Annual Evolution of Surface Energy Flux at Summit, Greenland

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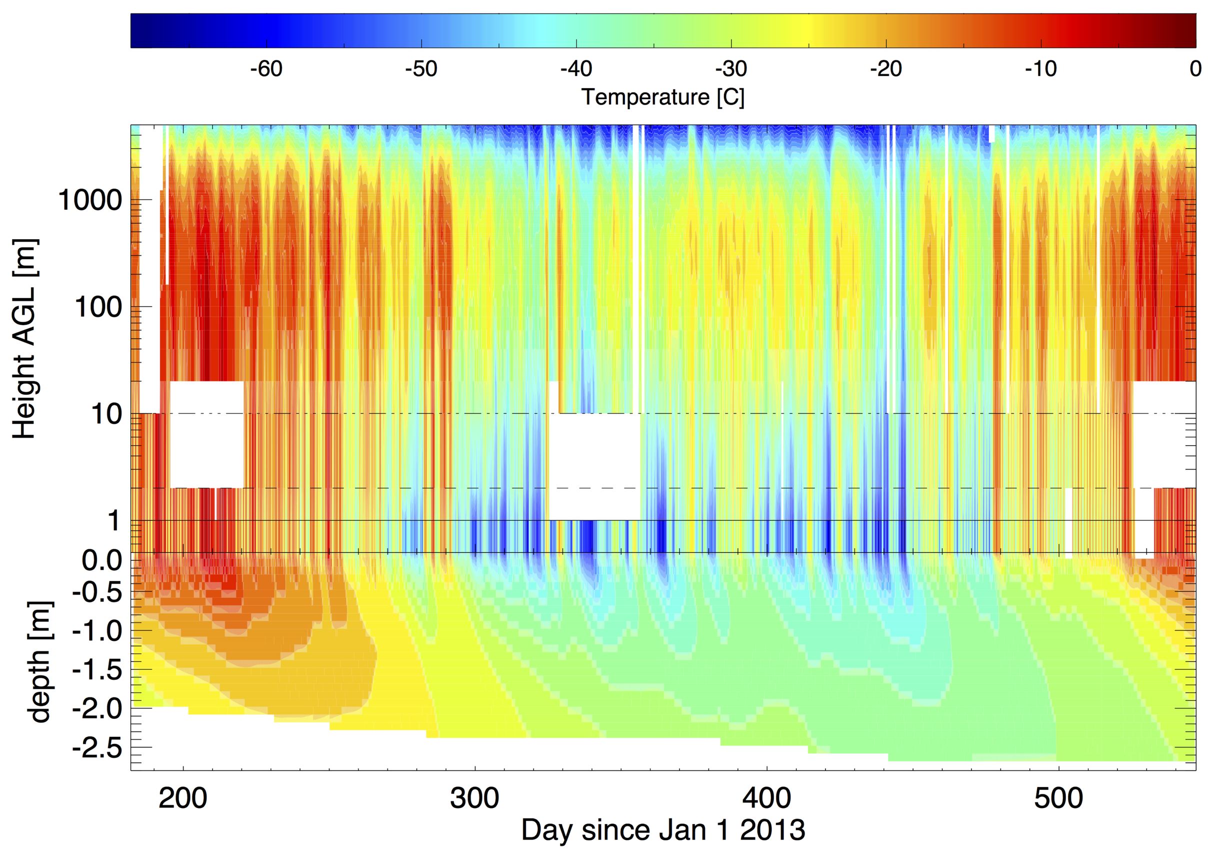
Surface Temperature



Temperature evolution from 1 July 2013 – 30 June 2014. Values between the solid horizontal lines indicate surface temperatures T_{surf}, the dashed (dashed-dotted) line at 2 m (10 m) level is NOAA/GMD measurements, and from 20 m to 5km above ground level (AGL) is derived from twice-daily soundings. The height scale AGL is logarithmic to emphasize the near-surface values where the atmospheric and GIS are physically coupled. Subsurface temps are on a linear scale.

