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

Authors response to Anonymous Referee #2

We thank the reviewer for taking the time to make a thorough and careful review of the manuscript. We are glad the research was found to be both new and relevant, and the conclusions sound. We have made the suggested revisions and are confident this has improved the presentation of the results and the overall manuscript greatly. A point by point response to the reviewer's comments is made below, including textual changes where appropriate.

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

Summary:
A study of the impact of cloud cover on the surface energy and mass balance for an in situ station on Brewster Glacier, New Zealand was conducted. Used measurements of atmospheric variables, fluxes, snow depth and density, in conjunction with a surface mass balance model to study the effects of clouds. They conduct a model sensitivity study to examine how clouds affect the sensitivity of SMB to air temperature. They find that for this location, clouds dramatically affect the SEB, and enhance the frequency, and to a lesser extent the magnitude of melting, primarily by changing the direction of net longwave radiation at the surface. A sensitivity study suggests that under cloudy conditions, SMB is more sensitive to fluctuations in temperature. The authors argue that the importance of clouds and atmospheric moisture should be recognized when studying glacier climate interactions.

General Comments:
This study is well written and I think that the conclusions are scientifically sound. The authors sometimes do not explain some statements carefully, and as a result, the results section is sometimes difficult to understand. I think that the study points to an important factor that is sometimes overlooked and should be considered, and therefore is new and relevant research. Therefore I believe the study should be published after the revisions suggested below, which are minor in the sense that they are related to the presentation of the material.

Some general points are:

1. The authors do not define what they mean by the "snowfall-albedo feedback" or "accumulation-albedo feedback", which is not necessarily a positive feedback. This should be clarified below (see specific comments). We have clarified the terms used – we now use "albedo feedback" to refer to the process where increased air temperature decreases the fraction of precipitation falling as snow, which reduces the duration of snow cover and increases the energy available for melt through the lower albedo of the ice surface. Thus the "albedo feedback" here can be seen as a positive feedback between air temperature and SMB as it increases the . Changes and additions to text:
P. 976, Lines 13-14: "The sensitivity of SMB to changes in air temperature was greatly enhanced in overcast compared to clear-sky conditions due to more frequent melt and changes in precipitation phase that created a strong albedo feedback."

P. 977, Lines 5-6: "Reduced solid precipitation often results in an albedo feedback that increases melt, thus increased air temperature can result in enhanced melt if the amount of precipitation that falls as snow decreases."
P 978, Lines 7 – 9 "While a change in precipitation phase and the associated albedo feedback has been shown to be an important component of the sensitivity of SMB to air temperature in New Zealand as in other glaciated regions, (Oerlemans 1997; Anderson et al., 2006), there is a suggestion that increased turbulent (mainly sensible) heat fluxes dominate variations in melt (Anderson et al., 2010)."
P 984, Line 23 "To enable the amount of solid precipitation to alter albedo within SEBpr,"
P990, Line 27 added: "It is worth clarifying here that changes in snowfall resulting from the perturbations in T_a in this analysis are due solely to changes in the fraction of precipitation falling as snow versus rain. This is distinct from the atmospheric feedback between air temperature and precipitation that can result in increased accumulation due to enhanced precipitation rates in a warmer climate."
P992, Line 13 added: "This albedo feedback occurs as increased air temperature decreases the fraction of precipitation falling as snow, thus decreasing the duration of snow cover and reducing summer snowfall. In order to isolate this albedo feedback, further runs of SEBpr were made for - 1 K and + 1 K scenarios."
P994, Line 17 "Indeed, roughly half of the sensitivity to T_a is due to an albedo feedback…"
P996 Line 16 "The high fraction of melt due to *SWnet* and large contribution of an albedo feedback to ΔSMB…"
P997, Line 11 "The large sensitivity of SMB to T_a was expressed primarily through changes in the partitioning of precipitation into snowfall and rainfall, as well as the associated albedo feedback."

2. The authors should comment further on the potential of the methods used to distinguish between cloudy and non-cloudy conditions to impact the results.

The paragraph describing the cloud metric has been extended to include a much through discussion of the method used, including the influence of atmospheric water vapour content on $LW\downarrow$, and a discussion of the uncertainty of the resulting cloud metric. Text changed/added on **page P. 981, Lines 8-15:**

"The longwave equivalent cloudiness ($N\varepsilon$) used in this study was determined from measurements of $LW\downarrow$ and theoretical upper (overcast) and lower (clear-sky) values of $LW\downarrow$ that are based on surface level meteorological variables, a method that has been used successfully in other glaciated areas (van den Broeke et al., 2006; Giesen et al., 2008). The dataset and specific methods used here are presented in Conway et al. (2015), but a brief summary is given below. At each half-hourly interval a theoretical upper limit for $LW\downarrow$ is set by applying the Stefan–Boltzmann law to the observed T_a and an emissivity of 1. A lower limit is set using the clear-sky model of Konzelmann (1994), which has both T_a and e_a as dependant variables. These two curves are assumed to represent the minimum and maximum $LW\downarrow$ at a given T_a and e_a, corresponding to cloudiness values of 0 and 1, respectively. By assuming that cloudiness increases linearly between these minimum and maximum values, $N\varepsilon$ is then calculated from measured T_a, e_a and $LW\downarrow$ at each half-hourly interval. 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 inclusion of e_a, as well as T_a, as a dependant variable in the calculation of theoretical clear-sky $LW\downarrow$ was necessary as clear-sky $LW\downarrow$ is strongly dependent on both variables at this temperate location (Durr and Philipona, 2004; 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 e_a (and $LW\downarrow$) would have been excluded had only T_a been used in the calculation of clear-sky $LW\downarrow$. A comparison to cloudiness derived from incoming shortwave measurements gave a correlation coefficient of 0.89 and a root-mean-square-difference (RMSD) of 0.19 (Conway et al. 2015), suggesting the method is a satisfactory approach to assess cloudiness at this site.

Though not directly comparable to traditional cloud fraction metrics based on manual or sky camera observations, $N\varepsilon$ effectively characterises the effects of clouds on surface radiation fluxes. It also has the advantage over metrics based on $SW\downarrow$, in that it provides 24 hour coverage and is not affected by solar zenith angle or multiple reflections between the surface and atmosphere."

3. In general some statements, particularly with regard to interpretation of results are unclear, as mentioned below. Each specific comment is address below.

Specific Comments

1. P. 976, Lines 13-14: The impact of precipitation on the surface-albedo feedback depends on whether the precipitation falls as rain or snow. Snow would induce a negative feedback, while rain would contribute to the positive feedback. See General Comments #1. In the sensitivity analysis the amount of precipitation did not change as a function of air temperature, only the precipitation phase. Therefore, the analysis contains no mechanism to produce the negative feedback associated with enhanced solid precipitation as a result of increased air temperature, described by Box et al. (2012). The feedback we describe is related soley to the transition from snowfall to rainfall and the corresponding change in albedo. Text changed:

P. 976, Lines 13-14: The sensitivity of SMB to changes in air temperature was greatly enhanced in overcast compared to clear-sky conditions due to more frequent melt and changes in precipitation phase that created a strong albedo feedback

2. P. 977, Lines 5-6: I am not sure what the authors mean by the "strong positive feedback between accumulation and surface albedo". Warmer conditions can lead to increased precipitation, which increases surface albedo if the precipitation falls as snow, reducing the energy available at the surface for melting and grain size metamorphism. This is a negative feedback. (e.g. Box et al., 2012). However, a transition from snowfall to rainfall can lead to a positive feedback. Please clarify here and throughout the paper.

Box, J.E., Fettweis, X., Stroeve, J.C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, The Cryosphere, 6, 821-839, doi: 10.5194/tc-6-821-2012, 2012. See General Comments #1 and above comment. Text changed:

P. 977, Lines 5-6: Reduced solid precipitation often results in an albedo feedback that increases melt, thus increased air temperature can result in enhanced melt if the amount of precipitation that falls as snow decreases.

3. P. 977, Line 15: I am not sure I agree that the effect of clouds is "far more pervasive". Perhaps the authors mean to say that clouds have a strong effect on *variations* in the SEB? What timescales are being considered here? I would argue that all of the factors mentioned by the authors are important, and may be more or less important depending on the location or timescale being examined (e.g. surface albedo variations may be most important for the seasonal SEB variability, while clouds may dominate day-to-day or hour-to-hour variability. The authors also mention differences in the SEB for different glaciers in the Discussion section.) I think the authors should not diminish the importance of other factors, which does not diminish the importance of clouds to the SEB. We agree that many elements of the meteorological forcing are important to SEB. We have changed the sentence to: "The strong effect of clouds on glacier SEB has received increased attention in the last decade".

4. P. 979, Line 2: Please include the years covered during the 22 month period. Added: "in 2010 – 2012"
5. P. 979, Line 9: Please indicate what the dataset is a hybrid of. The sentence has been changed to clarify the dataset used: "To test the sensitivity of SMB to changes in surface climate and radiative components, a more heavily parameterised version of the model is used. This model allows us to separate the effects of changes to surface climate and radiative properties as well as assess the influence of clouds on the sensitivity. The sensitivity analyses are run using a two-year time series (sensitivity period) that was constructed from data collected in the measurement period."
6. P. 980, Line 19: Clarify whether the bias introduced by the instrumentation is -0.7°C, or whether the correction to the original dataset is -0.7°C. Changed to: "Raw T_a data were corrected for the overestimation of T_a measured in the unaspirated shields during times of high solar radiation and low wind speed. This resulting in a mean correction to the original dataset of -0.7°C."
7. P. 981, Lines 8-15: Can the authors provide further discussion of errors that may be associated with this method, and validation of the emissivity model? Can the authors be certain that the changes in LW radiation are indeed associated with clouds, and not other factors, such as atmospheric water vapor content? See General comment #2. This paragraph has been extended to include a detailed discussion of the method used to derive cloudiness, including the influence of atmospheric water vapour content.
8. P. 981, Lines 22-24: This sentence is unclear. Are the effects of evaporation and condensation on surface meltwater accounted for in the model? Yes, evaporation and condensation remove/add mass to the liquid melt water at the surface. Text clarified.
9. P. 982, Lines 9-13: Can the dates covered by SMBmr and SMBpr be reiterated here? We have clarified SMBmr is run over the measurement period and direct readers to Sect. 2.5 for further details on SMBpr.
Also, specify where the inputs to SMBpr parameterizations come from for clarity. Table 2 provides references for each parameterisation.
10. P. 982, Line 18: How is upward heat flux at the bottom of the subsurface model determined? The model holds the bottom temperature fixed at 0 °C, and the heat flux at the bottom of the subsurface model is calculated based on the temperature gradient between the lowest two model levels (5 and 7 metres). Text added to clarify the specification of the bottom temperature.
11. P. 984, Line 10: What were the values used? Reference to Section 2.2 added: "The depth, density and temperature (iso-thermal at 0 °C) of the snowpack was prescribed at the start of the measurement period from snow-pit measurements (see section 2.2), while the bottom temperature in the subsurface module was held fixed at 0 °C."
12. P. 984, Lines 15-16: Why didn't the authors use the period 1 May to 24 October 2011? It seems that this would allow for a more continuous period of measurements. This period is included in the hybrid dataset. The particular periods used were (in order): 1 May to 1 September 2012, 2 September to 24 October 2011 and 25 October 2010 to 30 April 2012
13. P. 985, Line 5: How would this be a positive feedback? Does the increased albedo lead to more snowfall? The sentence was removed as it was not essential.
14. P. 985, Lines 10-12: This sentence should be moved to the previous paragraph, as it is describing another modification to the albedo scheme. It is not entirely clear, but I think this modification has also been applied in the generation of the modeled timeseries in Fig. 2a. The second paragraph describes the tuning of model parameters to local conditions, so it is preferred to keep the comment on t^* in this paragraph. The caption of Figure 2a has been modified to indicate that locally determined coefficients were used.

