Author's response to Anonymous Referee #2

We appreciate the review of Anonymous Referee #2, and to address the comments made we introduce changes in the manuscript in order to address the reviewer's concerns. Next, we answered point by point the general comments (enumerated) of the Referee #2:

Referee comments:

1) By approaching the task, the authors make clear on several occasions that, given the limited knowledge about Mid Holocene conditions, only differences between a reference (PI) and the target period (MH) can be addressed. It remains, thus, unclear why the major proportion of the paper (including 6 of the 10 Figures) deals with absolute values of temperature, precipitation, and ELA. Among many other expendable portions, e.g. the discussion about biases in the absolute values is not needed.

Author's response

The aim of showing absolute values of the PMIP2 models and comparing them with CRU and weather stations is to assess the climate models results that we use as an input of the mass balance models, in two aspects: the seasonal cycle and the longitudinal gradient, as these are important to give credibility to the mass balance calculations.

Author's change in manuscript (pages and lines correspond to the new final version without track changes)

We agree that dedicating 4 figures to this end is too much. We eliminate 4 figures (figs. 2-5) and the complete section 3.1 of the original manuscript. We add this section in a supplementary material. Results of those figures and conclusions taken can be explained without the figures.

Referee comments:

2) It remains obscure (probably because of the dominating discussion on absolute values) how recently observed conditions can hold to validate the PI as a reference period.

Author's response

Unfortunately PMIP2 no 20th century simulations were carried out by the groups. So the only reference period that can be used in this study is the pre-industrial control simulations.

We think that it is expected that pre-industrial and present-day climate followed the same spatial and temporal pattern. The only reason to compare the pre-industrial PMIP2 simulation and the the20th century climate data, is to verify that these patterns agree between these two databases

To address the issue of comparing Pre-Industrial simulations with 20th century data we will make those comparisons with 1901-2004 CRU data, as a proxy for more anthropogenically unperturbed conditions.

3) The key for explaining any climate forcing is the dating of the targeted proxies (glacier extends in this case). It seems that the problems associated with dating are large for glacier extends during the Mid Holocene in the southern mid latitudes. The authors must examine and clarify if this enables them to retrieve conclusions from their exercise.

Author's response

We in advance have this in mind in the original CPD manuscript (page 618, lines 14-17): *"…and the fact that we are comparing glacier fluctuations spread throughout the mid-Holocene with a precise time-slice, namely 6 ka BP, in addition to the already discussed uncertainties in the timing of glacial fluctuations."* However there are several sites in the Southern Alps where it is clear from precisely dated moraines (using 10Be) that mid Holocene glacier extents were larger than those during the preindustrial reference climate. For example, Kaplan et al., Schaefer et al. and Putnam et al. all show that glaciers were larger than present between 8-6000 years ago compared to several hundred years ago (during the LIA). In Patagonia there are more uncertainties in the timing of glacial fluctuation at MH. However we argue that this is sufficient knowledge to undertake a first-order modeling study that attempts to understand the driver of these different glacier extents. We take this point with extremely precaution because we understand that the data discussed in the paper does not allow us to state that Neoglacial advances happened around 6 ka but it can help in determining if the climatic conditions of the MH would permit to have glaciers larger than PI, and this could be part of the discussions around the timing and causes of glacier advances at 8-6 ka.

Author's change in manuscript

We add in the Introduction all the references of mid-Holocene evidence of glacier advance in Southern Alps and Patagonia as a justification of our work (page 3, lines 27-30). Also in the Introduction we add as final paragraph the scope of this exercise to clarify what conclusions we can obtain from this analysis (page 4, lines 18-25).

4) The use of ELA as the crucial variable requires a much clearer definition of the ELA the authors use.

Author's response

We do not know in what sense the referee wants us to explain and define the ELA. A reference it would be useful for us. Our definition of the ELA in the original CPD manuscript (page 606, lines 23-26) it seems to be appropriate, especially as we are talking about temperate glaciers (where internal accumulation and superimposed ice are negligible). But perhaps the comment is more about why we use the ELA as a 'crucial variable'? And the answer to that is that the ELA, as calculated by a degree-day model, is appropriate variable to consider for a regional study, where we are not considering individual glaciers and their specific responses to climatic variations. Rather, we are interested in translating the output of the PMIP2 models into a signal that the glaciers respond to.

Author's change in manuscript

In the new version of the manuscript we emphasize the definition of the ELA in two senses, first we define the ELA related to the mass balance profile (m w.e. versus altitude), indicating how the ELA is estimated. Second, we define the ELA indicating their use as a climatic variable of glaciers assuming that ELA is representative of a glacier in steady state or long term equilibrium (page 4, lines 10-15). Also we indicate the importance of the ELA as crucial variable for estimated the response of glacier to climate change also using previous modeling studies that used GCM data (page 5, lines 22-30) and considering that ELA is representative of regional climate (page 5, lines 9-14). With this in mind we can relate regional climate from GCM with glacier response. We use new references as Bakke and Nesje (2011) and from the manual of Mass Balances of IACS/UNESCO (Cogley et al., 2011)

5) A much clearer discussion is needed on how ELA changes are related to glacier extends under different landscape geometries in order to compare modeled ELA differences with reconstructed glacier extends.

Author's response

The reviewer rise an important problem. However, this problem is not relevant for this research. We did not aimed to quantify the impact of the ELA change in the glacial extent. Indeed, we use the ELA as our proxy of glacier change, because it is independent of the topography, however we mentioned in the manuscript that the value of change could impact glacier extent under different characteristics, as the hypsometry (page 618, lines 21-28 of CPD manuscript).

Author's change in manuscript

We add new paragraph discussing the importance of the sensitivity of glacier fluctuation to ELA change, specially associate to hypsometry, but we use previous work as references (page 15, lines 20 – 31 and page 16 lines 1 - 4), as De Angelis (2014) and Oerlemans (2012), discarding an own analysis in this topic.

6) It remains unclear how PMIP output enters the mass balance model (any downscaling procedure applied?) as well as on how reference levels are defined to which the vertical gradients of temperature and precipitation are applied.

Author's response

We clarify this point in the text. No downscaling procedure was applied considering the regional view that we have as a main aim. We just resize the PMIP2 models output with linear interpolation.

About the levels we indicate in the paper that we apply the mass balance model in an altitudinal range defined from 0 to 4000 m asl with a step of 20 m (original CPD manuscript, page 607, lines 10-13).

Author's change in manuscript

We add the interpolation procedure in the new manuscript (page 5, lines 2 – 7) and add more description about the vertical distribution of temperature and especially of the precipitation (page 8, lines 27 – 30 and page 9 lines 1 - 11).

7) What is the final significance of the differences in ELA (Figure 10)? What is the uncertainty of the obtained ELA differences?

Author's response

In a revised manuscript we change the question stated in the introduction as objective of the paper. Instead of stating the orbital control on glacier extends we will talk about climate controls. In the conclusions we can address the orbital part again.

About the second question the reviewer rise an important point. In the first version of the manuscript, we did not address the uncertainty and statistical significance of our results properly. In the new version we carried out a sensitivity test, in order to quantify the significance of our results.

Author's change in manuscript

We change the question/scope in the Introduction (page 4, lines 18 -25). We conducted and add sensitivity experiments to two parameters: Degree day factor of snow and ice and the precipitation lapse rate. We add to the Discussion (section 4.3) the results of these experiments with two new Figures (Figs. 7 and 8).

8) The paper needs, by addressing the above mentioned and some more issues, a major re-organization, a re-structuring, and a re-writing before a proper review is possible.

Author's response

The reviewer's comments helped us to recognize that the main goal of the paper was a bit disconnected with our analysis. In the new version of the manuscript we restructure the document, in function of our new main goal: Determine if the climate conditions during the MH would permit to have glaciers larger than PI.

Author's change in manuscript

We restructure the manuscript considerably. The main points are the following:

1. We change the question stated in the introduction as objective of the paper. Instead of stating the orbital control on glacier extends we will talk about climate controls. In the conclusions we can address the orbital part again.
2. We leave out figure 2-5 and leave those as supplementary material
3. We further assess uncertainty of the ELA results by doing sensitivity experiments to the degree day factor of snow and ice and precipitation lapse rate. We add two new Figures in a new Discussion section.
4. Some sections were eliminated and others were combined by other sections.
5. We rewrite a great portion of the manuscript.

Author's response to Ann V Rowan (Referee)

General comments

We appreciate the review of Ann V Rowan. There are several comments that help us to improve the manuscript including new and important references. We agree in the more quantitative look of our results. In the original manuscript we raised some cautions with our results considering the uncertainties, first in the PMIP2 model data and second in the parameterization in the glacier mass balance model. However the reviewer's comments indicate some points that we include in the manuscript as limitations of the glacier mass balance model, the input PMIP2 models and the resolution. In this sense we still consider that our approach is appropriate, given:

- the regional scale and the spatial differences in the latitudinal range in Southern Alps and Patagonia;
- the use of ELA as an indicator, instead of a complete glacier reconstruction that is more appropriate for a smaller spatial scale (a basin or a specific glacier),
- the coarse resolution of the PMIP2 model and that the ELA is closely associated to climate conditions and could be representative of the climate over spatial scales of up to 500 km (Bakke and Nesje, 2011).

We answer point by point the general comments (enumerated) of Ann V Rowan:

1) The experimental design for the application of the glacier model does not seem entirely suitable to achieve the aims of the paper.

Author's response

The glacier mass balance model calculates the accumulation and ablation from climate variables and is based on the works of Jóhanneson et al. (1995), Braithwaithe and Zhang (2000) and applied in the glacier Franz Josef, New Zealand (Anderson et al., 2006), and glaciers in Iceland, Norway and Greenland (Jóhanneson et al., 1995). In these works the model inputs correspond to data from weather stations. It is important to indicate that this type of model already has been applied with information from general circulation models, for example, for the LGM in tropical glaciers, where Hostetler and Clark (2000) with information obtained of simulations GENESIS (v. 2.01) inferred ELA positions across the determination of the curves of balance sheet of mass (m w.e. v/s altitude).

Using a degree day model Radíc and Hock (2011), with data from general circulation models (ECHAM/MPI-OM, CCSM3, CSIRO-Mk3, GFDL-CM2.0, etc) obtained from CMIP, modeled the future glacier mass balance for different glaciated regions to estimate sea level rise projected to 2011. Finally Rupper et al. (2009) applied this kind of model to the region of Central Asia, using data from re-analysis NCEP-NCAR for the present and data from general circulation models of the phase I of PMIP for the Holocene.

All of these cases used similar versions of the degree – day model that we used in the present work, nevertheless one of the big differences with the current work is that these applications of the model used climatological monthly information; while in the present work we used daily information. This point is not of small importance since according to Wagner et al. (2007), the statistical description of the relation between the circulation and the rainfall is better represented in a daily scale in the sense of catching events and synoptic-scale processes, so as we mentioned, we still consider that our approach is appropriate.

Author's change in manuscript (pages and lines correspond to the new final version without track changes)

We add many of the reference that we mentioned as example of the application of this kind of model with GCM data with the scope to estimated ELA (page 5, line 22 – 30). Also we explain in a new section (2.1.) the general set up of our experiment

2) Moreover, the manuscript is some what disorganised, and would benefit from more thorough editing for structure and clarity, particularly to be more quantitative than qualitative throughout

Author's response

As we indicated for a previous referee**,** we restructure the manuscript considerably.

Author's change in manuscript:

1. We change the question stated in the introduction as objective of the paper. Instead of stating the orbital control on glacier extends we will talk about climate controls. In the conclusions we can address the orbital part again.
2. We leave out figure 2-5 and leave those as supplementary material
3. We further assess uncertainty of the ELA results by doing sensitivity experiments to the degree day factor of snow and ice and precipitation lapse rate. We add two new Figures in a new Discussion section.
4. Some sections were eliminated and others were combined by other sections.
5. We rewrite a great portion of the manuscript.

3) Resolution of the glacier model. The glacier model was applied at the same grid spacing as the climate model results (0.5 degrees, about 50 km), and therefore does not capture the impact of the mountainous topography of the two study regions on mass balance. Topography exerts a major control on the extent and therefore ELA of small mountain glaciers such as those that are the subject of this paper, and these ELA reconstructions are likely to contain large uncertainties, potentially exceeding those given in the results, which already exceed by several times the inferred change in ELA between the PI and MH periods.