Surface Energy Budget:

In the absence of snow melt, the Surface Energy Budget (SEB) is composed of 4 components: Net Radiation (Q), Turbulent Heat Fluxes ($H_{sensible}$ and H_{latent}), and a Conductive Heat Flux (C).

$$\mathbf{0 = Q + H_{sensible} + H_{latent} + C}$$

where:

$$\mathbf{Q = LW_{down} - LW_{up} + SW_{down} - SW_{up}}$$

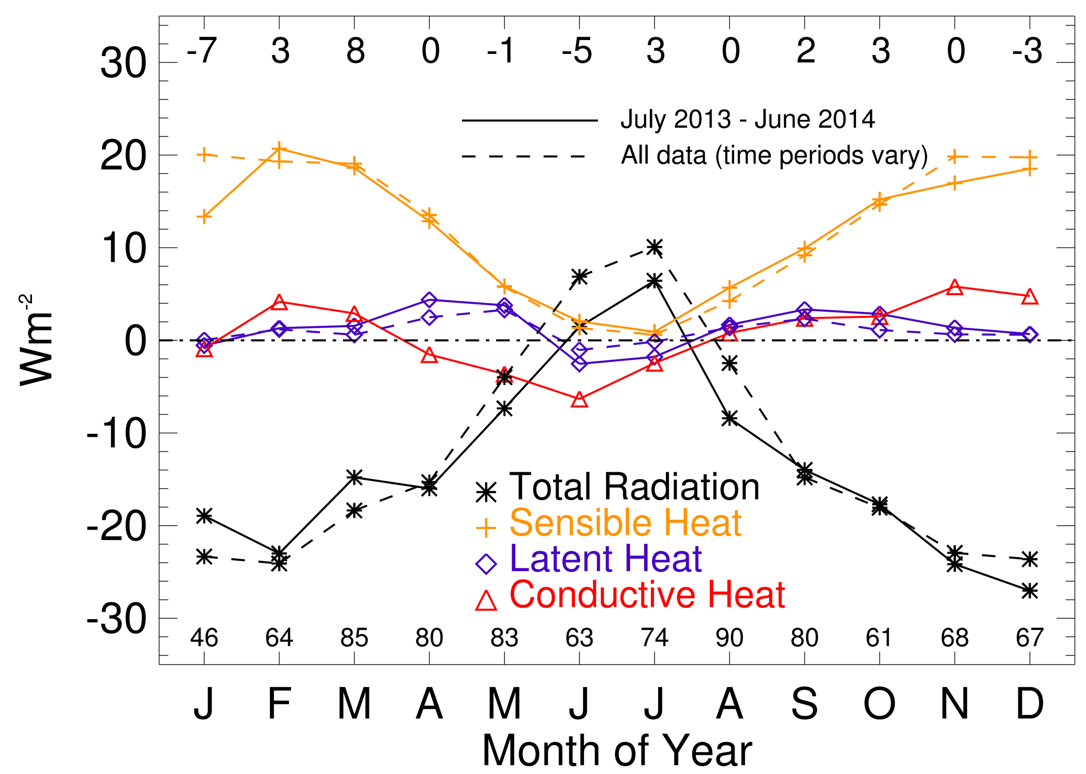
Surface temperatures are related to the upwelling longwave radiation via the snow emissivity (ϵ):

$$\mathbf{LW_{up} = \epsilon\sigma T^4}$$

In order to investigate surface temperature biases in a reanalysis product or global climate model we must first understand the energy exchange processes occurring at the ice/atmosphere interface. Specifically, how each SEB component responds to atmospheric forcing due to solar and/or cloud occurrence.

