Referee's comments are in black.

Author's responses are in blue.

Author's changes in the manuscript are in red.

P. Kuipers Munneke (Referee)

Received and published: 3 November 2016

Review of "Forcing and responses of the surface energy budget at Summit, Greenland" by Nathaniel Miller et al., submitted for publication in The Cryosphere.

GENERAL

This manuscript presents a multi-year data set of surface energy budget observations, including one year with sufficient observations for a full closure of the budget, from July 2013 to June 2014. While similar estimates and observations have been presented in earlier literature, this paper extends the analysis towards forcings, responses, and the role of clouds and cloud types on the SEB terms and surface temperature.

This paper is clearly written, well illustrated, and a relevant contribution to the recent surge in literature on the effect of clouds on Greenland climate. The efforts that went into the collection of these rich data definitely warrant publication. However, I feel that the manuscript could benefit from some restructuring, more condensed writing, and some additional analysis. Regarding the latter, I feel a bit of a disconnect between the presentation of the monthly-mean and annual SEB components on one hand (sections 3.3 and further), and the case studies of section 3.2 on the other. It would be worthwhile to improve the connection here, for example by looking at the SEB for different cloud types throughout the season. This illuminates the role of clouds year-round.

We appreciate the reviewer's detailed comments and suggestions for improvement. Below we explain changes we made and try to clarify the main points of the paper and address your comments and concerns.

Below, I detail my major and minor issues.

MAJOR ISSUES

- Section 3.2 presents a number of observational data sets that are not introduced in the Measurements and Methods section before. This should be added for a proper understanding of the data sets. Specifically, no information is given for the MMCR data, the balloon soundings, cloud radar, and perhaps additional methods that were used in the analysis of cloud cover and type.

The reviewer makes a good point. A lot of the information on the ICECAPS instrumentation and measurements are given in Shupe et. al. 2013 but more information regarding what was done in this paper is needed.

We have included Table 2, which summarizes all the measurements used in this study and added to the text:

"Table 2 summarizes the measurements made by the various instruments described below."

We added more radiosonde information in the measurement section:

"Twice daily Vaisala RS92 radiosondes (0 and 12 UTC) from the Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation at Summit (ICECAPS, Shupe et al., 2013b) project are used to directly measure the atmospheric temperature with an uncertainty of 0.5°."

In addition, we moved much of the information from the end of the Measurement section and created a new section "2.6 Cloud Properties and Precipitable Water Vapor".

In section 2.6 we added, "The liquid present cloud fraction for a given month is the number of LWP samples greater than 5 gm^-2 divided by the total number of samples. During May and June 2014 the microwave radiometer measuring 23.84 and 31.40 GHz was off site for repairs and thus LWP and PWV are unavailable for these months. A 35-GHz Millimeter Cloud Radar (MMCR) determines vertically resolved cloud presence. Monthly cloud fractions are calculated using a MMCR detection threshold of -60dBz, retaining sensitivity to most hydrometeors"

We added "MMCR derived cloud fraction (solid) and MWR derived liquid present fraction . . ." to the caption of Figure 6 to link these results to section 2.6.

- I am somehow struggling with the organization of the results in section 3. The whole section would benefit from some reorganization. In 3.1, surface temperature (being a response to terms in the SEB) is analyzed and discussed. Then, section 3.2 focuses on particular case studies. 3.3 presents annual cycles of SEB fluxes, and 3.4 is about forcings and responses. Personally, I would prefer a structure in which the entire SEB data set is presented first (more or less the current 3.3). After that, the discussion about forcing and responses. And finally, the elucidation of the role of clouds.

We think it is important to start with the temperature profiles to show how the surface temperature and subsurface temperatures correlate with the atmospheric temperatures. Then we can delve into how the energy is partitioned in section 3.2 and then investigate factors that affect the variability of the temperature at the surface in section 3.3 and section 3.4.

As you suggest, it is advantageous to cluster the case studies with the forcing and responses analysis. Thus we moved the case studies to after the presentation of the SEB. Yet, we think it is important to put the case studies before the Responses to Surface

Radiative Forcing Section in order to illustrate how the SEB responds to changes in downwelling radiation and provide justification for the processes-based relationships.

We reorganized Section 3:

3.1 Temperature

3.2 Surface Energy Budget

3.3 Case Studies

3.4 Responses to Surface Radiative Forcing

To clarify the reasoning behind the new organization of Section 3 we have added a paragraph at the beginning of Section 3.

