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A Scenario-Neutral Approach to Climate Change in Glacier Mass Balance Modelling

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ABSTRACT. In hydrology and water resources management, scenario-neutral methods are already common, mostly used to rapidly compare system responses to plausible changes in climate. As a first application in glaciology, a scenario-neutral approach, using climatic mass balance as a system response, is applied to four glaciers: Hintereisferner (AT), Peyto Glacier (CA), Austre Brøggerbreen (NO) and Abramov Glacier (KGZ). The Open Global Glacier Model (OGGM) is used to perform a scenario-neutral glacier sensitivity analysis, resulting in visual, two-dimensional response surfaces, and a glacier sensitivity index (GSI). In addition, four Coupled Model Intercomparison Project Phase 6 models (CMIP6) (FGOALS3, MPI-ESM1, EG-Earth 3, NorESM2), under four Shared Socioeconomic Pathways (SSP) (1-2.6, 2-4.5, 3-7.0, 5-8.5) are overlaid, for comparison. Assessing results shows that overall, Hintereisferner is most sensitive to changes in climate overall, and temperature especially, with a temperature GSI of 1.12 m w.e./°C - 1.96 m w.e./°C, versus, for example, a temperature GSI of 0.56 m w.e./°C - 0.81 m w.e./°C for Peyto glacier. Seasonally, we see differences in sensitivity between climatic variables and glaciers, too. Overlaying time slices of the CMIP6 models emphasizes how scenario-neutral approaches are suitable for use in glacier modelling, especially as a framework for sensitivity studies.

INTRODUCTION

Glacier mass change is of global interest, as it influences sea level, ecosystem hydrology, and is of significant importance for the water needs of communities downstream (Brighenti and others, 2019; Milner and others, 2017; Zemp and others, 2019). Glacier melt was the largest contributor to sea level rise over the 20th Century, and is projected to remain a significant contributor throughout the 21st Century (Farinotti and others, 2019; Frederikse and others, 2020; Marzeion and others, 2017; Slangen and others, 2017). In addition, glaciers' water storage capacity make their monitoring and prediction crucial to water resources management (Förster and van der Laan, 2022; Ultee and others, 2022; Jansson and others, 2003). With their surface mass balance predominantly governed by changes in precipitation and temperature, a robust understanding of glacier sensitivity to climate change is essential in making predictions for the future (Singh and others, 2018). Traditionally, predicting 21st Century glacier mass loss is done using a 'top-down' approach, forcing glacier models with regional climates, directly or indirectly derived from General Circulation Models (GCM), yielding glacier mass evolution under imposed scenarios, see e.g. Hock and others (2019) for a comprehensive overview.

However, with much of the manifestation of specific climate change scenarios being shaped by socio-economic and political development, there are significant uncertainties in the estimates of scenario likelihoods (Kemp and others, 2022; Reilly and others, 2001). This scenario uncertainty dominates sources of uncertainty in glacier model projections over decision-relevant timescales (Hinkel and others, 2019; Marzeion and others, 2020). In order to gain an understanding of system responses to a plausible range of potential changes in climate, regardless of exact scenario and its inherent uncertainty, the development of scenario-neutral approaches has been increasingly active over the past decade (Culley and others, 2021; Guo and others, 2017). Especially in hydrology and water resources management, with an emphasis on extreme events such as floods and droughts, 'bottom-up' approaches, using a number of scenario-neutral methods, are being utilized (e.g. Beylich and others, 2021; Guo and others, 2018; Keller and others, 2019; Prudhomme and others, 2010). Essential in these studies is the identification of and focus on the climate variables to which the system is most sensitive (Guo and others, 2017). In the case of climatic glacier mass balance, these variables are clearly identifiable as precipitation and temperature (Oerlemans and Reichert, 2000). These variables form the base for the widely used mass balance model type 'temperature index model', which assumes an empirical relationship - with a physical basis (Ohmura, 2001) - between melt and temperature. Adding an approximation of the ratio of precipitation that falls in solid form, approximating accumulation, yields a model estimate of glacier mass balance. The term mass balance, as used in this study, refers to the climatic or 'reference surface' mass balance Elsberg and others (2001), calculated over a fixed geometry, focusing solely on the influence of changes in climate.

