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Brief communication: Nonlinear sensitivity of glacier-mass balance attested by temperature-index models

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Abstract

Temperature-index models have been widely used for glacier-mass projections over the 21st century. The ability of temperature-index models to capture nonlinear responses of glacier mass balance (MB) to high deviations in air temperature and solid precipitation has recently been questioned by mass-balance simulations employing advanced machine-learning techniques. Here, we performed numerical experiments with a classic and simple temperature-index model and confirmed that such models are capable of detecting nonlinear responses of glacier MB to temperature and precipitation changes. Nonlinearities derive from the change of the degree-day factor over the ablation season and from the lengthening of the ablation season.

Introduction

Glacier surface MB projections in response to climate change over the 21st century can be analysed via physical approaches using energy-balance calculations and empirical approaches linking simple meteorological variables to MB such as temperature-index models. Most glacier-mass projections in response to climate change in large-scale studies over the 21st century have been based on temperature-index models (Huss and Hock, 2015; Fox-Kemper *et al*., 2021), given the lack of available or reliable information on detailed future meteorological variables (Réveillet *et al*., 2018). The deep artificial neural

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network (ANN) approach is a promising new empirical approach to simulate surface MB in the future (Bolibar *et al*., 2020).

Recently, Bolibar *et al*. (2022) analysed the sensitivity of glacier MB to future climate change using a deep ANN. They write that, unlike linear statistical and temperature-index models, their deep-learning approach captures nonlinear responses of glacier MB to high deviations in air temperature and solid precipitation, improving the representation of extreme MBs. Bolibar *et al*. (2022) argue that temperature-index models, widely used to simulate the large-scale evolution of glaciers, provide only linear relationships between positive degree-days (PDDs), solid precipitation and MB. Their paper questions the use of temperature-index models for projections of glacier-mass changes in response to global warming. Here, we performed numerical experiments with a classic and simple temperature-index model to show nonlinear responses of glacier MB to temperature and precipitation changes.

Data

For our numerical experiments, we selected two very different glaciers in the French Alps. The Argentière Glacier is located in the Mont-Blanc range (45°55' N, 6°57'E). Its surface area was about 10.9 km² in 2018. The glacier extends from an altitude of about 3,400 m a.s.l. at the upper bergschrund down to 1,600 m a.s.l. at the snout. It faces north-west, except for a large part of the accumulation area (south-west facing tributaries). Sarennes is a small south-facing glacier (0.51 km^2) with a limited altitude range between 2,820 and 3,160 m (mean values over the period used for the present study), located in the Grande Rousses range (45°07'N; 6°07'E). The field MB observations of the Argentière and Sarennes glaciers come from the French glacier monitoring program called GLACIOCLIM (Les GLACIers, un Observatoire du CLIMat; https://glacioclim.osug.fr/).

Method

We ran numerical experiments with a classic simple temperature-index model (Hock, 1999; Reveillet *et al*., 2017). For this purpose, we used the daily temperature and precipitation dataset from the SAFRAN (System d'Analyse Fournissant des Renseignements Adaptés à la Nivologie) reanalyses (Durand *et al*., 2009; Verfaillie *et al*., 2018). These numerical experiments were run on the two very different French

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glaciers, Argentière and Sarennes, observed over several decades (Thibert *et al*., 2013; Vincent *et al*., 2009). The surface MB model is expressed as:

$MB = DDF_{snow/ice} \,.\, T + k \,.\, P$,

Where:

- T is the difference between the mean daily air temperature and the melting point,
- $DDF_{snow/ice}$ is the degree-day factor for snow and ice (0.0035 and 0.0055 m w.e. $K^{-1}d^{-1}$ respectively) and DDF=0 if T<0°C,
- P is the precipitation (m w.e.),
- *k* is a ratio between snow accumulation and precipitation and *k*=0 if T>0°C.

Other enhanced temperature-index models including potential direct solar radiation could be used for our study, but here the purpose is to show that responses in MB are not linear to temperature or precipitation changes even using a simple degree-day model.