"The following observationally based results capture atmospheric/ice sheet interactions. This section will first examine temperature profiles at Summit, providing a foundational understanding for how the atmosphere and snowpack are related. Secondly, investigation of the partitioning of surface energy flux over the annual and diurnal cycles illuminates when various SEB terms are most influential. Finally, quantifying the response of the SEB to changes in downwelling radiation, predominately affected by cloud presence and insolation, shows how the non-radiative SEB terms effect the surface temperature variability. "

We changed the wording between sections to keep continuity of the paper.

The figures were reordered to match changes in Section 3.

- With such a rich data set on cloud properties, it is somewhat disappointing that the analysis in the present manuscript is limited to two - admittedly well chosen - case studies. It would be great if the year-round SEB data set could be split into cloud and non-cloud occurrences and do the analysis on the entire data set. Or bin the results by LWP, by cloud type, etc. This would give even more quantitative insight in the role of clouds on the SEB throughout the year. It would provide insight in the changes over central Greenland that we may expect in a warming climate.

The previous title put too much emphasis on forcing instead of the responses to radiative forcing, the latter being the intended emphasis of this paper. Our approach focuses on how we would expect the SEB to respond to a given change in forcing. There are a myriad of ways in which clouds can modulate downwelling radiation and we believe it is beyond the scope of this paper to address cloud radiative forcing (CRF) in addition to the responses to the forcing terms. We have linked the current analysis to previous analysis of CRF in Miller et. al 2015 via the case studies (Fig 5,6), Fig 7 and Fig 11. The process based-relationships go beyond reporting a temporally specific snapshot of the monthly SEB values for a given subset (clear-sky, large LWP, etc . . .). "Process-based relationships distill our understanding of the underlying physical processes into a succinct form that is informative, yet practical. While clouds, the solar cycle, and other processes can influence the downwelling radiation, process relationships between response terms and forcing terms reveal how variability in downwelling radiation affects the other SEB terms. "

Fig 4a shows that clouds are present much of the year (~90% of the time), yet the amount of liquid present has a distinct annual cycle. The magnitude of CRF (fig 11a) is associated with the presence of liquid water. Figure 7a, which bins the forcing terms according LWP and insolation scenarios, supports the conclusion that clouds radiatively warm the surface year round. In this study the forcing terms measured at the surface provide the link to clouds without investigating the myriad of factors that can result in changing the forcing terms at the surface. In fact, Fig 11 gives quantitative insight into the role of clouds on the SEB throughout the year and estimates the resulting effect on the surface temperature.

We have changed the title to "Surface Energy Budget Responses to Radiative Forcing at Summit, Greenland" in order to emphasize the responses of the surface energy budget.

For emphasis we have given the part of the paper that directly ties the new results with the previous CRF results its own subheading titled, "3.4.3 Cloud Effects on the SEB".

MINOR ISSUES

P1 L6: what do you mean by "primarily"

We changed the text to include both methods: "Turbulent sensible heat flux is estimated via the bulk aerodynamic and eddy correlation methods . . ."

P1 L23: icecap -> ice sheet

done

P2 L5: there exists newer literature on runoff increase under scenario forcings.

We added the reference:

Tedesco, M. and Fettweis, X.: 21st century projections of surface mass balance changes for major drainage systems of the Greenland ice sheet, Environ. Res. Lett., 7, 1–11, doi:10.1088/1748-9326/7/4/045405, 2012.

P3 L17: the literature cited here is focused a bit on the work at Utrecht University. There are more observations around the GrIS, like those done at Edinburgh and GEUS in Copenhagen (Denmark).

We added a mass balance reference:

Charalampidis, C., van As, D., Box, J. E., van den Broeke, M. R., Colgan, W. T., Doyle, S. H., Hubbard, A. L., MacFerrin, M., Machguth, H., and Smeets, C. J. P. P.: Changing surface atmosphere energy exchange and refreezing capacity of the lower accumulation area, West Greenland, The Cryosphere, 9, 2163–2181, doi:10.5194/tc-9-2163-2015, 2015.

P3 L23: a more recent example of sublimation analysis from Summit is found in Cullen et al., 2014 (http://onlinelibrary.wiley.com/doi/10.1002/2014JD021557/abstract)

This is a very interesting reference that we overlooked. Thank you for listing it.

We changed the text to include this reference.

"... some studies have targeted SEB annual cycles in 2000-2001 (Cullen, 2003), 2001-2002 (Hoch, 2005), and 2000-2002 (Cullen et al., 2014). "

Cullen, N. J., Mölg, T., Conway, J., and Steffen, K.: Assessing the role of sublimation in the dry snow zone of the Greenland ice sheet in a warming world, J. Geophys. Res. Atmos., 119, 6563–6577, doi:10.1002/2014JD021557, 2014.

