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The Cryosphere Discussions

Interactive comment on "Response of the ice cap Hardangerjøkulen in southern Norway to the 20th and 21st century climates" *by* R. H. Giesen and J. Oerlemans

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We like to thank the referee for his/her positive reaction on the manuscript and suggestions for further improvement. Below is our response to all comments.

Origin bedrock topography
The bedrock topography used in the model is indeed based on ice thickness measurements, which have been described in more detail in the PhD thesis (Giesen, 2009), together with the inter- and extrapolation methods. This information is added in the revised manuscript in a condensed form, together with the implications of uncertainties in the bedrock data.

Initialisation of the 20th century run
The 20th century run is initialised with a modelled initial ice cap geometry, because no accurate maps are available of Hardangerjøkulen in the early 20th century. However, the ice cap geometry for 1904 is not based on a calibration over the 20th century with the coupled model, but on a dynamic calibration of the ice model with a prescribed and simplified mass balance distribution, starting in the year 1600 to include the Little Ice Age maximum. The coupled model has not been calibrated in any way after coupling, but is based on separately calibrated surface mass balance and ice models. The good performance of the two models separately, does not at all guarantee good results of the coupled model, which has more degrees of freedom. The validation with 20th century observations provided in the paper shows that the coupled model is surprisingly well able to produce a realistic evolution of the ice cap. More details about the dynamic calibration are now given in the revised manuscript.

Calibration of the energy balance model
All parameterizations used in the energy balance model are existing parameterizations based on physical principles, only those parameters that depend on local climatic conditions were calibrated with the AWS data. Measurements from the AWS at the summit were not used for calibration of the surface energy flux parameterizations, only to determine values for the extrapolation of temperature and humidity over the ice cap. Modelled and measured shortwave and longwave incoming radiation for the summit site, as well as surface albedo show good correspondence, which is added to the manuscript. Because 95% of the total ice cap surface area is situated in the elevation range between the two AWS altitudes and these AWSs together represent both the accumulation and ablation area, the good performance at these two locations gives confidence in the results for the rest of the ice cap. Figure 6 demonstrates the ability of the model to produce realistic results for years with higher/lower temperatures and precipitation than the years it was calibrated with. We therefore expect the model to also produce representative values when the input meteorological data change, for example in a warmer climate. Of course, calibrated model parameters may also change

in a warmer climate, for example due to changing cloud or snow/ice properties. This has been investigated with additional simulations, which was already discussed in the manuscript.

Error bars for projections
The intention of the 21st century simulations is not to provide a 'true' future evolution of Hardangerjøkulen, but to investigate how the ice cap reacts to different changes in the present-day climate that are projected by climate models. The largest uncertainty in the future projections is caused by the unknown variability in the 21st century climate. Including error bars representing the uncertainty in model parameters and input meteorological data would require a Monte Carlo simulation with model parameters to include all possible combinations, as they are not independent. This is computationally not feasible and also may give the false impression that the ice volume will actually decrease continuously and steadily. For this reason, error bars have not been added.

Detailed comments
- p 949, line 13: A short review of previous studies with coupled mass balance – ice flow models on mountain glaciers is added to the introduction.

- p 950, line 22: Mass balance values can be either represented as a rate or as an integrated value over a certain time period, where the time period should be clear from the context. We agree with the referee that this is not always the case in the manuscript and have added the corresponding information in the revised manuscript, where needed.

- p 951, line 11-29: The Holocene history of Hardangerjøkulen is shortened to the information directly relevant to the scope of the paper.

- p 954, line 16: Ice layers formed by refreezing of percolating meltwater do occur on Hardangerjøkulen, but the formation of superimposed ice has not been reported. Our statement that the effect of refreezing on the mass balance is small is based on a simple calculation with representative values for Hardangerjøkulen. At the summit, the

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first melt occurs in early May, when the temperature of the snowpack is at maximum 5^{o}C below the melting point. The energy needed to heat the snowpack accumulated since October (about 2.5 m w.e.) to the melting point, assuming a snow density of 400 kg m^{-3}, is 2.6x10^{7} W m^{-2}. The total melt energy available through the summer season, based on a minimum ablation of about 1.5 m w.e., is 5.0x10^{8} W m^{-2}. Hence, a maximum of 5% of the total melt energy is needed to bring the entire snow layer to the melting point, a value that will only become smaller at lower elevations. Although this refrozen water has a positive effect on the mass balance, ablation is enhanced through the heat added to the snowpack. Based on these compensating effects and the relatively small amount of energy involved, we state that the effect of refreezing will be small. This paragraph is slightly extended in the revised paper.

- p 954, line 20: The description of the meteorological data is moved from the appendix to the main text in the revised manuscript.

- p 954, line 21: The range and application of the seasonal lapse rate is given in Section A3. Using a constant lapse rate of 6.5 K km^{-1} gives good correspondence between modelled and observed temperatures at the summit AWS, this is added to the revised manuscript. The sensitivity of the mass balance to the value used is also discussed.

- p 954, line 24: ‘observed’ refers to the actual input data used, because it is redundant here, it was removed.

