Cloud effects on the surface energy and mass balance of Brewster Glacier, New Zealand

Author's response to the review of Johannes Oerlemans

Firstly, we would like to thank the reviewer for taking the time to provide feedback on our research. We were pleased to receive the feedback that the modelling work and subsequent analysis, including the presentation of figures and tables, were of a high standard. To address the reviewer's comments about the originality and scope of the research we provide the following comments.

To our knowledge, this paper is the first to analyse a multi-annual dataset from a maritime glacier surface at a mid-latitude location in the Southern Hemisphere. It is certainly the first to analyse the linkages between cloudiness, boundary layer meteorological variables and melt through a full annual cycle in the Southern Alps of New Zealand. Given the continued interest in similar records from mid-latitude glaciers in the northern hemisphere (e.g. Giesen et al., 2008, 2014; van den Broeke et al., 2011), we feel it is justified to provide similar a similar analysis from a Southern Hemisphere setting, especially as there is strong interest in resolving past climate patterns from glacier records in the Southern Alps (e.g. Lorrey et al., 2007; Putnam et al., 2012).

It appears there may have been some confusion from the reviewer between our published research describing the derivation of cloud metrics (Conway et al., 2015; published online 23/05/2014) and the work under review that describes the seasonal variation of the meteorology and surface energy balance at Brewster Glacier (Cullen and Conway, 2015; in review). Had the reviewer accessed Conway et al. (2015) the rationale for this paper would have been much clearer, as it provides important information about the large and variable effect clouds have on net radiation over Brewster Glacier, in addition to describing the cloud metric used in the current paper. The effect of clouds on net radiation vary with surface cover and season, but are largely independent of elevation. Thus, we believe that we have a good rationale for extending this analysis to examine the effect of clouds on surface energy and mass balance using our unique dataset from the ablation area of Brewster Glacier. Moreover, it is still common practice to use point measurements to investigate the linkages between mass balance, surface energy balance and other meteorological forcing (e.g. Andreassen et al., 2008; Sicart et al., 2008; Giesen et al., 2008, 2014; van den Broeke et al., 2008b, 2011).

The main contribution of the paper is to show that the linkages between cloudiness, boundary layer meteorological variables (particularly air temperature, humidity and wind speed) and melt differ substantially from those reported at Northern Hemisphere locations. The strong association of air temperature and cloudiness seen in other studies (Pellicciotti et al., 2005; Sicart et al., 2008) is not observed at Brewster Glacier. We did not find a strong association between wind speed and cloudiness (Giesen et al., 2008) or a radiation paradox (van den Broeke et al., 2008a), which are responsible for enhanced melt during cloudy conditions at other maritime sites. Rather, we find that increases in vapour pressure greatly enhance the latent heat flux during cloudy periods which, together with positive net longwave radiation, serves to markedly lengthen the period of time melt occurs during cloudy periods. While previous studies have described the importance of large melt events during cloudy periods (Marcus et al., 1985), the data have not, until now, been available to assess in a systematic fashion the effect clouds have on energy and mass exchanges over a full annual cycle.

Finally, it is important to point out that we also present a novel analysis to assess surface mass balance response to atmospheric forcing. The analysis reveals that for a given change in air temperature, cloudy periods induce a much larger change in melt as compared to clear-sky periods, due in part to the length of time the surface is able to melt during cloudy periods. This divergence of sensitivity as a result of cloudiness is important in the assessment of the role changes in atmospheric circulation have on glacier behaviour in the Southern Alps (Clare et al., 2002; Fitzharris et al., 2007).

We will amend the introduction and conclusion to further highlight these unique and novel aspects of our data and analysis.

Responses to specific comments:
(Note the reviewers' text is quoted in blue)

Cloudiness as used in this paper is not observed, but inferred from the AWS measurements. Although central to the discussion, only a few lines are spent to describe the procedure (p. 991, lines 8-15). I cannot judge the quality of the reconstructed cloudiness. The paper referred to is not yet published. How is the discrimination between temperature, humidity and cloud actually done ? How large is the error in the cloudiness after removing the effects of temperature and humidity ? How does this work out on the later attempts to compare the effects of clouds with temperature and other parameters ?

As described in our earlier author comment, the paper describing the reconstructed cloud metric has been available online for almost 12-months, but a short summary of the method is given here below for convenience. We will also include a similar description of the reconstructed cloudiness, including further references, in Section 2.2 of the manuscript.

Cloudiness is determined from measurements of incoming longwave radiation and theoretical upper (overcast) and lower (clear-sky) values of incoming longwave radiation that are based on surface level meteorological variables. This is the same method as that employed by those in the reviewers' research group (van den Broeke et al., 2006; Giesen et al., 2008). The upper limit is set by applying the Stefan–Boltzmann law to the observed air temperature and an emissivity of 1. The lower limit is set using the clear-sky model of Konzelmann (1994), which has both air temperature and vapour pressure as dependant variables. These two curves are assumed to represent the minimum and maximum incoming longwave radiation at a given temperature and vapour pressure, corresponding to cloudiness values of 0 and 1, respectively. By assuming that cloudiness increases linearly between these minimum and maximum values, the cloud fraction for each half-hourly interval are calculated from measurements of air temperature, vapour pressure and incoming longwave radiation. Following Giesen et al. (2008), clear-sky conditions are defined when cloudiness values are smaller than 0.2 and overcast conditions are defined as cloudiness values larger than 0.8.

