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The Energy Balance at Summit, Greenland

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European Geosciences Union
1st General Assembly
Nice, France, 25.- 30. April 2004

Introduction

The heat budget is a key to understand the reaction of the Greenland ice sheet to a changing global climate and its effect on global sea level.
About 40 % of the ice sheet is occupied by the dry snow zone. It is characterized by a high surface albedo and plays an important role for the mass balance of the ice sheet, as 57% of the total annual net accumulation takes place in this region (Ohmura et al., 1999).
Greenland Summit Environmental Observatory lies in the middle of the dry snow zone of the ice sheet (72.58°N, 34.46°W) at an elevation of 3203 m. This site, with its homogeneous and smooth surface, its practically unlimited fetch, and frequent occurrence of strong stratifications, is an ideal laboratory for studying the stable atmospheric boundary layer.
The main components of the surface energy budget, net radiation (NR), subsurface heat flux (G), and the turbulent exchange of sensible (H) and latent (L_vE) heat are derived from measurements from the ETH field campaign at Summit Environment Observatory starting in June 2001 and ending in July 2002.
Over a longer time, in a stable climate, the sum of energy fluxes to towards the surface must be zero:

$$NR + H + L_vE + G = 0$$

Radiation Balance (NR)

Radiation Measurements at Summit

All shortwave and longwave components of the radiation budget, including direct beam measurements with an active solar tracking device, are monitored in high temporal resolution. Measurements follow closely the standards of the Baseline Surface Radiation Network (BSRN) (Ohmura et al., 1998). Instrumentation is set up to resist the harsh environment met at the Summit site: Instrument domes are ventilated with slightly heated air to greatly reduce riming of the domes of pyranometers and pyrgeometers. Riming has often been the cause of unreliable radiation measurements in the Arctic and Antarctic.

Annual cycles of radiative fluxes in 2001 are shown in Figure 1. Seasonal changes in cloud cover lead to a change in the ratio between diffuse and direct radiation: Clear sky weather dominates until June, which causes direct radiation to dominate over the diffuse. From July on, overcast skies prevail, making the diffuse the principal shortwave component.
During polar night, net radiation reduces to the longwave balance.

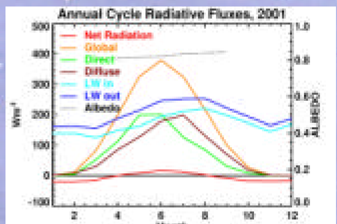

Figure 1

Subsurface Heat Flux (G)

Detailed information of the temperature profile and its temporal evolution on a diurnal and annual timescale is obtained with a vertical array of thermistors and thermocouples reaching a depth of 15 m. The vertical resolution is enhanced in the top layers. Surface temperature is derived from measurements of outgoing longwave radiation. The subsurface heat flux is calculated from the rate of change of thermal energy storage in each layer. It comprises conductive heat flux, sensible heat transport by wind pumping, latent heat transport caused by sublimation and resublimation within the snow layers, and shortwave radiative divergence within the snow.

Figure 2 shows monthly mean temperature profiles (tautochrones) within the snow pack for the months between July 2001 to June 2002. The annual temperature cycle reaches a depth of about 11 m.
Subsurface heat flux is an important heat source in winter and heat sink in summer. During summer, on a diurnal time scale, about half of the energy supplied by net radiation is directly withdrawn from the surface by the subsurface heat flux. A maximum is reached in January with 9 Wm^{-2} and a minimum in June with -9 Wm^{-2}.

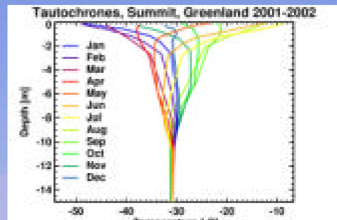

Figure 2

Sensible (H) and Latent (L_vE) Heat Flux

Turbulent fluxes of sensible heat H and latent heat L_vE have been directly measured by eddy correlation, using Gill R2A sonic anemometers and Krypton KH2O fast sampling hygrometers. They were also derived from measured temperature and humidity profiles, using bulk formulations based on Monin-Obukhov-Theory. The preliminary results from these calculations using the parameterizations from the ECHAM4 general circulation model (Roeckner et al., 1996) are presented here. A roughness length for heat, z_0, of 0.001 m, and a relative humidity of 100% were assumed for the snow surface.