Author's response

The idea in this work was to obtain a regional view of ELA change in two comparable zones (Patagonia and Southern Alps). As we indicate (original CPD manuscript, page 618, lines 17-18) the coarse resolution of PMIP2 models is a limitation for a direct comparison with geomorphologic evidence. In this sense this exercise represents a first step. Also, ELA for small mountain glaciers are representative of climate conditions (Bakke and Nesje, 2011). Despite this, we agree in that use of climate models in a specific glacier reconstruction need an appropriate process of downscaling, that escapes of the scope of the present work. However the coarse resolution of the PMIP2 models output and the uncertainty in model parameters, the general pattern in the modeled ELAs in both regions is reasonable.

We make this point clearer in the revised manuscript.

Author's change in manuscript

We emphasis the use of ELA as the most crucial variable to estimated the glacier response to GCM climate of both periods and that we are interesting in the ELA difference between periods more that the absolute values (page 5, lines 15 - 18. Using the ELA difference we reduce the uncertainties. We justify this, citing new add references that indicate the regional climate signal in the ELA (page 4, lines 4 – 14).

4) Validation of climate and glacier modelling results. The authors compare their climate model results with present-day measurements from automatic weather stations (AWS). However, as stated in the text, the climate model represents a period that predates the climate data by 250 years so this validation is poor. The authors would give more confidence in their results if they compared a present-day climate simulation with the AWS data, or if this is not possible, applied their glacier model to calculate present day ELAs using the AWS data for comparison to present day

observations. Moreover, the similarity in sign between results from NZ and Patagonia does not seem sufficient to justify the conclusions.

Author's response

The climate models used correspond to the PMIP2 outputs, an international initiative, and they did not perform a 20th century experiments, that would have made a better comparison. This is indicated in detail in section 2.2. The comparison with weather station (these are weather station from meteorological government office in Chile, Argentina and New Zealand and does not correspond necessary to an automatic weather station, AWS) and with CRU data, is in order to shows if the PMIP2 model represent the seasonality (Figure 2 and 4) and the spatially distribution (Figure 3 and 5) of the climate characteristics of each zone (section 3.1.). Hence comparison is just for show the model limitations.

About the glacier model we indicate that this model is used by Anderson et al. (2006) with present meteorological data. Also we conducted a test run to assess the performance of our model forced with climatological information coming from a regional climate model ran at 25-km resolution and the ERA40 reanalyses (PRECIS-ERA40, Rojas et al, 2015 *in prep*.) for the hydrological year 2003-2004 in the Mocho glacier in the Lake District of Chile (~40°S), corresponding to the same year analyzed in Rivera et al. (2005) with the glaciological method (stakes). We use two precipitation lapse rates: 0, and 0.00252. We compared the modelled ELA with the observations. This comparison showed a reasonable agreement between the observed and modelled ELA, for precipitation lapse rates (0 and 0.00252 mm/m).

Author's change in manuscript:

We add the results of the test run to the new manuscript (page 7, lines 24 - 29 and page 8 lines 1 – 10) to validate the model.

5) Treatment of precipitation data. Precipitation is poorly represented in the modelling as the authors assume a linear relationship between precipitation amount and elevation. The Southern Alps and Patagonian Andes are classic examples of orographic precipitation regimes, where the interaction of westerly circulation with high topography results in precipitation distributions that strongly deviate from the linear model used here. The use of a linear relationship to describe precipitation as an input to a glacier C300 model has been quantified for the Southern Alps, and will introduce a further uncertainty to the results equivalent to a difference in ELA of about 80 m (Rowan et al., 2014, JGR-ES). Certainly for New Zealand if not Patagonia, that availability of precipitation data are much better than implied in this

manuscript; both range profile and gridded precipitation data based on interpolation of AWS measurements are available (e.g. Tait et al., 2006, International Journal of Climatology; Henderson and Thompson, 2000, Journal of Hydrology) and it is not clear why the authors did not compare their results to or use these data in their modelling.

Author's response

We agree with this comment and we recognize that this is probably the main source of uncertainties in the model (page 618, lines 18-20, original CPD manuscript) because the distribution of precipitation is difficult to predict. However we use a linear relationship in precipitation to facilitate the process of mass balance modeling considering that this is a regional view of ELA change. We applied the same procedure for both time slice and in this sense we are interesting in the difference more than the absolute values of ELA, of course we expect a reasonable value for ELA. In the scientific literature a great range of linear precipitation lapse rate has been used (even for regional modeling, e.g. Radic and Hock, 2011). However we keep in mind that the difficulty here is that we are working across mountain ranges and that the PMIP2 models do not represent the precipitation gradient in the Southern Alps

Author's change in manuscript

We assess uncertainty of the ELA differences results by doing sensitivity experiments to precipitation lapse rate (and also to DDF's of snow and ice) in the Discussion section (new section 4.3.). Also we recognize the limitation of use a linear relationship in the precipitation (page 9, lines 3 – 8)

6) Link between glacier change and orbital forcing. The results presented here do not convincing achieve the aim of the paper to explore the influence of orbital forcing on glacier advance during the MH, as the model results cannot be linked to a particularly period. A very recent paper (Doughty et al., 2015, Geology) has demonstrated from moraine geochronologies that orbital forcing may not play a role in controlling Late Quaternary glacier behavior in New Zealand and the authors may wish to consider their results in light of this evidence.

Author's response

The results of the model correspond to 6 ka and PI. As we mentioned in the paper (page 618, lines 14-17 CPD original manuscript), the PMIP2 initiative use as an initial conditions the greenhouse gases and the orbital parameter corresponding to 6 ka and pre–industrial times (https://pmip2.lsce.ipsl.fr/), these boundary conditions are different between the two periods so we expect also differences in ELA.

Doughty et al. (2015) consider the orbital influence on glacier extent in the Southern Alps during the period between Marine Isotope Stage 4 and the Last Glacial Maximum. The climatic boundary conditions at this time were very different than during the Holocene and we are not surprised that (direct) orbital variations may not have played a critical role at this time, when large ice sheets existed in the Northern Hemisphere, CO2 varied considerably, and oceanic circulation was different. The Holocene is another matter; climate during this time was relatively stable and we believe it is important to carry out a first-order estimate of the effect of orbital forcing on Southern Hemisphere glacier fluctuations during this period.

However as we mentioned for a previous referee, we are going to take this point with extremely precaution because we understand that the data discussed in the paper does not allow us to state that Neoglacial advances happened around 6 ka but it can help in determining if the climatic conditions of the MH would permit to have glaciers larger than PI, and this could be part of the discussions around the timing and causes of glacier advances at 8-6 ka.

Author's change in manuscript:

We add and discuss the reference main conclusion suggested by the referee (page 3, lines 24 -26). Also we change the question stated in the introduction as objective of the paper. Instead of stating the orbital control on glacier extends we will talk about climate controls.

Modelled glacier equilibrium line altitudes during the mid-Holocene in the southern mid-latitudes

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Abstract

Glacier behaviour during the Mid-Holocene (MH, 6000 year B.P.) in the Southern Hemisphere provides observational data to constrain our understanding of the origin and propagation of pal~~a~~eo-climate~~ic~~ signals. In this study ~~W~~we examine the climatic forcing of glacier ~~expansion~~ response in the MH by evaluating modelled glacier equilibrium line altitudes (ELAs) and climatic~~e~~ conditions during the MH compared with pre-industrial time (PI, year 1750). We focus ~~in~~ on the middle latitudes of the Southern Hemisphere, specifically ~~in~~ Patagonia and the South Island of New Zealand. Climate conditions for the MH ~~are~~ were obtained from PMIP2 models simulations, which in turn were used to force a simple glacier mass balance model to simulate changes in ~~equilibrium line altitude~~ELA ~~during this period~~. In Patagonia, the models simulate colder conditions during the MH in

the austral summer (-0.2°C), autumn (-0.5°C) and winter (-0.4) , and warmer temperatures (0.2°C) during spring.

In the Southern Alps the models show colder MH condition in autumn (-0.7°C) and winter (-0.4°C) warmer conditions in spring (0.3°C) and no significant change in summer temperature.

~~Climate conditions during the MH show significantly ($p \leq 0.05$) colder temperatures in summer, autumn and winter, and significantly ($p \leq 0.05$) warmer temperatures in spring.~~

~~These changes are a consequence of insolation differences between the two periods.~~ Precipitation does not show significant changes, but exhibits a ~~temporal~~ seasonal ~~pattern~~ shift with less precipitation from April~~ugust~~ to September and more precipitation from October to April during the MH in both regions. ~~In response to these climatic changes,~~The mass balance model simulates ~~glaciers in both analysed regions have an~~ a climatic ELA that is 15 - 33 m lower during the MH compared with ~~than~~ PI ~~during the MH~~conditions. We suggest that ~~The~~ the main causes of this difference are driven mainly by ~~the~~ colder temperatures ~~during~~ associated to the MH simulation, ~~reinforcing previous results that mid-latitude glaciers are more sensitive to temperature change compared to precipitation changes~~. Differences in temperature have a dual effect on glacier mass balance~~.~~: ~~First,~~(i) less energy is available for melting during summer and early autumn ~~less energy is available for melting. Second in late autumn and winter,~~ and (ii) lower temperatures cause more precipitation to fall as snow rather than rain in late autumn and winter, resulting in more accumulation and higher surface albedo. For these reasons, we postulate that the modelled ELA changes, although small, may help to explain larger glacier extents observed ~~in the mid Holocene~~by 6000 yr BP in ~~both~~ South America and New Zealand.

1 Introduction

Deciphering the climate signals and glacial history of the mid-latitudes of the Southern Hemisphere (Fig. 1) during the Holocene is key to unravelling the mechanism of climate change that occurred during this period. During the last ~11500 years, a series of intervals of rapid climate changes occurred worldwide (Mayewski et al., 2004). Reduction in temperature and/or increases in precipitation during these periods have been recorded as multiple glacial advances in different areas of the planet. ~~A~~Solomina et al. (2015) recently provided a global review of Holocene glacier activity ~~is given in Solomina et al. (2015). These p~~. Periods of renewed glacial activity, known as Neoglaciations (Porter and Denton, 1967), were initially identified in the Northern Hemisphere. However, during the last decades, numerous studies have shown evidence of glacial advances, as well as climate variability during this period in the Southern Hemisphere (approximately between 35° to 55° S). Most of these studies have focused on Patagonia (e.g. Clapperton and Sugden, 1988; Porter, 2000; Rodbell et al., 2009; Strelin et al., 2014) and in the Southern Alps in New Zealand (e.g. Gellatly et al., 1988; Porter, 2000; Schaefer et al., 2009, Putnam et al. 2012, Kaplan et al. 2013).

In Patagonia (Fig. 1), a number of different Neoglacial chronologies have been produced (e.g. Mercer, 1982; Aniya, 1995; Clapperton and Sugden, 1988; Aniya, 2013~~; Strelin at al., 2014~~). However, significant differences between these chronologies have not been fully resolved. The ~~latest~~ most recent of these chronologies ~~shows~~ suggests that the largest advance in the Lago Argentino area (50°S) occurred~~ing~~ between 6000-5000 yr BP (Strelin et al., 2014).

In Southern Island of New Zealand (Fig. 1), on the other hand, notable periods of glacier still stand or re-advance occurred during the early to mid-Holocene, as well as during the last millennium (Schaefer et al. 2009, Putnam et al 2012). It appears that these ~~decadal to~~ centennial-scale glacial~~er~~ events have been superimposed on a long-term trend of decreasing ice extent that persisted for the entire Holocene (Schaefer et al. 2009, Putnam et al. 2012, Kaplan et al. 2013). ~~Putnam et al (2012) suggest that glacial advances in New Zealand were driven by the migration (southward shift) of the Inter-tropical convergence Zone (ITCZ).~~

In this context, it is clear that several aspects of the Neoglacial chronology of the southern mid-latitudes (~~30~~35°-~~50~~55°S) are still inadequately understood, and more ~~high-resolution~~detailed chronologies are needed. Particularly relevant for this study, is the lack of agreement regarding the timing ~~of the onset~~ of the Neoglaciations in the southern mid-latitudes (Porter, 2000).

Understanding the climate and glacial history of the southern mid-latitudes is a prerequisite for testing hypothesis regarding the origin and propagation of palaeoclimate signals, the coupling of the ocean–atmosphere in the extra-tropics, and the interaction of low- and high-latitude climate controls on hemispheric and global climate (Fletcher and Moreno, 2012, Moreno et al., 2010, Rojas et al. 2009, Putnam et al. 2012). The mid-Holocene ~~also~~ represents a key moment in our late climate history.~~,~~ This period, within the current interglacial cycle ~~given that it corresponds to the period within the current interglacial cycle, with an~~ had important differences in orbital parameters with respect to the present conditions and was devoid of influences from late-glacial climate change (Braconnot et al., 2007). Although recent work has demonstrated that orbital forcing may not have played a critical role in glacier behavior during cold phases of the last glacial cycle (Doughty et al., 2015), the climatic boundary conditions at that time were very different than during the Holocene. Considering the uncertainty in the timing of the beginning of the Neoglaciation, but that geologic evidence suggest that glaciers were larger than present between 8000-6000 yr BP in both regions (Kaplan et al., 2013, Schaefer et al., 2009, Putnam et al., 2012, Douglass et al., 2005, Harrison et al., 2012), the aim of this work is to undertake a first-order modelling study to assess if the climatic conditions during the mid-Holocene would permit the existence of more extensive glaciers than during the Pre-Industrial (PI) period.