The only difference in our procedure compared to that described in Giesen et al. (2008) is that modelled clear-sky longwave radiation includes vapour pressure, as well as temperature, as a dependant variable (Konzelmann, 1994; Durr and Philipona, 2004). Clear-sky incoming longwave radiation is strongly dependent on both variables at this maritime location (Conway et al., 2015). The effect of this is to include a larger proportion of days in the clear-sky category, as some clear-sky days with high vapour pressure (and incoming longwave radiation) would have been excluded had only temperature been used in the calculation of clear-sky emissivity. A comparison to cloudiness derived from incoming shortwave measurements gave a correlation coefficient of 0.89 and a root-mean-squares-difference of 0.19 (Conway et al. 2015).

There is no disscussion on the height at which the sensors are mounted on the AWS. Winter snowfall is large; does this cause any technical problems or issues that require corrections in the data ?

Cullen and Conway (2015) and Conway (2013) provide careful accounts of the change in height of the sensors, though we note that the scaling of temperature and wind speed data to a standard height had a minimal effect on the analysis in the current paper. Sensor height varied between 0.4 and 4.4 m during the measurement period, and was scaled to 2 m before analysis using logarithmic profiles and site specific roughness lengths obtained from eddy covariance data (Conway and Cullen, 2013). The single pole platform was regularly raised and lowered to prevent burial by the large winter snowfall and to keep up with the large surface lowering (up to 6 m) experienced at the site during summer. Given the logistical challenges we faced to maintain an automatic weather station in this environment, we are not altogether surprised that no one else has managed to obtain a multi-annual record from a glacier in the Southern Alps.

The discussion of scale is virtually avoided in the paper. It is known that the components of the SEB vary widely over a glacier surface, and one may wonder to what level of detail the analysis of the situation at a single point should be taken to remain meaningful in view of this spatial variability. In the end, the interest is in the total surface mass budget of a glacier, or at least in the distribution of the balance rate over the glacier. This is particularly relevant because the strength of the snow- albedo feedback on the SMB, an important factor in determining the climate sensitivity and discussed in detail, depends strongly on the altitude relative to the ELA. This paper would have been much more interesting if the calculations would have been done in a spatially-distributed way (on a grid), or at least for some other points with different altitudes.

We are careful to discuss the validity of using point measurements to assess the response of glacier mass balance to atmospheric forcing. While spatial variability in surface energy balance components is quite likely, we strongly believe that measurements from a single point are still valuable. There are a number of recent publications that use point measurements effectively to investigate the linkages between mass balance, surface energy balance and other meteorological forcing (e.g. Andreassen et al., 2008; Sicart et al., 2008; Giesen et al., 2008, 2014; van den Broeke et al., 2011). As demonstrated in these papers, much can be gained from the high level of detail and accuracy that can be achieved from an analysis at single location on a glacier, without the uncertainty that is introduced when meteorological variables and forcing are scaled across an entire glacier surface.

The description of results and model output analysis in section 3 is way too lengthy. It is more a listing of observations and thoughts than a clear presentation of the key results. In the text one should not describe in detail what is seen in the figures.

The results section (7 of 21 pages) could be shortened, though some of the patterns described in the text may not be evident to every reader. Many of the results shown differ substantially from those seen at other sites, so we feel it is important to provide a thorough description of the observations before reflecting on their importance and relevance in the discussion and conclusions.

There is nothing special about clouds as compared to other meteorological variables. Clouds occur frequently and affect the SEB in a significant way, but they are just part of the meteorological forcing. The analysis performed here is interesting from an (sic) didactical point of view (although not very original), but does not help to improve existing models or projections of future glacier mass balance. One could do a similar analysis for days with low wind speed and days with high wind speed, and conclude that wind speed is important. A statement like *Efforts to characterise glacier-climate connections need to consider the effects of changing atmospheric moisture on melt rate as well as accumulation* is just too general. I would like to see ideas or attempts on how to do that. For instance, what about the use of high-resolution climate models, or just re-analysis data, or weather station data, to hindcast or forecast the conditions at the glacier spot and drive the mass balance model for 20 years ?

Conway et al. (2015) show that clouds have a fundamental effect on net radiation in the Southern Alps and we believe it is important to assess this further by characterising linkages between clouds and surface energy and mass balance. It should be noted that we do provide suggestions for new avenues of research to model mass balance in Section 4.3., but would be happy to extend our discussion to include further insights about how variations in moisture could be included in modelling studies assessing future glacier behaviour.

It is state of the art now that data from AWS on glaciers are used to test and calibrate spatially-distributed mass balance models or even high resolution meteorological models that have SMB as an inherent 'product'. Testing and calibration implies a careful quantitative consideration of how processes in the model compare with those measured in the field. The authors have done this only for a single point, and therefore I find the scope too limited.

We strongly believe that to achieve state of the art modelling of glacier-climate interactions in the Southern Alps it is still necessary to establish a more robust understanding of the key physical processes controlling glacier behaviour. This research contributes to building that foundation, which until this time has been hampered by a lack of high quality observational data and model uncertainty. By taking the approach to focus on a single point we mitigate some of the uncertainties that are introduced when distributing data spatially. In our opinion, this does not prevent us from being able to provide a detailed account of the role clouds play in controlling the energy and mass exchanges in the ablation zone of Brewster Glacier, and as discussed compliments similar research undertaken in the northern hemisphere recently. We are confident that the findings presented in this research will serve as a useful platform from which to develop more sophisticated models of glacier behaviour in the Southern Alps.

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