The aim of the current study is to use a scenario-neutral approach on four case-study glaciers, located in different climatic zones. We estimate overall and seasonal glacier sensitivity to plausible changes in climate, expressed through glacier mass balance. The resulting response surfaces offer a framework in which to analyze and compare critical system thresholds and explore the timing of pre-defined climate change scenarios. We showcase the latter by superimposing the results from a traditional top-down approach, using four Coupled Model Intercomparison Project Phase 6 (CMIP6) models, driven with four Shared Socioeconomic Pathways (SSP), on the response surfaces.

STUDY AREA

For the purpose of highlighting the differences in climate sensitivity between glaciers, we look at four glaciers in different climatic zones: Hintereisferner (AT), Peyto Glacier (CA), Austre Brøggerbreen (NO) and Abramov Glacier (KGZ), see figure 1. All four glaciers are World Glacier Monitoring Service (WGMS) reference glaciers, meaning they have an observational record of more than 30 years, and are largely governed by climatic factors, rather than debris cover, calving or surging (WGMS, 2022b; Wijngaard and others, 2019; Zemp and others, 2009). They have been the subject of numerous glaciological studies throughout the past decades, (e.g. Denzinger and others, 2021; Dirmhirn and Trojer, 1955; Etzelmüller and others, 2000; Kuhn and others, 1999; Young, 1981). The availability of data and previous work to understand these glaciers makes them ideal test sites for our novel approach.

Hintereisferner

Hintereisferner (46.798814°N 10.770068°E), located in the Ötztal Alps in Austria, is a clean-ice valley glacier. Its 2011 area was approximately 6.78 km^2, about 15 % smaller than in 2001 (Klug and others, 2018). Its elevation ranges from 2238 m a.s.l. at the Little Ice Age (LIA) terminus, to about 3661 m a.s.l. (Wijngaard and others, 2019). Meltwater from the Hintereisferner runs into the Hintereisbach, which converges with runoff streams from nearby glaciers such as the Kesselwandferner. It finally drains into the Ötztaler Ache, one of the main tributaries of the river Inn (Klug and others, 2018). The glacier is