15. P. 985, Line 21: Table 6 is mentioned before Tables 4-5. Perhaps the authors can refer to the results section rather than Table 6, move Table 6, or simply mention the parameters that were changed here. Changed to "(introduced in Sect. 3.4)"
16. P. 985, Line 26: Change "multiplying" to "multiplying half-hourly ΔSMB" for clarity. changed
17. P. 986, Line 8: Figure 2b is mentioned after Figure 3. I think Fig. 2b needs to be mentioned sooner, perhaps when albedo is discussed, or a separate figure that follows Fig. 3 should be created. Fig. 2 has been split into two separate figures, with Fig. 2b (now Fig. 4) following Fig. 3.
18. P. 986, Lines 10-11: This sentence is unclear. What is meant by "winter accumulations", the total amount of accumulation during winter months? Please clarify. Changed to "Accumulation during each winter was similar"
19. P. 988, Line 15: The sentence makes it sound as if changes in *e*a are caused by increases in Ts. Perhaps change "associated with" to "accompanied by". Changed
20. P. 989, Line 14: Suggest changing "similar source of energy as Rnet" to "producing an amount of incoming energy comparable to that of Rnet". Changed to: "producing a source of energy comparable to that of…"
21. P. 989, Lines 20-21: This sentence is unclear. Isn't the higher level of melting during cloudy conditions a consequence of differences in the energy budget, rather than a cause? Or are the authors trying to say that if there weren't melting, the energy available for melting would be even larger? Please clarify. The sentence has been reworded to clarify meaning: "While mean QM was similar in clear-sky and overcast conditions, melting occurred much more frequently in overcast conditions (Fig. 6)."
22. P. 990, Lines 4-5: Do the authors mean "LWnet and QS" rather than "LWnet and QC"? Perhaps change "diverged strongly with cloudiness" to "changed dramatically during cloudy conditions" for clarity. LWnet and QC are both negative terms and sentence has been modified for clarity "On average, LWnet and QC were energy sinks during melting periods."
23. P. 990, Line 9: Change "large" to "large sensitivity of" for clarity changed to "large SMB sensitivity (ΔSMB)"
24. P. 990, Line 10: Can the authors briefly reiterate the meaning of ΔSMB here and in Table 7? Is this the average per year value over the two-year sensitivity period? We have added the following to Sect. 3.4: "The mass balance sensitivity (ΔSMB) is defined as the average change in SMB per year for both positive and negative perturbations in each climate variable. For clarity, ΔSMB is expressed as the SMB response to an increase in a given input variable or parameter."
Caption for Figure 7 changed to: "ΔSMB (mm w.e. a^{-1}) to perturbations in surface climate and shortwave radiation terms. While the values shown are the average change in SMB per year for both positive and negative perturbations in each climate variable, for clarity, ΔSMB is expressed as the SMB response to an increase in a given input variable or parameter."
25. P. 990, Lines 9-22: I think it would be helpful to reiterate here that the magnitude of perturbations is determined but the estimated errors for the input variables. The magnitude of the perturbations has been defined using regular steps in these variables that are similar to previous studies. It is noted in the text where the uncertainty in a variable has been used to define the perturbations.
26. P. 990, Lines 9-22, Table 7: I believe that ΔSMB is the difference between the + and – perturbation runs. This is not entirely clear from this section, and from Table 7. Please clarify this here and in the caption to Table 7. Also, while the left column of Table 7, always shows +/- values, this section discusses the effect of "increases" and "decreases". I think the authors mean an increase from the negative to the positive perturbation, and vice versa; but it appears as if the impact of positive vs. negative perturbations is being examined. Please clarify in the

text and caption. See comment #24. We have clarified the mass balance sensitivity is assessed using the average of both positive and negative perturbations. In order to clarify the direction of mass balance response in the text, "increase" and "decrease" are used to describe the change in an input variable that elicits this response.

27. P. 991, Lines 15-17: Can this calculation be explained in a bit more detail? We have added an extra row to Table 9 and text to clarify the calculation: "By multiplying the contribution of each SEB term to the increase in melt by the fraction melt contributes to the total ΔSMB (77%; Table 8), we find the contribution of each SEB term to the ΔSMB (Table 9, F).

28. P. 991, Line 25: Change "on the ΔSMB to Ta" to "on the relationship between ΔSMB and Ta" or something similar. Changed to: "relationship between SMB to T_a"

29. P. 991, Line 28: "accounting for 50%". Since the sentence begins with "In absolute terms", the absolute amount should be mentioned here, rather the percentage. The percentage values are also interesting, and could still be included. Alternately, the sentence could begin with "In relative terms". The sentence has been reworded: "Overcast periods exhibit the largest change in melt between T_a perturbation runs, accounting for 50% of…"

30. P. 992, Lines 9-10: Change "ΔSMB in clear-sky conditions showed a long period of minimal ΔSMB from May…" to "During May through October (inclusive) ΔSMB during clear sky conditions was minimal." Changed to: "From May through October (inclusive) ΔSMB in clear-sky conditions is minimal."

31. P. 992, Line 14: What is meant by "perturbing Tr/s with Ta"? This is unclear. Changed to "…perturbing $T_{r/s}$ by the same magnitude as T_a…"

32. P. 992, Lines 16-24: I'm not sure that Figure 9 supports the assertions being made here. An annual plot of ΔSMB (direct) as a fraction of ΔSMB (full) would reveal whether this argument is supported by the graph. Also it is not clear how changes in snowfall during cloudy conditions affect the change in SMB; is this due to a switch from snow to rain? Please clarify, and include the additional plot if possible. See earlier comment on snowfall in cloudy conditions. I presume the reviewer is referring to Figure 8 here. The argument made in this paragraph is that cloudiness has a strong influence on ΔSMB, which Figure 8 shows sufficiently. The separation of the change in accumulation and albedo are only one component of this, and the annual contribution of each is discussed in the preceding section, so we feel an additional figure is not needed. We have clarified the feedbacks contained in the model and that changes in snowfall are due soley to changes in the fraction of snowfall versus rainfall, rather than a change in the magnitude of precipitation. A Δ was missing from line 19 which should read "somewhat less than the full ΔSMB…"

33. P. 993, Line 3: Please clarify "The strong divergence of SEB with cloud condition", perhaps changing the phrase to "The large difference in SEB terms between clear and cloudy conditions…" Changed

34. P. 994, Line 11: Change "high sensitivity of SMB" to "high sensitivity of SMB to Ta". Changed

35. P. 994, Line 13: Suggest changing "overcast conditions which" to "overcast conditions which this study suggests", as it is not clear whether different conditions in the Alps would produce different effects. Changed

36. P. 994, Lines 25-26: Can the authors be sure of this, given that this study only covers one location? Perhaps change "appears to have been" to "may have been". Changed

37. P. 997, Line 11: I think the authors mean changes from snowfall to rainfall. Please clarify. Changed to "the partitioning of precipitation into snowfall and rainfall"

38. Table 8, Caption: Perhaps "sum" should be changed to "cumulative sum" for clarity. Changed

39. Figure 3: Can the authors include the 1:1 line as in Fig. 4, for clarity? A 1:1 line is included and caption has been changed to mention this.

Technical Corrections:

1. **P. 977, Line 25:** Change "properties" to "properties," Changed
2. **P. 981, Line 23:** Change "surface temperature" to "surface" Changed
3. **P. 983, Line 23:** Do the authors mean "evolution" rather than "evaluation"? Changed to "simulation"
4. **P. 985, Line 9:** Change "responsible for decreased" to "responsible for reducing" for clarity. Changed to "responsible for reduced albedo at other sites"
5. **P. 989, Line 27:** Change "experienced" to "experienced during". Changed
6. **P. 991, Line 1:** Change "snow fall" to "snowfall". Changed
7. **P. 991, Line 24:** Change "cloud" to "clouds". Changed
8. **P. 992, Line 19:** Change "SMB" to "ΔSMB". Changed
9. **P. 998, Line 28:** This reference should be updated as the article has been published online. Updated

Cloud effects on ~~the~~ surface energy and mass balance in the ablation area of Brewster Glacier, New Zealand

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Keywords:

Energy Balance Obs/Modelling, Alpine Glaciers, Atmospheric Interactions, Southern Alps, New Zealand

Abstract

~~A thorough understanding of the influence~~ The effect of clouds on glacier surface energy balance (SEB) ~~and~~ has received increased attention in the last decade but how clouds interact with other meteorological forcing to influence surface mass balance (SMB) is ~~critical for forward and backward modelling of glacier – climate interactions. A validated 22-month time series of~~ not as well understood. This paper resolves the SEB~~/~~ and SMB ~~was constructed for~~at a site in the ablation zone of the Brewster Glacier over a 22-month period, using high quality radiation data to carefully evaluate SEB terms and define clear-sky and overcast conditions. A fundamental change in glacier SEB in cloudy conditions was driven by increased effective sky emissivity and surface vapour pressure, rather than ~~the~~a minimal change in air temperature and wind speed. During overcast conditions, positive net longwave radiation and latent heat fluxes allowed melt to be maintained through a much greater length of time compared to clear-sky conditions, and led to similar melt in each sky condition. The sensitivity of SMB to changes in air temperature was greatly enhanced in overcast compared to clear-sky conditions due to more frequent melt and ~~the occurrence of~~changes in precipitation~~, which enabled~~ phase that created a strong~~ accumulation –~~ albedo feedback. During the spring and autumn seasons, the sensitivity during overcast conditions was strongest. ~~There is a need~~To capture these processes, future attempts to ~~include~~explore glacier-climate interactions should aim to resolve the effects of atmospheric moisture (vapour, cloud and precipitation) on melt ~~processes when modelling glacier-climate interactions~~as well as accumulation, through enhanced statistical or physically based methods.

1 Introduction

The response of glaciers to atmospheric forcing is of interest as glaciers are seen as useful scalable proxy records of past climate (e.g. Mölg et al., 2009a) and because the rapid changes occurring in many glaciated regions have implications for both global sea level rise (Kaser et al., 2006) and water resources (e.g. Jost et al., 2012). Reliable attribution of past glacier states and prediction of future ones is dependent on a thorough understanding of the physical processes operating at the glacier surface that link glacier change with climate, that is, the surface mass balance (SMB) and surface energy balance (SEB). For debris free, mid-latitude glaciers, the SMB is primarily a product of the relative magnitudes of accumulated solid precipitation and melt. While, in general, incoming shortwave radiation ($SW\downarrow$) is the major source of energy for glacier melt, variations in SMB are considered to be forced by changes in air temperature and precipitation (Oerlemans, 2005~~)~~), through both accumulation and melt processes. ~~A strong positive ~~Reduced solid precipitation often results in an albedo feedback ~~between accumulation and surface albedo accounts for much of the sensitivity to both~~that increases melt, thus increased air temperature ~~and precipitation, along with the often ~~can result in enhanced melt if the amount of precipitation that falls as snow decreases. Other mechanisms responsible for the efficient relationship between air temperature and~~ melt. The mechanisms responsible for the temperature dependence of~~ melt vary widely (Sicart et al., 2008), and include the variability of turbulent sensible (QS) and latent (QL) heat fluxes, incoming longwave radiation ($LW\downarrow$), and a (somewhat spurious) covariance between air temperature and $SW\downarrow$ in many continental areas. The primary influence of air temperature on melt rate is also nuanced by other influences on the SEB such as surface albedo (Oerlemans et al., 2009), humidity (Gillett and Cullen, 2011), and cloud transmission (Pellicciotti et al., 2005).

The ~~influence~~strong effect of clouds on ~~the~~glacier SEB ~~is,~~has received increased attention in ~~fact, far more pervasive. Recent~~the last decade. Advances in AWS deployment on glacier surfaces (Mölg et al., 2009b), the availability of high-quality radiation measurements (van den Broeke et al., 2004), and development of methods to extract information about cloud cover in data sparse areas (Kuipers Munneke et al., 2011), have allowed the variation of SEB and SMB with cloud cover to be characterised in many areas. Sicart et al. (2010) show clouds dominate day to day variations in $LW\downarrow$ in mountainous areas while numerous studies detail the fundamental changes in SEB with cloudiness that are often co-incident with changes in glacier surface boundary layer (SBL) properties (van den Broeke et al., 2006; Giesen et al., 2008; Gillett and Cullen, 2011). Given their strong control on the SEB, and coincidence with changes in SBL properties it is vital that the role of clouds in altering the sensitivity of SMB to changes in atmospheric state variables (especially air temperature) be assessed.

The glaciers of the Southern Alps of New Zealand occupy a unique position in the westerly wind belt of the Southern Ocean, a region dominated by mid-latitude atmospheric circulation (Tait and Fitzharris, 1998; Ummenhofer and England, 2007). The large barrier the Southern Alps poses to the prevailing winds creates a high precipitation environment, which, coupled to the relatively low elevation of glacier termini (Hoelzle et al., 2007), creates high mass turnover glaciers that have shown high sensitivity to climatic variations in temperature-index glacier modelling studies (Anderson et al., 2006; Oerlemans, 2010). For these reasons the glaciers of the Southern Alps are seen as useful indicators of regional atmospheric circulation in the southwest Pacific and form a vital component of paleoclimate work (e.g. Lorrey et al., 2007). While ~~accumulation~~ a change in precipitation phase and the associated albedo ~~feedbacks have~~feedback has been shown to be an important ~~to~~component of the sensitivity of SMB to air temperature in New Zealand as in other glaciated regions (Oerlemans 1997; Anderson et al., 2006), there is a suggestion that increased turbulent (mainly sensible) heat fluxes dominate variations in melt (Anderson et al., 2010). This has led some authors to interpret past glacier fluctuations as a linear and direct proxy for regional air temperature (e.g. Putnam et al., 2012), at the exclusion of most other elements of the glacier-climate system.

It has been well established that synoptic scale processes exert a strong control on the SMB in the Southern Alps, with periods of 20th century glacier advance and retreat associated with anomalies in the regional climate system (Fitzharris et al., 2007). Given that this synoptic variability is closely linked to inferred changes in cloudiness as well as airmass properties (Hay and Fitzharris, 1988), and that these synoptic controls are thought to have varied over paleo-climatic timescales (Drost et al., 2007; Ackerley et al., 2011), it is vital that the influence of clouds on SMB is separated out from the influence of air mass properties (in particular air temperature). Recent field studies on ~~the~~ Brewster Glacier~~,~~ in Southern Alps, have shown the high frequency of cloudy conditions during all seasons (> 50% overcast conditions) as well as the significant and variable effect of clouds on $SW\downarrow$, $LW\downarrow$ and net radiation (*Rnet*) (Conway et al., 2014). In this context it is timely to examine in detail the influence of clouds on glacier surface climate, SEB and melt, as well as the manner in which clouds alter the sensitivity of SMB to air temperature in the Southern Alps.

This paper addresses these issues by resolving the SEB and SMB at a site in the ablation zone of ~~the~~ Brewster Glacier over a 22 month period in 2010 - 2012. High quality surface climate data presented in Cullen and Conway (2015) are used to force a SMB model (Mölg et al., 2008) to estimate both SEB and SMB terms over this period (measurement period). The cloud metrics presented in Conway et al. (~~2014~~2015) are used to identify clear-sky and overcast conditions and thus characterise surface climate, SEB and melt energy during each condition. To test the sensitivity of SMB to changes in surface climate and radiative components, a more heavily parameterised version of the model is ~~run over a hybrid two-year dataset (sensitivity period), allowing~~used. This model allows us to separate the ~~effect~~effects of changes ~~in~~to surface climate and radiative properties~~ to be assessed independently and~~, as well as assess the influence of clouds on ~~this~~the sensitivity. The sensitivity ~~to be assessed~~analyses are run using a two-year time series (sensitivity period) that was constructed from data collected in the measurement period. The following section provides a brief description of the site, datasets and modelling methods before the results and discussion are presented in subsequent sections.

