Description of the Composited SHEBA Data Set

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DATA SET OVERVIEW

The data set described here is a composited data set created for a study of observations of the onset and end of the summer melt at the Surface Heat Flux of the Arctic Ocean (SHEBA) site, described by Perovich et al (1999, 2002, 2003), Grenfell and Perovich (2004), Uttal et al (2002), and Persson et al (2002). The melt transition study (Persson 2011) has been submitted to Climate Dynamics. The hourly values of the 31 parameters are a combination of primarily observations from the ASFG SHEBA site and from other SHEBA sites when AFSG observations are missing. The net result is a data set with a data recovery of > 93% for all parameters for the one-year time period Oct. 9, 1997 - Oct. 8, 1998 as the SHEBA drifted with the pack ice in the Beaufort and Chukchi Seas. The list below gives the individual parameters, while the text below and the bibliography describe how the different parameters were created and provides references for the original measurement techniques.

INSTRUMENT DESCRIPTION

DATA COLLECTION AND PROCESSING

Descriptions of the instruments making the original measurements and the original data collection and processing are found at Perovich et al (1999, 2002, 2003), Grenfell and Perovich (2004), Uttal et al (2002), Persson et al (2002), and Intrieri et al (2002b). The concatenation of the measurements from the various data sources into the parameters given in these files is described below in sections 2 and 3 taken from Persson (2011). There are actually two data files. One includes the Quebec 2 snow depth, surface temperature, and conductive fluxes in the energy budget (sheba_composite_data_qb2_op), while the other one (sheba_composite_data_op) relies on only the ASFG, Pittsburgh, and Mainline sites as described in section 3.

DATA FORMATS

There are two data files (sheba_composite_data_qb2; sheba_composite_data), and each one has been saved as an ASCII file and as a Matlab binary file. The Matlab binary save command for the second file was:

```
save sheba_composite_data jd lat lon press Tsfc Tice snwdpthi icethck cf_immcr lwp_immcr
iwp_immcr swd swu lwd lwu lwnet swnet alb swtransm radnet hsmed usmed hlmed hturb
cflxmed fatm fnet t q rh ws wd ;%
```

A similar command was used for the first file

As described above, the two files have different snow depth, surface temperature, and conductive fluxes. The files have 8785 hourly records of the parameters listed below. The ASCII file has 8785 data records (rows) with 37 variables (columns), and contains additional header information, including units.

the 1-D basic parameters have length 8785 and are:

1) jd - year day starting Jan. 1, 1997 (e.g., March 1, 1998 is YD425)

2,3) lat, lon - latitude and longitude (negative is degrees S and W, respectively) of SHEBA site (composite of data from ASFG, ARM, FLA, and ship sites).
4) press - sea-level pressure (mb) - composite of FLA and SPO data
5) Tsfc - surface temperature (deg C)
6) Tice - ice/snow interface temperature (deg C)
7) snwdpthi - snowdepth(m; median snow depth from the ASFG, Pitt, (Quebec2 -- in "qb2" file), and Snowline data - the Snowline data is linearly interpolated in time to hourly values)
8) icethck - ice thickness(m; mean thickness from Pittsburgh (and Quebec2 in qb2 file) sites)
9) cf_immcr - cloud fraction (%) from cloud radar system
10) lwp_immcr - liquid water path (g/m2) from microwave radiometer
11) iwp_immcr - ice water path (g/m2) from cloud radar

the 1-D surface energy budget parameters also have length 8785, are all in units of W/m2 (except albedo and friction velocity). The parameters are:
12) swd - downwelling shortwave radiation
13) swu - upwelling shortwave radiation
14) lwd - downwelling longwave radiation
15) lwu - upwelling longwave radiation
16) lwnet - net longwave radiation (=lwd-lwu)
17) swnet - net shortwave radiation at the surface (=swd-swu-swtransm)
18) alb - surface albedo (0-1) (swu/swd)
19) swtransm - solar radiation transmitted to bottom of sea ice (see text below for description)
20) radnet - net surface radiation (= swnet + lwnet)
21) hsmed - surface layer sensible heat flux (combination of available sonic anemometer observations and bulk flux estimates when sonic data is missing-- see text below)
22) usmed surface layer sensible heat flux (combination of available sonic anemometer observations and bulk flux estimates when sonic data is missing -- see text below)
23) hlmed surface layer latent heat flux (combination of sonic anemometer observations and bulk flux estimates when sonic data is missing-- see text below)
24) hturb - surface layer turbulent heat flux (= hsmed + hlmed)
25) cflxmed - median value of the conductive flux from the ASFG site, FLA, and Pittsburgh thermistor strings -- also from Quebec 2 in file with qb2 label -- see text below)
26) fatm - surface energy flux from atmospheric components (= swnet+lwnet-hsmed-hlmed)
27) fnet - surface net energy flux from all components (= fatm + cflxmed)