~~These orbital~~ At the mid Holocene (MH hereafter) orbital differences resulted in ~~an increase of incoming solar radiation at the top of the atmosphere in the Northern Hemisphere, and a decrease in the Southern Hemisphere (Braconnot et al., 2007). The~~ southern mid-latitudes ~~, in particular, exhibit~~ negative insolation anomalies from November through March and positive anomalies from June to October in climate models (Rojas and Moreno, 2011).We expect that these orbital/insolation differences had a major impact on the glacial extent and especially in the equilibrium line altitudes (ELA) of glaciers. The equilibrium line altitude is a climatic~~e~~ sensitive parameter marking the location on a glacier where accumulation of snow is exactly balanced by ablation (net surface mass balance equals zero) (Porter 1975, Cogley et al., 2011).~~-~~ELA can be estimated by fitting a curve to data representing surface mass balance as a function of altitude or a mass balance profile (Cogley et al., 2011). Also it is possible to estimate a climatic ELA as an average of ELA during 30 or more years (Bakke and Nesje, 2011). In this sense the most appropriate definition for a climatic ELA is the steady-state ELA or long term ELA that could be estimated by modelling (Cogley et al., 2011). Fluctuations of ELA have been extensively used in paleoclimatic reconstructions because the ELA is primarily controlled by temperature and precipitation (Porter, 1975, Sagredo et al., 2014).

In this paper, we explore the differences in the estimated regional climatic ELA between the MH mid-Holocene (MH, hereafter) and the pre-industrial (PI, hereafter) conditions, using a degree day model with data based on Paleoclimate Modelling Intercomparison Project 2 (PMIP2) PMIP2 climate models output in the Southern Alps in New Zealand and Patagonian Andes in South America (Fig. 1). We hope to answer the question 'To what degree was orbital forcing responsible for the larger MH glacier extents apparent from moraine records in Patagonia and the Southern Alps of New Zealand?'

Therefore this study goes a further step towards linking PMIP2 model simulations, and hence orbital forcing, with the MH glacial record, by explicitly calculating the regional ELAs in Patagonia and New Zealand at 6000 yr BP. The ELA difference between the PI and MH provides information on the scale of glacier change at this key time.

2 Data and methods

2.1 Experimental setup

With the aim of obtaining comparable results we use a glacier mass balance model forced with Paleoclimate Modelling Intercomparison Project 2 (PMIP2) models for both periods, MH and PI. In the next sections we explain both, the model and the data. General approach consists in resize all PMIP2 models output to a resolution of 0.5° using linear interpolation. Due to the coarse resolution of the PMIP2 models, and the regional nature of this study, we used the ELA as a general indicator of glacier behaviour as we are not considering individual glaciers and their specific responses to climatic variations. For each grid point we obtained surface mass balance as a function of altitude. From this mass balance profile we obtained the ELA. Rather, we are interested in translating the output of the PMIP2 models into a signal that the glaciers respond to. Although the ELA is also determined by local climate or topography factors, it is a good indicator of regional climate because glacier mass-balance are commonly correlated over distances of 500 km (Bakke and Nesje, 2011) or even more distance. For example, in the Southern Alps of New Zealand today, glacier end of summer snowlines (a proxy for the ELA) monitored by aerial survey correlate over the ~800 km length of the Southern Alps (Chinn et al. 2005).

We applied the same procedure for both time slices (mid-Holocene and pre-Industrial) as we are interested in a regional view of ELA change, hence we focus in the difference between the two periods more than the absolute values of ELA, although we expect a reasonable value for the ELA.

~~2.1~~2.2 Glacier Mass Balance Model

We applied a ~~A~~ simple glaci~~eral~~er mass balance model ~~was used~~ to explore the regional differences in the ~~equilibrium line altitudes~~ELA between the MH and the PI in the southern mid-latitudes.

Although many of the ELA reconstructed are based in geologic evidence, ELA modelling studies has been made. Degree-day models, as used in this study, have previously been applied for palaeoclimate studies using data from general circulation models (GCM). As examples, Hostetler and Clark (2000) used data from GENESIS (v. 2.01) simulations and inferred ELA positions from mass balance profile curves for the LGM on tropical glaciers. Rupper et al. (2009) also applied this kind of model to the region of Central Asia, using data from re-analysis NCEP-NCAR for the present and data from general circulation models of the phase I of PMIP for the Holocene. The aim was to reconcile Holocene glacier history with climate by quantifying the change in ELA for simulated changes in Holocene climate.

~~-~~Details of t~~his~~he glacier mass balance model, which has been previously applied to Franz Josef glacier, in New Zealand's Southern Alps, can be found in Anderson et al. (2006) and are briefly described here. This model calculates the mass balance gradient for any specific location, based on daily data of temperature and precipitation as a function of elevation. Elevation in the model is defined, for each grid point from 0 to 4000 m above sea level (asl) with steps of 20 m. For each elevation, the mass balance is calculated based on:

$$\dot{m}(t,z) = \dot{c}(t,z) + \dot{a}(t,z) \quad (1)$$

Where $\dot{m}$ is the mass balance rate, $\dot{c}$ the accumulation rate and $\dot{a}$ the ablation rate at time t and elevation z.

In glacier mass balance~~this~~ model, accumulation is defined as the portion of the daily precipitation that falls as snow when the daily average temperature is below certain temperature threshold (T_{crit}). Previous studies have considered T_{crit} being in the range of 0°C to 2°C (Radic and Hock, 2011). Therefore, water equivalent (w.e.) accumulation is calculated based on the daily information of mean temperature(T_{mean}) and total daily precipitation (p_d), and calculated as:

$$c(t,z) = \delta_m p_d \begin{cases} \delta_m = 1, & T_{mean} < T_{crit} \\ \delta_m = 0, & T_{mean} \geq T_{crit} \end{cases} \quad (2)$$

In this case, T_{crit} was assumed as 1°C (Anderson et al., 2006).

~~At~~ In the middle-latitudes, the ablation process is mainly controlled by melting (Rupper and Roe 2008). Temperature is a good predictor of melt because incoming longwave radiation~~,~~ and turbulent heat fluxes are important terms in the energy balance that are closely related to air temperature (Ohmura, 2001; Oerlemans, 2001). The other major component of the energy balance, shortwave radiation, is also closely correlated to air temperature.

Ablation in the model is proportional to the mean daily temperature, and occurs for values above 0°C (Braithwaite, 1985; Hock, 2005). In this study, we calculated ablation using T_{mean} when this is positive:

$$T_d^+(t,z) = \begin{cases} (T_{mean}(t,z) - 0), & T_{mean} > 0°C \\ 0 \quad , & T_{mean} \leq 0°C \end{cases} \quad (3)$$

Where T_d^+ is a positive daily temperature.

Ablation is calculated by multiplying the T_d^+ by a factor that relates temperature and ablation, the degree day factor (DDF). The DDF (mm w.e. d^{-1} ~~K~~C^{-1}) corresponds to the amount of melting (of ice and snow) per day, which occurs when temperatures are higher than 0°C. This parameter shows great spatial variability and, in general, is higher for ice and lower for snow due to the high albedo of the latter that reduces the absorption of shortwave radiation~~the available energy for melting~~ (Braithwaite, 1995). In this study we use~~d~~ values of 6 and 3 mm w.e.d^{-1} ~~K~~C^{-1} for ice and snow, respectively. These values correspond to the same values used by Woo and Fitzharris (1992) for reconstructing the mass balance for Franz Josef glacier in the Southern Alps. Therefore ablation is estimated by the following relationship:

$$a(t,z) = DDF_{ice/snow} * T_d^+(t,z) \quad (4)$$

In this study, we use a DDF_{snow} when the snow depth is greater than zero, and DDF_{ice} when the snow depth is equal to zero.

Note that, in this study, we assume that temperatures below zero do not contribute to melting (Hock, 2003), and any potential contribution of sublimation to the total ablation is neglected because it is likely small compared to melting.

By applying this model at different elevations, we obtain a glacier mass balance curve (specific mass balance change with altitude). The ELA occurs where the mass balance equals zero.~~, and thus an ELA.~~

For the purpose of this study we assumed that some parameters such as temperature and precipitation lapse rates, DDFs and temperature threshold T_{crit} , are constant and equal for both the MH and the PI. Although this might not be strictly correct ~~In this sense, although the absolute value of modelled ELA may not be completely accurate, we are interested in~~ our focus here is on the relative differences between the two periods rather than absolute values. ~~The regional differences in ELA between the MH and the PI are still meaningful, given the uncertainties of the chosen parameters (Rupper et al., 2009).~~

~~This model has been previously applied to Franz Josef glacier, in New Zealand's Southern Alps, using present-day meteorological data (Anderson et al., 2006).~~

Given that the model has not previously been used in South America before, a preliminary validation was carried out by comparing model results with existing glacier mass balance data. Unfortunately, very few *in situ* glaciological mass balance measurements exist in southern South America (> 40°S). The most recent published mass balance study in this area was at Mocho glacier, located on the Mocho-Choshuenco volcano (39 ° 55 ' S, 72°02°W), which includes the hydrological year 2003/2004 (Rivera et al. 2005).

We assessed the performance of our model forced with climatological information coming from a regional climate model at 25-km resolution and forced by the ERA40 reanalyses

(PRECIS-ERA40) in Mocho glacier in the Chilean Lake District (~40°S). Because the ERA40 cover the period 1957-2001, we run the mass balance model for a 10 year period (1980-1989) that does not correspond to the same year analysed in Rivera et al. (2005) with the glaciological method (stakes). We hope that by running 10 years a climatological ELA can be assessed. We use three precipitation lapse rates: 0, 0.00252 and 0.02 mm m^{-1}. This comparison (not shown) showed a reasonable agreement between the observed and modelled ELA, for the low precipitation lapse rates (0 and 0.00252 mm m^{-1}), with a modelled ELA about 100 to 150 m below the observed, which is according to the glacier recession documented for this glacier (Rivera et al., 2005).

~~2.2~~2.3 Model inputs: PMIP2

~~As mentioned above, the mass balance model requires daily temperature and precipitation data as inputs. This information was obtained from simulations carried out under the Paleoclimate Modelling Intercomparison Project 2(PMIP2), see Braconnot et al. (2007) for model setup and boundary conditions.~~ We use daily GCM temperature and precipitation values for computing the degree – day model obtained from simulations carried out under the Paleoclimate Modelling Intercomparison Project 2 (PMIP2), see Braconnot et al. (2007) for model setup and boundary conditions.

Although PMIP is currently in its third phase (PMIP3) we used the modelling outputs of PMIP2 given that daily data were not available for the most recent phase when this study began. We analysed 7 models of the PMIP2 initiative (Table 1).

We compared the PI outputs with gridded temperature and precipitation data from CRU TS3.10 and CRU TS3.10.01 (Harris et al., 2014) respectively and with weather station observations to assess the climate model results (Supplement Figs. S1 to S4).

The glacier mass balance model was driven for 50 years to be able to capture the averaged influence of inter-annual variability, with daily temperature and precipitation data derived from the MH and PI experiments. With the purpose of comparing the ELA between the two periods we calculated the mean mass balance for 50 years. Hence, the ELA calculated for each period corresponds to a long-term or climatic ELA.

~~For the validation of the PI climate (section 3.1), and the MH-PI climate differences (section 3.2), we used monthly PMIP2 files.~~

Temperature data ~~was~~ were calculated for different elevations using a standard lapse rate of 6.5 °C km^{-1}. Due to the scarcity of available precipitation observations at high altitude, especially in Patagonia (Garreaud et al., 2013), precipitation was corrected using a regional mean~~n~~ observed gradient (in mm m^{-1}) in both regions. The observed gradient was obtained using available latitudinal and altitudinal distributions of climate station data in both regions. Fitting the precipitation versus altitude distribution yielded a mean value of 0.00252 mm m^{-1} in Patagonia and 0.0038 mm m^{-1} in New Zealand. Given that the distribution of precipitation in mountainous regions is difficult to predict even under present-day conditions (Rowan et al., 2014) we use this simple approach to facilitate the process of mass balance modelling. In doing this, we are mindful that we are working at mountain range scale, and that the PMIP2 models do not represent the precipitation gradient very well, especially in the Southern Alps (Supplement Fig. S4). In addition a constant precipitation factor (of 1.55) was also applied to account for the underestimation that low resolution ~~of~~ global ~~precipitation~~ models have of precipitation at high elevations (e.g. Rojas, 2006).

