by using the observations made during a partly cloudy day, which show erratic variations due to passing clouds, and creating a careful estimate of what the radiation budget along the observed line would have been under uniform sky conditions, clear or overcast. Other data from the setup’s first deployment, in June 2011 on fast ice near Point Barrow, Alaska, are also shown; these illustrate the rapid changes of the radiation budget during a cold period that led to refreezing and new snow well into the melt season.

Keywords: Radiation budget, Sea ice, Snow, Albedo, Radiometers

1. Introduction

The radiation budget of sea ice, especially during the melt season, is affected by many processes that take place at small (order of 1 to 10 m) scales, such as the existence of melt ponds, the variation of their depth and color, and the variable distribution of snow or a surface scattering layer. Often data or models cannot resolve these small-scale features, but instead represent the combined effect of them on the scale of a satellite pixel or model grid cell. It is therefore useful to study these processes with measurements that capture the small scales and can be integrated over larger scales to see how the individual processes and surface types are combining to affect the overall energy budget of the ice.

Spatial variability of spectral and broadband albedo has been measured during multiple projects (e.g. Grenfell and Perovich, 1984; Perovich et al., 2002; Grenfell and Perovich, 2004). Other relevant measurements, coincident in space and time, are often lacking from such spatial surveys, including observations of long-wave radiation, sky and surface conditions, and surface and air temperatures. Here we present a sled-based instrument package that allows for the simultaneous collection of all components of the surface radiation budget along with various supporting data that allow for increased interpretation and extension of the observed radiation data. Earlier work with sled-based radiation measurements have largely focused on obtaining observations over very large areas by towing the sled behind a snowmobile (e.g. Maslanik et al., 1999; Schnell, 2004; Walden et al., 2006). That approach is useful for getting many data for statistics, but here we focus on a mobile platform that is moved between measurements, but allows the user to accurately level instruments and observe specific locations, providing high-quality, useful data for process studies. The goal of such a system is...
to be able to better exploit the observed radiation data, using the supporting data to account for variability not driven by surface properties, to understand the connection between the development of the large-scale energy budget and the small-scale processes driving that development, ultimately leading to the ability to evaluate model parameterizations and satellite algorithms.

2. Instrument setup

The setup, shown in Figure 1, is based on a lightweight, modified wooden dog sled on skis. For the radiation measurements it uses a Kipp & Zonen CNR4 four-component net radiometer to observe broadband upwelling and downwelling shortwave (solar) and longwave (thermal terrestrial) radiation and a single-channel ASD FieldSpec Pro spectroradiometer (Kindel et al., 2001), fitted with the Remote Cosine Receptor manufactured by ASD, to observe spectral albedo and calibrated solar fluxes at wavelengths from 350 to 2200 nm (signal loss in the five-meter fiber optic cable precludes the use of the data from 2200 to 2500 nm). The length of the sensor arm, from the sensor side of the sled to the broadband radiometer, was 1.4 m, and the height of the sensors was 1.2 m over the ice. Supporting data include surface and sky photos taken at the time of each observation, surface temperature observed with a Campbell IR-120 infrared thermometer, air temperature and humidity observed with a Vaisala HMP45 sensor, and time and location from GPS.

The observation sequence is carried out automatically by the controlling computer when, using a weatherized keyboard, a given command is entered in the LabView application that communicates with the sensors. Upon receiving the measurement command all data are recorded from all sensors and the sky and surface photographs are taken, a sequence that takes about 5 seconds. The only remaining task, a result of the single-face, care must be taken when trying to repeat a transect so that measurements are not affected by previous disturbances along the transect. Based on 2011 data from an ice mass balance installation at the site (Druckenmiller et al., 2009, http://seaice.alaska.edu/cgi/data/barrow_massbalance), we know that surface temperatures first rose to the melting point in mid-May and snow melt completed around 1 June; during the measurement period the surface was bare ice with a thin surface scattering layer and some melt ponds, shallow in the middle of the line and deep near the far end of the line. Air temperatures were often just below freezing during the period, with moderately strong winds coming from the east, leading to some refreezing of the surfaces; some very light snowfall on 10 and 11 June further brightened the surface. The changes in
the surface at two locations along the measurement line are shown in Figure 2. All data are published on PAN-GAEA (Hudson et al., 2012), making them freely available to the community.