Results

The reconstruction of the glacier-wide MBs of these glaciers from our simple temperature-index model shows good agreement with data (Fig. 1). Using these data, we calculated the MB sensitivities to temperature and winter precipitation at 2,750 metres and 3,100 metres on the Argentière and Sarennes glaciers respectively. These altitudes were selected because they correspond to the approximate center of the glaciers. For each day of each series, we calculated an annual MB anomaly by adding a temperature anomaly or a precipitation anomaly. We report the results in Figure 2 to mirror Figure 3 of Bolibar *et al*. (2022) and make the comparison easier. We also ran these numerical experiments at different altitudes and over the entire glacier surface (Fig. 3).

From our experiments, we found first that the response of MB to temperature, using a temperature-index model, is not linear, contrary to the conclusions of Bolibar *et al*. (2022) relative to temperature-index models. As expected, the sensitivity of annual MB (i.e. the slope of the green curves in the graphs of Figure 2) increases with the PDD anomaly. To explain the physical processes involved in nonlinearity, we again used our PDD model, but using synthetic data for atmospheric temperature changes over a year (Fig. 4a). As shown in Figure 4, this nonlinearity (the spread between MB plots in Fig.4c) comes

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from (i) the lengthening of the ablation season (Fig.4a) and (ii) the earlier disappearance of the winter snow cover which increases the ablation rate due to the change in the degree-day factor from snow to ice (Fig. 4b).

Concerning the winter balance, we found a nonlinear response of MBs to winter precipitation with our PDD model and this is also inconsistent with the conclusions of Bolibar *et al*. (2022) relative to the sensitivity of temperature-index models. Runs of our PDD model on synthetic data under different conditions of winter balance (Fig. 5) used a reference scenario of 1,700 mm of winter balance changed by increments of ±300 mm in precipitation. Results show that the increase in sensitivity can be physically explained by the earlier disappearance of the winter snow cover. The earlier and abrupt increase in the ablation rate under lower conditions of winter balance (Fig.5a) results in nonlinearity attested by the spread between MB plots in Figure 5b. Surprisingly, we detect sensitivity to winter accumulation, contrary to the Bolibar *et al*. (2022) findings using their ANN (Fig. 2 and 3). Indeed, MB sensitivity increases with low winter-accumulation anomalies using our model, but decreases in the deep-learning model of Bolibar *et al*. (2022). The opposite results obtained from the deep-learning model are paradoxical and may be due to an issue in the calibration of the model.

Summing up, the ability of PDD models to provide nonlinear sensitivity to air temperature and solid precipitation is due to the different ablation rates and the associated change in the degree-day factor that can be involved depending on snow or ice conditions at the glacier surface. An additional nonlinearity to temperature forcing is caused by changes in the ablation duration.

Another question arises in the Discussion section of Bolibar *et al*. (2022), concerning the comparison between their results and those from other studies. The authors claim that all glacier models in the Glacier Model Intercomparison Project (GlacierMIP) (Hock *et al*., 2019) rely on MB models with linear relationships between PDDs, melt and precipitation. The authors argue that these PDD models present behaviour very similar to the linear-build statistical LASSO model. This is erroneous given that, except for one model (that of Marzeion *et al*., 2014), all temperature-index models used in GlacierMIP include two degree-day factors. Consequently, they cannot provide a linear response to climate forcing as shown above. In the Bolibar *et al*. (2022) paper, the MB anomalies in response to climate forcing were obtained using a linear LASSO MB model. The choice of the LASSO model is even more surprising given that

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the authors also used the GloGEMflow model in their paper (see their Discussion section), which is a temperature-index model widely used for glacier projections (Huss and Hock, 2015).

Conclusions

From our numerical experiments with a classic and simple temperature-index model, we found nonlinear responses of glacier MB to temperature and precipitation changes. These results refute those of Bolibar *et al*. (2022), which argue that temperature-index models provide only linear relationships between positive degree-days (PDDs), solid precipitation and MB.

We tried to understand the cause of this discrepancy. Bolibar *et al*. (2022) compare the response of MB to climate forcing (air temperature, winter and summer snow falls) using a deep-learning approach and a LASSO model. From this comparison, the authors conclude that deep learning provides a nonlinear response, contrary to the LASSO model. The conclusions of Bolibar *et al*. (2022) may be due to the use of a linear LASSO MB model instead of a temperature-index model. We would suggest testing the capability of an ANN to capture nonlinearity by comparing its results with that of the GloGEM Positive Degree-Day (PDD) model that they used in their paper.