2 Methods

2.1 Site description and instrumentation

~~The~~ Brewster Glacier is a small mountain glacier situated in the Southern Alps immediately west of the main divide (Fig. 1). It experiences a temperate maritime high precipitation environment~~, with~~. Annual precipitation ~~around~~is approximately 6000 mm water equivalent (w.e~~.) and an~~.), while the annual air temperature ~~of 1.2 °C~~ over the glacier surface at 1760 m a.s.l. is 1.2 °C (Cullen and Conway, 2015). In comparison to other glaciers in the Southern Alps, it has a somewhat lower average slope (16°) but similar mean and terminus elevation ~~and elevation of the glacier snout~~ (Hoelzle et al., 2007). As it is located on the main divide with relatively high exposure to synoptic weather systems, at the midpoint of the north-south distribution of glaciers in the Southern Alps (Chinn et al., 2012), it is likely to experience the atmospheric controls on SMB that affect the Southern Alps in general.

[Fig. 1 here]

Data from an automatic weather station (AWS) situated in the ablation area of Brewster Glacier ($AWS_{glacier}$) were used in this study (Fig 1.). Table 1 gives details of instrumentation and annual average surface climate variables at $AWS_{glacier}$, while further details of the locality and AWS instrumentation can be found in Cullen and Conway (2015). Measurements at $AWS_{glacier}$ ran for 22 months from 25 October 2010 to 1 September 2012 (inclusive). Air temperature (T_a) shows a moderate seasonal cycle (8 °C), and airmass changes appear to override the subdued diurnal range in T_a. Wind speed (U) is moderate with a persistent down-glacier flow despite the small fetch and exposed location (Conway, 2013). Humidity is high with average vapour pressure exceeding that of a melting surface through 4 months during summer. Cloud cover is frequent and associated with on-glacier wind direction (Conway et al., 2014). Annual mass balance in the vicinity of $AWS_{glacier}$ is generally negative, despite the large accumulation (> 3 m w.e.) of winter snowfall during May through September. The significant annual ablation (> 4 m w.e.) generally starts during October, exposing an ice surface in early January and continuing till April or later.

[Table 1 here]

2.2 Data treatment and cloud metrics

Cullen and Conway (2015) describe the treatment of the AWS data in detail but a summary of the main steps is given here. Raw T_a data were corrected for the ~~(large) influence~~overestimation of ~~solar radiation on~~ T_a measured in the unaspirated shields~~, resulting~~ during times of high solar radiation and low wind speed. This resulted in a ~~0.7 °C decrease in~~ mean ~~annual T_a~~correction to the original dataset of -0.7°C. To facilitate SMB modelling, a continuous precipitation dataset (P_{scaled}) was constructed by comparing summer rain gauge observations from a second AWS situated in the pro-glacial area (AWS_{lake}) to a nearby lowland rain gauge (R^2 = 0.9 at a daily level).

To construct a high temporal resolution record of observed SMB, surface height observed using a sonic ranger (Cullen and Conway, 2015) was combined with periodic snow density measurements. Snow pits near the start of snowmelt indicated a consistent density approaching 500 kg m^{-3} during late October (443 kg m^{-3} on 23 October 2010; 483 kg m^{-3} on 27 October 2011), while density during mid-winter was more moderate (320 kg m^{-3} on 18 July 2011). Thus, while the density of melting snow during spring is relatively well constrained, the increasing density due to subsurface processes (e.g. viscous compaction and melt – refreezing) during the winter months produces some uncertainty in the relationship between surface height and SMB. Beyond the snow-ice transition in early January, a standard ice density of 900 kg m^{-3} was assumed, while short periods of new snowfall were assigned a fresh snow density of 300 kg m^{-3} (Gillett and Cullen, 2011).

~~A record of cloudiness was constructed using measurements of $LW\downarrow$ and a clear-sky emissivity model (Conway et al., 2014). The longwave equivalent cloudiness ($N\varepsilon$) scales the effective sky emissivity (from observed $LW\downarrow$) between the modelled clear-sky emissivity and an overcast emissivity of 1.~~ The longwave equivalent cloudiness ($N\varepsilon$) used in this study was determined from measurements of $LW\downarrow$ and theoretical upper (overcast) and lower (clear-sky) values of $LW\downarrow$ that are based on surface level meteorological variables, a method that has been used successfully in other glaciated areas (van den Broeke et al., 2006; Giesen et al., 2008). The dataset and specific methods used are presented in Conway et al. (2015), but a brief summary is given below. At each half-hourly interval a theoretical upper limit for $LW\downarrow$ is set by applying the Stefan–Boltzmann law to the observed T_a and an emissivity of 1. A lower limit is set using the clear-sky model of Konzelmann (1994), which has both T_a and e_a as dependant variables. These two curves are assumed to represent the minimum and maximum $LW\downarrow$ at a given T_a and e_a, corresponding to cloudiness values of 0 and 1, respectively. By assuming that cloudiness increases linearly between these minimum and maximum values, $N\varepsilon$ is then calculated from measured T_a, e_a and $LW\downarrow$ at each half-hourly interval. 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 inclusion of e_a, as well as T_a, as a dependant variable in the calculation of theoretical clear-sky $LW\downarrow$ was necessary as clear-sky $LW\downarrow$ is strongly dependent on both variables at this temperate location (Durr and Philipona, 2004; 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 e_a (and $LW\downarrow$) would have been excluded had only T_a been used in the calculation of clear-sky $LW\downarrow$. A comparison to cloudiness derived from incoming shortwave measurements gave a correlation coefficient of 0.89 and a root-mean-square-difference (RMSD) of 0.19 (Conway et al. 2015), suggesting the method is a satisfactory approach to assess cloudiness at this site.

Though not directly comparable to traditional cloud fraction metrics based on manual or sky camera observations, $N\varepsilon$ ~~very~~ effectively characterises the ~~effects~~impacts of clouds on surface radiation fluxes. It also has the advantage over metrics based on $SW\downarrow$, in that it provides 24 hour coverage and is not affected by solar zenith angle or multiple reflections between the surface and atmosphere.

2.3 Model description

A SMB model (Mölg et al., 2008) was used to resolve surface energy and mass fluxes at $AWS_{glacier}$ for the full 22-month study period. A full description of the model is given in Mölg et al. (2008, 2009a), but a short description of the parameterisation of each term is given here. The model computes SMB as the sum of snow accumulation, melt, refreezing of liquid water in the snowpack and mass fluxes of water vapour (deposition and sublimation) while surface temperature (T_s) is less than 0 °C. Fluxes of vapour while the surface ~~temperature~~ is melting are not included directly in the SMB~~,~~ as condensation and evaporation~~ are assumed to~~ add and remove mass from the liquid melt water at the surface, respectively. The model uses T_s as a free variable to close the SEB (equation 1) at each 30-minute timestep:

$$QM = SW\downarrow(1-\alpha) + LW\downarrow - \sigma\varepsilon T_s^4 + QS + QL + QR + QC \qquad (1)$$

where (QM) is the energy for surface melt while T_s = 0 °C, $SW\downarrow$ is the incoming solar radiation, α is the albedo, $LW\downarrow$ is the incoming longwave radiation, σ is the Stefan-Boltzman constant (5.67 × 10^{-8} W m^{-2}), ε is the emissivity of snow/ice (equal to unity), T_s is the surface temperature (K), QS and QL are the turbulent sensible and latent heat fluxes, respectively, QR is the rain heat flux and QC is the conductive heat flux through the glacier subsurface. The convention used is that energy fluxes directed towards the surface are positive.

Two different configurations of the model are presented in this paper, distinguished only by their treatment of surface radiation fluxes. For the first, SEBmr, we used measured values of $SW\downarrow$, $LW\downarrow$ and ~~α~~albedo from $AWS_{glacier}$ (Table 2) to provide best estimates of SEB and SMB terms for analysis over the measurement period. For the second, SEBpr, we used parameterised radiation fluxes (Table 2) to assess the sensitivity of the SMB to changes in surface climate (detailed further in section 2.5). All other energy fluxes are calculated consistently between configurations. QR is calculated using P_{scaled} assuming rain temperature is equal to T_a. New snow was calculated from P_{scaled} using a rain/snow threshold ($T_{r/s}$) of 1 °C and a fixed density of 300 kg m^{-3}. The iterative SEB closure scheme of Mölg et al. (2008) was used to calculate T_s, with *QC* being calculated as the flux between the surface and the top layer of the twelve layer subsurface module (subsurface levels: 0.1, 0.2, 0.3, 0.4, 0.5, 0.8, 1.4, 2, 3, 5, and 7 m). Penetrating shortwave radiation was not included in the model, as the sub surface temperature profile was not measured throughout the study period;, hence the optimisation of a penetrating shortwave radiation scheme would be subject to large uncertainty. The depth, density and temperature (iso-thermal at 0 °C) of the snowpack was prescribed at the start of the measurement period from snow-pit measurements (see section 2.2).Sect. 2.2), while the bottom temperature in the subsurface module was held fixed at 0 °C.

[Table 2 here]

The turbulent heat fluxes, *QS* and *QL*, were calculated using a bulk-aerodynamic approach using the C_{log} parameterisation as described by Conway and Cullen (2013). The roughness lengths for momentum (z_{0v}), temperature (z_{0t}) and humidity (z_{0q}) over an ice surface at $AWS_{glacier}$ are well constrained by in-situ measurements (z_{0v} = 3.6 × 10^{-3} m, z_{0t} = z_{0q} = 5.5 × 10^{-5} m; Conway and Cullen, 2013), though spatial and temporal variability is still probable. A further period of eddy covariance measurements over a spring snow surface (27 October to 3 November 2011) showed a log-mean value for z_{0v} of 1.8 × 10^{-3} m (σ = 1.3 × 10^{-2} m, n = 31), using the same filtering criterion as Conway and Cullen (2013). No reliable estimates of z_{0t} or z_{0q} were possible because of the large uncertainties involved with the small temperature and vapour pressure gradients experienced during this period. Given the similar, but more uncertain, z_{0v} over snow and the large effect of z_{0t} on the effective roughness length which tends to counter a change in z_{0v} (Conway and Cullen, 2013), roughness lengths derived over ice were adopted for the entire period.

2.4 Estimation of uncertainty using a Monte Carlo approach

To estimate uncertainty in modelled SMB, a series of Monte Carlo simulations were made covering the range of input data and parameter uncertainty expected for each configuration of the model (SEBmr and SEBpr). Table 3 shows the parameter uncertainty introduced for each configuration, while input data uncertainty was kept consistent with that used in Conway and Cullen (2013) and is given in Table 1. For both configurationconfigurations, 5000 runs of the measurement period were made, with systematic and random errors being assigned to each input variable before each simulation and time step, respectively. Errors were calculated by multiplying the uncertainties associated with each input variable (Tables 1 and 3) by normally distributed random numbers ($\mu = 0$; $\sigma = 1$), with the exception of z_{0v} which was logarithmically transformed before the uncertainty was applied. The 5000 SMB time series computed for each configuration were subjected to a first order check, using measured T_s as a proxy for a realistic ~~evaluation~~simulation of the SEB. Runs were removed when 30-minute modelled T_s had ~~root mean squared differences (~~RMSD~~)~~ > 1.5 K or $R^2 < 0.9$, which removed ~ 10% of runs from each ensemble. The remaining runs were then used to compute an ensemble mean and standard deviation for the SMB accumulated over one-day and 10-day periods in addition to the full measurement period. Runs that did not correctly predict the accumulated SMB at the end of the measurement period were not removed, as it was unknown if any systematic errors would remain constant over the study period. Thus, the model uncertainty over a shorter time period (e.g. one or 10 days) was kept independent of the final ‘correct’ accumulated SMB.

[Table 3 here]

2.5 Mass balance sensitivity configuration

To assess the mass balance sensitivity (ΔSMB) at $AWS_{glacier}$ further runs were made with the SEBpr configuration using a hybrid 2-year dataset (sensitivity period). The goal was not only to show the extent to which elements of the climate system could force SMB changes but also to understand how uncertainty in model input data or parameterisation impacted estimates of SMB. Because the measurement period started in spring, the initial depth and density of the snowpack was prescribed in these runs. However, a realistic evolution of snowdepth with perturbations in surface climate (especially T_a) is required to assess ΔSMB, i.e. ΔSMB is assessed with accumulation seasons preceding ablation seasons. To this end, a hybrid two-year dataset was constructed using data from $AWS_{glacier}$ by rearranging the measurement period timeseries. The particular periods used were (in order): 1 May to 1 September 2012, 2 September to 24 October 2011 and 25 October 2010 to 30 April 2012. This gave two full SMB seasons (1 May – 30 April) in sensitivity runs and retained variability in the input data without relying on data from off-glacier sources. Fortunately, the snowdepth predicted by SEBpr at the end of the first hybrid accumulation season matches that at the start of the measurement period (25 October 2010) so the evolution of snowdepth (and ~~α~~albedo) during the remainder of the sensitivity run is comparable with that in the measurement period.