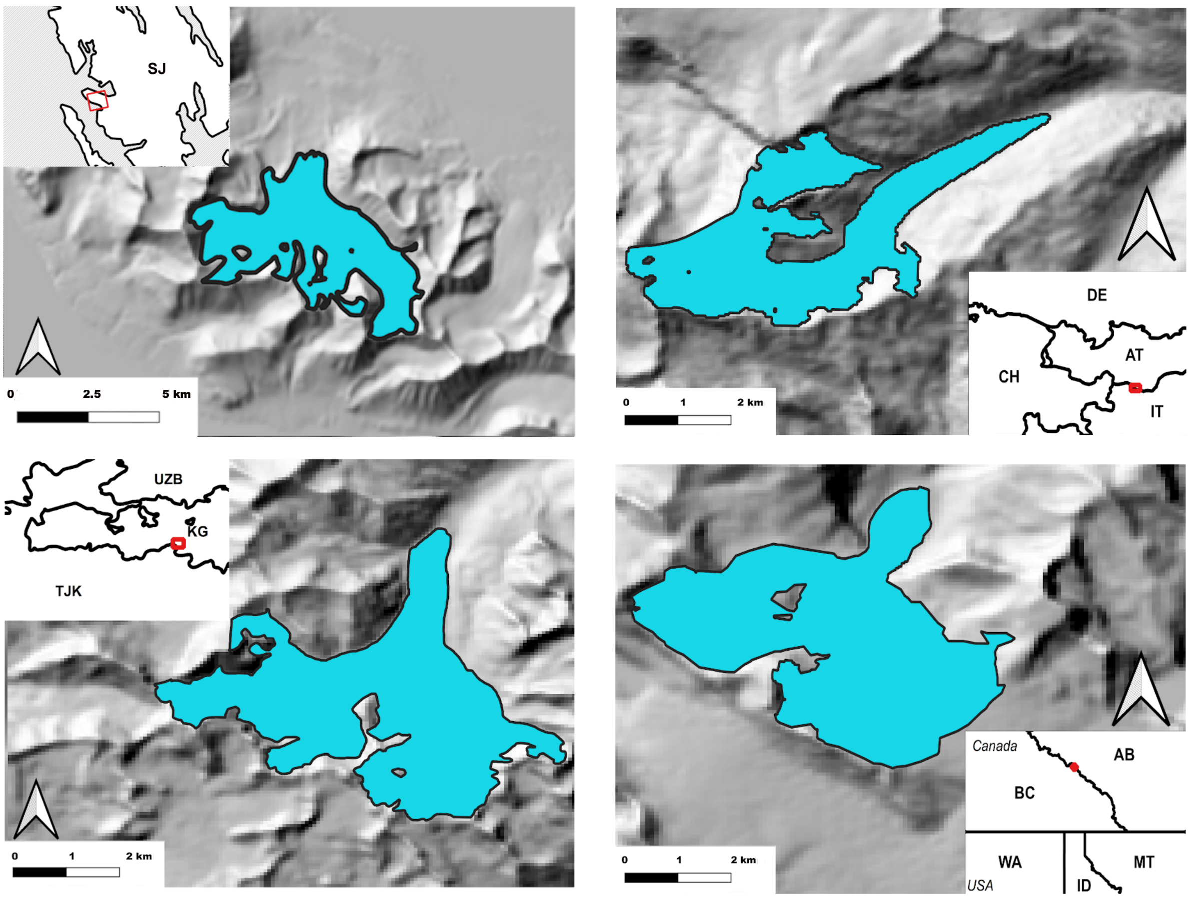

Fig. 1. Glacier outlines according to the (RGI Consortium, 2017), from top left in clockwise order: Austre Brøggerbreen (NO), Hintereisferner (AT), Peyto Glacier (CA) and Abramov Glacier (KGZ). Inset shows location of the map in their respective country, labels depicting state and/or country codes.

located in the "inner dry Alpine zone", one of the driest places in the European Alps. At the meteorological station in Vent, located approximately 8 km West of the glacier, at 1900 m a.s.l., annual mean precipitation is approximately 750 mm/a (1987-2016) and annual mean temperature is approximately 3°C (Klug and others, 2018). Annual mean precipitation at the glacier is often up to double the amount of Vent (Fischer, 2013), confirmed by totalisator measurements, see Strasser and others (2018).

Peyto Glacier

Peyto glacier (51.678056°N, -116.547222°E) is a mountain glacier located in Banff National Park, Canada. With its continued observation, Peyto glacier is considered an important "index glacier for the region" (Kehrl and others, 2014). It had an area of 9.699 km^2 in 2006, and its elevation ranges from 2647 m a.s.l. to 3032 m a.s.l. (Kehrl and others, 2014; Pradhananga and others, 2021). The glacier drains into Peyto lake through Peyto Creek, which flows from a proglacial lake that has formed since 2002, and has been informally named Lake Munro (Pradhananga and others, 2021). The glacier has continuously been losing mass since at least the 1920s. It is located in a continental climatic regime, characterized by relatively low precipitation inputs and large variability in temperature (Young, 1981). Temperature records from a meteorological station on the glacier, set up by and available from (Pradhananga and others, 2021), show that the daily average temperature varied between 15°C and -30°C during the period 20132018. Based on records from the closes meteorological station at Bow Summit, approximately 15 km from the glacier, show that total precipitation varies between 400 and 800 mm for winter (summed over 1 October - 31 March) and between 200 and 500 mm for summer (summed over 1 April to 30 September) (Mukherjee and others, 2022).

Austre Brøggerbreen

Austre Brøggerbreen (78.89092°N, 11.84745°E) is a valley/ cirque glacier located on the archipelago of Svalbard, Norway. It has an area of 6.12 km^2 (2012), and ranges in elevation from 50 to 650 m a.s.l. (RGI Consortium, 2017; Bruland and Hagen, 2002). Like many glaciers on the archipelago, e.g. Longyearbreen (78.1653°N, 15.4306°E), Austre Brøggerbreen has lost over 50% of its area since 1936. Austre Brøggerbreen is situated in a High Arctic climate, characterized by low temperatures and relatively low precipitation, though the meteorological stations in Longyearbyen and Ny-Ålesund, the latter approximately 4km from the glacier, show the local climate to be comparatively warm to other locations between 70 and 80°N

(Eckerstorfer and Christiansen, 2011). The mean annual air temperature, measured at the equilibrium line (approximately 300 m a.s.l.), is -8.0°C, while the mean annual temperature in Ny-Ålesund was -6.3 °C in the period 1969-1990, with an increase to -5.2°C from 1981-2010, due to arctic amplification (Førland and others, 2011; López-Moreno and others, 2016). Mean annual precipitation in the area was 385 mm and 427 mm for the periods 1961-1990 and 1981-2010, respectively (Førland and others, 2011).

