Using automatic weather station data to quantify snowmelt

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Motivation

Snowmelt constitutes an important part of the surface energy and mass balance of the ice sheets of Greenland and Antarctica. In Greenland, the entire ice sheet experiences occasional melt, as indicated by thin, isolated ice lenses in firn cores drilled at the highest part of the ice sheet and supported by regional atmospheric climate models (Ettema *et al.*, 2010). In Antarctica, melt is limited to the coastal areas, but is especially significant in the Antarctic Peninsula, where the melt season may last as long as three months (Tedesco and Monaghan, 2009). On both ice sheets, the largest fraction of the melt energy is invested in the melting of snow rather than ice. The reason is that the Greenland ablation zone is relatively narrow and constitutes less than 10% of the total surface area. In Antarctica, ablation areas form at locations where sublimation (not melt!) locally exceeds snowfall. These so-called blue ice areas constitute less than 1% of the total surface area and as a result, nearly all surface melt in Antarctica is due to snowmelt.

The energy associated with the melting of glacier ice can be deduced from surface height changes, obtained from re-measuring stakes that are fixed deep in the ice, or monitored continuously using sonic height rangers (Van den Broeke *et al.*, 2011). The conversion from height change to melt energy is simple, because glacier ice has a density that is known to within 1% (910 +/- 10 kg m^{-3}). A correction must be made for the effect of mass transport by sublimation/deposition (riming), but usually this is a second order effect.

Snow height changes can be measured equally well, but the conversion to melt energy is much more problematic. The reason is that, apart from melting and sublimation/deposition, snow surface height is also influenced by erosion/deposition of blowing snow and densification of snow layers between the anchor point of the instrument and the surface. Even if one could be certain that melt is the only process affecting local snow height, the height change can only be converted to melt energy if the density of the surface snow is known. Surface snow density is hard to measure and, because no international standard exists for the depth to which surface snow should be sampled, it is an ill-defined quantity anyway.

Not being able to directly observe snowmelt energy constitutes an important problem in climate and surface mass balance research, because (regional) climate models calculate snowmelt energy (or melted snow mass, which is equivalent), and thus require observed snowmelt energy (or mass) for model evaluation.

Surface energy balance model

An indirect yet sufficiently accurate way to quantify snowmelt energy is to use a surface energy balance (SEB) model in combination with data of manned weather stations (MWS) or automatic weather stations (AWS). The SEB of a melting 'skin' layer of snow is given by:

$$M = SW_{net} + LW_{net} + SHF + LHF + G_s \qquad [Wm^{-2}]$$

where M is melt energy, SW_{net} is absorbed (net) shortwave radiation, LW_{net} is net longwave radiation, SHF and LHF are the turbulent fluxes of sensible and latent heat and G_s is the subsurface (conductive) heat flux, evaluated at the surface. All terms are defined positive when directed towards the surface. To calculate G_s, a snow model that simulates snow temperatures and meltwater percolation/refreezing is required. To calculate SHF and LHF requires instrument height and surface momentum roughness (z_0) to be known. The scalar roughness lengths for heat (z_h) and moisture (z_q) can then be calculated using the expressions of Andreas (1987), with the adjustments for rough ice surfaces of Smeets and van den Broeke (2008). If z_0 varies significantly in time, its value can be obtained from two-level measurements of wind speed during neutral conditions (Van den Broeke *et al.*, 2009).

For a sufficiently accurate determination of the SEB components, the MWS/AWS measurements should be of good quality and with few data gaps. Especially important is the availability of a complete series of radiation measurements. For use on AWS, the Kipp and Zonen CNR1 has proven to be a good choice; this sensor measures all four radiation components in a single housing, with sufficient accuracy once corrections have been applied for the relatively poor cosine response at low sun elevations. Being single-domed, the shortwave sensors are relatively insensitive to riming (Van den Broeke *et al.*, 2004). For a more detailed description of the SEB solving technique and AWS sensors used in Greenland and Antarctica, we refer to Van den Broeke *et al.* (2011) and references therein.