To enable ~~snowdepth α feedbacks~~the amount of solid precipitation to alter albedo within SEBpr, ~~α~~albedo was simulated using the parameterisation of Oerlemans and Knap (1998). This scheme computes albedo from three values representative of fresh snow~~,~~ (α_{frsnow}), firn (α_{firn}) and ice~~,~~ (α_{ice}), accounting for the evolution of fresh snow to firn through an e-folding constant (t*) which describes the characteristic albedo timescale. Two modifications were made to the scheme (Mölg et al., 2012). Firstly, when new snowfall is removed by melt, the albedo reverts back to the albedo of the underlying surface. Secondly, a daily total snowfall in excess of 5 cm (depth) was introduced as a threshold above which the new snowfall impacts albedo, as small ~~snowfalls are~~snowfall is most likely ~~to be~~ redistributed into crevasses and hollows on the glacier surface and have a minimal impact on the albedo. ~~These two modifications removed large positive feedbacks in the scheme that often caused small snowfalls to increase albedo long after the model had removed the new snow by melting.~~

An analysis of measured albedo (α_{acc}) at AWS$_{glacier}$ allowed local values of α_{frsnow} (0.95), α_{firn} (0.65) and α_{ice} (0.42) to be defined (Fig. ~~2a~~2). The higher local values are likely indicative of lower levels of contaminants that are responsible for ~~decreased~~reduced albedo at other sites (Oerlemans et al., 2009) and a lack of debris surrounding ~~the~~ Brewster Glacier. A better fit to the evolution of measured albedo was also found by decreasing t* to 10 days, which seems reasonable given the higher rate of melt (and therefore snow metamorphism) in this maritime environment. Figure ~~2a~~2 also shows a marked difference ~~between the~~in ice surface albedo between the two seasons. It is unclear if this difference reflects changes over a large spatial scale or if a localised increase in sediment observed in the vicinity of AWS$_{glacier}$ during the summer of 2012 contributed to the decrease in albedo during the second season. Without a clear basis for this variation, a mean value of α_{ice} = 0.42 ~~is~~was adopted for both seasons.

[Fig. 2 here]

ΔSMB was computed by conducting runs with SEBpr over the sensitivity period, introducing a range of systematic perturbations to input data and parameters (introduced ~~with the results in Table 6~~in Sect. 3.4) and comparing SMB between each run. To calculate variations in ΔSMB with cloudiness, ΔSMB was computed at each model timestep (i.e. mm w.e. 30-minute^{-1}) for each perturbation run. Model timesteps were then selected based on cloudiness (N_{ε}) and a monthly average produced for clear-sky and overcast conditions. For ease of interpretation, ΔSMB was converted to a daily rate (mm w.e. day^{-1}) by multiplying half-hourly ΔSMB by the number of model timesteps within a day (48). By definition, the sum of ΔSMB for each timestep within a year is equal to the accumulated ΔSMB of the entire year, which is the more commonly reported value (e.g. 1.5 m w.e. ~~annum~~yr^{-1}).

3 Results

3.1 Model evaluation

Both configurations of the SMB model (SEBmr and SEBpr) were ~~first~~ validated against observed T_s and SMB during the measurement period. Modelled T_s from reference runs of both configurations agreed well with T_s calculated from measurements of outgoing longwave radiation (Fig. 3). ~~Both mean bias error (MBE) and RMSD~~Errors at the 30-minute ~~timesteps~~timestep were comparable to ~~similar~~other studies (van den Broeke et al., 2011), and monthly averages indicated no seasonally dependant errors in the SEB. ~~Figure 2b shows~~Both configurations successfully simulated the large accumulation and ablation ~~experienced~~observed at AWS$_{glacier}$ during the measurement period~~. Winter accumulations were fairly consistent between 1.5 and 1.8 m w.e., while summer ablation was more variable. In general, both configurations of the model gave fairly close agreement to the observed accumulated SMB over the measurement period. Both gave~~ (Fig. 4). SMB during the first accumulation season was within ± 10% of that observed (Table 4), which was encouraging given the uncertainties in the scaled precipitation dataset and rain/snow threshold. SEBmr showed small discrepancies in modelled ablation (around 10%) for the ice surface in the first season and the snow surface in the second season (Table 4). SEBpr showed a similar performance, with an underestimate of ablation for ice surface in the second season likely related to the lower ~~measured α in~~albedo observed during this season (Fig. ~~2a~~4). Despite these small deviations, both configurations produced ~~SMB~~SMBs over the two seasons that ~~was~~were well within the accumulated uncertainty due to measurement and parameter errors (grey shading in Fig. ~~2b~~4). The small discrepancies between modelled and observed ablation could have been removed, perhaps through specifying different z_{ov} for snow and ice surfaces. However, given ~~that~~ the deviations were not consistent between each season and model, ~~that~~ both models exhibited large accumulated uncertainty, and ~~that~~ our interest was primarily at shorter timescales, we found no strong reasoning for tuning model parameters to fit model values precisely.

[Fig. 3 here]

[Fig. 4 here]

[Table 4 here]

We also compared SMB over one-day and 10-day periods to ensure we could correctly simulate the large temporal variability in accumulation and ablation with each configuration of the model ~~we also compared SMB over one-day and 10-day periods (Fig. 4~~(Fig. 5). SEBmr effectively captured the large variability in SMB during both accumulation and ablation seasons with maximum 10-day ablation and accumulation rates on the order of 50 mm w.e. day^{-1} (Fig. ~~4b~~5b). A consistent bias in ablation was not observed, confirming our decision not to tune modelled melt exactly over the season. The significant number of large daily ablation events (> 50 mm w.e. day^{-1}) observed in the ablation record were, in general, captured by SEBmr (Fig. ~~4a~~5a). If anything, a bias toward under-prediction of these events was seen. This bias is likely related to an under-prediction of *QR*, as the time-averaging P_{scaled} underestimated the very intense rainfall rates (> 100 mm day^{-1}) associated with the largest ablation events (Gillett and Cullen, 2011). 10-day accumulation rates were captured well while daily totals exhibited ~~much~~ larger scatter, reflecting the difficulty of determining observed winter SMB from surface height records as well as the large combined uncertainty due to P_{scaled}, T_a and $T_{r/s}$. The good agreement of modelled and observed SMB at these short temporal resolutions suggests SEBmr is able to capture the variations in melt and accumulation forced by the key synoptic atmospheric controls.

[Fig. ~~4~~5 here]

SEBpr showed similar agreement to observed SMB at both daily and 10-day level (Fig. ~~4c~~5c, d). The larger uncertainty in modelled ablation was expected given the uncertainties involved in parameterising incoming radiation fluxes and albedo. A positive bias in modelled ablation rates was exhibited, though the 1:1 line is still well within the model uncertainty (2 σ). This bias was likely an artefact of the limited value of the cloud extinction co-efficient *(k)*, which produced a positive bias in ensemble mean $SW\downarrow$ as compared to the reference run (not shown). However, this bias was of less concern as the remaining analysis used the reference run and not the ensemble mean from the Monte Carlo runs to explore cloud effects on SMB and ΔSMB. That the temporal variability of SMB was effectively captured by SEBpr gives us confidence that this configuration captures the same atmospheric controls on SMB as SEBmr and as such provides a reliable and useful tool for sensitivity analysis.

3.2 Variation of SBL climate with cloudiness

The seasonal variation of surface climate in both clear-sky and overcast conditions during the measurement period is shown in Figure ~~5~~6 (a, b). Air temperature (T_a) exhibited a clear but relatively small (~ 8 °C) seasonal cycle and was only slightly lower in overcast conditions compared to clear-sky conditions (Table 5). Vapour pressure (e_a) was significantly higher in overcast conditions, due to the similar T_a but markedly higher *RH*. Consequently in overcast conditions, mean e_a was above the saturated vapour pressure of a melting snow/ice surface (6.11 hPa) during December through April, while in clear-sky conditions mean e_a only reached this condition during February. Average T_s exhibited pronounced differences, being significantly higher in overcast conditions during every month. Average wind speed (*U*) was somewhat higher (0.1 to 0.7 m s^{-1}) in overcast conditions during most of the ablation season, while only small or non-significant differences with cloudiness were noted in other seasons ~~().~~(Table 5). Thus, the main changes in surface climate observed during cloudy periods were an increase in e_a, which, despite slightly lower T_a, were ~~associated with~~accompanied by a large increase in T_s.

[Table 5 here]

[Fig. ~~5~~6 here]

3.3 Variation of SEB and melt with cloudiness

Monthly average SEB terms diagnosed using SEBmr showed marked variation with cloudiness and season during the measurement period (Fig. ~~5c~~6c, d). Clear-sky conditions were characterised by large and opposing fluxes. *SWnet* dominated the seasonal cycle, provided the largest source of energy during the summer months and peaked after the summer solstice in response to decreased albedo associated with the transition from a snow to ice surface in early January. *LWnet* remained a large sink throughout the year, creating strongly negative *Rnet* during the winter months (JJA) that ~~drove~~were responsible for cooling of the glacier surface. Low T_s in clear-sky conditions allowed *QS* to remain directed towards the surface throughout the year. *QS* was of a similar magnitude to *LWnet* and peaked during the winter months in response to an increase in both *U* and the surface-air temperature gradient (Fig. ~~5a~~6a, b). *QL* was much smaller in magnitude than *QS* and of a generally negative sign, indicating that during clear-skies, sublimation or evaporation dominated over deposition or condensation. *QR* was absent and positive *QC* indicated that nocturnal cooling of the surface and subsurface was occurring. *QM* in excess of 20 W m^{-2} (equivalent to 5 mm w.e. day^{-1}) was present for a 7-month period between October and April (inclusive). In general the seasonal cycle of *QM* followed that of *SWnet*, but was modulated by variations in *QL* and *QS*.

In contrast~~ to clear-skies,~~, average energy terms in overcast conditions were smaller in magnitude and directed towards the surface ~~on average~~ (Fig. ~~5d~~6d). *SWnet* was still the largest source of energy to the surface. *LWnet* was positive through most of the year, due to the enhancement of $LW_{\downarrow}$ by low cloud cover and the T_s being limited to 0 °C. Consequently, *Rnet* was positive throughout the year and larger than in clear-sky conditions from March to November (inclusive). *QS* and *QL* were nearly equal in magnitude and both directed towards the surface, together producing a ~~similar~~ source of energy ~~as~~comparable to the contribution from *Rnet*. A distinct seasonal cycle in *QS* and *QL* was driven by the strong seasonal variation in surface-air temperature and moisture gradients in overcast conditions (Fig. ~~5b~~6b). *QR* made a small contribution to *QM* during the summer and *QC* was negligible. The net result was that despite the moderate magnitude of individual energy fluxes in overcast conditions, mean *QM* was similar to ~~that~~values observed in clear-sky conditions during most months. The exception was between February and May, where *QM* in overcast conditions exceeded ~~that~~values in clear-sky conditions~~ from February through May~~.

~~The similarity of~~ While mean *QM* was similar in clear-sky and overcast conditions~~ was due to a large extent to the fraction of time the surface was~~, melting ~~in each condition (Fig. 6). In clear-sky conditions, melt~~ occurred ~~for a~~ much ~~smaller fraction of time, reaching a maximum of 58% during December, while~~more frequently in overcast conditions~~, melt occurred between 70% and 95% of the time over the~~ (Fig. 7~~ months from October through April (inclusive).~~). Given that day length ~~during this period varied~~varies between 11.5 and 15.5

hours, implying that during October through April (inclusive) and that melt occurred during 70% to 95% of overcast conditions, nocturnal melt in overcast conditions was a significant feature in overcast conditions during these months. While clear-sky and overcast conditions were experienced accounted for 36% and 45% of the measurement period, respectively (Conway et al., 20142015), they accountedwere responsible for 30% and 50% of total melt, respectively, assimply because melt occurred more frequently in overcast conditions accounted for a much higher proportion of all melting periods.

[Fig. 67 here]

[Table 6 here]

When all meltmelting periods were considered together (42% of measurement period), *SWnet* made the largest contribution to *QM*, with *QS* and *QL* together contributing a little over one third and *QR* providing a non-negligible fraction (Table 6). On average, *LWnet* and *QC* were energy sinks during melting periods, though as noted earlier they diverged strongly with cloudiness.. Considering the average SEB terms induring all periods, a shift towards *QS* at the expense of *Rnet* was observed, due to the inclusion of non-melting clear-sky periods, where negative *LWnet* was largely balanced by *QS*.

3.4 Sensitivity of SMB to changes in surface climate

Model runs with SEBpr over the sensitivity period (see sectionSect. 2.4) revealed ahighlight the large Asensitivity of SMB to T_a (Table 7). The mass balance sensitivity (ΔSMB) is defined as the average change in SMB per annum for both positive and negative perturbations in each climate variable. For clarity, ΔSMB is expressed as the SMB response to a ± 1 K change in T_a was much larger than that of a 20% an increase in a given input variable or parameter. The modest change in SMB to P_{scaled} and this± 20% indicates an extremely large sensitivity is explored further in the following section.increase in precipitation would be needed to offset the mass loss associated with moderate atmospheric warming. Increased *RH* inducedinduces a small mass loss, due to increased *LW*↓ and *QL*. Similarly, a mass loss of 0.79 m w.e. annumyr^{-1} occurredoccurs for a 1 m s^{-1} increase in *U*, due to an increased contribution of turbulent heat fluxes to melt. The ΔSMB to terms controlling *SWnet* is surprisingly high, though no study has assessed this in the Southern Alps to date. A change inwith α of ± 0.1 inducedinducing over half the SMB response of T_a ± 1 K (Table 7), while a 6% decrease in SW_{TOA} (the approximate change in the solar constant during the last 10,000 years) only

~~resulted in a modest change in SMB.~~). Variations in the cloud extinction coefficient (*k*), within the uncertainty range of the radiation scheme optimisation (Conway et al., ~~2014), induced~~2015), induce large ~~mass~~ changes~~, emphasising~~ in SMB, emphasizing the ~~fact that *SWnet* still makes the largest~~important contribution of *SWnet* to melt during overcast conditions (Table 6). A 6% decrease in SW_{TOA} (the approximate change in the solar constant during the last 10,000 years) results in only a modest mass loss.