Abramov Glacier

The Abramov glacier (39.6022°N, 71.5508°E) is a valley glacier in the Koksu Valley, Pamir-Alay range, in Kyrgyzstan (Barandun and others, 2015). It has an area of 24 km^2 and spans an elevation range of 3650 to 5000 m a.s.l. (in 2015) (Kronenberg and others, 2021). Between 1975 and 2015, the glacier has lost about 5% of its area, and retreated approximately 1 km (Barandun and others, 2015). The Abramov glacier is located in a continental climate. Mean annual temperature recorded at the glacier meteorological station (3837 m a.s.l.) was -4.1°C for the period period 1968–1998 (Pertziger, 1996). Mean annual precipitation was 750 mm from 1968-1998, with maximum precipitation occurring from March to May (Pertziger, 1996).

DATA AND METHODS

The Open Global Glacier Model

The Open Global Glacier Model (OGGM) is an open-source model framework for global past and future glacier modelling developed by Maussion and others (2019). It is a modular framework with a glacier-centric approach, of which we use only the mass balance model (v. 1.5.3) for the current study. The Randolph Glacier Inventory (RGI) v. 6 forms the base of OGGM, while the digital elevation models (DEM) are selected per glacier, from various available datasets in OGGM, depending on the region. For the current study, the DEMs stem from NASADEM and COPDEM (Crippen and others, 2016; Fahrland and others, 2020, respectively). As needed, the model can also be operated on user-input DEM data.

These are then are applied to each glacier outline. After the preprocessing, glacier centerlines are computed, according to the Kienholz and others (2014) algorithm. These centerlines are then converted into flowlines. For climate data, we timeseries of temperature and precipitation (TS: Harris and others, 2014) from the Climate Research Unit (CRU) dataset (Harris and others, 2014). These are then downscaled to the CRU 1961-1990 CE climatology (New and others, 2002), by applying the 1961-1990 anomalies: a robust statistical method, often referred to as the delta method or change factor method (e.g. Getahun and others, 2021; Prudhomme and others, 2010). This is done in order to obtain time series with elevation data, which is not a feature of CRU TS. Temperature and precipitation are then applied in an extended 'temperature index melt model', in which monthly mass balance is calculated according to:

$$m_i(z) = p_f P_i^{solid}(z) - \mu^* max(T_i(z) - T_{melt}, 0), \tag{1}$$

in which $m_i(z)$ represents monthly mass balance at altitude z, P_i^{solid} is solid precipitation, calculated from the total monthly precipitation, according to a temperature threshold. In case monthly mean temperature $T_i(z)$ is below 0 °C all precipitation is considered solid; when the temperature is above 2 °C all precipitation is considered liquid. When the temperature is between these, the solid fraction decreases linearly. The default temperature lapse rate is set to 6.5 °C/km and the threshold temperature for melt to -1 °C. The precipitation correction factor p_f, that we apply to adjust precipitation in our scenario neutral approach (see Section Scenario-Neutral Approach), can generally be considered a correction for orographic precipitation, wind-blown snow and avalanches, when set to its default value of 2.5.

Finally, temperature sensitivity parameter μ^* comes from an automated calibration procedure. OGGM contains various modules to calibrate the mass balance model. Here μ^* is calibrated with observed WGMS mass balance data for the four glaciers in our case study. When modelling on a larger scale, the model can also be calibrated with all WGMS reference glaciers, geodetic mass balance data (e.g. Hugonnet and others, 2021) or the user's own mass balance data. For more detailed information visit: https://docs.oggm.org and (Maussion and others, 2019).