The results were averaged over 6 study zones. These zones correspond to: the Chilean Lake District (CLD, approximately between 40°-43° S), Northern Patagonian Icefield (NPI, between 43°-48°S), Southern Patagonian Icefield (SPI, between 48°-53°S) and Cordillera Darwin (CD, between 54°-55°S) in South America, and the northern and southern sector of the South Island of New Zealand (NZN, between 41.5°-43.5°S; and NZS, 43.5°- 46°S, respectively) (Fig. 1). Also ~~W~~we calculated climate differences between MH and PI over these 6 zones~~,~~ using monthly PMIP2 data and tested their significance using a t –test in the case of temperature, and a non-parametric Wilcoxon-Mann-Whitney test in the case of precipitation with a significance level of 95 %.

~~We compared the PI outputs with gridded temperature and precipitation data from CRU TS3.10 and CRU TS3.10.01 (CRU hereafter), respectively, to assess the climate model results. CRU is a 0.5° latitude/longitude resolution datasets of mean monthly surface climate over global land areas, excluding Antarctica, which are based on data provided by~~

more than 4000 weather stations for the period 1901 to 2009 (Harris et al., 2014).

In addition, we compared the PI model outputs with meteorological data of stations from both Patagonia and New Zealand (from the Chilean and Argentinean Meteorological Service, and the National Institute of Water and Atmospheric Research, NIWA, respectively).

3 Results

3.1 Model Inputs: validation of PMIP2 outputs

We compared the annual cycle of temperature and precipitation of the PI simulations with the CRU data over the 6 zones of interest (Fig. 1). Given that we are using the PI simulations to evaluate the climate, we compared against the complete 20th century observations. CRU data were averaged over the 1901-2009 period.

Comparison of the annual cycle of monthly temperature between PMIP2 model output and CRU climatological data (Fig.2) shows that the models are able to reproduce the seasonality and absolute values of the CRU temperature data from the South American sector. The FOAM model, with a very coarse spatial resolution, is the one that exhibits the largest offsets in terms of absolute values. Although the models are able to capture the CRU temperature annual cycle in the New Zealand sectors, they cannot reproduce the absolute temperature values, which are somehow non systematically offset. Once again, the FOAM model is the one with the lowest performance. Note that some of discrepancies observed can be due to the fact that we are comparing 20th Century climate data with PI climate simulations. Figure 3 shows a longitudinal cross section at 41.1°S (Patagonia) and 43.3°S (South Island, New Zealand), with the models and station climate data. In both regions, but especially in New Zealand, the models do not capture the full longitudinal variations in temperatures. We suggest that, despite its elevation, due to the narrow width of the Southern Alps, the coarse resolution models are not able to capture the impact of this topographic barrier in their temperature estimation.

Annual precipitation cycle (Fig. 4) shows that models have more difficulties at reproducing the present-day monthly precipitation derived from the CRU data, compared with

~~temperature. In general terms, all PMIP2 models reproduce the present-day monthly precipitation in the Chilean Lake District and Northern Patagonian Icefield zones. Precipitation is overestimated in the Southern Patagonian Icefield and Cordillera Darwin sectors. In the case of New Zealand, precipitation is underestimated in both zones fairly well. Despite this, overall, all models are able to reproduce the seasonality of precipitation.~~

~~Figure 5 shows a longitudinal cross section of annual mean precipitation. Once again, the PMIP2 models are not able to simulate longitudinal precipitation gradients over the narrow Southern Alps.~~

~~3.2~~3.1 Climate differences between the mid-Holocene and the pre-industrial

Seasonal temperature differences between the MH and the PI (Fig. ~~6~~2) are consistent between most models~~shows that most models are consistent~~, ~~showing~~ with temperature anomalies of the same sign ~~pointing in the same direction~~ and small inter-model spread. Overall, in Patagonia, the models simulate colder conditions during the MH in the austral summer (DJF), ~~austral~~ autumn (MAM) and ~~austral~~ winter (JJA), with average temperature anomalies of ~-0.2°C, ~-0.5°C and ~-0.4°C, respectively. During spring (SON) the PMIP models shows temperatures 0.2°C warmer.

In New Zealand (Fig. ~~6~~2) the models show colder MH condition in austral autumn (~-0.7°C) and winter (~-0.4°C), and warmer conditions in spring (~0.3°C). In summer the intermodel spread is larger, so that on average, the temperature anomalies are not significant. In the annual mean, the temperature anomalies for South America and New Zealand are identical (~-0.2°C). These temperature differences reflect the seasonal insolation difference between the two periods.

Estimates of precipitation change show less consistency than for temperature~~s~~ (Fig. ~~7~~3), and in several cases the models show precipitation anomalies of different sign within regions. Nevertheless, there are some regions and seasons for which the models show consistent precipitation changes. For example, during austral summer and autumn the models suggest that the climate was wetter during the MH compared to PI, in the CLD and the Patagonian Icefields. In general all zones exhibit drier winters than the PI; ~~austral~~ spring was drier in the CLD and NPI, somewhat wetter in the SPI and CD and marginally drier in the New Zealand zones. We find that the CLD was wetter in ~~austral~~ summer and ~~austral~~

autumn, no change in ~~austral~~ winter and dryer in ~~austral~~ spring. Note that none of the precipitation changes are statistically significant.

~~3.3~~3.2 ELA calculations and differences

~~Next we calculated the Equilibrium Line Altitudes over the 6 study zones (Fig. 8 and 9).~~

~~We excluded the FOAM model due to its unsatisfactory simulation of the PI climate.~~

For ELA calculations, we excluded the FOAM model due to its unsatisfactory simulation of the PI climate results (Supplement Figs. S1 to S4). The spatial distribution of the PI mean ELA based on six PMIP2 models in Patagonia (Fig. ~~8~~4), shows~~, as expected,~~ that the ELA values are higher in the northern section of the study area, with maximum values above 2000 m asl (mean value of ~~1797~~ 1800 m asl) in the CLD. To the south, the ELA decreases gradually, reaching altitudes below 1000 m asl in SPI (mean value of ~~956~~ 960 m asl) and CD (mean value of 840~~839~~ m asl, see Table 2). Our results also show that, in general, the inter-model variability (one standard deviation) of the ELA estimation is small. One exception is the inter-model variability observed in the SPI, where the maximum standard deviation is 250 m (mean value of 140 m), in a region with mean ELA of about 950 m asl.

ELA estimates in New Zealand (Fig. ~~9~~5) are higher in the northern part of South Island (maximum values around 1800 m asl), and slowly decrease to values of 1400 m asl at the southern tip of South Island (Table 2). These values show an approximate~~ly~~ 200-400 m offset (too high) in absolute terms, compared with observed values (e.g. Chinn et al., 2005). The intermodel spread evaluated with the standard deviation is small in the northern part (148 m). South of 43°S, the intermodel spread becomes larger, with values between 150-180 m on the western flank and up to 200 m on the eastern flank of the Southern Alps. The mean value in this zone is ~~1528~~ 1530 m asl (Table 2).

As for the multi model mean ELA differences, in Patagonia (Fig. ~~10~~6a) and in the Southern Alps (Fig. ~~10~~6) the ELA was lower during the MH compared to PI, however the magnitude of change is relatively small: in Patagonia the mean difference is ~20 m in all zones, in the Southern Alps is ~30 m in both zones. Besides the small estimated ELA variations, it is important to highlight the consistency between ELA differences calculated ~~based on~~by the ~~different~~ PMIP2 models~~ outputs~~. In the Southern Alps, all of the six models indicate a negative sign in the ELA differences between the MH and the PI (Fig. ~~10~~6). In Patagonia at least four models show negative differences between MH and the PI in almost the entire domain, with five models showing a lower ELA during the MH in some parts of the CLD and SPI zones and six models showing the same result in the west coast of the SPI zone (Fig. ~~10~~6).

~~Given these small differences in ELA we performed sensitivity experiments to assess the impact of the value of the precipitation lapse rate on modelled ELA. The sensitivity runs where performed only for Patagonia, because the intermodel spread is largest relative to New Zealand. The values of precipitation lapse rate are 0, 0.00252, 0.01 and 0.02. These values were chosen in order to sample around the empirical value obtained from the observed precipitation gradient (0.00252 mm m^{-1}).~~

~~From the six models used, five models indicate that the MH lower ELA is a robust result, as shown by the estimation performed using the four precipitation lapse rates used in the mass balance model. Moreover, for higher precipitation lapse rates values, the MH ELA becomes lower, increasing the ELA differences between the two periods. We therefore conclude that the small ELA differences in Patagonia are significant and robust to this parameter.~~

4 Discussion

4.1 Difference between mid-Holocene and pre-industrial climates

~~In~~ Rojas and Moreno (2011) evaluated the full PMIP2 MH simulations ~~were evaluated~~ for the climatic conditions in Patagonia and New Zealand. They found that both regions received less precipitation during a colder accumulation season, and more precipitation during a warmer ablation season. Therefore they suggested, on a qualitative basis, that the temperature and precipitation anomalies could effectively lead to larger glacier during the MH and hence explain Neoglaciation in both regions.~~Neoglacial advances~~.

~~Our~~ This paper goes a step further towards understanding the effects of climatic conditions on glaciers and neoglaciations, and used those conditions to drive a glacier mass balance model.

~~With respect to the climatic conditions, first of all we notice that t~~The differences in temperatures between the MH and the PI found in this study are similar to those determined by Ackerley and Renwick (2010) for New Zealand, as well as Rojas and Moreno (2011) for South America and New Zealand. Both studies analyzed data from PMIP2 model, but used a different subset of models. Ackerley et al. (2013) use a regional simulation of higher spatial resolution ~~(with corresponding higher spatial resolution)~~ to simulate the MH climate, and also find a similar temperature pattern found in this study. Given that all these studies ~~determine a cooling during the~~indicate that the MH ~~with respect to~~was cooler than the PI in the autumn months and a warming in the spring months, we conclude that the temperature signals are robust across different subset of PMIP2 simulations for the MH.

~~With respect to precipitation, in South America, this study~~Our results indicate~~s~~ mostly wetter conditions during summer (DJF) and drier condition in winter (JJA), in accordance with Rojas and Moreno (2011). For the autumn (MAM) and spring (SON) seasons there is dipole-like signal, with positive precipitation anomalies in the northern regions and drier conditions in the southern regions in MAM and the opposite for SON. These results are also in fair accordance with Rojas and Moreno (2011). ~~For~~ In the New Zealand case, we find ~~the other seasons show~~ large inter-model spread between seasons, except during JJA where we find a clear ~~dry~~ drier condition. Precipitation changes are slightly different than those shown in Ackerly and Renwick (2010), which in turn do not agree with Rojas and Moreno (2011) results. In summary, we ~~find~~ found small changes in precipitation and large inter-modal spread, so that existing studies discussed here give slightly different results.

4.2 Differences between mid-Holocene and pre-industrial ELAs

We observe~~d~~ that the mass balance model applied to Patagonia and New Zealand is able to capture the expected differences in the climatological ELA associated with the climate conditions estimated for the MH and the PI ~~(e.g. Rojas and Moreno, 2011; Ackerley and Renwick, 2010)~~. Our results show that during the MH the ELA ~~may~~ could have been between 20-30 m lower than during the PI ~~times~~ in ~~both~~ Patagonia and New Zealand.

We propose that the results of the modelled ELA differences can be explained mainly by the significant and consistent differences in modelled temperature~~s~~ observed ~~between both periods~~. The impact of the precipitation anomalies are more difficult to assess, given that the climate data is heterogeneous.~~, as precipitation differences are more variable~~. This suggestion is consistent with the idea that glaciers from mid-latitudes are more sensitive to changes in temperature than to changes in precipitation (Anderson and Mackintosh, 2006). Moreover, we suggest that the observed differences of in climatological ELA are principally mainly driven by related to the changes in the annual temperature cycle of temperature in these temperate glacier regions. In Patagonia ablation dominantly occurs between September and March (spring and summer months); whereas accumulation occurs from April to August (autumn and winter months) (Rodbell et al., 2009). In New Zealand most of the ablation occurs between November and April (summer and parts of spring and autumn), whereas accumulation occurs from May to October (winter and parts of autumn and spring). However both regions experience significant interannual variations, where accumulation or ablation sometimes persists for longer period.