[Table 7 here]

To examine how the large ΔSMB to T_a ~~was~~is expressed, a breakdown of SMB terms was constructed for the +1 K and -1 K perturbation runs (Table 8). A change in snowfall ~~accounted~~accounts for 21% of ΔSMB, while a small change in refreezing (2%) and a dominant change in melt ~~accounted~~(77%) account for the remainder~~ (77%).~~. Changes in deposition and sublimation ~~were~~are negligible. ~~The large change~~It is worth clarifying here that changes in snowfall resulting from the perturbations in T_a in this analysis are due solely to changes in the fraction of precipitation falling as snow versus rain. This is distinct from the atmospheric feedback between air temperature and precipitation that can result in increased accumulation ~~with T_a emphasises~~due to enhanced precipitation rates in a warmer climate (e.g. Box et al., 2012). The temperate nature of the glacier SBL in the vicinity of $AWS_{glacier}$~~, where mean~~ increases the ΔSMB to T_a ~~during~~as most precipitation ~~is 1 °C~~falls within a few degrees of the rain/snow threshold and ~~snow fall~~snowfall can occur at any time of the year (Cullen and Conway, 2015). Indeed, despite the large ablation at $AWS_{glacier}$ over the 22 month measurement period (> 9 m w.e.), a decrease in T_a of 1.3 K ~~was~~would be sufficient to produce a net zero SMB~~ (not shown).~~.

[Table 8 here]

The change in melt between T_a perturbation runs can be attributed to ~~changes in *QM* that are direct, i.e. a change in the~~SEB components whose magnitude ~~of~~ is either directly dependent on T_a (i.e. *LW*↓, *QS*, *QL*, and *QR*~~;~~), or indirectly altered by changes to melt and~~ indirect,~~/or snowfall that alter albedo (i.e. ~~a change in~~ *SWnet* ~~driven by snowdepth – α feedbacks.~~). Table 9 shows mean SEB components for each T_a perturbation run. The most striking feature is that while a 100% increase in melt ~~occurred~~occurs between -1 K and +1 K runs (Table 8), there ~~was~~is only a 40% increase in *QM* during melt (Table 9, A & B final column). The majority of ~~the~~ increased melt ~~was~~is due to a large increase in the fraction of time melt ~~occurred~~occurs, from 34% to 48% of all periods. Thus, a better indication of the contribution of each SEB term to ΔSMB can be found by examining the change in SEB terms between runs for the melting periods in the + 1 K run, (Table 9, E). By multiplying the contribution of each SEB term to the increase in melt by the fraction melt contributes to the total ΔSMB (77%; Table 8), we find the contribution of each SEB term to the ΔSMB (Table 9, F). *SWnet* ~~showed~~makes the largest contribution to the increase in ~~*QM* between these scenarios,~~melt and ~~considering that melt made up 77% of the total ΔSMB, it follows that *SWnet* accounted~~accounts for ~~36%~~over one third of the ΔSMB. ~~In the same way~~The turbulent heat fluxes, *QS* ~~(15%)~~ and *QL* ~~(14%)~~, together ~~accounted~~account for less than a third of the ΔSMB~~. Adding~~, while *LWnet* ~~(9%)~~ and *QR* ~~(2%) to the contribution from the turbulent heat fluxes, direct~~make smaller contributions. Thus, changes in *QM* ~~accounted for under~~that are directly dependent on T_a contribute less than half of the ΔSMB, ~~with changes in snowfall and indirect~~while changes in ~~*QM* dominating.~~snow accumulation and the albedo feedback account for the majority. Given the covariance of cloudiness and SEB terms shown in ~~section~~Sect. 3.3 and the obvious link between cloudiness and precipitation, further examination of the interplay between cloudiness and ΔSMB is made in the following section.

[Table 9 here]

3.5 Impact of ~~cloud~~clouds on SMB sensitivity

To begin to describe the influence of cloud cover on the ~~A~~relationship between SMB ~~to~~and T_a, the amount of melt that occurred under clear-sky, partial cloud and overcast conditions was calculated for each T_a perturbation run (Fig. ~~7). In absolute terms~~8). Overcast periods ~~showed~~exhibit the largest change in melt between T_a perturbation runs, accounting for 50% of the ΔSMB to T_a. Clear-sky and partial cloud conditions ~~showed~~show more modest changes in melt~~, accounting~~ and account for 29% and 21% of the ΔSMB, respectively. By calculating the mean ΔSMB ~~for~~in clear-sky and overcast conditions ~~in~~for each month, a distinct seasonal cycle as well as a clear dependence on cloudiness emerged (Fig. ~~8~~9). In general, the ΔSMB ~~was~~is greatly reduced during winter months, as T_a ~~was~~is well below $T_{r/s}$ ~~at AWS$_{glacier}$~~ and ablation ~~was~~is minimal~~. On average,~~ at AWS$_{glacier}$. Overcast conditions almost always ~~produced~~produce higher ΔSMB than clear-skies, especially during spring and autumn. A peak in ΔSMB ~~observed~~ during October ~~was~~is associated with ~~T_a around $T_{r/s}$ and~~ a higher fraction of marginal melt conditions~~. ΔSMB in clear-sky conditions showed a long period of minimal ΔSMB~~ and average T_a around $T_{r/s}$. From May through October (inclusive~~).~~) ΔSMB in clear-sky conditions is minimal. January and February, however, show ~~a~~ large ΔSMB in clear-sky conditions, as the magnitude of *SWnet* ~~was~~during these months is greatly influenced by changes in albedo driven by the timing of the transition to an ice surface and occurrence of summer snowfall. This albedo feedback occurs as increased T_a decreases the fraction of precipitation falling as snow, thus decreasing the duration of snow cover and reducing summer snowfall.

In order to ~~isolate~~remove the ~~snowdepth – α~~albedo feedback, further runs of SEBpr were made for - 1 K and + 1 K scenarios. By using measured ~~α~~albedo and perturbing $T_{r/s}$ ~~with~~by the same magnitude as T_a, both accumulation and *SWnet* remained consistent between these runs and the resulting ΔSMB (direct) ~~was~~is due to ~~direct~~only changes in *QM* ~~only~~ directly caused by increased T_a (Fig. ~~8~~9., dashed lines). The divergence of full and direct ΔSMB in clear-skies conditions confirmed that changes in melt due to ~~snowdepth – α feedbacks dominated~~an albedo feedback dominate clear-sky ΔSMB, especially in the summer. In overcast conditions, the direct ΔSMB is somewhat less than the full ΔSMB in each month, as periods with altered snowfall are removed. Still, the direct ΔSMB remained approximately twice as large as that in clear-sky conditions through each month. Thus, it is evident that cloudy conditions have a much stronger influence on ΔSMB to T_a than clear-sky conditions, with an increased ΔSMB in cloudy conditions being due to changes in both snowfall and melt, and being strongest in the spring and autumn seasons.

[Fig. ~~7~~8 here]

[Fig. ~~8~~9 here]

4 Discussion

4.1 Cloud impacts on SBL and SEB

~~The strong divergence of SEB with cloud condition~~The large difference in SEB terms between clear and overcast conditions seen in these results is driven in large part by changes in e_a, rather than changes in T_a. The increase in e_a in overcast conditions is enabled by the poor association of T_a and cloud cover, in addition to the obvious covariance between *RH* and cloudiness. That T_a is not markedly decreased in overcast conditions differs from similar studies in the European Alps (e.g. Pellicciotti et al., 2005) and Norway (Giesen et al., 2008), and is indicative of the maritime setting where airmass properties, rather than a positive association between summertime insolation and air temperature (Sicart et al., 2008), are the primary control on SBL variations (Cullen and Conway, 2015). The availability of moist and relatively warm air masses to the glacier surface also creates positive *LWnet* in overcast conditions, which along with increases in *QL*, allows for steady melt through much greater periods of time. Consequently, average daily melt rates are similar in clear-sky and overcast conditions, again in contrast with studies in the European Alps that show increased melt in clear-sky conditions (Pellicciotti et al., 2005). Glaciers in Norway (Giesen et al., 2008) show higher total melt during overcast conditions due to higher *U* that increase turbulent heat fluxes during frequent cloud cover. While increased *U* and turbulent heat fluxes are observed for the largest melt events on Brewster Glacier (Gillett and Cullen, 2011), mean *U* was not well differentiated by cloudiness over the measurement period, leaving T_a and e_a as the primary controls of mean *QS* and *QL*, respectively.

While *LWnet* was substantially increased during overcast periods, a ‘radiation paradox’ (Ambach, 1974) does not occur during most of the melt season ~~at~~in the ablation zone of Brewster Glacier, due to high SW_{TOA}, large cloud extinction coefficients and a smaller difference in sky emissivity in clear-sky and overcast conditions ~~in~~at this mid-latitude ~~environment~~location. In contrast, maritime sites on the melting margin of the Greenland ice sheet show clouds act to increase *Rnet* throughout the melt season at a range of elevations (van den Broeke et al., 2008a). At the lowest site where the surface is melting over 80% of the summer period, the presence of a strong ‘radiation paradox’ implies that melt rates are higher during overcast conditions, which is supported by the absence of increased summer melt during more frequent clear-sky conditions (van den Broeke et al., 2011). The lack of a ‘radiation paradox’ during the summer months ~~at~~on the lower part of Brewster Glacier emphasises the role of airmass properties that are advected from the surrounding ocean areas in maintaining T_a and enabling enhanced *LWnet* and *QL* during overcast periods. In the same way, during the transition periods, especially in the autumn, increased melt rates were enabled by a ‘radiation paradox’.

4.2 Cloud impacts on SMB sensitivity

The increased sensitivity of SMB to T_a in overcast conditions may help explain some of the high sensitivity of SMB to T_a in the Southern Alps. Importantly, average melt is not reduced in overcast conditions and cloud cover is frequent in the Southern Alps. Therefore, a large fraction of melt occurs in overcast conditions which the results from this research suggest are more sensitive to changes in T_a. In conjunction with increased e_a, clouds extend melt into periods of marginal melt that are more sensitive to changes in T_a, as well as being strongly associated with frequent precipitation around $T_{r/s}$. Indeed, roughly half of the ~~T_a~~ sensitivity to T_a is due to ~~accumulation~~ an albedo ~~feedbacks~~feedback, in line with previous work in the Southern Alps (Oerlemans, 1997), emphasising the turbulent heat fluxes play a secondary role, despite the assertions of recent paleo-climatic research (Putnam et al., 2012). In addition, the largest melt events – which constitute a large fraction of melt over a season (Gillett and Cullen, 2011) – are associated with overcast conditions and contribute to proportionally larger changes in melt. Thus, airmass variability, in particular air temperature associated with high water vapour content, appears to be the primary control on melt during the summer ablation season.

Aside from their role in the ΔSMB to T_a, the contribution of turbulent heat fluxes to melt ~~appears to~~may have been overstated in a number of studies, at the expense of *Rnet*. In fact, the contribution of *Rnet* to ablation in the present study is similar to that found over mixed snow/ice ablation surfaces in Norway (68%; Giesen et al., 2008) and coastal Greenland (~ 70% (S6); van den Broeke et al., 2008b), and similar to that found for a neve area in New Zealand (Kelliher et al., 1996). There are a number of possible reasons for the deviation of the current study from previously reported values for glacier surfaces in the Southern Alps (e.g. Marcus et al., 1985; Hay and Fitzharris, 1988; Ishikawa et al., 1992; Anderson et al., 2010). Firstly, in earlier studies simplifications were usually made in the calculation of the turbulent heat fluxes, including the assumption that the surface is always melting. Secondly, average SEB terms were traditionally reported for the entire study period, rather than only those during periods of melt. Table 6 clearly shows full-period average SEB terms are biased towards ~~turbulent heat fluxes~~*QS*, as non-melting nocturnal and winter periods ~~where enhanced *QS* balances~~are included. These periods have higher values of *QS*, which serve to balance negative *LWnet* ~~are included~~. Lastly, a number of the studies have been conducted in low elevation areas, where turbulent heat fluxes are increased, despite these areas being atypical in the Southern Alps (mean elevation of glacier termini > 1500 m a.s.l.; Hoelzle et al., 2007).

4.3 Implications for modelling glacier-climate interactions

While the present study does not make an assessment of glacier wide ΔSMB and therefore is somewhat limited in discussing atmospheric controls on glacier fluctuations, it shows that the response of glacier melt to changes in T_a can be altered by clouds. ~~Two points follow from this:~~This has two important implications for our understanding of glacier climate interactions.

~~First~~Firstly, efforts to characterise glacier-climate connections need to consider the effects of changing atmospheric moisture on melt rate as well as accumulation. New avenues to model glacier melt with enhanced temperature index models (TIM) or other empirical descriptions of the temperature dependant fluxes (e.g. Giesen and Oerlemans, 2012) need to consider the variance of atmospheric moisture with respect to melt. This is both due to the strong increase in *LW*↓ by clouds, but also the association with increased positive *QL* in moist environments. This may be important for other maritime areas, as well as the Southern Alps where TIM's have already been shown to break down in large melt events (Cutler and Fitzharris, 2005; Gillett and Cullen, 2011). The use of coupled glacier mass balance – atmospheric models also present an avenue to represent past and future interactions in a physically realistic way (e.g. Collier et al. 2013).

