

## Responses to Referees

### Anonymous Referee #2

The authors use Ben Marzeion's minimal model to reconstruct the mass balance of a glacier in the central Andes with the longest record of direct mass balance observations. They show that the model is capable of accurately reconstructing mass balance, and use stream-flow data to extend the modeling to the last 100 years. The paper is well written and the conclusions are generally sound, although I have a concern (see below). The discussion and conclusion sections are slightly repetitive and can be trimmed.

My concern is related to the sensitivity analysis where the mass balance changes are attributed primarily to precipitation forcing. Because the mass balance model is so simple, it is not clear that this experiment is robust. In the case of a full energy balance modeling study, there is the potential to examine uncertainties in each of the energy balance terms, and how these might influence the finding. Specifically, if the model sensitivities to temperature and precipitation are incorrect, then the finding might be spurious.

Simply showing that the model does a good job of simulating mass balance history is not sufficient, because of the equifinality issues involved. In other words, many different combinations of temperature, precipitation and model parameter choices could produce a similar mass balance reconstruction. Each of these simulations would show a different sensitivity to temperature and precipitation forcing. I suggest that the authors remove or de-emphasize this component.

We partially agree with the reviewer in that it is possible for these simplistic sensitivity analyses to produce spurious results or similar outcomes given different combinations of model parameters and temperature and precipitation data. If assessed in isolation and looking only at the results from the annual mass balance model described in Eq. 1, this could also be true for the simple ECH model. However, the results shown in Fig. 3C indicate that holding temperatures constant and using only the precipitation variations as forcing, we can successfully reproduce the overall annual mass balance variations observed at ECH. In contrast, if we use only the temperature variations as forcing, the model does a poor job in capturing annual mass balance variations at ECH. This is the same kind of sensitivity assessment performed in Marzeion et al. (2012a), and in our opinion, it provides at least a first clue that precipitation is playing a main role modulating this glacier's year-to-year mass balance changes.

This result is supported by additional evidence, which now includes

- a) The results from the cross-validation of the simple mass balance model, which showed that the parameters  $\alpha$  and  $\mu$  are quite stable over the entire calibration period.
- b) The strong, time-stable similarities of the annual mass balance series with the regional snowpack (and streamflow) records. These clear similarities also extend to the annual precipitation record from Santiago de Chile, an official station located roughly 50 km from ECH (see new Fig. 2).

These figures and correlation patterns do not mean that temperature variations are unimportant at this site, but simply suggest that variations in precipitation are likely those that ultimately define the sign and overall magnitude of the annual mass balance values at ECH.

In the context of our study, this result is important because it provides an empirical evidence in support of the use of the longer regional streamflow record (also directly modulated by variations in winter precipitation patterns in the Andes, see Fig. 2) to reconstruct the ECH mass balance series back to 1909.

In more detail, the model captures the melt process by using monthly temperature data \* by a tunable melt factor. Such a model attempts to capture the influence of long-wave radiation, turbulent heat fluxes and albedo within a single term. In reality, a small, high-elevation glacier such as Glaciar Echaurren Norte must have a relatively complicated surface energy balance. I see that for example, penitentes form on its surface, indicating an important role for albedo and turbulent fluxes. Understanding the sensitivity of such a glacier to climate change (rather than reconstructing mass balance), requires something a bit more thorough, e.g. a full-energy balance model and on-glacier observations. See for example Molg et al. 2008. *International Journal of Climatology* 28: 881–892 (2008).

Agreed. This is certainly the kind of studies that we would require to understand the energy balance of this glacier and fully elucidate the sensitivity of this type of glaciers to climate changes. However, as discussed in the text and mentioned above, the main objectives of our study were not to elucidate these in-depth issues for which data-intensive measurement programs would be required. Instead, given the valuable (but still limited) data available, we were interested in identifying first order forcings of the glacier mass balance variations, and then use these relationships to extend these variations back in time using other longer and well correlated records already available from this region.

We now mention the main objectives of the study in the Introduction section to clarify these points.

The paper should include a figure that shows the modelled and measured surface mass balance profiles (how  $b$  varies with elevation) so that we can get a sense of how much accumulation and melt actually occurs on Glaciar Echaurren Norte.

As mentioned above, the data reported to the WGMS only includes, for each year, the winter balance, the summer balance and the annual mass balance of Glaciar Echaurren Norte. Gathering the additional information from each measurement point and calculating and modeling mass balance profiles over the study period was not considered relevant given the main purposes of this study, which were focused on testing the ability of very simple models to capture the year-to-year changes in mass balance at ECH.

#### **Minor comments:**

Title: 'mass balance' (rather than balances)

Fixed

4951, Lines 8-11. See above. This finding should be de-emphasised or removed until more complete modeling is carried out.

Agreed. We have re-written this and other related portions of the text to better address this issue.

4952, Line 4. 'touristic' isn't used by native English speakers. Replace.

Fixed. "tourist attractions" used instead of touristic.

4954, Lines 1-3. This statement about snow remaining frozen is not supported by data or a reference. It may be correct but it either needs a citation or more speculative language should be used.

Fixed. We had only one general reference to support this statement (Masiokas et al. 2006). Now we have also included a more specific study (Cara et al. in press) that shows the characteristic seasonal pattern of snow cover in the Andes at these latitudes. This pattern shows a maximum coverage during the winter months, followed by a clear decline that starts at the onset of the melting season (October-November) and reaches a minimum during the warmest months of the year (December-February).

Lines 16-20. This sentence is too complicated and needs to be rewritten.

Fixed. This now reads: "In contrast to the well known similarities between precipitation (solid and liquid) and hydrologic variables, the spatial and temporal patterns of high-elevation temperature records in the Central Andes of Chile and Argentina are still poorly understood."

4955, Line 1. Please provide elevational range of glacier.

Fixed. The elevational range and other specific characteristics of the glacier are now included in the more detailed description of the glacier (see section 2.1).

Lines 20-26. I disagree that this approach provides 'solid evidence' for 'objective testing' of the relative significance of temperature and precipitation on mass balance. See discussion above and revise this text appropriately.

Agreed. This sentence was removed and a better discussion of the limitations of the methodology is included in the text.

4956, \_ line 5. The paper would benefit from a clear list of objectives.

Fixed. See last paragraph of the Introduction.

4957, Line 27. 'Values' of what?

The sentence refers to the winter mass balance values measured at ECH.

4959, Line 4. Add space 'predictand'.

Fixed.

4966, lines 10-11. A hypothesis can not be 'validated'. Use 'support' instead.

Fixed.