Regarding specifically MB changes due to solid precipitations, the deep-learning model used by Bolibar *et al*. (2022) foresees decreasing sensitivity under low winter-accumulation conditions. We point out that this result directly contradicts PDD model outcomes. We explain in physical terms why a PDD model expects higher sensitivity to low winter accumulation, but do not yet understand why the approach of Bolibar *et al*. (2022) does not.

Given that detailed meteorological variables are highly unpredictable in the future, most glacier-mass projections in response to climate change in large-scale studies over the 21st century are still today based on temperature-index models with simple temperature and precipitation variables. It follows that the questions raised here relative to the nonlinear responses of surface MB to meteorological variables are crucial.

Data availability

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This commentary does not include original data. All data referred to in the text have been published elsewhere. Data are accessible through the project website at https://glacioclim.osug.fr

Author contributions: ET and CV ran the numerical modelling calculations and produced the analysis. CV supervised the study and wrote the paper. Both authors contributed to discussion of the results.

Competing interests: The authors declare that they have no conflicts of interest.

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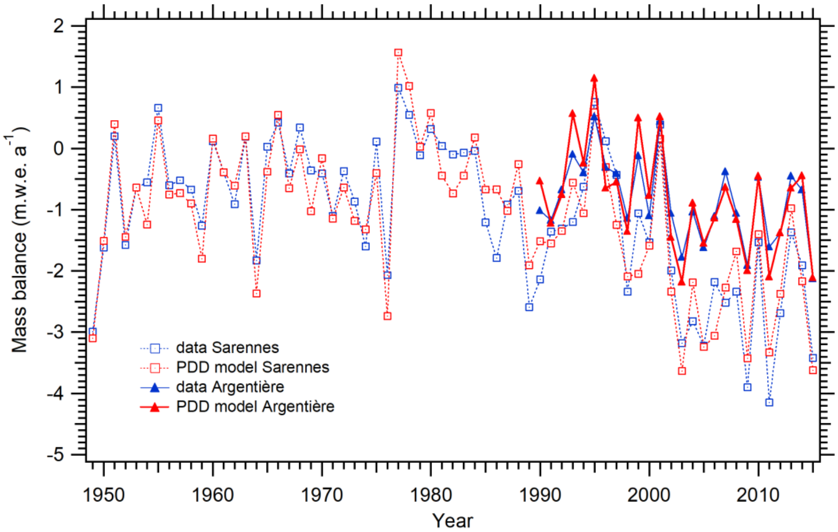

Figure 1. Glacier-wide mass balance of the Argentière glacier (1990-2015) and the Sarennes glacier (1949-2015). Observations and simulations from the simple degree-day model used in our experiments.

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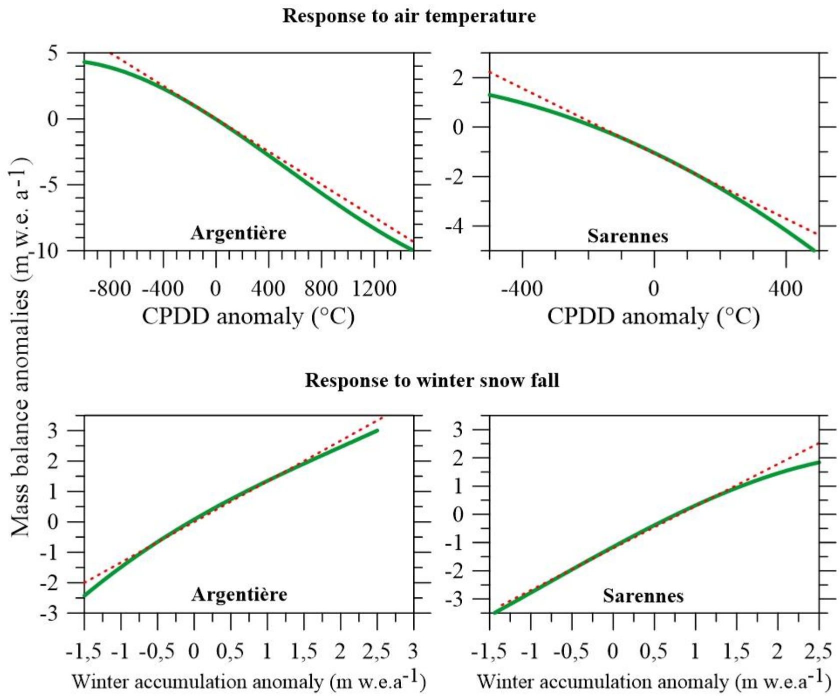

Figure 2. Response of mass balance to climate forcing using a temperature-index model (green line) at 2 750 m and 3 100 m on the Argentiere (left panel) and Sarennes (right panel) glaciers, respectively. The red dashed lines are the best linear fit. Note that in such graphs, the sensitivity of the mass blance to temperature and winter accumulation changes is the slope of the curves.