~~Second~~Secondly, it follows that a change in the frequency of cloud cover or synoptic regime may enhance/dampen the SMB response to T_a. For example, a decrease in ΔSMB from west to east across the Southern Alps is likely, in association with the strong gradient of precipitation and cloudiness (Uddstrom et al., 2001). It is enticing to reduce the relationship between glacier mass balance and climate to the main causal mechanisms (i.e. temperature / precipitation paradigm). However, there is also the possibility that changes in atmospheric circulation coincident with changes in state variables in the past (i.e. during the last glacial maximum; Drost et al., 2007; Ackerley et al., 2011) may alter empirical relationships (i.e. TIM's) informed during the present climate, altering the climate signals derived from glacier fluctuations. For the Southern Alps, the most compelling analysis of the controls on SMB points to changes in the regional circulation patterns (Fitzharris et al., 2007), which are in turn associated with strong changes in both airmass properties and cloudiness (Hay and Fitzharris, 1988). Thus, it is likely that average relationships between melt and air temperature may indeed be changed if a shift to drier or wetter conditions is experienced.

The high fraction of melt due to *SWnet* and large contribution of ~~snowfall~~ an albedo ~~feedbacks~~feedback to ΔSMB also implies that local or regional influences on albedo may have an important role in modifying melt rate as seen in other areas (Oerlemans et al., 2009). Indeed, the LGM period shows higher rates of glacial loess deposition in New Zealand (Eden and Hammond, 2003), thus the role of terrigenous dust in modifying glacier ablation rates during the onset of glacier retreat (e.g. Peltier and Marshall, 1995) is a topic that should be explored further in the context of the Southern Alps.

5 Conclusions

We have presented ~~here~~ a validated timeseries of SEB/SMB ~~for~~ in the ablation zone of a glacier ~~surface~~ in the Southern Alps of New Zealand during 2 annual cycles. High quality radiation data allowed a careful evaluation of the magnitude of SEB terms, as well as the selection of clear-sky and overcast conditions. An analysis of SBL climate and SEB showed a fundamental change in SEB with cloudiness that was driven by an increase in effective sky emissivity and vapour pressure at the glacier surface. The only slightly diminished T_a during overcast periods created positive *LWnet* and also allowed both *QS* and *QL* to remain large and directed toward the surface. This created a strong increase in the fraction of time the surface was melting in overcast conditions, which led to a similar average melt rate in clear-sky and overcast conditions. Given the frequent cloud cover at the site, cloudy periods accounted for a majority of the melt observed, especially during autumn when *SWnet* inputs were lower.

A parameterisation of radiation components allowed the sensitivity of SMB to independent changes in SBL climate and shortwave radiation components to be assessed. The large sensitivity of SMB to T_a was expressed primarily through changes in the partitioning of precipitation into snowfall and rainfall, as well as the associated ~~positive α~~albedo feedback. The remainder of this sensitivity was due to changes in the fraction of time the surface was melting and changes in the magnitude of *QS*, *QL*, *LWnet* and *QR*~~, –~~ (in that order~~.~~ of importance). We also presented a novel analysis to show the sensitivity of SMB to T_a diverged strongly when partitioned into clear-sky and overcast periods~~, with~~. Enhanced sensitivity ~~during~~was found in overcast periods due to ~~both their covariance with~~the occurrence of precipitation and ~~their~~an ability ~~to produce~~for melt to be produced over ~~large~~larger fractions of time. Increased sensitivity during overcast periods may explain some of the high sensitivity of SMB in the Southern Alps, and raises the possibility that the response of SMB to T_a in the past or future may be altered by changing synoptic patterns that are strongly associated with cloud cover. Thus, it highlights the need to include the effect of atmospheric moisture (vapour, cloud and precipitation) on both melt and accumulation processes when modelling glacier-climate interactions.

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Tables

Table 1. Variables measured, sensor specifications and mean annual values at $AWS_{glacier}$.

Variable	*Instrument*	*Accuracy*	*Mean annual value*
Air temperature (T_a)	Vaisala HMP 45AC	0.3 °C	1.2 °C
Relative humidity (*RH*)	Vaisala HMP 45AC	3%	78%
Wind speed (*U*)	RM Young 01503	0.3 m s^{-1}	3.3 m s^{-1}
Atmospheric pressure (*p*)	Vaisala PTB110	0.5 hPa	819 hPa
Incoming shortwave radiation ($SW\downarrow_{meas}$)	Kipp and Zonen CNR4	5%*	140 W m^{-2}
Outgoing shortwave radiation ($SW\uparrow$)	Kipp and Zonen CNR4	5%*	93 W m^{-2}
Incoming longwave radiation ($LW\downarrow_{meas}$)	Kipp and Zonen CNR4	5%*	278 W m^{-2}
Surface temperature (T_s)	Kipp and Zonen CNR4	1°C**	-2.7 °C
Precipitation (P_{scaled})***	*TB4 + Scaled****	25%***	6125 mm***
Surface and sensor height	SR50a	±1 cm	n/a

* Uncertainty is estimated to be less than the manufacturer's specifications as noted in van den Broeke et al. (2004) and Blonquist et al. (2009).

** Based on a 5 W m^{-2} uncertainty in ~~LW↑.~~outgoing longwave radiation.

*** From AWS_{lake} during snow free period only. P_{scaled} is based on scaled relationship between AWS_{lake} and a lowland station (Cullen and Conway, 2015). Uncertainty is estimated from fit of scaled relationship.

Table 2. Configuration of SEBmr and SEBpr, showing input data and references used in the calculation of radiation terms in each configuration.

Variable	Model version	Reference and /or input data
α	SEBmr	Accumulated albedo (van den Broeke et al., 2004)
	SEBpr	Oerlemans and Knap (1998) (P_{scaled}, T_a)
$SW\downarrow$	SEBmr	$SW\downarrow_{surface}$
	SEBpr	Conway et al., 2014 (N_ε, T_a, RH)
$LW\downarrow$	SEBmr	$LW\downarrow_{meas}$
	SEBpr	Conway et al., 2014 (N_ε, T_a, RH)

Table 3. Input parameter uncertainty introduced in Monte Carlo simulations of SMB uncertainty.

Input parameter	Value(s)	Systematic [random] error	Model
Roughness length for momentum (z_{0v})[a]	3.6×10^{-3} m	$z_{0v} \times$ 10^NORMRND(0,0.274)	SEBmr,pr
Rain/snow threshold ($T_{r/s}$) [b]	1.0 °C	0.3 [0.5]	SEBmr,pr
Albedo of surface (α_{snow}, α_{firn}, α_{ice}) [b]	0.95 (α_{snow}) 0.65 (α_{firn}) 0.42 (α_{ice})	0.05	SEBpr
Constant for cloud extinction coefficient [c]	0.1715	0.0048 [0.0048]	SEBpr
Multiplier for cloud extinction coefficient [c]	0.07182 hPa^{-1}	0.0324 [0.0324]	SEBpr
Albedo of surrounding terrain [d]	0.45	0.1	SEBpr
Clear-sky emissivity constant [e]	0.456 Pa^{-1} K	0.0204 [0.0204]	SEBpr

[a] standard deviation of z_{0v} (Conway and Cullen, 2013). NORMRND is a MATLAB function that selects a random number from a normal distribution with mean of 0 and standard deviation of 0.274
[b] Macguth et al. (2008)
[c] 95% confidence interval of optimised coefficients (Conway et al., ~~2014~~2015). Limited to 0.95
[d] Assumed; no random errors as terrain albedo will not vary at this timescale (30 minutes)
[e] RMSD of clear-sky values (Conway et al., ~~2014~~2015)

Table 4. Observed and modelled SMB (m w.e) for selected periods between stake measurements in ablation (Abl) and accumulation (Acc) seasons. Figure 2b4 shows the length of each period.

Period	Observed	SEBmr	SEBpr
Abl 1Abl1 snow	-1.74	-1.78	-1.67
Abl 1Abl1 ice	-3.35	-2.92	-3.28
Acc1	1.52	1.40	1.46
Abl 2Abl2 snow	-1.51	-1.78	-1.48
Abl 2Abl2 ice	-1.94	-1.87	-1.66

Table 5. Mean differences in surface climate between clear-sky and overcast conditions. Positive values indicate an increase in overcast conditions.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	*Annual*
T_a (°C)	**-1.3**	-0.2	**-0.8**	**-3**	**-0.9**	**-0.5**	**-1.3**	**-1.2**	**-0.7**	-0.1	**-1.4**	**-1.2**	*-1.1*
RH (%)	**35**	**25**	**35**	**53**	**44**	**39**	**52**	**37**	**45**	**33**	**34**	**37**	*39*
e_a (hPa)	**2.5**	**2.2**	**2.5**	**3.1**	**2.6**	**2.2**	**2.6**	**1.7**	**2.3**	**2.1**	**2**	**2.7**	*2.4*
U (m s^{-1})	**0.6**	0.1	**0.6**	**-0.2**	**-0.1**	0	0	**-0.2**	-0.1	-0.1	**0.2**	**0.7**	*0.1*
T_S (°C)	**0.5**	**0.3**	**0.9**	**1.5**	**4.7**	**5.4**	**6.3**	**5.2**	**5.8**	**2.6**	**1.5**	**0.6**	*2.9*
p (hPa)	**-7**	**-4**	**-8**	**-6**	**-10**	**-7**	**-12**	**-4**	**-9**	**-3**	**-7**	**-8**	*-7*

Bold face indicates monthly differences are significant at the 95% level using a two sided t-test assuming unequal variances. Temperature and wind speed are normalised to 2-metre values.

Table 6. Average surface energy fluxes (W m^{-2}) for melting periods in clear-sky and overcast conditions, all melting periods, and all periods during the measurement period. Bracketed italics show the proportion of *QM* for each condition.

	SWnet	*LWnet*	*Rnet*	*QS*	*QL*	*QR*	*QC*	*QM*
Melting + clear-sky periods	240 *(121)*	-67 *(-34)*	173 *(87)*	39 *(20)*	-7 *(-3)*	0 *(0)*	-6 *(-3)*	199
Melting + overcast periods	36 *(33)*	15 *(14)*	51 *(46)*	30 *(27)*	24 (22)	7 *(7)*	-2 *(-2)*	110
Melting periods	96 *(70)*	-8 *(-6)*	88 *(65)*	32 *(24)*	15 *(11)*	5 *(3)*	-3 *(-2)*	136
All periods	49 *(83)*	-27 *(-46)*	22 *(37)*	31 *(53)*	2 *(3)*	2 *(4)*	2 *(3)*	58

Melting conditions are selected as periods where *QM* > 0 in SEBmr.

Table 7. ΔSMB (mm w.e. yr^{-1}) to ~~changes~~perturbations in surface climate and shortwave radiation terms. ~~Values~~ While the values shown are ~~averages of~~the average change in SMB per year for both positive and negative ~~perturbation runs of SEBpr over the sensitivity period, while the sign of~~perturbations in each climate variable, for clarity, ΔSMB is ~~shown for~~ expressed as the SMB response to an ~~increased~~increase in ~~each~~a given input variable or parameter.

Variable and perturbation	ΔSMB
T_a ~~±~~+ 1 K	- 2065
P_{scaled} ~~±~~+ 20%	+ 770
RH ~~±~~+ 10%	- 380
U ~~±~~+ 1 m s^{-1}	- 790
α ~~±~~+ 0.1	+ 1220
Solar constant - 6%	- 260
k ~~±~~+ 0.17	- 740

Table 8 Cumulative sum of SMB terms for selected runs of SEBpr over the two year sensitivity period. All units are in mm w.e., except for ∆ which is in mm w.e. K^{-1} yr^{-1}.