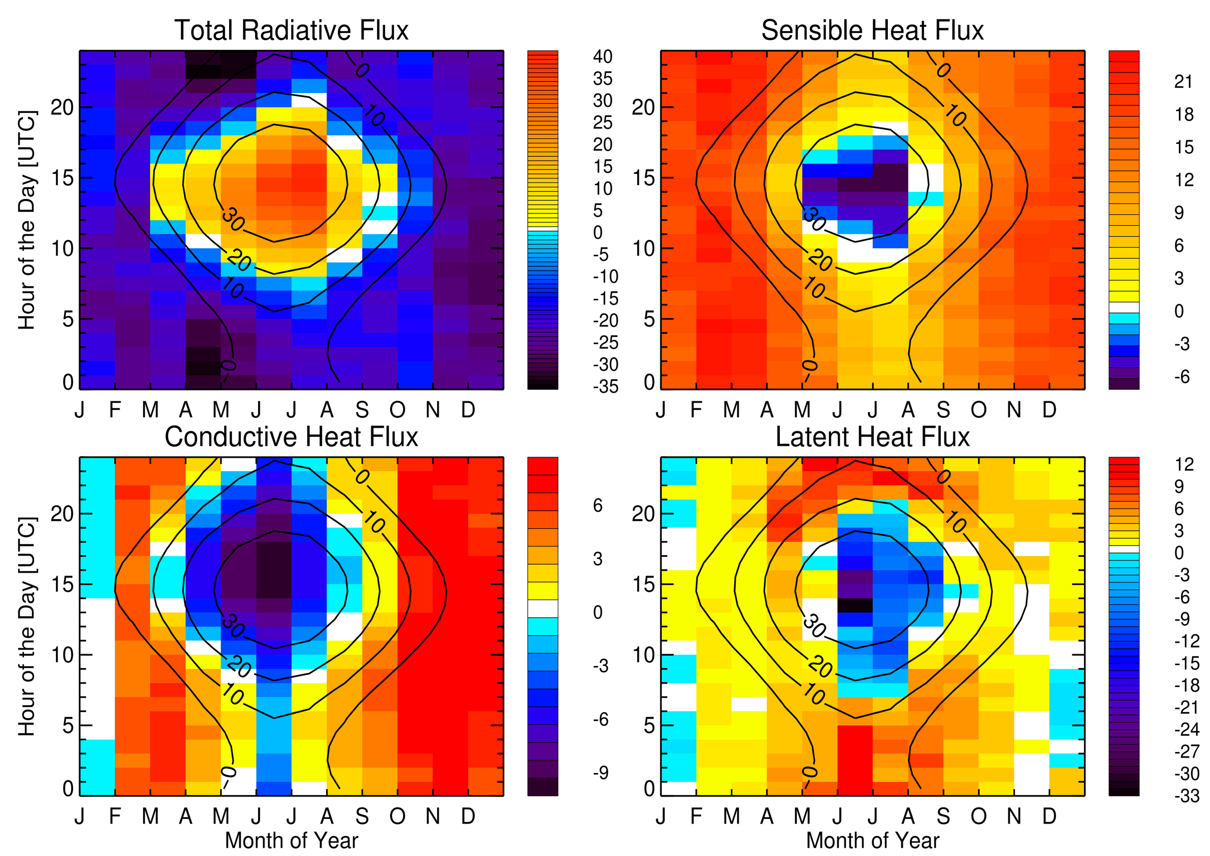
Annual Cycle of Surface Flux

The monthly mean values of each of the SEB terms. A positive value represents a warming of the surface and a negative value is a cooling of the surface. The monthly residuals are shown in red at the top of the panel [Wm^{-2}].



Monthly percentages of the occurence of all four 30-minute SEB values are at the bottom of the figure.

Monthly Diurnal Cycles



Hourly mean values from July 2013 – June 2014. Black contour lines indicate the solar elevation angle. Units on the color bars are all in $W\ m^{-2}$.