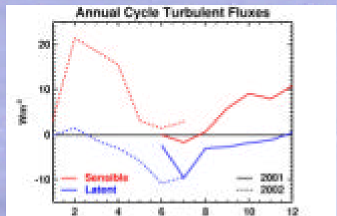

Figure 3

The annual cycle of the turbulent heat fluxes are presented in Figure 3. During the cold months, sensible heat flux is generally positive, directed towards the surface. It compensates to a large extent the heat loss caused by a negative radiation balance, and reached more than 20 Wm^2 in February 2002. In the summer months, sensible heat flux is small, and even has been negative in July 2001.

Latent heat flux is generally negative, with the exception of February 2002, when resublimation led to a net energy source for the snow surface. In summer, sublimation dominates, and latent heat flux ranges around -10 Wm^2.

Direct measurements of sublimation and resublimation are obtained using snow lysimeters, and can be compared to results from the bulk method. In Figure 4 latent heat fluxes are presented for a two day period in June 2001. Lysimeter measurements suggest that results from bulk parameterization tend to underestimate latent heat fluxes.

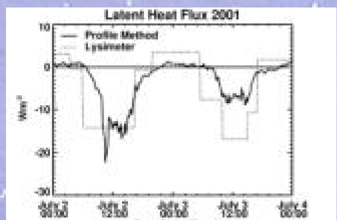

Figure 4

Snow Lysimeter

Diurnal Cycles

During the winter months, the surface is cooled due to a negative longwave radiation balance. This cooling effect is mainly balanced by a positive sensible heat flux, and to approximately 1/3 by the subsurface heat flux. Latent heat flux is slightly positive. As the sun is below the horizon between mid November and late January, no significant diurnal variation of energy fluxes occur.
In summer, monthly mean net radiation is positive, and net radiation is positive throughout the larger part of the day. Monthly mean sensible heat flux is close to zero, but a transport of sensible heat away from the surface can be seen as early as in the mean diurnal cycle of April. Negative sensible flux dominates for 10 hours in June, indicating unstable conditions close to the surface.
Positive net radiation is balanced in equal parts by the cooling due to sublimation (loss of latent heat) and by a negative subsurface heat flux. Warming of the surface by a positive latent heat flux can be observed during clear-sky summer nights, but in the monthly mean diurnal cycle, latent heat flux remains directed away from the surface.
The residuals of the seasonal energy balance are relatively large, ranging from -6 Wm^2 in fall to 4 Wm^2 in spring.

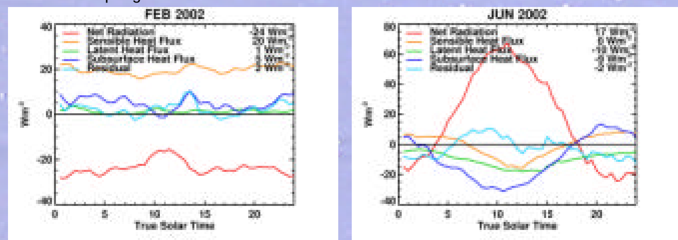

Figure 5: Monthly mean diurnal cycles of surface energy balance components for winter month February and summer month June, 2002.

Energy and Mass Balance

Season 01/02	Net Radiation (NR)	Sensible Heat Flux (H)	Latent Heat Flux (L_vE)	Subsurface Heat Flux (G)	Residual
DJF	-20	12	1	6	-2
MAM	-3	12	-3	-2	4
JJA	11	1	-6	-6	-1
SON	-15	8	-2	4	-6
YEAR	-7	8	-3	1	-1

Table 1: Seasonal energy balance at Summit, Greenland. All values are in Wm^{-2}.

Season 01/02	Precipitation (P) mmWE	Sublimation (E) mmWE	Mass Balance (M) mmWE
DJF	61	-2	63
MAM	39	9	30
JJA	67	18	50
SON	104	5	99
YEAR	272	31	242

Table 2: Seasonal mass balance at Summit, Greenland. All values in mmWE.

The seasonal mass balance for the summit site, neglecting melt and mass changes due to snow drift, is shown in Table 2. The connection between energy and mass balance can be illustrated for the summer season: Although the energy input from net radiation is small, 25 % of the precipitation can be sublimated. In summer, when sensible heat flux is negligible, the high subsurface heat flux prevents an even higher mass loss due to sublimation.
On an annual average, sublimation amounts to about 10 % of the mass gain through precipitation.

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Acknowledgements

Swiss National Science Foundation,
PMOD/WRC Davos,
US National Science Foundation,
Veco Polar Resources, US National Guard

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Greenland Summit Environmental Observatory