CMIP6 Models

For the scenario projection approach, we force OGGM with temperature and precipitation from four GCMs, obtained from CMIP6 archived model output. These models are FGOALS3, MPI-ESM1, EG-Earth 3 and NorESM2. The specifications of each model are shown in Table 1, and we use the r1i1p1f1 realization of all models. In order to obtain datasets spanning 2000-2100, we merge GCM output from the CMIP6 experiment 'historical', which spans the years 1850-2015, and GCM output under four SSPs (2015-2100): SSP 1-2.6, 2-4.5, 3-7.0 and 5-8.5 (O'Neill and others, 2016). These are driven by emissions and land-use scenarios and refer to climate mitigation, adaptation and impacts. SSP 1-2.6 (updated Relative Concentration Pathway 2.6 (RCP;(Van Vuuren and others, 2011)) refers to a level of radiative forcing of 2.6 Wm^{-2} in 2100 and represents the low end of the future forcing pathways. SSP 2-4.5 (updated RCP 4.5)

Table 1. CMIP6 GCMs applied in scenario projection approach

Model	Acronym	Components	Coupler
Version 3 of the Flexible Global Ocean Atmosphere Land System model (Li and others, 2020)	FGOALS 3	Version 3 of the Grid-Point Atmospheric Model of LASG-IAP (GAMIL3), Version 3 of the LASG-IAP Climate System Ocean Model (LICOM3), Version 4 of the Los Alamos sea ice model, the CAS-Land Surface Model (CAS-LSM)	Common Flux Coupler
Max Planck Institute Earth System Model (Müller and others, 2018)	MPI-ESM1	Atmospheric Model ECHAM6.3, Ocean Model MPIOM Version 1.6.2	Ocean-Atmosphere-Sea-Ice Coupler Version 4
EC-Earth 3 Earth System Model (Döscher and others, 2022)	EC-Earth3	Various Physical Domains and System Components describing Atmosphere, Ocean, Sea Ice, Land Surface, Dynamic Vegetation, Atmospheric Composition, Ocean Biogeochemistry and the Greenland Ice Sheet	OASIS3-MCT Coupling library
Version 2 of the Coupled Norwegian Earth System Model (Seland and others, 2020)	NorESM2	CIME: Configuration Handler, CAM6-Nor: Atmosphere and Aerosol, CICE5.1.2: Sea Ice, CLM5: Land and Vegetation, MOSART: River Transport, BLOM: Ocean, iHAMOCC: Ocean Carbon Cycle	CESM2 Coupler

refers to 4.5 Wm^{-2} as representing the medium level. SSP 3-7.0 is a newly added level at the high end of the range referring to 7 Wm^{-2} radiative forcing in 2100. SSP 5-8.5 (updated RCP 8.5), representing the high end of the future pathways, refers to 8.5 Wm^{-2}.

Comparison with Observed Data

In order to create a set of reference - unperturbed - results, we force the OGGM mass balance model with a baseline climate, from here on referred to as 'unperturbed'. These are the downscaled CRU time series of precipitation and temperature from 1985 until 2015. For the sake of simplicity, computational efficiency and consistency with the scenario-neutral method, we use fixed geometries throughout our model runs, corresponding to the outline at the glacier's RGI date. To ascertain that our baseline results are reliable, we compare the mass balance results of all four glaciers with the WGMS observed mass balance data (WGMS, 2022a), assessing skill via the calculation and analysis of the mass balance error (MBE), mean absolute error (MAE) and Pearson correlation. For the MBE, we subtract observed mass balance from modeled mass balance in the same year, for each glacier, over the period 1985-2015 (N=107, because of lack of observation for Abramov Glacier from 2000-2012). For the MAE, we take the absolute values of the 107 calculated MBEs, from which we calculate a mean MAE per glacier. The MAE, as it considers the direction of error, provides more information about the magnitude of the discrepancy between modeled and observed values. Finally, we calculate the Pearson correlation coefficient, as a a measure of agreement between modeled and observed values.

Scenario-Neutral Approach

We define scenario-neutral as looking at the impact of changes in climate attributes, independently of each other, of timing or other variables affecting the system. In our particular case, that means we analyze the impact of changes in precipitation and temperature, relative to a baseline, in a multitude of combinations (e.g. a 20% increase in precipitation and no change in temperature, a 10% decrease in precipitation and 5°C increase in temperature, or both attributes remaining at baseline in summer, while changing in winter), without these changes being associated with a particular climate change scenario. Scenario-neutral methods look at system response, in this case the system 'glacier', where we define the response as a change in climatic glacier mass balance. The magnitude of the response is a means to assess and convey system sensitivity.