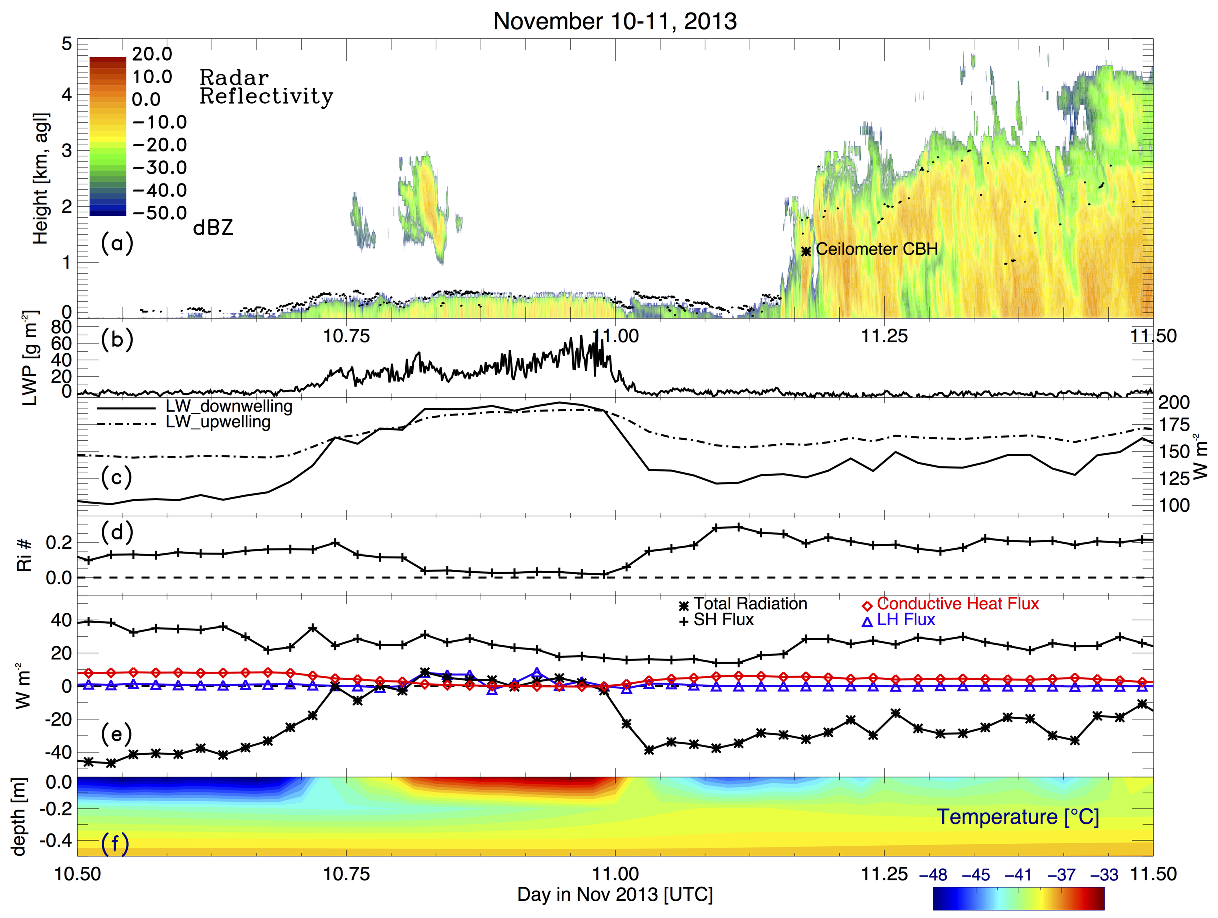
A Case Study

The case study is for the time period: November 10 (12UTC) to November 11 (12 UTC), 2013, illustrates the contrast between a clear-sky scene, a scene containing a liquid-bearing cloud and a scene containing an ice-cloud.