the 2-D parameters have dimensions 8785 X 2 and are:
28,29) t - air temperature at nominally 2 m and 10 m
30,31) q - specific humidity at nominally 2 m and 10 m
32,33) rh - relative humidity at nominally 2 m and 10 m
34,35) ws - wind speed at nominally 2 m and 10 m
36,37) wd - wind direction at nominally 2 m and 10 m

DESCRIPTION OF DATA SET AND CONCATENATION METHOD

2. Surface Energy Budget and Definitions

To define the SEB, we take an approach similar to Persson et al (2002). Consider a surface slab of finite thickness of a few centimeters up to one meter consisting of snow on top of sea ice, bare sea ice, or sea ice with melt ponds, depending on the time of year. This represents the conditions within a few hundred meters of the Atmospheric Surface Flux Group (ASFG) measurement site at SHEBA. The net energy flux, F_{net}, into this surface slab is given by

$$F_{net} = F_{atm} + C = Q_{net} - H_s - H_l + C, \tag{2.1}$$

where F_{atm} is the total atmospheric energy flux, Q_{net} is the net radiative flux given by

$$Q_{net} = SW_n + LW_n = SW_d - SW_u - SW_t + LW_d - LW_u \tag{2.2a}$$
$$= SW_d(1-\alpha) - SW_t + \varepsilon_s(LW_d - \sigma T_s^4), \tag{2.2b}$$

H_s (H_l) the turbulent sensible (latent) heat flux, C is the upward conductive flux through the ice and/or snow, SW_d (SW_u) and LW_d (LW_u) are downwelling (upwelling) shortwave and longwave radiative fluxes, SW_t is the shortwave radiation transmitted through the ice to the water below, α is the surface albedo, T_s is the surface temperature, ε_s (= 0.985) is the surface emissivity, and σ is the Stefan-Boltzmann constant. The turbulent heat fluxes will later be combined into one term as $H_{turb} = H_s + H_l$. In 2.2, T_s is related to the longwave radiation by

$$LW_u = (1-\varepsilon_s)LW_d + (\varepsilon_s\sigma)T_s^4 . \tag{2.3}$$

The shortwave radiation transmitted to the bottom of the ice can be expressed as a function of the SW_d, α, and an extinction function f dependent on the snow depth (D_s) and ice thickness (D_i) as

$$SW_t = SW_d(1-\alpha)\ f(D_s,D_i). \tag{2.4}$$

The expression for $f(D_s,D_i)$ used in this study is given by (3.3) in the next section.

The total energy flux F_{net} at a given time may be positive, negative, or zero. If F_{net} is positive, the surface slab of snow and/or ice gains energy, which can be used to either increase its temperature (energy storage) or, if the temperature is already at the melting point, to produce melting. If F_{net} is negative, energy is lost by the surface slab, and the surface water freezes or the slab temperature decreases. Note that we will only be discussing the change of phase in this surface slab, and not the change of phase at the bottom of the ice.

Since we are interested in the contribution of changes of individual terms to the changes of F_{net} during the summer transitions, we use (2.1) – (2.4) to obtain the change in F_{net} at a transition between two arbitrary time periods, designated as time periods 1 and 2 (e.g., before and after a transition, respectively), by:

$$\begin{aligned}\Delta F_{net} &= F_{net2} - F_{net1}\\ &= \Delta Q_{net} - \Delta H_s - \Delta H_l + \Delta C, \qquad (2.5)\end{aligned}$$