Example applications

Figure 1 shows two examples of the seasonal cycle of SEB components based on multiyear AWS data from Greenland (S9, 67°03' N, 48°14' W, 1520 m asl, data period 1 Sep. 2003 - 31 Jul. 2010) and MWS data from Antarctica (Neumayer station, 70°39' S, 8°15' W, 40 m asl, data period 1 Jan. 1995 - 31 Dec. 2007). Note the different scales on the vertical axes. Using daily-maintained, ventilated and heated radiation sensors, the MWS radiation data quality is clearly superior to that of the AWS data, and the calculated SEB components therefore more accurate. Yet, a direct comparison of observed and SEB-modelled surface temperature under non-melting conditions shows that the RMSE for the AWS in Greenland (0.97 K)

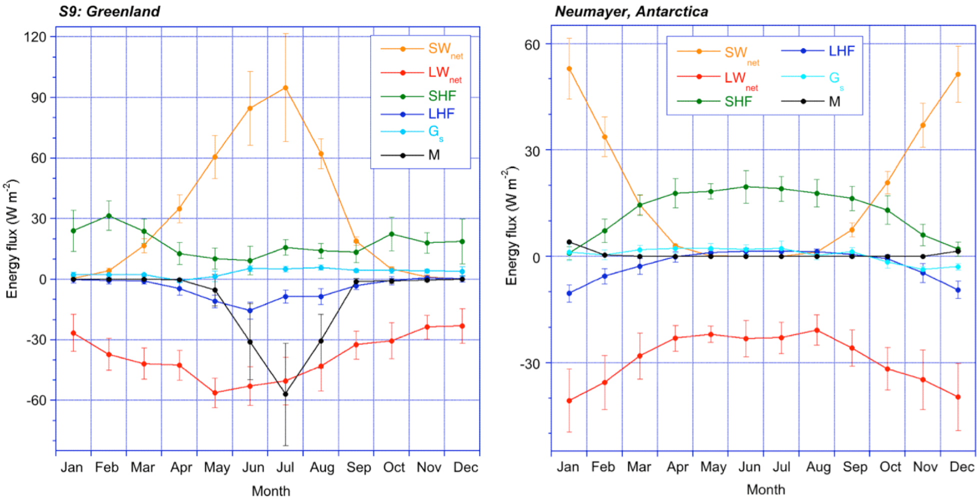

Figure 1. Seasonal cycle (based on monthly means) of SEB components at AWS S9 situated on the Greenland ice sheet (67°03' N, 48°14' W, 1520 m asl, data period 1 Sep. 2003 - 31 Jul. 2010) and Neumayer station in Antarctica (70°39' S, 8°15' W, 40 m asl, data period 1 Jan. 1995 - 31 Dec. 2007). Error bars indicate standard deviation of the monthly means. Note the difference in vertical scales.

is only marginally larger than for the MWS in Antarctica (0.73 K). Note that at both locations, the net radiation components to a large extent determine the SEB. Melting at the Greenland location lasts 3-4 months and peaks after the summer solstice in July, when the shortwave reflectivity (albedo) of the metamorphosed snow surface is lowest and SW_{net} as a result largest. At Neumayer, melt is marginal and peaks around the summer solstice in December and January, the months with the largest SW_{net} values. In spite of the very different climatological conditions and melt intensities, the SEB model generates realistic melt energy for both locations that can be used to evaluate regional climate models that are applied to the full ice sheets and/or satellite melt detection products. The great advantage of using an SEB model is that not only melt energy, but all individual SEB components are quantified, which is very valuable for the evaluation of physical processes that determine surface heat exchange in atmospheric models.

References

Andreas, E.. 1987. A theory for the scalar roughness and the scalar transfer coefficients over snow and sea ice. *Boundary-Layer Meteorol.*, **38**(1-2), 159–184.

Ettema, J., M. van den Broeke, E. van Meijgaard and W. van de Berg. 2010. Climate of the greenland ice sheet using a high-resolution climate model – part 2: Near-surface climate and energy balance. *The Cryosphere*, **4**, 529–544.

Smeets, C. and M. van den Broeke. 2008. The parameterisation of scalar transfer over rough ice. *Boundary-Layer Meteorol.*, **128**, 339–355.

Tedesco, M. and A. Monaghan. 2009. An updated antarctic melt record through 2009 and its linkages to high-latitude and tropical variability. *Geophys. Res. Lett.*, **36**(L18502). Doi: 10.1029/2009GL039186.

Van den Broeke, M., D. van As, C. Reijmer and R. van de Wal. 2004. Assessing and improving the quality of unattended radiation observations in antarctica. *J. Atmos. Oceanic Technol.*, **21**(9), 1417–1431.

Van den Broeke, M., C. Smeets and J. Ettema. 2009. Surface layer climate and turbulent exchange in the ablation zone of the west greenland ice sheet. *Int. J. Climatol.*, **29**, 2309–2323. Doi: 10.1002/joc.1815.

Van den Broeke, M., C. Smeets and R. van de Wal. 2011. The seasonal cycle and interannual variability of surface energy balance and melt in the ablation zone of the west greenland ice sheet. *The Cryosphere*, **5**, 377–390.