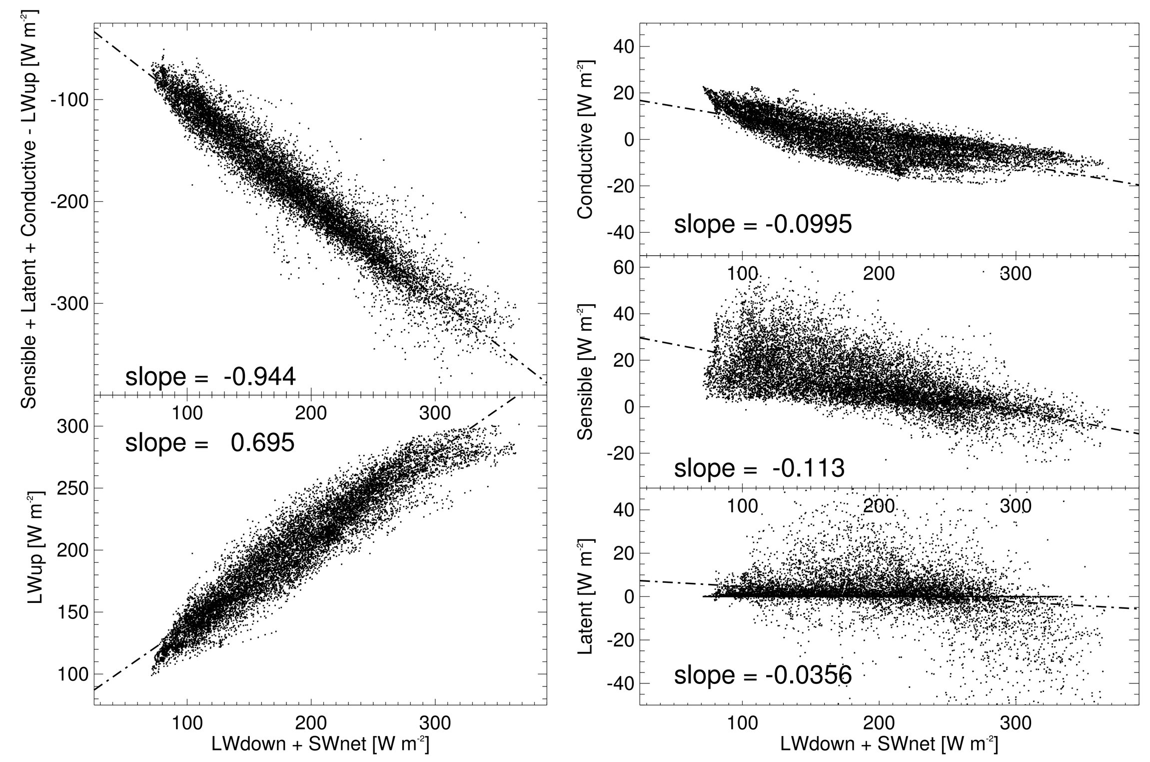
The liquid-bearing cloud increases the downwelling longwave radiation drastically. Consequently, the near surface layer changes from stable to a more neutral situation, as indicated by the gradient richardson number.

The sensible heat flux decreases in the presence of the liquid-bearing cloud and the latent heat flux increases slightly as more mixing occurs during times of near neutral stability.

The conductive heat flux initially warms the surface during the clear-sky period, then has a cooling effect in the presence of the liquid-bearing cloud. Overall, the clouds act to warm the ice sheet.