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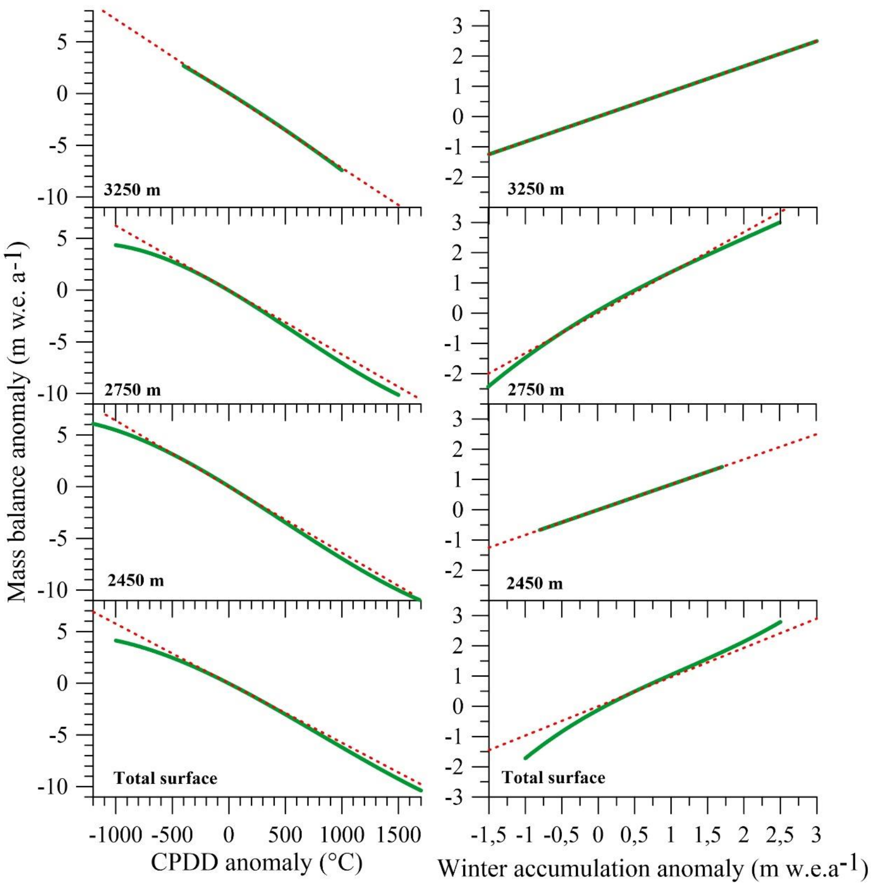

Figure 3. Response of annual mass balance to air temperature (left panel) and to winter accumulation (right panel) using a temperature-index model (green line) on the Argentiere glacier. The red dashed lines are the best fit forced through the origin.