In Patagonia and New Zealand the lower summer temperatures observed during the MH imply less energy input and hence lower amounts of melting. Although the opposite happens in spring, where the higher temperatures of the MH indicate greater melting, we suggest that this change was not sufficient to balance the impact of the lower summer temperature on the mass balance. In addition, the lower temperatures observed during autumn and winter would increase the percentage of precipitation falling as snow rather than rain during the MH, as hypothetically suggested by Sagredo and Lowell (2012) and Rodbell et al. (2009). This is particularly critical in the Southern Alps, where at present a significant portion of the modern precipitation falls roughly at the elevation of the ELA. A temperature drop in this area would result in a increment in snow precipitation, constituting a snow resource if cooling occurs (Rother and Shulmeister, 2006). This can be especially particularly important in autumn and spring, when temperatures in the vicinity of the ELA are typically -1 to 2 °C. Additionally precipitation during winter is higher during the MH in almost all the PMIP2 models in all zones (Fig. 73), this also contributes to accumulation and therefore a lower ELA in the MH with respect to PI. In Patagonia, where the ELA results showed more spatial variations, sensitivity experiments using the precipitation lapse rates, indicated that when lapse rate value used is bigger the MH ELA value is lower. Given that we have little empirical information to constrain this parameter in Patagonia, the results presented in this study correspond to a lower limit, giving the smallest ELA differences, and therefore represent to most conservative modelled ELA differences.

~~**Geomorphic evidence of mid-Holocene glacier expansion**~~

~~As discussed in the introduction, geomorphic and chronological evidence support the idea that glaciers were more extensive during some time of the MH than in the PI and present. Although an exact comparison between our modelling at MH (6000 yr B.P.) with timing of glacier advances is not possible a couple of examples is given below. In Lago General Carrera (named Lago Buenos Aires in the Argentinean side, ~46° 30' S), central Patagonia, it has been shown that glaciers advanced around 6200 yr B.P. (Douglass et al., 2005). Geomorphic evidence at this site suggests that during this glacial advance the ELA dropped to 1100 m asl, a 300 m difference with respect to the present position estimate for small isolated cirque glaciers. Further evidence of glacier activity is found by Harrison et al. (2012) who determined ages of 5700 yr B.P. for a moraine located to the west of the North Patagonian Icefield (46 ° 36 ' S / 73 ° 57 ' W) associated with San Rafael glacier.~~

~~Recently Strelin et al. (2014) found evidence for glacier advance between 6000 – 5000 yr B.P. based in moraine dating in the east side of Southern Patagonia Icefield (Lago Argentino), specifically associated with the Upsala, Agassiz and Frías glaciers.~~

~~In the Southern Alps, geomorphic and geochronological evidence suggest that Tasman and Mueller glaciers (43º50' S/170°E) advanced around 6740 ±160 yr B.P. (Schaefer et al., 2009, age updated in Putnam et al., 2012). Putnam et al. (2012) estimate for a MH glacial advance at Cameron glacier (~43°20'S/171°E) at 6890 ± 190 yr B.P., suggesting a regional event. In Putnam et al. (2012), ELA estimated for MH was ~140 m lower than present, and 110 m lower than present 180±48 years ago. This suggests a fairly modest change (~30 m) between the MH and PI, consistent with the results of the ELA modelling in this work.~~

4.3 ELA sensitivity to model parameters

We performed sensitivity runs to increase the robustness of the modelling results in the Patagonian and Southern Alps sectors. This motivated by the small differences in modelled ELAs and the lack of constraints on important parameters owing to the scarcity of measurements, especially in Patagonia. We investigated the sensitivity of ELA to the precipitation lapse rate and the Degree Day Factor (DDF) of snow and ice.

We assessed precipitation lapse-rate values of 0, 0.001 and 0.02 mm m^{-1} considering the observed precipitation gradient in Patagonia and the Southern Alps of New Zealand

(0.00252 and 0.0038 mm m^{-1} respectively). The sensitivity in the ELA difference to the precipitation lapse rate has a maximum of 15 m in the northern part of Southern Island (Fig.7) (glaciers do not exist in this zone). At the latitude of the northern glaciers of the Southern Alps (approximately 43°S) the sensitivity is close to 10 m. Sensitivity declines southward (see Fig. 7). In Patagonia (Fig. 8), the Chilean Lake District has a maximum sensitivity of 6 m. This value is lower in the Northern Patagonia Icefield zone (2 to 3 m) and close to 5 m in the Southern Patagonia Icefield. From both Figures it is clearer that in almost all the study zone, for higher precipitation lapse rates values, the ELA differences between the two periods become larger. We therefore conclude that the small ELA differences in Patagonia and Southern Alps are significant and robust to this parameter and therefore the results presented are the most conservative modelled ELA differences.

We assessed DDF values of 4, 8 and 10 mm d^{-1} $°C^{-1}$ for ice and 2 and 4 mm d^{-1} $°C^{-1}$ for snow, within range of theoretical values used in the glacier modelling (3 mm d^{-1} $°C^{-1}$ for snow and 6 mm d^{-1} $°C^{-1}$ for ice). DDF sensitivity is even lower in Southern Alps with a maximum of 3 m in the northern part and also a reduction in the sensitivity to the south (Fig. 7). In Patagonia sensitivity is 3 to 4 m along the Andes (Fig. 8).

4.4 Comparison of geomorphically-reconstructed ELA and model results

In the following paragraphs we assess our estimates of ELA change against some records of neoglacial activity in both study areas

In Lago General Carrera (named Lago Buenos Aires in the Argentinean side, ~46° 30' S), central Patagonia, it has been shown that glaciers advanced around 6200 yr B.P. (Douglass et al., 2005). Geomorphic evidence at this site suggests that during this glacial advance the ELA dropped to 1100 m asl, a 300 m difference with respect to the present position estimate for small isolated cirque glaciers. Further evidence of glacier activity is found by Harrison et al. (2012) who determined ages of 5700 yr B.P. for a moraine located to the west of the North Patagonian Icefield (46 ° 36 ' S / 73 ° 57 ' W) associated with San Rafael glacier. Recently Strelin et al. (2014) found evidence for glacier advance between 6000 – 5000 yr B.P. based in moraine dating in the east side of Southern Patagonia Icefield (Lago Argentino), specifically associated with the Upsala, Agassiz and Frías glaciers. However, in the latter two studies, ELA differences were not calculated.

In the Southern Alps, geomorphic and geochronological evidence suggest that Tasman and Mueller glaciers (43º50' S/170°E) advanced around 6740 ±160 yr B.P. (Schaefer et al., 2009, age updated in Putnam et al., 2012). Putnam et al. (2012) demonstrated that a MH glacial advance also ocurred at Cameron glacier (~43°20'S/171°E) at 6890 ± 190 yr B.P., suggesting a regional event. In Putnam et al. (2012), ELA estimated for MH was ~140 m lower than present, and 110 m lower than present 180±48 years ago. This suggests a fairly modest change (~30 m) between the MH and PI, consistent with the results of the ELA modelling in this work. While there is a systematic difference between the PI ELA calculated by the model and modern observations, it is clear that relative changes in ELA are very similar between our work and the estimates by Putnam et al. (2012).

The qualitative agreement in the direction of change between our modelling results and geomorphic studies~~ological reconstructions~~ in these regions, despite absolute differences that are significantly smaller (in the order of the tens of meters), ~~makes~~ lead us to conclude that the mass balance modelling accounts for some but not all of the climatic differences between this two periods.

Several caveats in our study account ~~There are a number of reasons why we do not expect a~~ for more quantitative agreement in the absolute value of the ELA. ~~First of all, because of modeling data availability, this study used~~ 1) We compare the MH simulations ~~and~~with PI conditions, which are different from late 20th century ~~climatic~~ climate~~conditions, for which the~~. R~~r~~econstructions based on geologic evidence, on the other hand, are compared against late 20th century conditions. ~~with, and the fact that we are comparing glacier fluctuations spread throughout~~ 2) Glacier advances during ~~–~~the mid-Holocene did not necessarily coincide with a precise time-slice, namely 6 ka B.P.~~, in addition to the already discussed uncertainties in the timing of glacial fluctuations. Second~~ 3) ~~the~~ The spatial scale of individual glaciers and the coarse resolution of climate models ~~also~~ hinder a direct comparison. ~~Thirdly there are a number of~~4) Important ~~uncertainties~~ uncertainties are present in model parameters, especially those related with the spatial distribution of precipitation and degree day factors. 5) The magnitude of the glacier expansion and mass balance from a given ELA change depends on local conditions and characteristics of the glaciers, for example, glacier bed slope and hypsometry (Oerlemans, 2012; De Angelis, 2014). Glacier bed slope is a primary control on length sensitivity (Oerlemans, 2012) where a glacier with a gentle bed slope, such as Upsala ~~Glacier~~glacier in South Patagonia Icefield, shows a high length sensitivity to ELA changes, estimated at ~-50 metres of glacier length per metre of ELA increase (Oerlemans, 2012). With this in mind we expected large change of the accumulation and ablation areas even if the ELA oscillation is small (Mercer, 1965, Furbish and Andrews, 1984). In contrast, the steep Franz Josef Glacier shows a much smaller length sensitivity of ~-10 metres of glacier length per metre of ELA increase~~(dimensionless)~~. Glacier hypsometry is also an important control on the sensitivity of mass balance to change in ELA, according to De Angelis (2014) glaciers where the bulk of the area is located below the ELA are subject to the largest changes of mass balance for any given changes in ELA. ~~Other parameters not considered in this study are surface debris cover (Anderson and Mackintosh, 2012), and iceberg calving (Koppes et al., 2011).~~

Considering all these aspects and limitations of the glacier mass balance model, we highlight ~~this qualitative~~ agreement ~~in~~ among both, the sign of change and regional homogeneity within and between both study regions. This in-phase ELA response in Patagonia and New Zealand's South Island, is also in agreement with ~~the~~ glacier~~s~~ fluctuations observed during the 20th century ~~in Patagonia and the Southern Alps,~~ where glaciers seem to be in phase to similar climate forcing (Fitzharris et al., 2007).

5 Conclusions

A glacier mass balance model forced with PMIP2 simulations showed that southern mid-latitude glacier ELAs during the mid-Holocene (MH) were lower compared to pre-industrial (PI) conditions. The robustness of these results are evaluated by using six different climate model data to run the mass balance model, as well as additional simulations varying a number of not well constrained parameters of the model such as the precipitation lapse-rate and the snow and ice degree day factors. The results of those sensitivity simulations showed ~~The fact~~ that the ELA differences, although small ~~had~~, had always the same sign ~~in the two time slices, and in all the models used~~ in New Zealand i.e., lower ELAs during the MH compared to PI~~'s South Island~~ and in most of the models in Patagonia.~~,~~ We have therefore ~~gives~~ confidence that climatic conditions, as simulated by six PIMIP2 models for MH conditions could lead to larger glaciers extents during this period~~ in the obtained results~~. The main forcing of the modelled ELA differences are temperature differences~~ resulting from changing insolation at the top of the atmosphere~~. Significantly colder conditions during the summer, autumn and winter months prevailed during the MH compared to the PI.~~ These temperature changes were driven by orbitally controlled insolation variations.~~ In contrast, modelled precipitation changes were small and with disagreement between models for the sign of change~~ less robustly simulated, indicating a slight annual increase~~. Given that ~~Our~~ ELAs for the MH were consistently lower despite the range of precipitation data they were forced with, our ELA results ~~results for the MH~~ underline the evidence that temperate glaciers show a greater sensitivity to temperature changes ~~than changes in precipitation~~ (Anderson ~~&~~ and Mackintosh, 2006).

Temperature changes cause a double effect in glacier mass balance. First, in summer and early autumn in the MH, less energy is available for melting and second, from autumn to late winter, lower temperatures cause a larger portion of precipitation to fall as snow, resulting in higher accumulation in the MH with respect to the PI, as well as a higher surface albedo which reduces the amount of short-wave radiation available for melt.

~~Coming back to our initial question expressed in the introduction,~~ T~~t~~his study provides new insights towards understanding southern hemisphere mid-Holocene glacier conditions, demonstrating that orbital forcing inducing relatively coherent temperature changes are ~~is~~ consistent with a hemispheric pattern of larger glacier extent at MH compared to the PI period~~.~~

~~There is qualitative agreement between our modelling results, and ELA reconstructions based on geomorphic and geochronologic evidence, which shows that glaciers in both Patagonia and New Zealand exhibited a lower ELA during the MH than in PI times.~~

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Table 1. PMIP2 models used in this study.