Scenario	SMB	Snowfall	Melt	Sublimation	Deposition	Refreezing
+1 K	-9181	3900	13064	32	134	85
- 1 K	-920	5670	6692	38	135	198
∆ (mm w.e. K^{-1} yr^{-1})	-2065	443	-1593	2	0	28

Table 9. Mean SEB terms (W m^{-2}) during melting periods in the +1 K (A) and -1 K (B) perturbation runs of SEBpr. Also shown are mean SEB terms (W m^{-2}) in the -1 K perturbation run, for the same periods as A, i.e. melting periods in the +1 K perturbation run (C), and the increases (W m^{-2}) between each scenario (D, E). The percentage contribution of each flux to *QM*, or the increase in *QM*, is given in bracketed italics. The percentage contribution of each flux to ΔSMB is given in the last row (F)

Scenario	*SWnet*	*LWnet*	*Rnet*	*QS*	*QL*	*QR*	*QC*	*QM*
A: +1 K melting periods	89 *(62)*	-4 *(-3)*	85 *(59)*	37 *(26)*	19 *(14)*	5 *(3)*	-2 *(-1)*	144
B: -1 K melting periods	70 *(68)*	-9 *(-8)*	61 *(60)*	28 *(27)*	11 *(11)*	4 *(4)*	-2 *(-2)*	103
C: -1 K for same periods as A	56 *(76)*	-13 *(-17)*	43 *(59)*	23 *(32)*	7 *(9)*	3 *(4)*	-2 *(-2)*	74
D: Increase from B to A	19 *(46)*	5 *(11)*	23 *(57)*	9 *(22)*	8 *(20)*	1 *(2)*	0 *(0)*	41
E: Increase from C to A	33 *(47)*	8 *(12)*	41 *(59)*	14 *(20)*	13 *(18)*	2 *(3)*	0 *(0)*	70
F: Contribution to ΔSMB	*36%*	*9%*	*45%*	*15%*	*14%*	*2%*	*0%*	*77%*

Figures

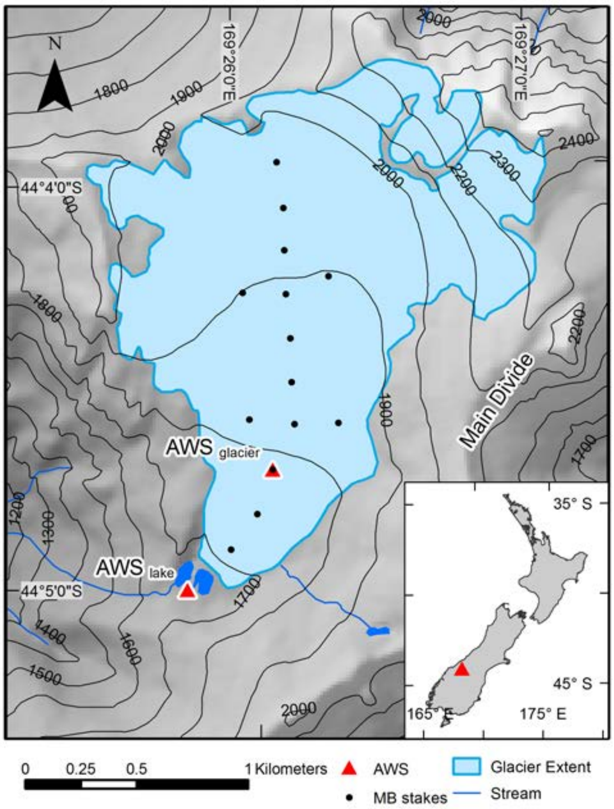
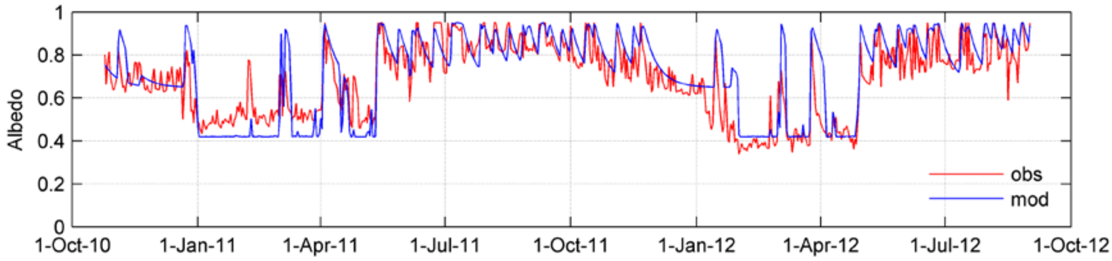
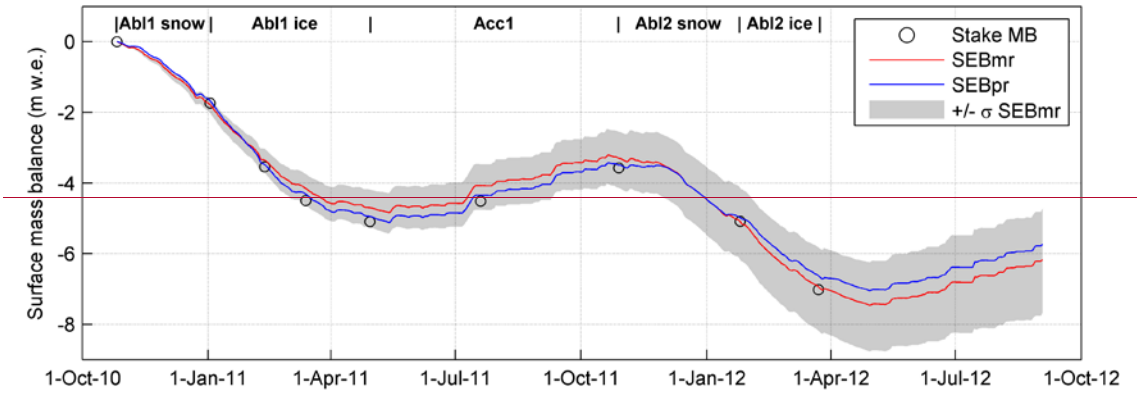


Fig. 1. Map of Brewster Glacier showing AWS locations and surrounding topography. Contour lines are at 100 m intervals. Long-term mass balance network (MB stakes) shown as filled circles. The glacier margin shown is based on a 1997 GPS survey (Willis et al., 2009). The ridgeline to the southeast of the glacier is the main divide of the Southern Alps. The inset map shows the location of Brewster Glacier within New Zealand.

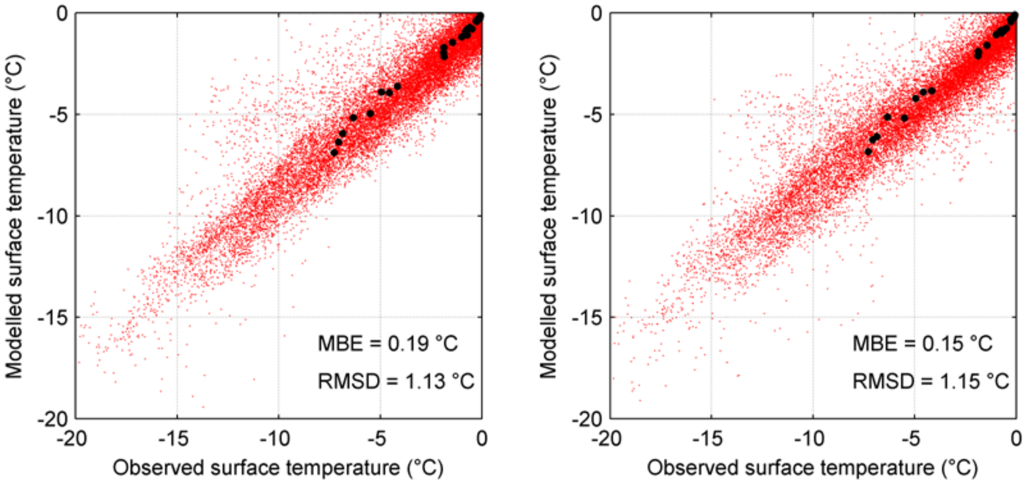


~~(a) Albedo~~



~~(b) SMB~~

Fig. 2. ~~(a)~~ Daily average albedo observed at AWSglacier (red) during the measurement period and modelled in SEBpr (blue) using the expressions of Oerlemans and Knap (1998), with locally optimised coefficients.



(a) SEBmr **(b) SEBpr**

Fig. 3. Observed versus modelled surface temperature for (a) SEBmr and (b) SEBpr runs. Red dots are 30-minute averages, while black dots are monthly averages.

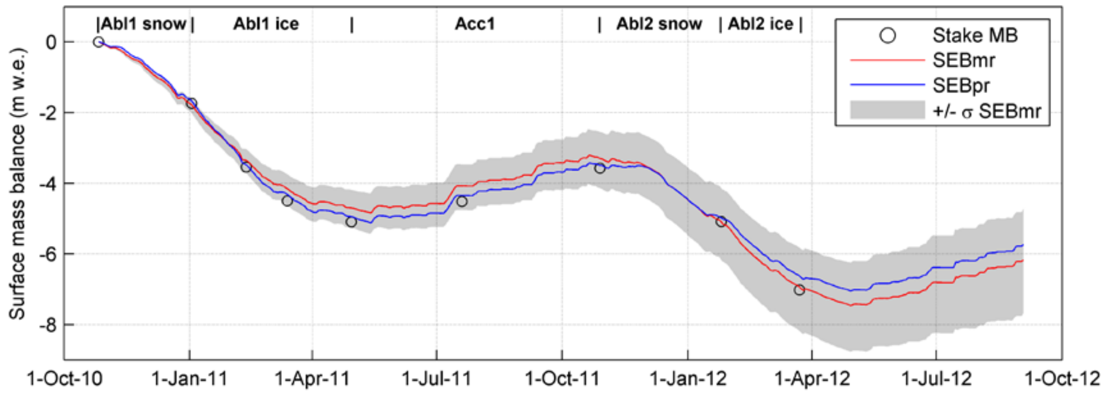
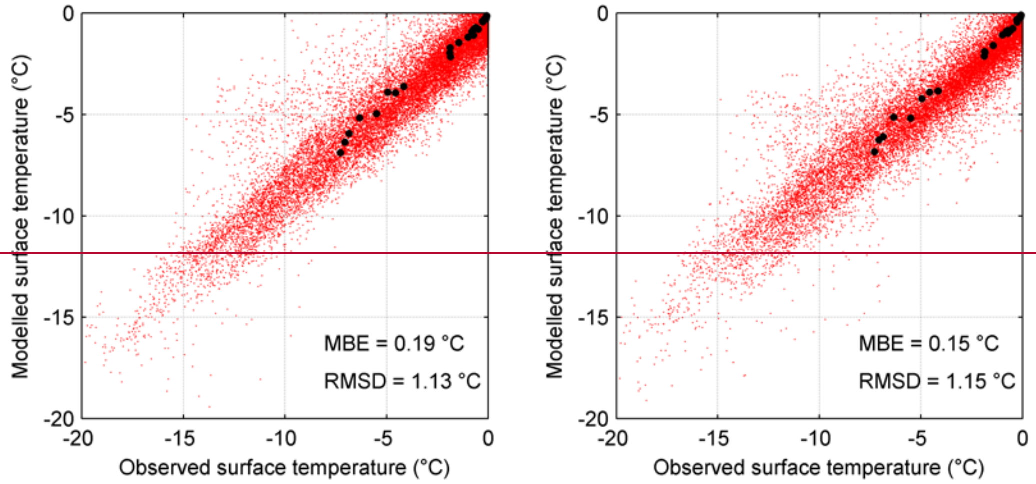


Fig. 4 Accumulated SMB during the measurement period as modelled by the reference runs of SEBmr and SEBpr. The points give observed mass balance from periodic stake and snow pit measurements. The SMB for selected ablation and accumulation periods (shown as Abl1 snow etc.) are given in Table 4. The shaded envelope shows ±1 standard deviation from the mean of SEBmr, calculated using Monte Carlo simulations (see ~~Section~~Sect. 2.4 for details).



(a) SEBmr **(b) SEBpr**

~~**Fig. 3.** Observed versus modelled surface temperature for (a) SEBmr and (b) SEBpr runs. Red dots are 30-minute averages, while black dots are monthly averages.~~

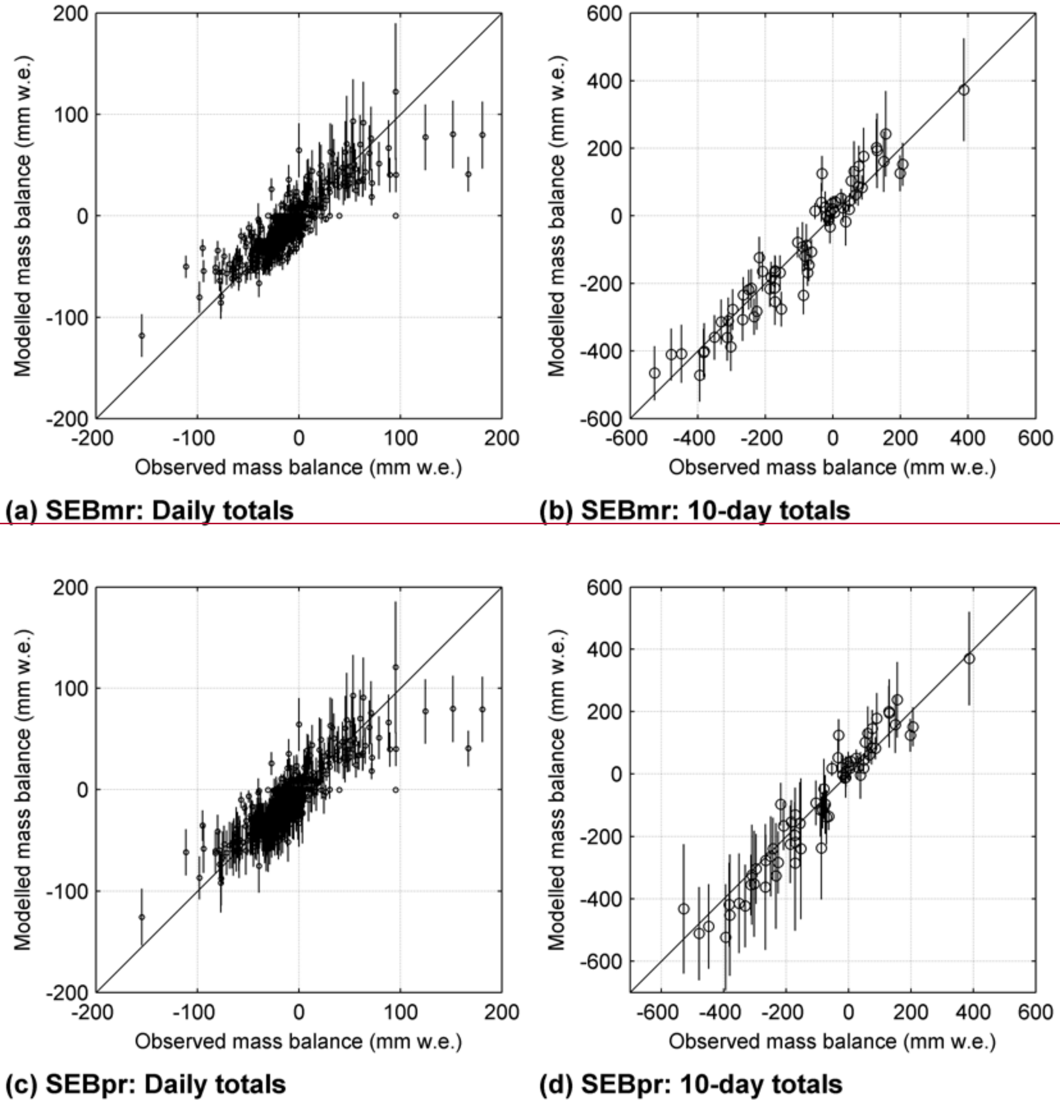

200
100
0
-100
-200
-200
-100
0
100
200
Modelled mass balance (mm w.e.)
Observed mass balance (mm w.e.)
(a) SEBmr: Daily totals
600
400
200
0
-200
-400
-600
-600
-400
-200
0
200
400
600
Modelled mass balance (mm w.e.)
Observed mass balance (mm w.e.)
(b) SEBmr: 10-day totals
(c) SEBpr: Daily totals
(d) SEBpr: 10-day totals