where

$$\begin{aligned}\Delta Q_{net} &= \Delta SW_n + \Delta LW_n \qquad (2.6a)\\ &= \Delta SW_d - \Delta SW_u - \Delta SW_t + \Delta LW_d + \Delta LW_u \qquad (2.6b)\\ &= (1-\langle\alpha\rangle)\Delta SW_d - \Delta SW_t + \varepsilon_s \Delta LW_d - \varepsilon_s \sigma \Delta(T_s^4) - \langle SW_d\rangle \Delta\alpha \qquad (2.6c)\\ &= [(1-\langle\alpha\rangle) - \langle f\rangle(1-\langle\alpha\rangle)]\Delta SW_d + \varepsilon_s \Delta LW_d - \varepsilon_s \sigma \Delta(T_s^4) - \langle SW_d\rangle(1-\langle f\rangle)\Delta\alpha - \langle SW_d\rangle(1-\alpha)\Delta f, \qquad (2.6d)\end{aligned}$$

and

$$\Delta SW_t = -\langle SW_d\rangle(1-\langle\alpha\rangle)\Delta f - \langle f\rangle(1-\langle\alpha\rangle)\Delta SW_d + \langle SW_d\rangle\langle f\rangle\Delta\alpha\ . \qquad (2.7)$$

The subscripted numbers indicate values for either period 1 or 2, $\langle\ \rangle$ indicates a mean value, and Δ indicates the difference of period 2 minus period 1. Equation (2.6c) shows that changes in downwelling short- and long- wave radiation, changes in T_s and α, and changes in SW_t contribute to changes in net radiation. If $\Delta SW_t > 0$ (e.g., at melt onset) or $\Delta SW_t < 0$ (e.g., at melt end), it will contribute as a slight negative feedback to a likely associated increase or decrease in Q_{net}, respectively. Equation (2.6d) uses equation (3.3) for the extinction function f and shows how it, and changes in it (i.e., Δf), impact the changes in Q_{net}.

We will also make use of the definition of effective sky temperature

$$T_{sky} = (LW_d/\varepsilon_{sky})^{0.25}, \qquad (2.8)$$

where we assume that the sky behaves as a black body with $\varepsilon_{sky} = 1.0$.

3. Concatenation of SHEBA Data Sets

During SHEBA, all of the energy fluxes in (2.1) and (2.2) except SW_t were continuously measured, and some terms were measured at multiple sites. For example, at least hourly values of SW_d and LW_d were measured at four sites [Atmospheric Surface Flux Group (ASFG), Atmospheric Radiation Measurement (ARM), SHEBA Project Office (SPO), and a Portable Automated Measurement (PAM) station called Florida (FLA)] near the main SHEBA camp and at 3 remote PAM stations up to 6 km away. Measurements of SW_u and LW_u were also made at the ASFG, FLA, and ARM sites. Covariance measurements of H_s were made at the ASFG site and the 4 PAM stations. Direct measurements of C using heat flux plates were made at the PAM stations, and C at FLA will be designated by C_{FLA}.

Temperature profiles in the snow and ice appropriate for calculating C were made at the ASFG site and several sites operated by the Ice Physics Group (IPG), including the Pittsburgh (PITT) and Quebec 2 (Q2) multi-year ice sites located ~100 m and ~500 m from the ASFG site, respectively [see Fig. 1 in Persson et al (2002) and Fig. 2 in Perovich et al (2003)]. Both of these IPG sites were multi-year ice sites. At the ASFG site, C is calculated from the measured surface and snow/ice interface temperatures (T_s and T_{ice}) and the measured snow depth using

$$C_{ASFG} = -k_s[(T_s - T_{ice})/D_s]\ , \qquad D_s > 0.06\ \text{m} \qquad (3.1a)$$

$$C_{ASFG} = -k_i\ [(T_s - T_w)/D_i]\ , \qquad D_s \le 0.06\ \text{m} \qquad (3.1b)$$

where k_s (= 0.3 W m^{-1} K^{-1}; Sturm et al 2002) and k_i (= 2.0 W m^{-1} K^{-1}) are the thermal conductivities of snow and ice, respectively; D_s and D_i are the snow depth and ice thickness, respectively; and T_w (= -1.8° C) is the temperature of the ocean water below the ice. Snow depth was not measured at the ASFG site after snowfall began in early August, so C_{ASFG} is only available until July 27, 1998 (YD573).