Models	Atmosphere lon x lat	Vertical levels	Years of data used
CSIRO-Mk3L-1.1	5.625 x ~ 3.18	18	50
ECHAM5-MPIOM1	3.75 x 2.5	20	50
FOAM	7.5 x 4.5	18	50
MIROC3.2	2.8 x 2.8	20	50
MRI-CGCM2.3.4fa	2.8 x 2.8	30	50
MRI-CGCM2.3.4nfa	2.8 x 2.8	30	50
UBRIS-HadCM3M2	3.75 x 2.5	19	50

Table 2. Mean values of ELA for each zone

Region	Zones	ELA MH [m asl]	ELA PI [m asl]	Difference [m]
Patagonia	Chilean Lake District	1776 ± 99	1797 ± 93	-21±6
	Northern Patagonia Icefield	1333 ± 125	1354 ± 106	-21±3
	Southern Patagonia Icefield	939 ± 148	956 ± 140	-17±5
	Cordillera Darwin	821 ± 90	839 ± 89	-18±4
South Island, New Zealand	North	1667 ± 144	1697 ± 148	-30±10
	South	1501 ± 176	1528 ± 176	-27±6

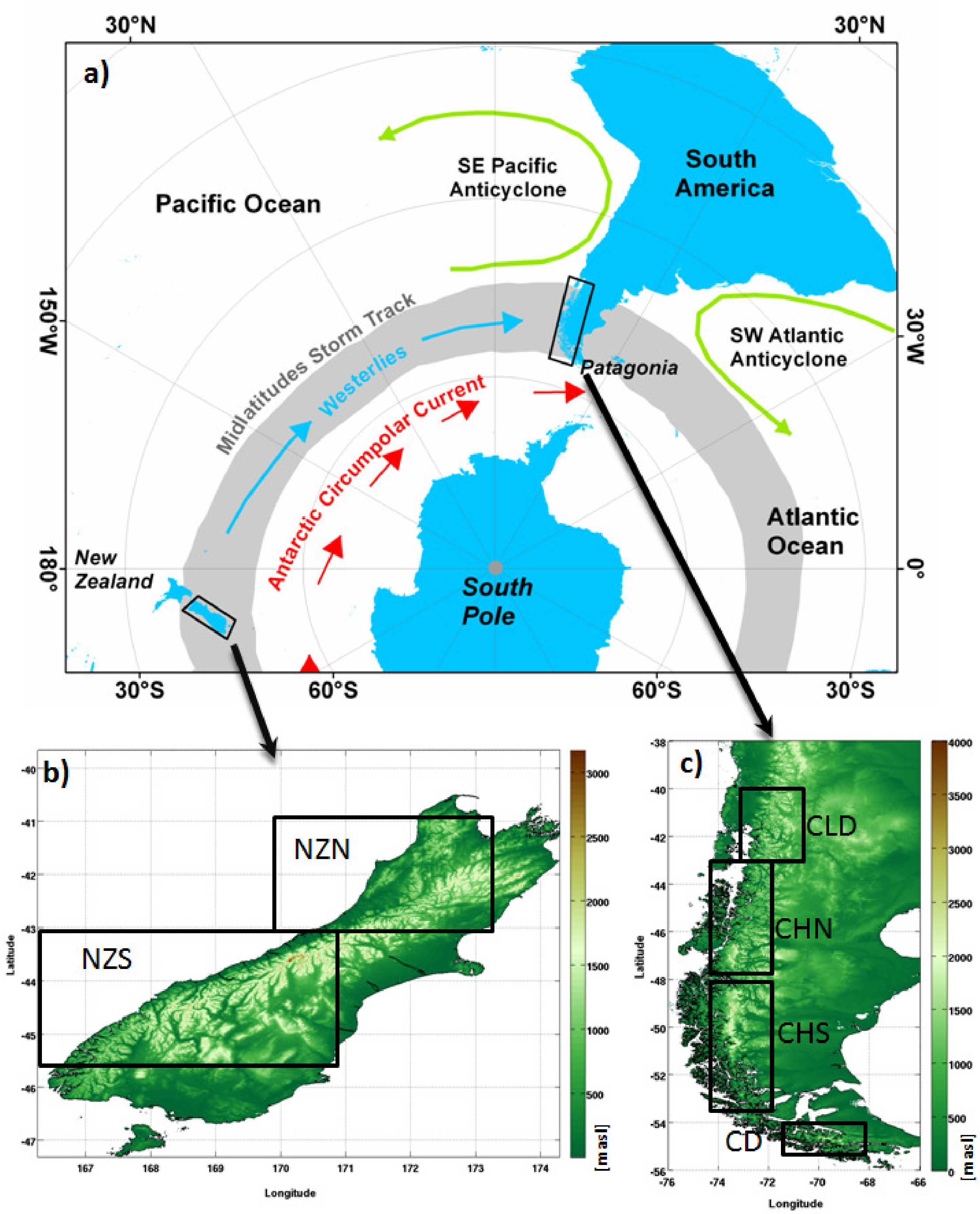
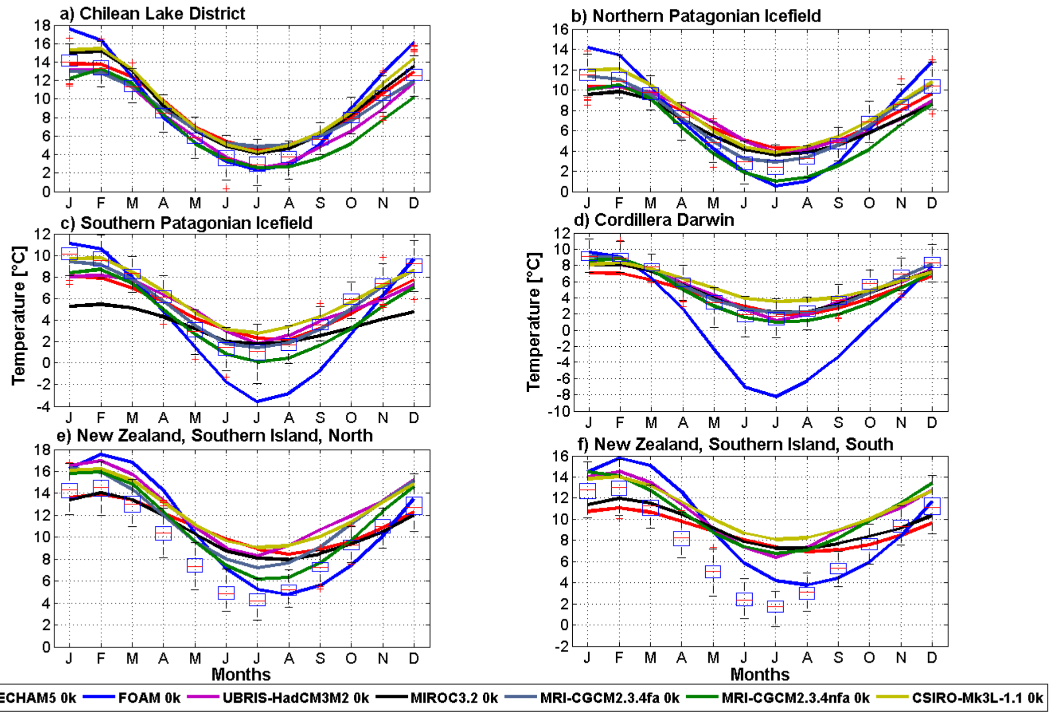
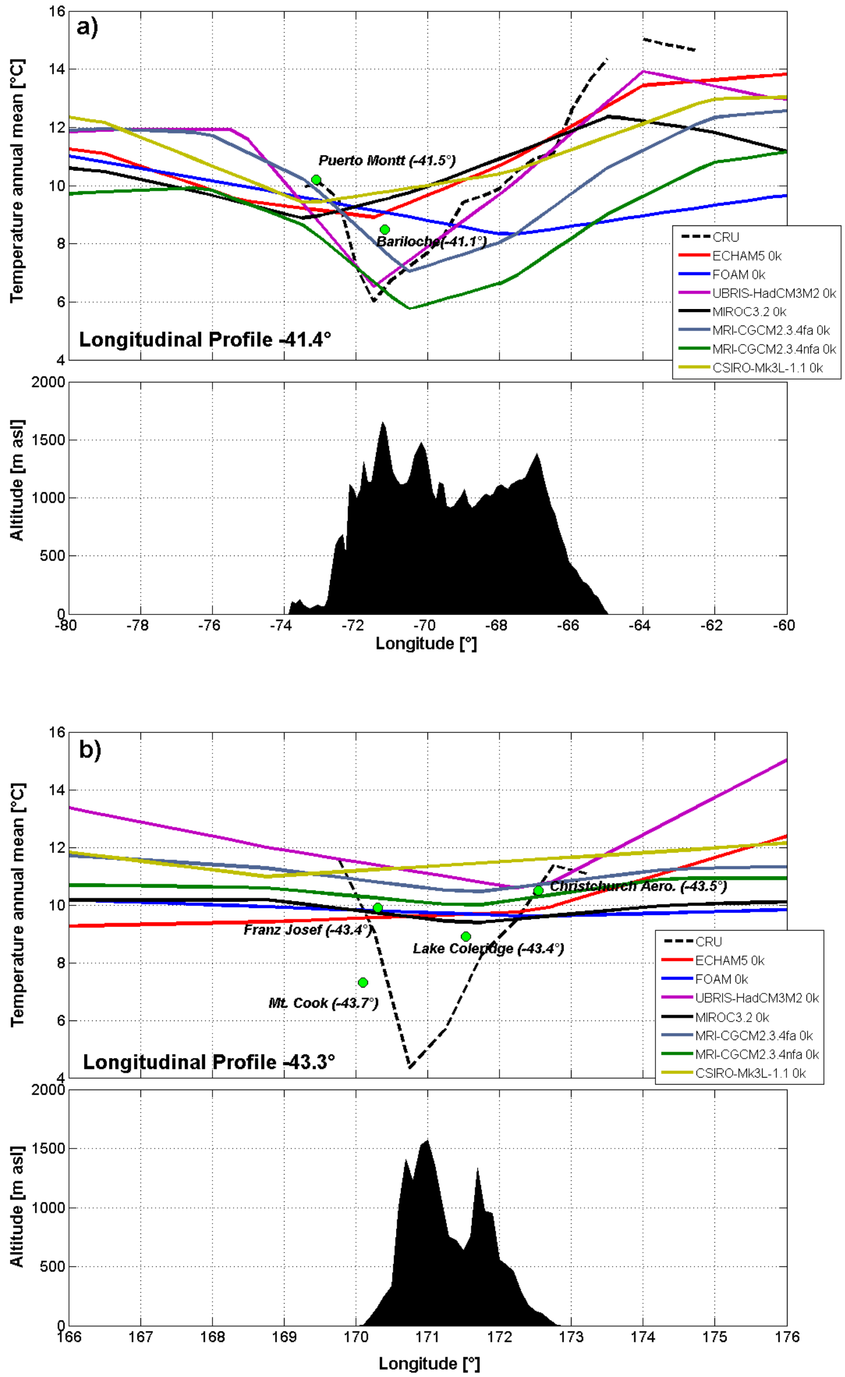


Figure 1. Study area. (a) Schematic diagram showing some of the main climate characteristics in the southern mid-latitudes. (b) New Zealand southern island topography and the two zones of analysis (NZN: New Zealand north, NZS, and New Zealand south). (c) Patagonia topography and the four zones of analysis (CLD: Chilean Lake District, CHN: North Patagonian Icefield, CHS: South Patagonian Icefield and CD: Cordillera Darwin).