The measurement sequences were carried out around solar noon each day, with solar zenith angles between 48° and 55°. On 5 June the measurements were made under mostly clear skies; on 12 and 13 June there was a fairly uniform thick overcast, and the other days had broken cloud cover. All measurements were made with the radiometers to the south of the sled, thus avoiding any shadowing of the direct radiation.

Figure 3 shows the broadband albedo measured along the line on four days. On 5 June there was a contrast between the brighter bare-ice albedos around 0.5 and the darker pond albedos around 0.2. As colder weather again set in, most of the line became significantly brighter as the surfaces refroze and were then covered by a little new snow on 10 and 11 June. During this one week period, the spatially averaged albedo increased from just below 0.4 to just over 0.6, corresponding to a nearly 40% decrease in the solar energy absorbed under the same sky conditions. However, the albedo of the darkest pond, near 190 m, remained almost unchanged throughout the period, illustrating a situation in which, at the grid-cell or satellite-pixel scale, it might appear that melt in the region has significantly slowed or stopped, but in which small-scale variability allows it to continue unabated in some locations. Even once refrozen and covered with new snow, the melt ponds remained darker than the surrounding bare ice since the new snow layer was not optically thick. The spatial standard deviation of the albedo increased from 0.105 to 0.134 from 5 to 10 June, and then decreased to 0.122 on 12 June, as more of the dark surfaces became covered with snow. The albedo and its variability in our measurements are similar to observations by Grenfell and Perovich (2004, their Figure 5, Chuckchi site) on 9 and 12 June 2001 at a nearby location.

The net radiation budget along the line on the same four days is shown in Figure 4. Here, over the course of the week, we see a nearly 70% decrease in the amount of energy gained by the area through radiative fluxes. While some of this decrease is due to the increased albedo, reduced incoming solar fluxes caused by increased cloud cover also contributed. The importance of small-scale variability is clearly visible in the net radiation budget as well, with melt ponds often leading to a doubling of the net radiative energy gained by the ice, but some of what appears to be spatial variability could be caused by variability in cloud cover. The standard deviation of the net radiation along the line on the four days ranged from 20% to 30% of the mean value.

Figure 5a shows how the four components of the radiation budget each contributed to the net budget along the line on 5 June, a clear day. Along the whole line, the surface was losing about 318 W m⁻² by emission of longwave radiation, with the lack of variability illustrating the nearly uniform temperature of the melting surface. At the same time, the entire line was receiving about 247 W m⁻² of longwave radiation from the atmosphere, with the lack of variability illustrating the lack
Figure 2: Photos taken by the integrated surface camera at two points along the line, 75 m on the left, where there was a shallow melt pond at the beginning, and 55 m on the right, where there was a bare scattering layer at the beginning. Photos are shown from four days to illustrate the changes at the two locations; from top to bottom the photos are from 5, 7, 10, and 12 June. The x in the top-right photo shows the approximate location that is directly below the broadband radiometer.
of clouds or other atmospheric changes during the measurements. Longwave radiation processes on this clear day were thus driving a slight cooling of the surface. The surface was also receiving about 700 W m$^{-2}$ in incoming solar radiation, but between 15% and 58% of this was reflected, causing significant variability in the absorbed solar radiation and therefore in the net radiation budget.

4. Discussion

4.1. Using the additional observations

The effects of the melt ponds and other surface variations on the radiation budget can be easily seen in the broadband radiation data from 5 June, shown in Figure 5a, because the sky condition was very stable. Were things always so simple, the additional instruments and observations that are incorporated onto the sled platform might be unnecessary, simply providing added bulk, which increases shadowing and decreases maneuverability. However, such uniformly clear days are not common over Arctic sea ice, especially during the interesting and important melt season, and clouds often complicate the interpretation of radiation measurements.

An example of the complications caused by passing clouds during a sequence of observations along the line is shown in Figure 5b, which presents the broadband radiation data observed on 9 June. Here we see a very different picture than that from the data on the cloud-free day, when observed variability along the line was almost completely driven by spatial variability of the surface. The one similarity is a nearly uniform longwave emission of about 313 W m$^{-2}$, but here the incoming fluxes of both longwave and shortwave radiation vary considerably along the line due to variability in passing clouds. The result is a net longwave budget that varies between $-75$ W m$^{-2}$ and $-17$ W m$^{-2}$, and incoming shortwave fluxes that vary between 325 W m$^{-2}$ and 924 W m$^{-2}$. In the absence of additional information about the spectral albedo and cloud conditions at the time of each measurement, these variations in the incoming fluxes make it very difficult to isolate the effect of the surface variability.