At the IPG PITT and Q2 sites, a string with thermistors located every 5-10 cm provided temperature profiles through the snow and ice. The tops and bottoms of the snow and ice are given by the averages of these quantities from the four depth gauges at each site (see Perovich et al 2003). The near-surface temperature gradient is determined by the average gradient across the two thermistor layers below but closest to the surface. The average site snow depth (D_{sP}) determines whether these layers consist of the same medium, or if weighted averages of the thermal conductivity is necessary. The conductive flux at these IPG sites (e.g., C_{Pitt}) is computed by:

$$C_{Pitt} = k_{si}\,[(T_1-T_2)/(z_1-z_2) + (T_2-T_3)/(z_2-z_3)]/2\,, \qquad (3.2)$$

where

$$k_{si} = k_s \qquad D_{sP} > 0.10 \text{ m}$$
$$k_{si} = [(0.1-D_{sP})k_i + D_{sP} * k_s]/0.1 \qquad D_{sP} \le 0.10 \text{ m}$$
$$k_{si} = k_i \qquad D_{sP} = 0$$

and (z_1, z_2, z_3) and (T_1,T_2,T_3) are the heights and temperatures of the three thermistors defining the nearest two subsurface layers. C at Quebec 2 (C_{Q2}) is similarly computed.

Though the ASFG data set provides more than 80% of most of the SEB terms (Table 1; also see Persson et al 2002), to optimize the data recovery we combine the available SHEBA observations to obtain more than 93% of a full year of high-quality hourly values of all of the SEB terms from October 9, 1997, through October 8, 1998. To accomplish this goal, the following steps are used:

1) Meteorological data and all SEB terms are initially filled with ASFG data, excluding snow depth and ice thickness.
2) Missing meteorological data (T, ws, wd, q, rh, p) are filled in from the two-level SPO tower. This includes temperatures, humidity, and wind at both 2 and 10-m levels.
3) Ice thickness (D_i) is computed from the four Pittsburgh (IPG) depth gauges. Missing values within the time series are interpolated. Missing values at the beginning and end of the time series are assumed to be the same as the first and last measured values, respectively.
4) Snow depth (D_s) is computed as the mean value of the following three values: the ASFG snowstake depth, the mean snow depth from the four Pittsburgh depth gauges, and the mean snow depth from four manual snowlines (Mainline, Tuk, Atlanta, and Baltimore – see Perovich et al 2003). Missing values within the time series are interpolated. Missing values at the beginning and end of the time series are assumed to be the same as the first and last measured values, respectively.
5) Missing SW_d and LW_d are filled in first from the ARM data, then from the FLA data, and finally from the SPO data. Because the SPO measurements were the first ones started and the last ones to be packed, much of the October data are from this source.
6) Missing LW_u values are filled in first from the FLA measurements and then computed from available LW_d and T_s values using (2.3).

7) Missing SW_u values are estimated from observed SW_d values and smoothed and interpolated albedo values from the ASFG data. Missing albedo values before May 27 and after August 16 are set to 0.85.
8) Missing T_s values are filled in from other sources in the following priority: a) computed from the Florida PAM station LW_u measurements, b) computed from the Pittsburgh thermistor string, and c) set equal to the observed 2-m temperatures.
9) C is estimated as the median of the following three values: a) C_{ASFG}; b) C_{FLA}, and c) C_{Pitt}. If any are missing, only the remaining ones are used. No C_{ASFG} values are available after July 27 since the ASFG snow depth measurements weren't made after that date.
10) Missing values of H_s are first filled in with covariance-measured values from FLA. The remaining missing values are filled in with bulk estimates computed from the values of T_s, and 2 and 10-m winds and temperatures. If bulk fluxes are available for both 2-m and 10-m levels, the mean is used; otherwise the available value is used. The bulk scheme is that used by Persson et al (2002), except that the stability correction is done using the relationships of Grachev et al (2007).
11) Missing values of H_l are filled in with bulk values determined by the same scheme as above and the 2 and 10-m absolute humidity observations.