~~Figure 2. Annual cycle of temperature of six zones. a),b),c), and d) correspond to Patagonia and e) and f) correspond to New Zealand. PMIP2-PI simulations (colour lines), CRU temperatures (boxplots), including inter-annual variability.~~



~~Figure 3. Longitudinal profile showing PMIP2 PI temperature simulations (colour lines) and CRU temperature (dash line). Green points are observed station data. a) Patagonia profile at 41.1 °S and b) New Zealand profile at 43.3 °S.~~

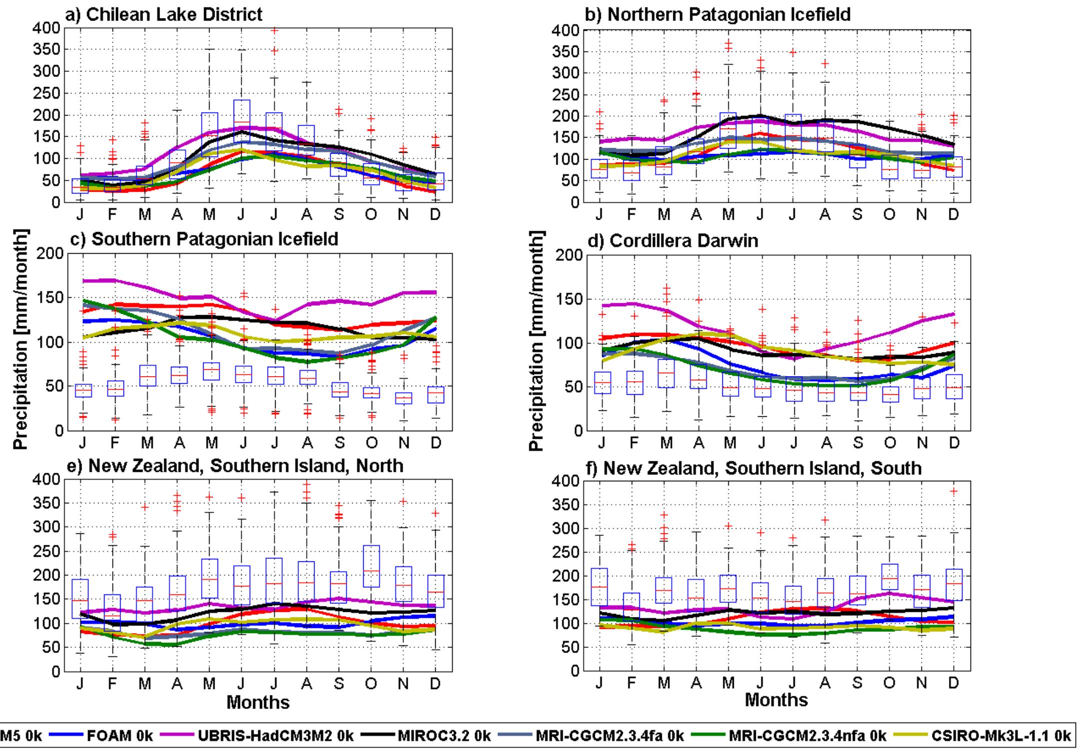
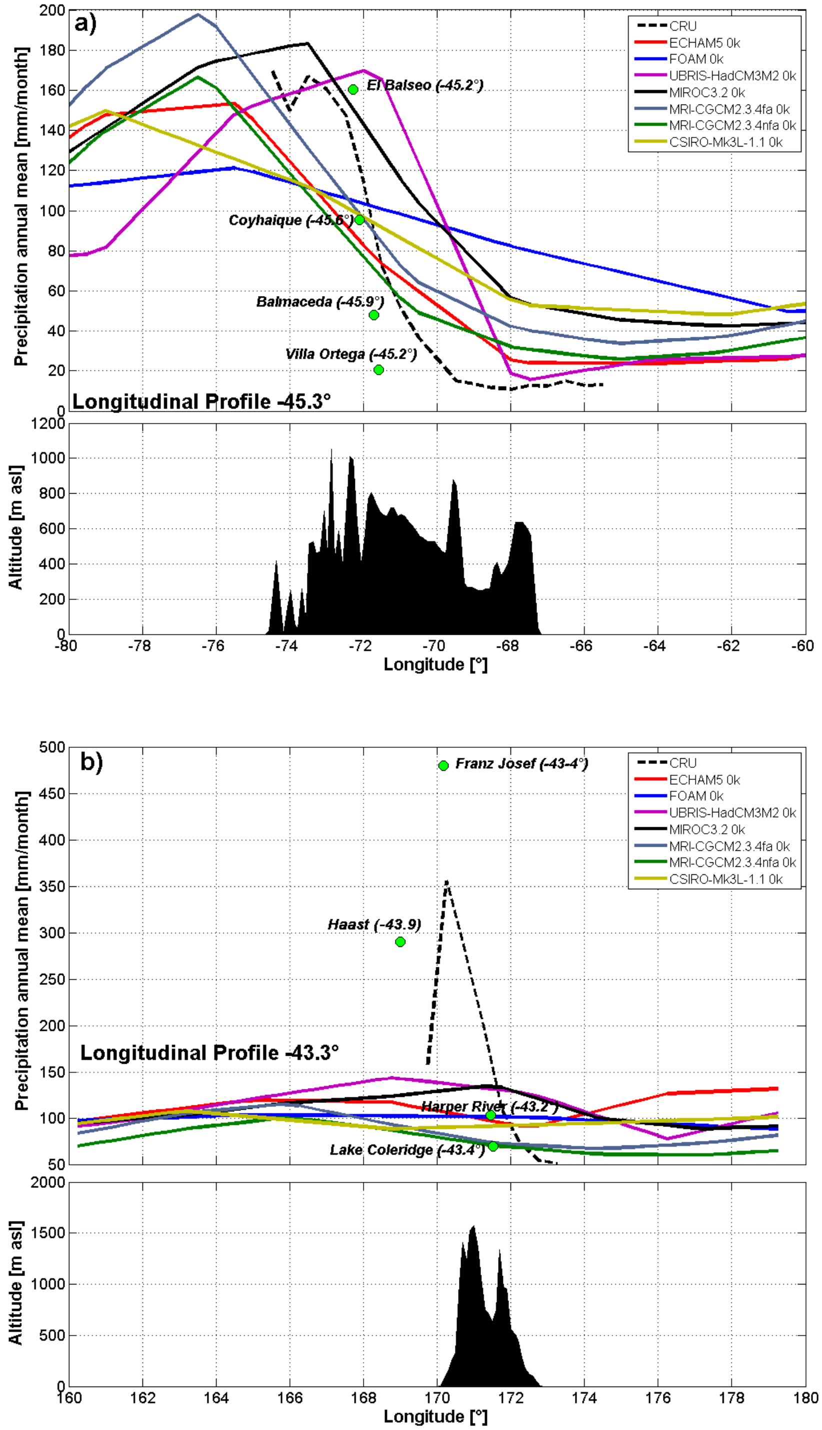


Figure 4. Annual cycle of precipitation of six zones. a),b),c), and d) correspond to Patagonia and e) and f) correspond to New Zealand. PMIP2-PI simulations (colour lines), CRU precipitation (boxplots), including inter-annual variability.



~~Figure 5. Longitudinal profile showing PMIP2-PI precipitation simulations (colour lines) and CRU precipitation (dash line). Green points are observed station data. a) corresponds to a Patagonia profile at 45.3 °S and b) to a New Zealand profile at 43.3 °S.~~

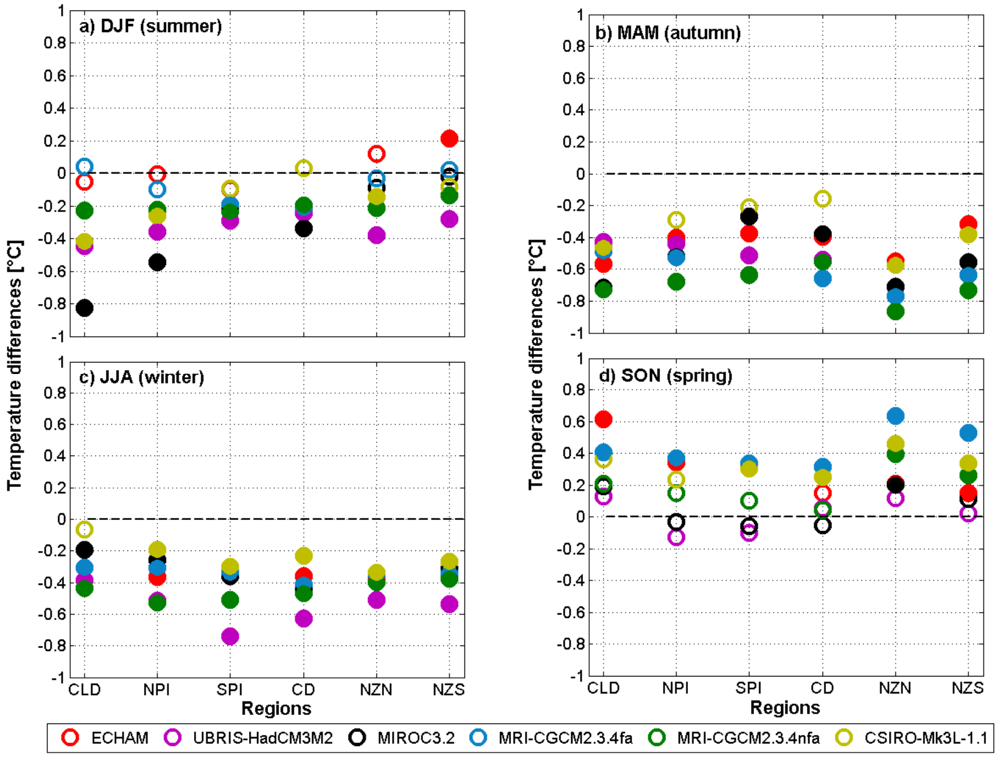


Figure ~~6~~2. Temperature differences: Mid-Holocene minus Preindustrial, over the 6 zones of analysis. (a) DJF, (b) MAM, (c) JJA, (d) SON. Filled circles correspond to statistically significant differences ($p \leq 0.05$).

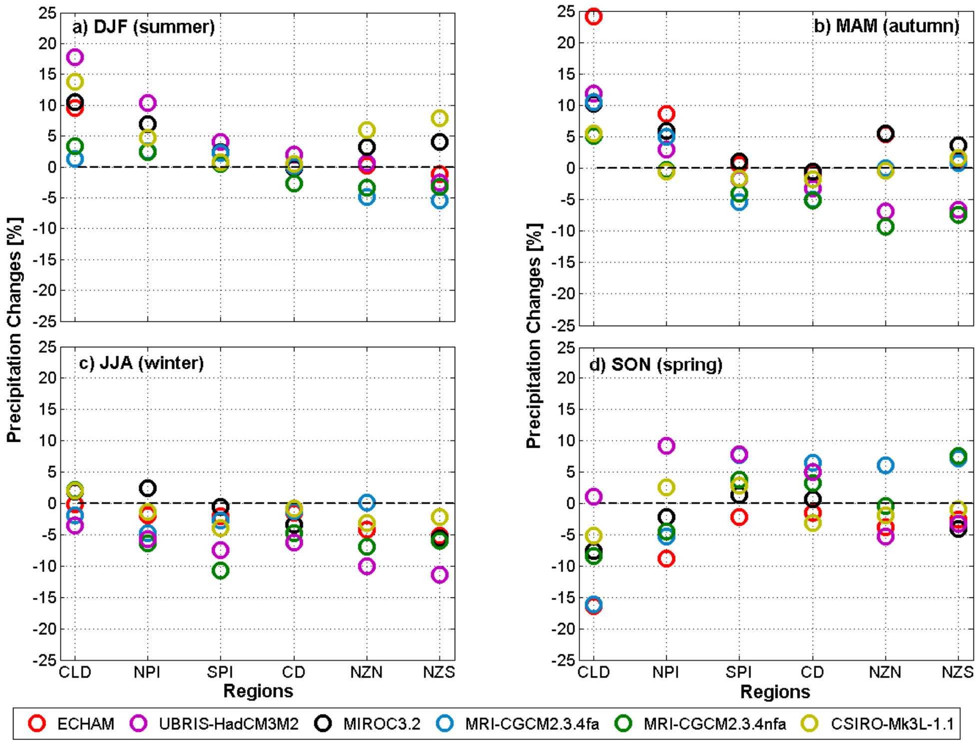


Figure ~~7~~3. Precipitation differences: Mid-Holocene minus Preindustrial, over the 6 zones of analysis. (a) DJF, (b) MAM, (c) JJA, (d) SON. Filled circles correspond to statistically significant differences ($p \leq 0.05$).