Though we cannot always observe the processes we are interested in under ideal, controlled conditions, we can try to use the observations we are able to make to get a good estimate of what we would see under those ideal conditions, thereby isolating the effects we are trying to learn about, in this case the effect of surface variability. One way to do this is to use the incoming fluxes measured at a time with clear or nearly clear skies or with fairly uniformly overcast skies, together with the albedo and longwave emission observed at each location along the line to estimate the net radiation budget at each location for clear and overcast conditions. However, doing this based only on the broadband radiation data is not so straightforward for two main reasons.

First, we must identify a time when it was most clear

Figure 3: Albedo measured along the 200-m observation line on 5, 7, 10, and 12 June 2011. The dotted lines show the mean albedo along the line for each day.
and most uniformly overcast. The first instinct may be to choose the times with the maximum and minimum incoming solar radiation, but this turns out not to work so well since scattered clouds can increase the incoming solar flux, as long as the direct beam is unobscured, by scattering more light to a location than the clear sky would do. Likewise a non-uniform cloud cover could have a particularly thick patch of cloud blocking the direct beam and result in a lower incident flux than a thinner, uniform cloud cover.

Second, the spectral distribution of incoming solar radiation is changed by clouds, which preferentially absorb the near-infrared wavelengths so that a greater fraction of the incident flux is at ultraviolet and visible wavelengths under a cloudy sky than under a clear sky. Since the spectral albedo of ice and snow is much greater at these shorter wavelengths, the broadband albedo under a cloud is higher than that under clear sky (Warren, 1982). Thus, we cannot use the broadband albedo observed at each location along the line to find the net shortwave flux at each point under clear sky. The net longwave flux under clear sky is determined by subtracting the emitted longwave flux observed at each point from the incoming longwave flux observed at 135 m. The results of this analysis, an estimate of what Figure 5b would look like if we had had continuously clear skies during the measurements on 9 June, are shown in Figure 6a.

Using some of the additional observations we get from the upward looking camera to identify the time with clearest skies, which for the data from 9 June (Figure 5b) was the observation at 135 m. Then we can use the incident spectral solar flux observed at that time with the spectroradiometer along with the spectral albedo observed at each location along the line to find the net shortwave flux at each point under clear sky. The net longwave flux under clear sky is determined by subtracting the emitted longwave flux observed at each point from the incoming longwave flux observed at 135 m. The results of this analysis, an estimate of what Figure 5b would look like if we had had continuously clear skies during the measurements on 9 June, are shown in Figure 6a.

Here, the variations due to passing clouds have been removed and we are left with a good picture of the effects of the variable surface conditions. This clear sky estimate from 9 June can be compared to the clear sky observations from 5 June, shown in Figure 5a. The spatial variability now looks quite similar, though the net radiation is somewhat lower in the 9 June clear-sky estimate, by 43 W m⁻², or 11.7%, on average. The incoming shortwave flux for the clear-sky estimate on 9 June is 21 W m⁻² (3%) higher than the average on 5 June, and the slightly colder surface on 9 June emitted 5 W m⁻² (1.6%) less thermal radiation than on 5 June. However these gains to the surface are more than offset by a 10 W m⁻² (4%) reduction in incoming thermal radiation and, most importantly, by an increase of 0.069 (18%) in the average broadband albedo in the 9 June clear-sky estimate.
Figure 5: Variation of the components of the radiation budget along the 200-m observation line on (a) 5 June, a clear day, and (b) 9 June 2011, a day with passing clouds. The bottom of the shaded area shows the total upwelling longwave radiation; the thickness of the gray area shows the total downwelling longwave radiation, making the top of the gray area the net longwave radiation. The combined thickness of the light and dark red areas shows the total incident shortwave radiation; the thickness of the light red area shows the total reflected shortwave radiation, making the thickness of the dark red area the net shortwave radiation and the black line the net radiation.
Figure 6: Estimates of the fluxes that would have been observed on 9 June under hypothetical (a) clear sky and (b) uniformly overcast conditions. The actual fluxes observed under variable sky conditions are shown in Figure 5b. The meanings of the fields and lines are the same as in Figure 5.
A similar analysis was done using the incoming longwave flux and spectral solar flux observed at 165 m, when the photos showed relatively uniform overcast conditions. The results, shown in Figure 6b, let us see both what the radiation budget would have looked like on this day under overcast conditions, and, by comparison with Figure 6a, the effect of going from clear to overcast conditions, which almost eliminates longwave cooling but also significantly reduces shortwave heating, both by reducing the incident flux and by raising the broadband albedo.