- p 955, line 2-4: The prescribed altitudinal gradient in accumulation was derived from the mean winter balance profile on Rembesdalsskåka, based on profiles reported for 33 years by NVE. This is added to the text. No other information on the precipitation pattern is available from in situ measurements, except for the accumulation at the AWS site on Midtdalsbreen. However, accumulation on Midtdalsbreen and Rembesdalsskåka were found not to be related in a simple way. Because precipitation measured at stations around Hardangerjøkulen indicate a regional south-west to north-east gradient in precipitation, we used preciptitation measured at two synoptic stations south-west (Liset) and north-east (Finse) of the ice cap to prescribe a linear south-west to north-east gradient in precipitation over the ice cap. The origin of the precipitation gradient is added to the manuscript.

- p955, line 13: With 'measured ablation' we mean the mean summer balance profile computed from values reported for 33 years by NVE. This is made clear in the revised manuscript.

- p959, line 18: The term 'local' is better described in the appendix, which is now incorporated in the main text, to improve clarity.

- p960, line 18-26: The aim of this section is to separately show the model performance for winter (precipitation) and summer balance (air temperature, humidity, cloudiness and pressure), using input meteorological data from different sources. The current explanation of this method is indeed difficult to understand and is rewritten in the revised manuscript.

- p961, line 1: A comparison of modelled and measured snow depth shows that for the period 2001-2005, accumulation is overestimated with data from Bergen (+0.12 m w.e. a^{-1}) and the net balance is underestimated (+0.26 m w.e. a^{-1}). Local data give almost exactly the correct winter balance (-0.03 m w.e. a^{-1}) and net ablation (0.00 m w.e. a^{-1}). This is now briefly mentioned in the manuscript. The large annual differences and the small sample of five years do not allow for drawing general conclusions about the total modelling period. We extended the discussion on the uncertainty in modelled precipitation in the revised manuscript, indicating that modelled precipitation is more uncertain for other parts of the ice cap than Rembesdalsskåka.

- p962, line 8: We used +15 m because the surface of Rembesdalsskåka has almost everywhere increased in elevation over the period 1961-1995. For clarity, a value range [-2, +15 m] is presented in the revised manuscript.

- p963, line 1-13: The spatial distribution of the modelled mass balance is provided to give the reader insight into the typical pattern obtained and should not be regarded as the true distribution. We agree with the referee that the real distribution may differ significantly from the modelled pattern, principally for other drainage basins than Rembesdalsskåka. However, the mass balance variability due to topographic effects is expected to be realistic. We shortened the discussion, addressing only the main features in the spatial distribution.

- Section 5.5: We do not agree with the referee that mass balance sensitivity is not related to the rest of the paper. The annual values give a first indication on how much precipitation is needed to balance the effect of a 1 K temperature increase, which is referred to in Section 5.5 to explain the small effect of a 10% precipitation increase compared to 3 K warming. The SSC values are a valuable tool to explain why climatic changes in winter/summer have a larger effect than changes in spring/autumn. Furthermore, mass balance sensitivities are used in various studies to estimate the contribution of melting glaciers to sea level rise and are therefore important to be reported. The readability of the section was improved by moving the mass balance sensitivities to a table.

- p 967, line 23/page 968, line 3: We do not understand exactly what the referee means with 'relative to the location of the maximum in temperature change'. We compare the winter balance modelled with and without a seasonal variation in the prescribed change. This was not obvious from the text, which has been rewritten.

- p 972, line 12: The meteorological records from stations in the vicinity of the ice cap have not been thoroughly tested for inhomogeneities and biases, although the records have been inspected for outliers and compared to records from other stations to identify regional differences in meteorological conditions. The synoptic station in Bergen is one of the main stations used for climatic studies in Norway, these records have been analysed by the Norwegian Meteorological Institute and are therefore of high quality. This information is added to the manuscript.

- p972, line 17: The distance of the weather stations to the ice cap is added in a table, together with the station altitudes.

- p973, line 3: The correlation coefficient of the cloud observations at Finse and Eidfjord Bu is r=0.75. This is added to the text.

- p 974, line 10: The seasonal lapse rate variation can only be based on five years, as AWS data is not available earlier. Lapse rates based on a direct comparison of air temperatures at a station outside and on the ice cap, provide the best estimate of the air temperature at the AWS site and are therefore used. A comparison of modelled and observed daily air temperatures at the AWS location shows much more scatter using data from Bergen than from Finsevatn, probably due to the close proximity and the small difference in altitude. We obtain a good correlation for both data sets: r=0.94 for daily values calculated from Finsevatn data and r=0.93 with data from Bergen. This information is added in the revised manuscript. The correlation for Finsevatn is significantly affected by a few clear-sky winter days with a large difference between modelled and observed temperatures, due to local cooling effects.

Reference

Giesen, R. H.: The ice cap Hardangerjøkulen in the past, present and future climate. Ph.D. thesis, Institute for Marine and Atmospheric research Utrecht, The Netherlands, 2009. http://igitur-archive.library.uu.nl/dissertations/2009-1104-200130/UUindex.html

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