Fig. 4

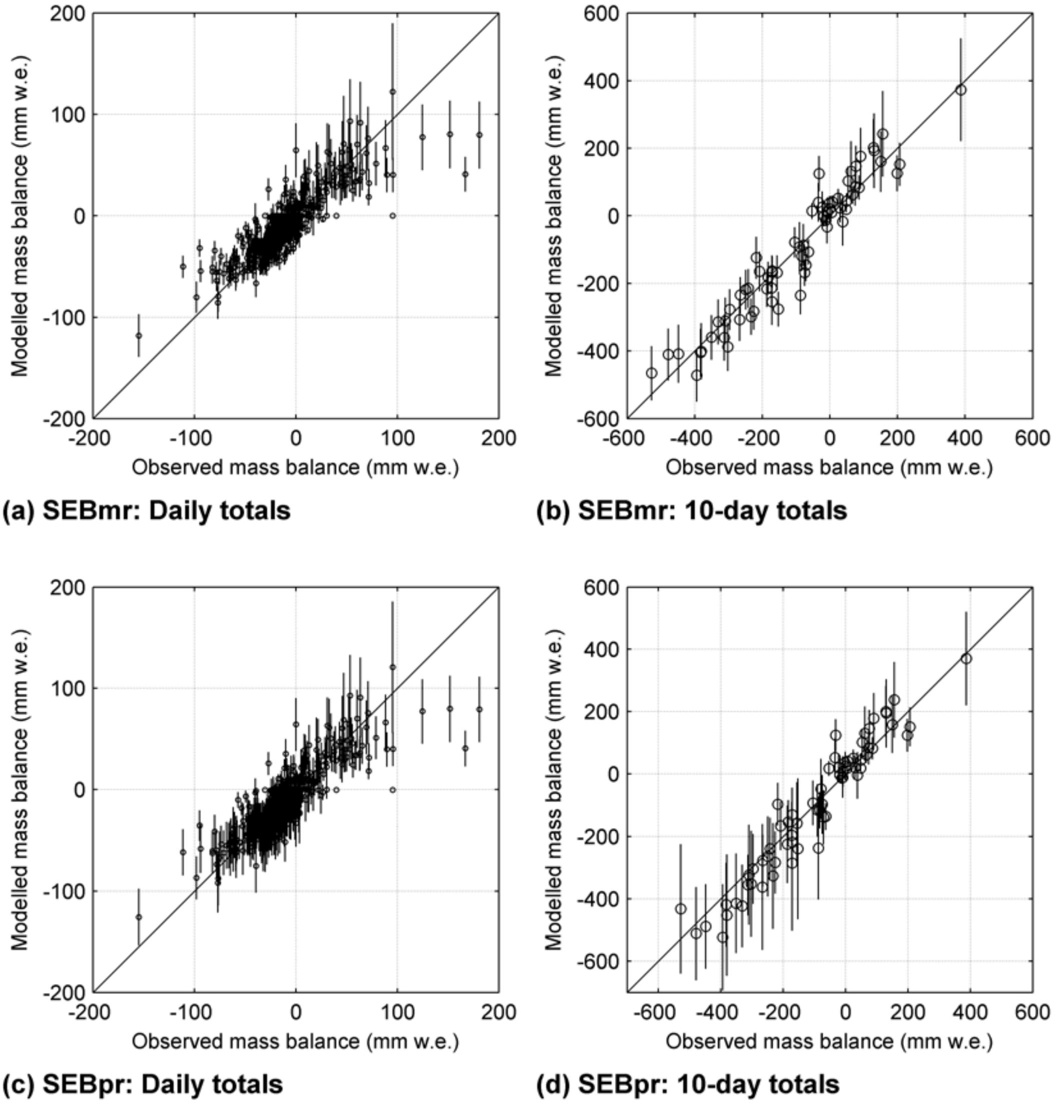


Fig. 5. Observed versus modelled mass balance for (a, b) SEBmr and (c, d) SEBpr over 1-day and 10-day periods. Error bars show ±2 σ from the ensemble mean values. The solid diagonal line is a 1:1 line.

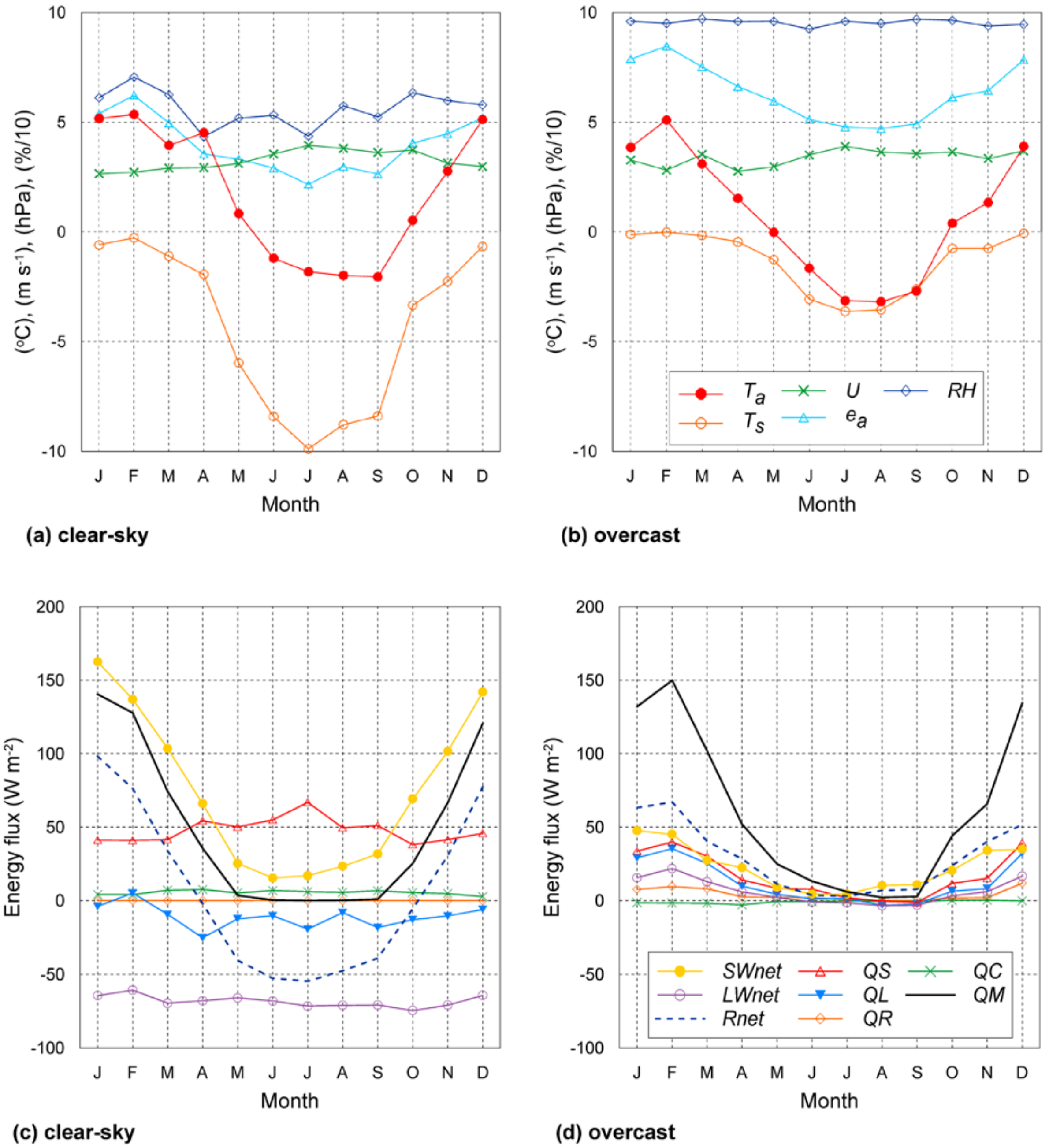


Fig. 56. Monthly mean surface climate (a, b) and surface energy fluxes (c, d) at $AWS_{glacier}$ in (a, c) clear-sky and (b, d) overcast conditions. Partial cloud conditions are a graduation between the two extremes and are not shown for brevity. Surface climate variables include air and surface temperature (°(T_a and T_s; °C), wind speed (U; m $^{-2}$s^{-1}), vapour pressure (e_a; hPa), and relative humidity (RH) on a scale from 0 to 10 (i.e. %/10).

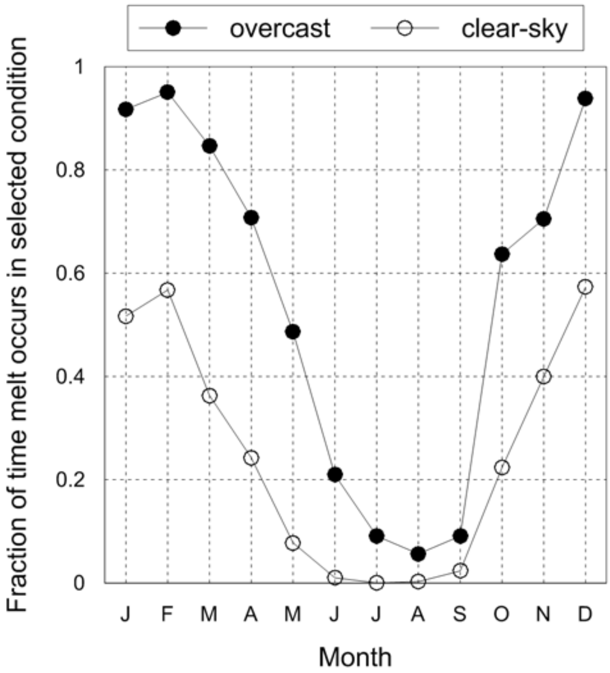


Fig. ~~6~~7. Fraction of time surface melting occurred in clear-sky (open circles) and overcast (closed circles) conditions during each month. Melting conditions are selected as periods where *QM* > 0 in SEBmr.

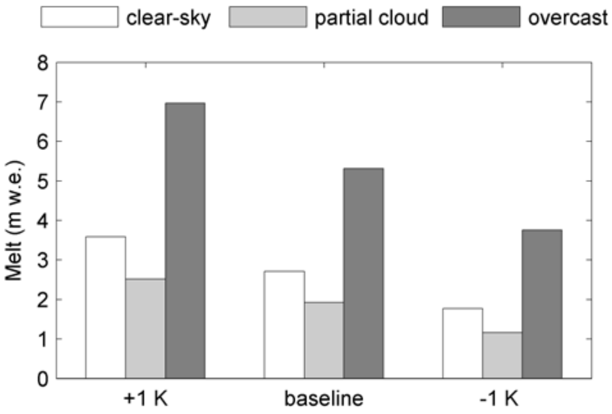


Fig. ~~7~~8. Total surface melt in each cloud cover category for ~~reference~~baseline and climate perturbation scenarios.

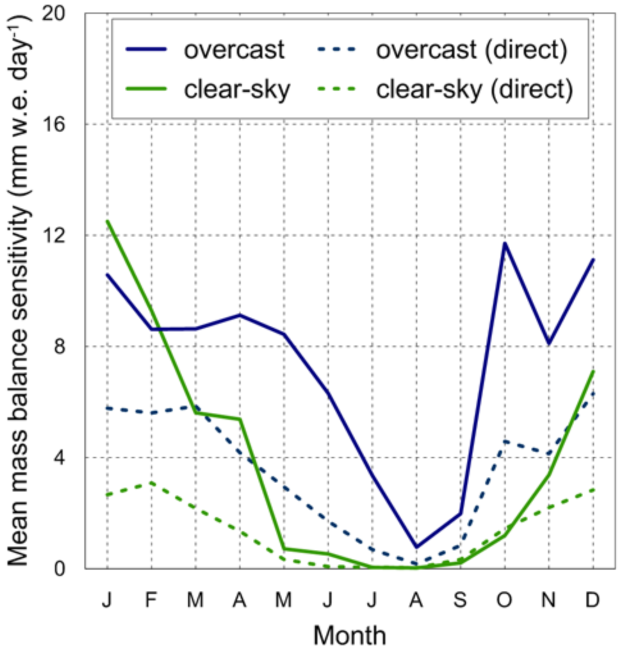


Fig. ~~8~~9. The mean daily mass balance sensitivity (ΔSMB) to a 1 K change in T_a, separated into clear-sky (green) and overcast (blue) conditions, in each month of the year. The dashed lines show ΔSMB resulting from only a direct change in *QM,* which was derived from a further model run using measured albedo and perturbing $T_{r/s}$ with T_a. The positive values indicate mass loss for increased T_a.