P3 L33: compliment -> complement

done

P4 L5: remove "in central Greenland"

done

P4 L11: visa versa -> vice versa

done

P4 L17: it's -> its

done

P5 L26: longer term -> longer-term

done

P6 L13: add Delta to LWP and PWV

We are already using the Delta symbol in another section of the paper.

We changed the wording to:

" . . . effectively reduce uncertainty in LWP (≈ 5 gm^{-2}) and PWV (≈ 0.35 mm) (Crewell and Löhnert, 2003). "

P6 L15: hydrometers -> hydrometeors (meteor refers to the Greek word for falling, rather than meter which refers to the Greek word for observing)

done

P6 L31: I had never heard of the word "thusly" before

It is a word.
: in this manner :

P7 L15: Is the linear relation between albedo and Z also used under cloudy conditions? If so, the should be reconsidered as the dependence of albedo on Z vanishes if clouds are sufficiently thick.

Yes, you are correct that clouds will increase the albedo compared to clear-sky scene. The parameterization of the upwelling SW is why the uncertainty the upwelling SW went from 1.8% prior to 2014 to 2.8% during 2014. The parameterization was needed to capture the diurnal cycle of SWnet end develop a dataset where all SEB components were estimated on the 30-minute averaged time scale. The relationship between albedo and solar zenith angle was made under all conditions, taking into account all conditions from 2011-2013.

We have reworded this paragraph and added information because it was rather confusing:

"The surface albedo is determined by dividing the measured SW↑ by the measured SW↓ and for clear-sky days should have a minimum at solar noon. During 2014 an asymmetry in the diurnal cycle is observed in the measured albedo, where the albedo in the morning is up to 10% lower than in the evening. The NOAA/GMD measurements, which are mounted on the same fixed arm, indicate the same issue (possibly a gradual slope to the surface due to snow drifts). There is good agreement between the ETH SW↓ measurements and the total direct plus diffuse SW↓ values, suggesting that asymmetry in the diurnal cycle of albedo is likely a problem in the SW↑ component. . . . These uncertainty estimates are larger than the reported uncertainty in the measured SW components of 1.8% (Vuilleumier et al., 2014) because, in addition to Z, albedo is dependent on other factors such as the optical thickness of overlying clouds and surface snow properties."

P10 L2: Ric -> Ri

done

P10 L5: very-stable -> very stable

done

P11 L18: LW derived -> LW-derived

done

P11 L27: simliar -> similar

done

P13 L8: boundary-layer -> boundary layer

done

P13 L32: visa versa -> vice versa

done

P14 sec 3.3.1: it would be useful here to contrast observations in other studies (from other years and summers) with the numbers you find.

Please see the Summary Section and our response to your last comment below.

P16 L25: decrease -> decreases

done

P17 L2: replace the two >'s by <'s.

done

P20 L25: please provide numbers from the other studies, so that the reader doesn't have to go and look for the differences himself. A table could be useful here.

We changed the focus of the SEB data comparison to the Cullen et. al. 2014 manuscript and removed the vague paragraph that was comparing to the earlier Cullen reference studying a similar time period.

"A previous study by Cullen et al. (2014), spanning the time period 17 June 2000 – 18 June 2002, also reports the annual cycle of the surface energy budget components at Summit Station. Comparing the annual mean values of this study to the earlier study reveals that Q is 6.8 Wm^{-2} smaller and SH, LH and G are 1.6, 0.9, and 4.8 Wm^{-2} larger, respectively. The differences in the annual mean values could be due to possible decreases in cloud cover (Comiso and Hall, 2014), since the recent annual forcing value is 7.3 Wm^{-2} smaller than the 190.1 Wm^{-2} reported by Cullen et al. (2014). July 2014 had the largest occurrence of liquid-bearing clouds for the current study resulting in an average Q of 6.1 Wm^{-2} compared to 15.6 Wm^{-2} reported by Cullen et al. (2014). The July 2014 forcing terms are 265.3 Wm^{-2} compared to 268.0 Wm^{-2} in 2000 - 2002, suggesting that a 6.8 Wm^{-2} increase in LW↑ is likely due to synoptically-driven warmer air masses above Summit Station in 2014 and not due to changes in cloud radiative forcing."

We added Section 5, making the current dataset easily available, allowing the reader to compare our results with other studies.

"The surface energy budget dataset is available online in the National Science Foundation's Arctic Data Center. [Matthew Shupe and Nathaniel Miller. 2016. Surface energy budget at Summit, Greenland. NSF Arctic Data Center. doi:10.18739/A2Z37J]"