Some caution was needed in combining the spectral solar data with the broadband data due to differences in spectral coverage, calibration, and noise in the spectral albedo at long wavelengths. The problems and solutions are discussed in Appendix A.

The ability to minimize the effect of cloud variability in the observations is just one example of how the extra sensors on the sled-based system can assist in interpretation of the data, or provide other possibilities. The combination of the spectral data with the broadband data will provide other opportunities for examining the effects of changes to the incident light field, and also allow for better identification of the causes of features and changes observed in the radiation budget through their spectral signatures. Photos of the surface that is being observed are very useful for understanding exactly what is causing the variability in the radiation data, but also show promise for development and validation of techniques for interpreting satellite data. The platform also provides ample opportunity for the inclusion of any additional sensors that may prove useful for future applications.

4.2. Improvements to the sled design

As shown in Figure 1, the system was initially set up on a very simple sled, similar to a dog sled. This was convenient and lightweight, but it was not very practical later in the melt season when melt ponds became too deep to safely enter with the equipment on the sled platform. To improve on this, the system has been redesigned around a heavy-duty plastic sled that provides a watertight basin in which the boxes sit and gives ample buoyancy to float the entire setup in a pond if necessary. This modification will allow for straighter and easier profiles, without the need to wind around areas of deep water.

The slowest step in the measurement process, and therefore the greatest constraint on the number of measurements that could be made in a given time, was the levelling of the arm supporting the radiation sensors. An ideal system might level itself, but it is questionable whether the multiple motors and sensors necessary to accomplish this would prove reliable during regular use on ice surfaces, where they will face exposure to low temperatures, moisture, and high winds that can cause the arm to vibrate or expose it to forces that might be difficult for the levelling system to deal with. Instead, new manual systems are being tried that will hopefully prove to be faster than the current system. In particular, the three-axis pan-tilt tripod head that was originally used for levelling will be replaced by either a ball head or other system allowing adjustment in all three axes at once, without three separate controls. Various systems will be tried during the next deployment to find what works best in different conditions and a small electronic tilt sensor will be mounted near the radiometers to aid levelling and record the result.

Additional improvements are being considered for future use. An automated system for turning the cosine collector for the spectral radiometer from upward to downward looking would likely reduce the measurement time by about 20 seconds at each location. The addition of a survey grade GPS would allow for better comparison of exact observation locations from day to day when repeating profiles. For use on drifting ice, a GPS base station would need to be set up, ideally with two stationary units logging during the measurement sequence to get both the drift and rotation of the floe and allowing for correction of the sled-based GPS locations to locations relative to the ice floe. Measurements of the snow or pond depth at each measurement location would be useful for interpreting the data, but at this time these need to be made manually.

5. Conclusion

A sled-based instrument setup that measures the four components of the broadband surface radiation budget (downwelling and upwelling terrestrial and solar fluxes) has been developed, and it was used for the first time on landfast sea ice in June 2011 just offshore from Point Barrow, Alaska. In addition to the broadband flux measurements, at each measurement location it also measures the incident and reflected spectral solar flux, the air temperature and humidity, the surface temperature, and the position from GPS, in addition to taking photos of the sky and observed surface. Using the setup, measurements of the radiation budget components can be made at many locations in a given area, providing a picture of the effect of specific meter-scale features in individual measurements and the ability to integrate over the whole area to see how these features combine to affect the large-scale radiation budget, as seen from satellites
or represented in models. From such observations, we see that spatial averages of radiation budget components can easily hide the effects of specific smaller-scale features, such as ponds that remain very dark while the average albedo is increasing significantly. These features and their spatial distribution can play important roles in the melting and freezing of sea ice and are generally not resolved in large-scale observations or modelling.