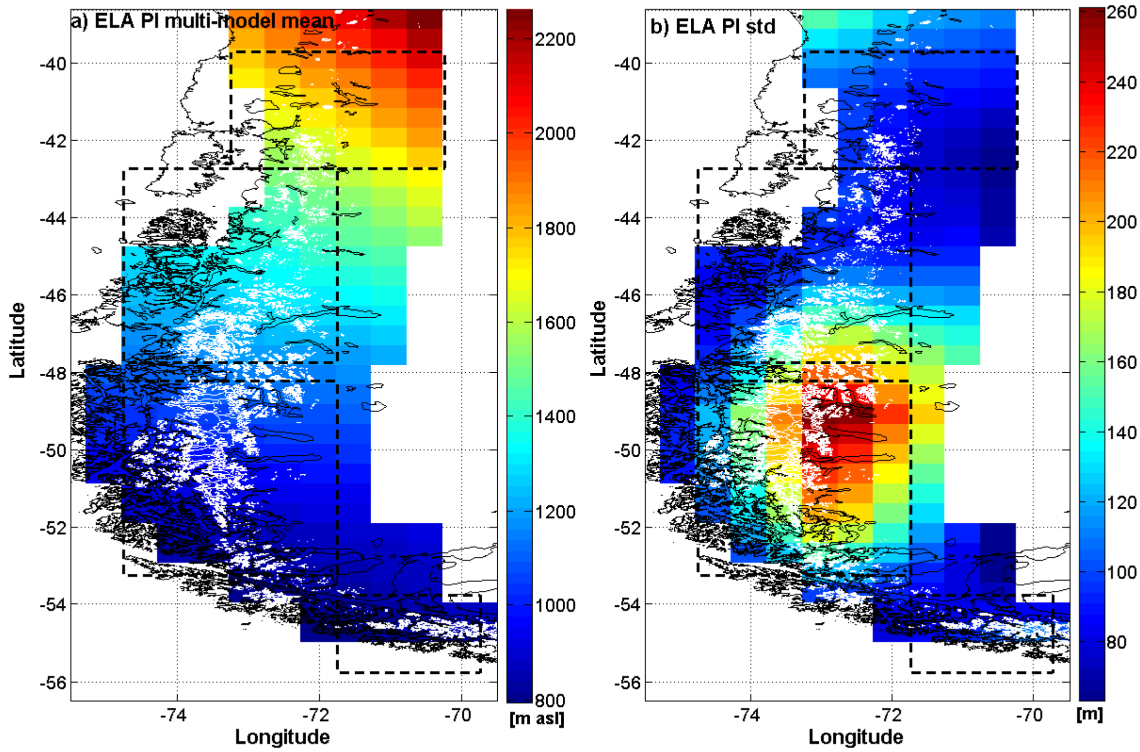


Figure ~~8~~4. Spatial distribution of pre-industrial equilibrium line altitude (ELA) in South America based on six PMIP2 simulations. (a) mean ELA (m asl) and (b) inter-model variability of the ELA (one standard deviation). White lines correspond to actual glacier extension according to the Randolph Glacier Inventory (RGI 3.2)

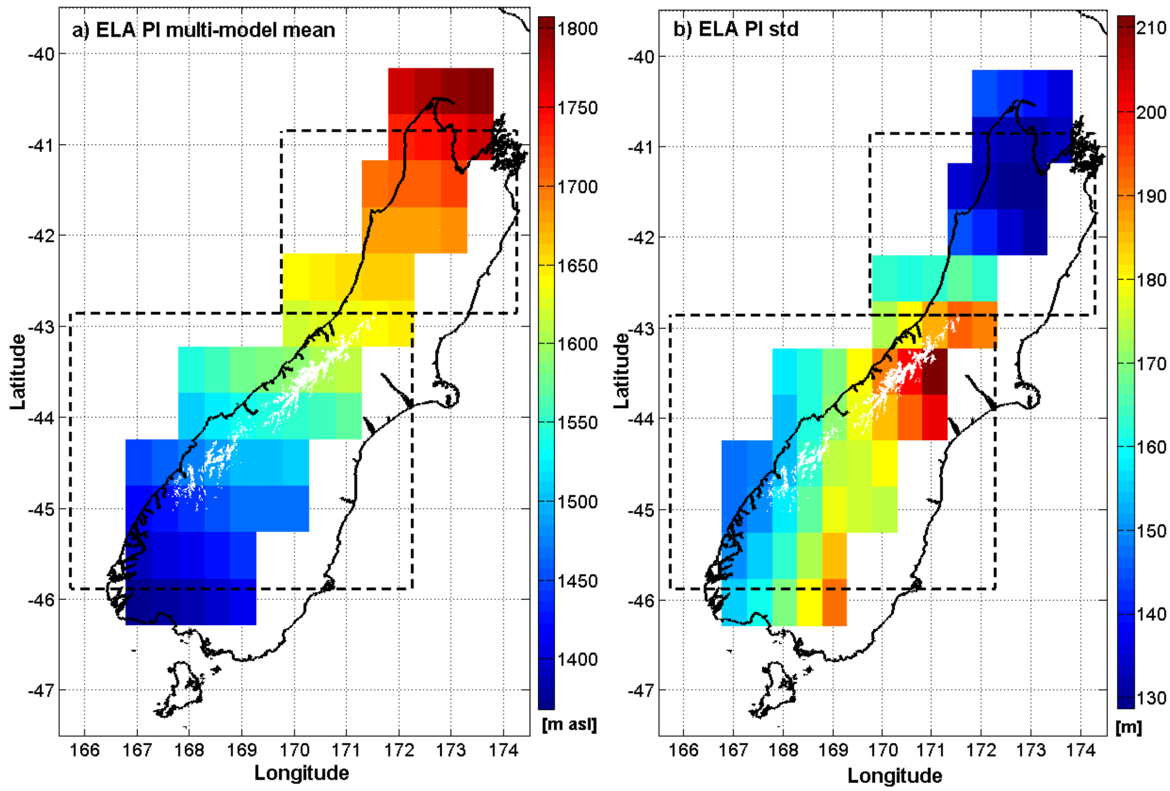


Figure 95. Spatial distribution of pre-industrial equilibrium line altitude (ELA) in Southern Island of New Zealand based on six PMIP2 simulations. (a) Mean ELA (m asl) and (b) inter-model variability of the ELA (one standard deviation). White lines correspond to actual glacier extension according to the Randolph Glacier Inventory (RGI 3.2)

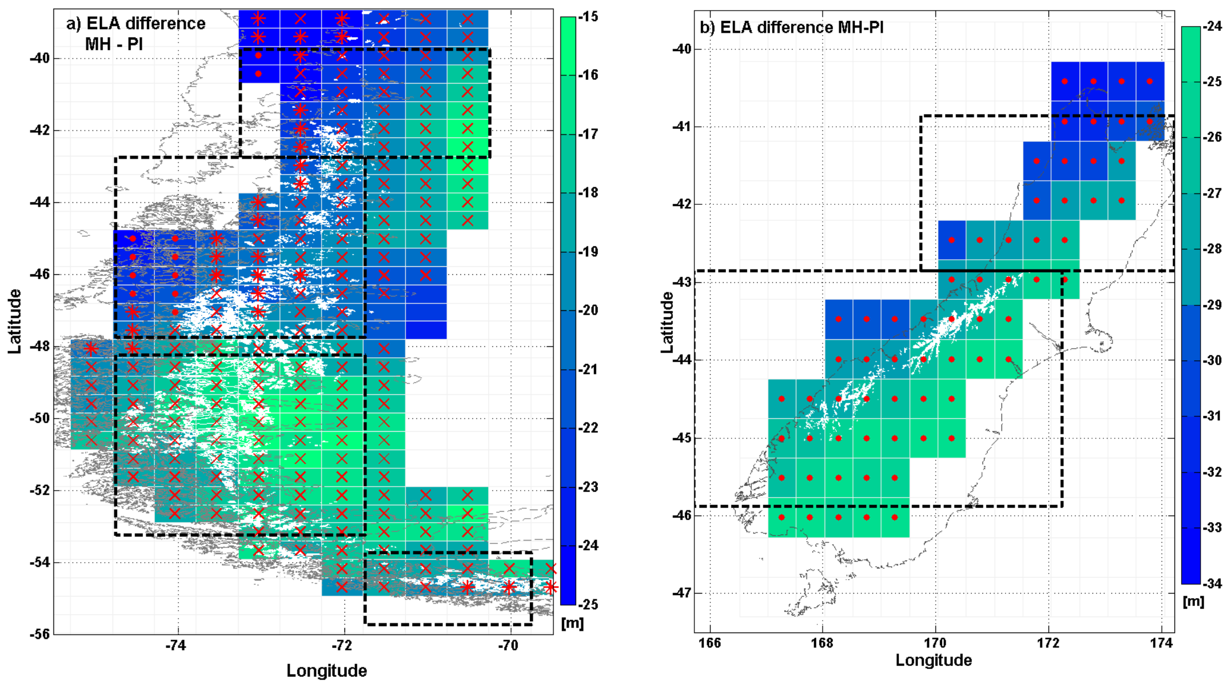


Figure ~~10~~6. Holocene minus pre-industrial equilibrium line altitude differences. Points indicate that the six models have a negative sign in the differences; asterisks indicate that five models have a negative sign and crosses indicate that four models have a negative sign. White lines indicate actual glacier outlines (Randolph Glacier Inventory 3.2). a) Patagonia, b) New Zealand.

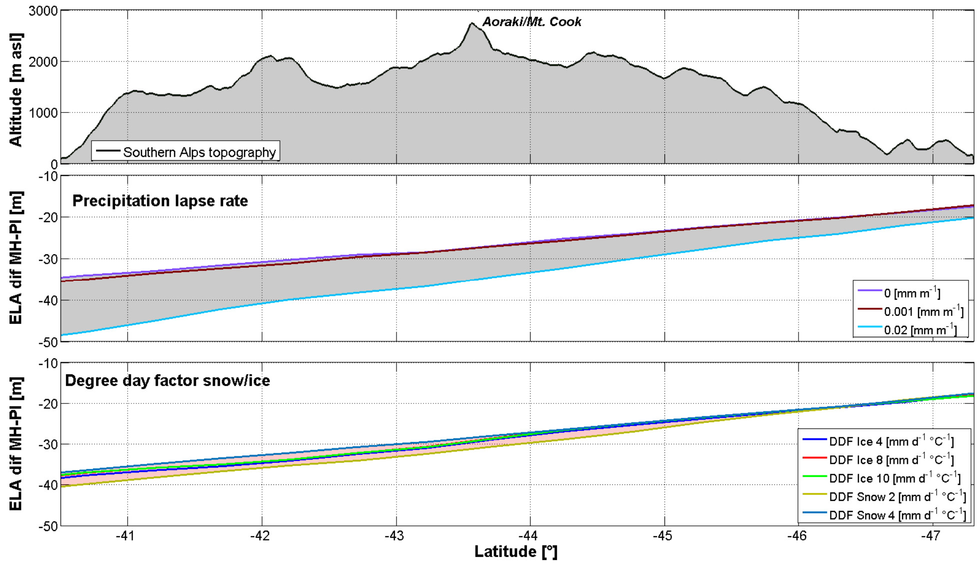


Figure 7. Sensitivity of ELA in Southern Alps to precipitation lapse rate and degree day factor of snow and ice. a) Latitudinal topography profile of Patagonia (SRTM 1 km) b) ELA sensitivity to precipitation lapse rate and c) ELA sensitivity to degree day factor of snow and ice. Gray and pink areas in b) and c) represent the range in ELA differences between MH and PI.

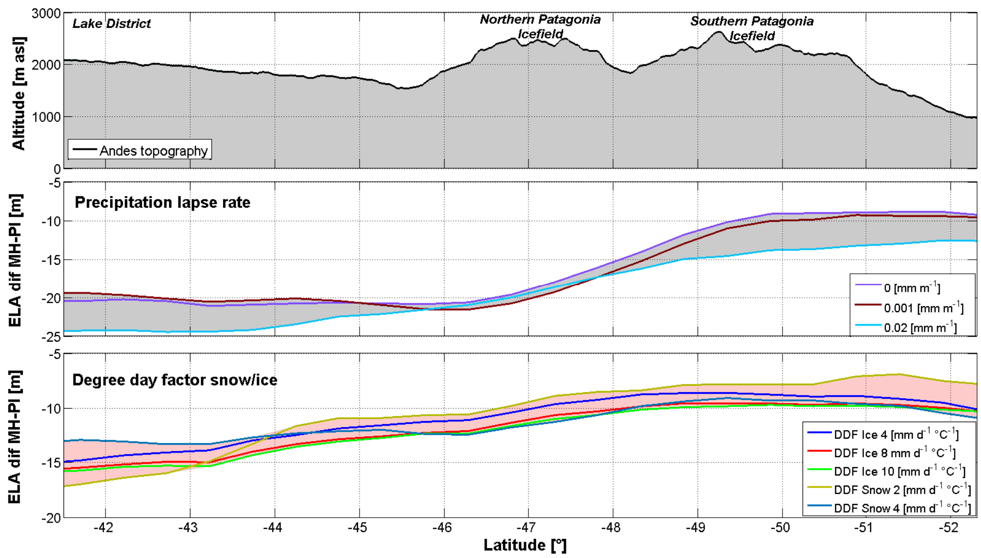


Figure 8. Sensitivity of ELA in Patagonian Andes to precipitation lapse rate and degree day factor of snow and ice. a) Latitudinal topography profile of Patagonia (SRTM 1 km) b) ELA sensitivity to precipitation lapse rate and c) ELA sensitivity to degree day factor of snow and ice. Gray and pink areas in b) and c) represent the range in ELA differences between MH and PI.