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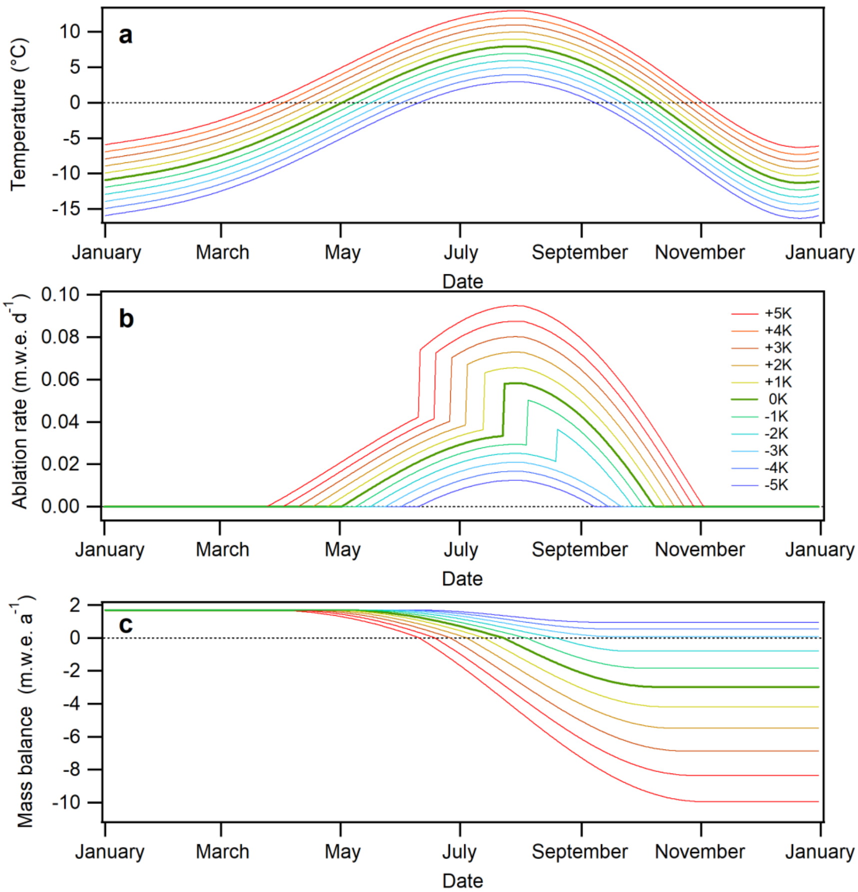

Figure 4. Positive degree-day model running on synthetic data (response to air temperature). Evolution of air temperatures (a), ablation rates (b) and mass balance (c) over the year, according to different temperature scenarios, calculated at 2 800 m. Note the jump in ablation rates when ablation shifts from snow to ice. This occurs earlier with temperature forcing. Note also the lengthening of the ablation season with rise in temperature.

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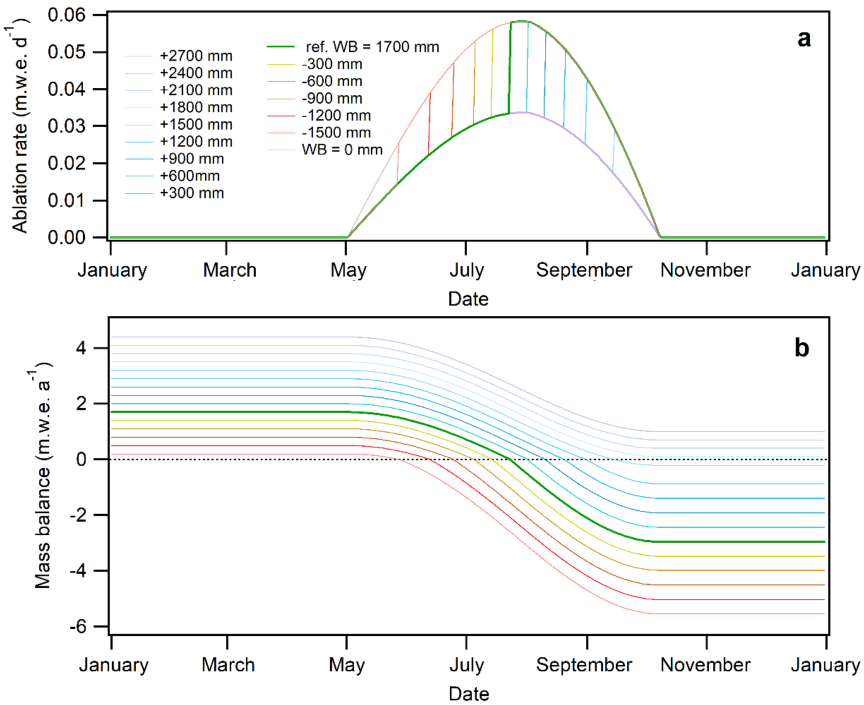

Figure 5. Positive degree-day model running on synthetic data (response to winter balance). Change in ablation rates (a) and mass balance (b) over the year, according to different winter-balance scenarios calculated at 2 800 m. Note the jump in ablation rates when ablation shifts from snow to ice. This occurs earlier under lower winter-balance conditions. Note that the ablation season duration is unchanged under variable winter-balance conditions.