The additional observations and photographs allow for extended analysis of the broadband data. An example of this is using the dataset from a partly cloudy day to carefully create a picture of the radiation budget along the observed line as it would have been with the same surface conditions but with uniformly clear or cloudy sky conditions. Other such manipulations could also be done, for example, to see the effect of different kinds of clouds or other solar geometries.

The first deployment of the setup provided an interesting dataset showing the radiation budget of the sea ice during a cold period with refreezing and new snowfall well into the melt season. The deployment was quite successful, though it did lead to some improvements to make the sled better able to be used in melt ponds and to speed the process of levelling the sensor arm. The updated version of the setup will be deployed during campaigns in spring and summer 2012, and the addition of an eddy covariance setup in the measurement area for measuring turbulent fluxes of heat and moisture from the atmosphere will allow for a complete picture of the energy budget of the sea ice surface under a variety of different conditions.

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Appendix A: Combining spectral and broadband solar data

While the spectroradiometer is designed to measure wavelengths up to 2500 nm, the instrument used here is fitted with a five meter long fiber optic cable, and absorption in this cable reduces the signal too much to use data at wavelengths longer than 2200 nm. Excluding the longest wavelengths in the spectral data, possibly combined with calibration differences between the spectroradiometer and the pyranometers on the CNR4, resulted in integrated fluxes from the spectroradiometer that were somewhat lower than the observed broadband fluxes. The mean difference, root mean squared error, and coefficient of determination ($R^2$) between the integrated spectral and broadband datasets are 29 W m$^{-2}$, 42 W m$^{-2}$, and 0.955, respectively, for the incoming datasets, and 15 W m$^{-2}$, 26 W m$^{-2}$, and 0.954, respectively, for the reflected datasets. Linear fits were calculated to separately correct the incident and reflected integrated spectral fluxes for this difference. These statistics and corrections were determined using all 389 pairs of measurements made during all 9 days of the observation period, except that, for the upwelling statistics and correction, 9 outliers were excluded; these were measured under rapidly changing conditions, when the incident flux could change in the 20 to 30 seconds between the CNR4 measurement and the reflected spectral measurement (while the spectroradiometer’s cosine collector was turned from facing up to down).

Furthermore, at longer wavelengths the albedo, which becomes the quotient of two small numbers, gets quite noisy. To compensate for this, the spectral albedos used to create Figure 6 were constructed using a 7-nm running mean of the observed albedo at each location from 350–1335 nm, a 19-nm running mean from 1425–1650 nm, and the albedo at each wavelength averaged over observations from all locations along the line on that day (a spatial average, varying with wavelength) from 1675–1763 and 1967–2200 nm. The gaps from 1335 to 1425 nm and from 1763 to 1967 nm (both regions where the incoming flux approached zero) were filled by cubic spline interpolation, and the gap from 1650 to 1675 nm was filled by linear interpolation. Between 91% and 95% of the incident solar flux and between 98% and 99.5% of the reflected solar flux was at wavelengths shorter than 1335 nm, where the albedos were simply lightly smoothed. This procedure for obtaining the spectral albedo at each location is illustrated in Figure 7.
Figure 7: The light grey curves show the spectral albedo measured at each location along the line on 9 June. To show an example of the development of the spectral albedo for a given location for the analysis shown in Figure 6, one of these measured spectral albedo curves is highlighted in light red. The resulting spectral albedo used for this location is shown by the black curve. The thick, light blue curve shows the mean spectral albedo over the whole line on 9 June. The dashed lines separate the spectrum into regions where the black curve was determined by different methods. In the region labeled 7-nm, the black curve is a 7-nm running mean of the red curve; likewise, in the region labeled 19-nm, it is a 19-nm running mean of the red curve. In the two regions labeled M, the black curve is equal to the mean spectral albedo along the line. In the two regions labeled C, the black curve is a cubic spline interpolation through the regions, based on the surrounding points in the black curve; similarly, a linear interpolation was used to fill the region labeled L. The thin, blue curve shows the cumulative fraction of mean incoming solar radiation in the spectral region, illustrating that almost all of the incoming energy is at wavelengths where the albedo is just smoothed by a running mean.
References