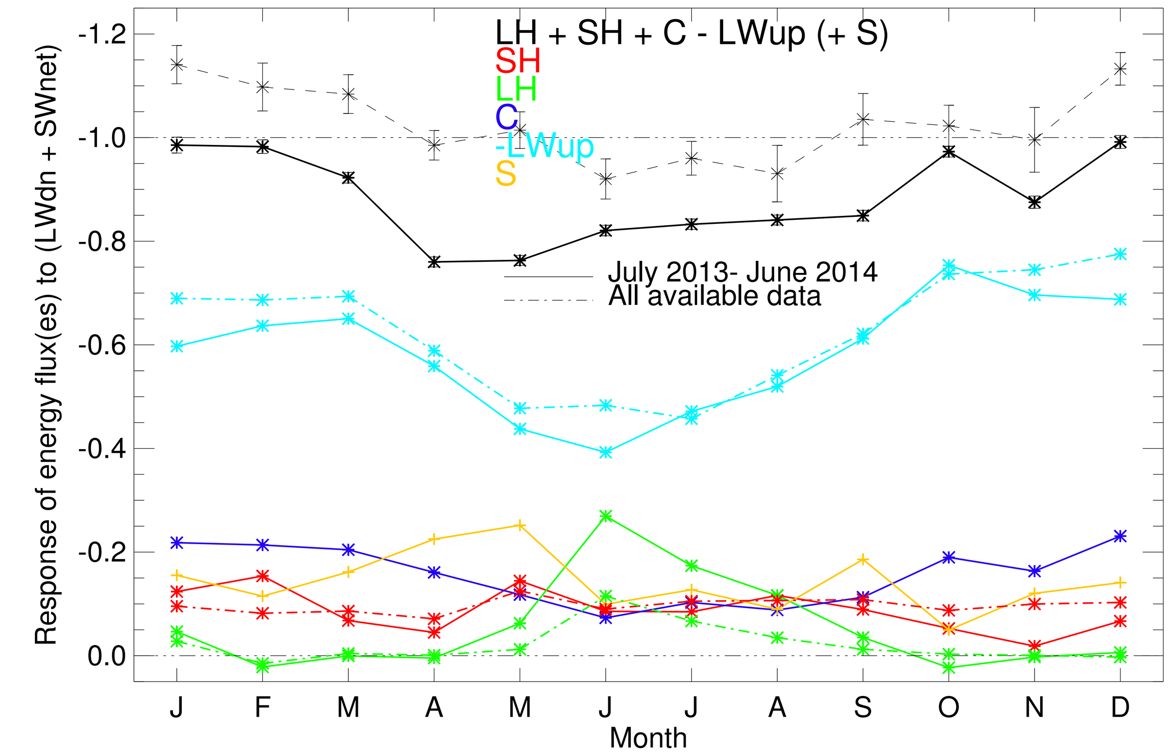


Response to Cloud Radiative Forcing



Clouds and/or insolation radiatively warm the central GIS surface (Miller et. al. 2015, *J. Climate*) effectively increasing the radiative forcing terms (LW↓ + SW_{net}). The surface energy budget responds to the increase in the radiative forcing by decreasing H_{latent}, $H_{sensible}$, and C, while increasing LW↑ (a proxy for surface temperature). Linear regression analysis estimates annual responses to radiative forcing (Figure above).

Due to seasonal changes in near-surface atmospheric stability, available moisture, snow density, and the subsurface temperature gradient the response of the non-radiative terms, and consequently LW↑, changes throughout the year (Figure below).



It is important to also consider the response of the ground heat flux (S), to account for solar penetration in the upper most layer of the snowpack. By including the response of S during the non-winter months the total monthly response (dashed black line) is closer to -1.

$$\mathbf{S = -c_{ice}\,\rho\,\frac{\Delta T(z_0)/\Delta t + \Delta T(z_1)/\Delta t}{2}\,(z_0 - z_1)}$$

where z_0 is the surface level and z_1 is the level of the shallowest thermistor (≈ -20 cm).

Measurements

- ICECAPS project – Atmospheric state and cloud properties. (Shupe et. al. 2013, *BAMS*)
- Broadband Radiometers – Upwelling and Downwelling Shortwave and Longwave Radiation
- Bulk Aerodynamic Method – Turbulent sensible heat flux estimates based on differences between the temperatures and wind speeds at 2m and the surface. (Persson et. al. 2002, *JGR*)
- Gradient 2-level method – Turbulent latent heat flux estimates based upon the gradient of moisture and wind speed between 10m and the surface.
- Thermistor String – Subsurface temperature sensors used to calculate the conductive heat flux.

Data and Funding

This research is supported by the National Science Foundation under grants PLR1303879 and PLR1314156. For ICECAPS data access or questions contact: Von Walden (**v.walden@wsu.edu**), Matthew Shupe (**matthew.shupe@noaa.gov**), David Turner (**dave.turner@noaa.gov**), or Ralf Bennartz (**bennartz@aos.wisc.edu**). For inquiries regarding the ETH measurements contact Konrad Steffen (**konrad.steffen@wsl.ch**).