The majority of hours of missing fluxes in the combined data set are in October 1997 or October 1998 when radiation, T_s, or ice/snow temperature profile data are missing (Table 1). Gaps also occur in March. The observed ARM SW_u and LW_u are not used as they appear contaminated, producing unrealistically low albedos and high T_s (not shown). The albedos from FLA are not used because this station was moved ~200 m twice during the year; however, they are similar to the ASFG albedos, though with artificial "jumps" at the moves. Figure 1 shows that the ARM, SPO, and FLA downwelling radiation values are comparable to the ASFG ones (biases of -6-+3 W m^{-2}; RMSD of 3-14 W m^{-2}), with the ARM data being in particularly good agreement with the ASFG data. Figure 2 shows that the FLA and PITT T_s and the ASFG and SPO T_{a1} values are in reasonable agreement with the ASFG T_s at times when both are present (biases of +0.2 - +0.9° C; RMSD of 0.7-1.5° C), with the FLA T_s showing particularly good agreement. The T_{a1} values are biased high by a few degrees for the colder T_s temperatures (Fig. 2b). Hence, with these generally good agreements, the data uses as described in steps 5 and 8, respectively, are justified.

Solar transmission through sea ice (SW_t) has recently been shown to be an important SEB component (Perovich et al 2003; Light et al 2008), especially at the end of the summer melt season when no snow cover is present. It is therefore included in our budget. As it was not continuously measured during SHEBA, it is parameterized using the observed SW_d, α, snow depth (D_s), ice thickness (D_i), and Beer's Law. This requires estimates of the solar extinction coefficient in snow (kx_s = 10 m^{-1}; Liljequist 1956, Fig. 4 in Bohren and Barkstrom 1974) and in ice. The latter has been divided into coefficients for the visible (kx_{iv}= 0.72 m^{-1}) and near-infrared (kx_{in}= 4.6 m^{-1}) portions of the solar spectrum. These ice extinction coefficients and the ice surface transmission parameters (I_{0v} = 0.95; I_{0n} = 0.37) are averages of those given by Light et al (2008) for multi-year melting ice and multi-year ponded ice and these spectral bands. Weighting the solar radiation into 60% visible (f_v = 0.60) and 40% near-infrared (f_n = 0.40) radiation produces reasonable estimates of the solar albedo from the visible and near-infrared albedos given by Light et al. These values are used to calculated SW_t from

$$\begin{aligned} SW_t &= SW_d\,(1-\alpha)\; f(D_s,D_i) \\ &= SW_d\,(1-\alpha)\; e^{-k\,x_s\,D_s}(I_{0v}\,f_v\,e^{-k\,x_{iv}\,D_i} + f_n\,I_{0n}\,e^{-k\,x_{in}\,D_i}). \end{aligned} \tag{3.3}$$

Comparisons to the Aug. 6 SHEBA observations of transmitted light described by Light et al. with the same snow, ice and downwelling radiation conditions produce solar transmission of 9.8 W m^{-2} and 2.3 W m^{-2} for 1 m and 3-m thick ice, respectively. These values are slightly lower than the observed (15.2 W m^{-2} and 3.2 W m^{-2}, respectively), but much greater than the values produced by the Community Climate Model (CCSM3) as shown by Light et al. Hence, our parameterization of SW_t provides a reasonable, but perhaps somewhat conservative, estimate of the true value. Because of large α and kx_s, the amount of solar radiation transmitted through the SHEBA springtime snowpack of $D_s \approx 0.35 - 0.40$ m is small, so hourly values of SW_t at the end of May are only about 0.1 W m^{-2} despite SW_d values approaching 600 W m^{-2} at solar noon. However, by the end of June when the snow cover is greatly reduced, SW_t reaches hourly (daily) values up to 5 -7 (2.5) W m^{-2}. Later in July when all of the snow is gone, the surface albedo is reduced, and the ice is thinner, hourly (daily) SW_t values reach up to 30-37 (15) W m^{-2}. The direct energy flux to the snow and ice is reduced by SW_t. However, this energy is absorbed by the top layers of the ocean below and some of it may later be used to melt the bottom of the sea ice (or delay the bottom formation of sea ice).

Other SHEBA data sets used in this study include the 2-4 times daily rawinsonde launches, radar reflectivity from a 8-mm cloud radar (MMCR) (Intrieri et al 2002a; Uttal et al 2002), National Meteorological Center (NMC) surface and 500 mb analyses, and NOAA infrared and visible satellite imagery. Detailed descriptions of these and other SHEBA data sets, including the data, can be found at http://www.eol.ucar.edu/projects/sheba/. General descriptions of the SHEBA data collection effort are provided by Perovich et al (1999) and Uttal et al (2002), while details are given in Persson et al (2002), Intrieri et al (2002b), Grenfell and Perovich (2004), and Perovich et al (2002, 2003).

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