Because glacier mass balance is, in reality, also influenced by changes in glacier geometry, impacting volume and area, we model mass balance using a fixed geometry. This allows us the advantage of modeling glacier response to climate attribute changes under which the real-world glacier would have significantly changed geometry or vanished entirely. The mass balance calculated from this diminishing volume and area would be much lower, which would misrepresent the severity of the system response. Modeling glacier mass balance with fixed geometries (here, the outline at their RGI date) allows comparison of sensitivity on a glacier-to-glacier basis, regardless of their real-world mass loss over time, and is considered the more climatically relevant type of mass balance (Elsberg and others, 2001).

Finally, in order to assess and convey system sensitivity at a glance, we make use of response surfaces. These are two-dimensional, gridded plots, with each of the axes representing a climate attribute and the system response depicted in a colour-coded grid.

For each of the four glaciers in our case study, we follow the steps towards construction of a scenario-neutral space outlined in (Culley and others, 2021), which consist of the following:

1) **Selection of Climate Attributes:** As we consider four reference glaciers, whose mass balance is principally governed by precipitation and temperature (Shea and Marshall, 2007; WGMS, 2022b), these are the climate attributes against which we measure glacier response. These attributes form the axes

of our response surface, too. Our choice of climate attributes is also in line with the selection of our system model for the calculation of system response: OGGM's mass balance model, which uses monthly time series of precipitation and temperature as input.

2) Development of Perturbed Attribute Values: This considers the plausible changes in the selected climate attributes. Since we consider the CMIP6 SSP scenarios, until 2100, within our response surface boundaries, these give a guideline of the magnitude of our plausible changes. To calculate upper boundaries for the perturbation, for mean annual temperature and annual precipitation, we calculate the difference between the unperturbed mean values and SSP585 (most extreme) values over the year 2100, for all four glaciers. The largest temperature difference is found for Austre Brøggerbreen, with a mean annual temperature over the unperturbed period of -7.2°C and of 3.6°C in 2100. To include this scenario in our boundaries, we apply a plausible perturbation of +11°C.

For precipitation, in order to take into account the large differences in precipitation amount the four glaciers get, we use a multiplicative factor rather than fixed amounts in- or decreased. Also here, we find the largest differences from baseline in SSP585, and in this case for Hintereisferner and Peyto glacier. For Hintereisferner, we see a decrease of 10%, from 1480 mm per year to 1330 mm per year between the unperturbed period and 2100. For Peyto glacier, we see an increase of 48% in precipitation, from 1148 mm per year to 1706 mm per year. To include these scenarios, we include perturbations of -20% to +50% in precipitation. For the time slice 2010-2040, we adapted the precipitation boundary for Austre Brøggerbreen to a decrease of 70%, to fit the CMIP6 scenarios within the boundaries.

3) Generation of Climate Perturbed Time Series: To reflect these perturbations in our climate attribute time series, we make use of a temperature bias and the precipitation factor (for the latter, see Equation 1). The temperature bias simply adds a specified anomaly in °C to the unperturbed time series, according to the increments of the response surface axes. Depending on the glacier, we use increments of 0.5°C or 1°C. The precipitation factor is a multiplicative factor, which is calibrated to 2.5 for our baseline climate. We adjust percentages according to our selected perturbations, in increments of 5% to 10%, depending on the glacier. For the seasonality sensitivity experiments, either winter (October-March) or summer (April-September) are kept constant, while the other season is perturbed.

4) **Assessment of System Performance:** The system performance, here defined as climatic glacier mass balance, is calculated by forcing the OGGM mass balance model with each incrementally perturbed 30-year time series, for each glacier. The mean mass balance over the 30-year time period is calculated and depicted in the response surface grid.

Glacier Sensitivity Index

To quantify and support the visual impact of the response surface, we calculate the glacier sensitivity index (GSI), building upon the idea by Oerlemans and Reichert (2000) that mass balance can be related to precipitation and temperature with a sensitivity characteristic. The GSI is calculated per glacier, for temperature and precipitation. We only calculate the GSI in instances where the relevant climate attribute is perturbed, and the other is not, to isolate its impact. The calculation is done as follows:

$$GSI_T = (m_k - m_{ref,k})/bias_T, \tag{2}$$

and

$$GSI_P = (m_k - m_{ref,k})/factor_P, \tag{3}$$

in which m_k and $m_{ref,k}$ represent the mass balance in year k of the perturbed run, and year k of the unperturbed, baseline run. $Bias_T$ and $factor_P$ refer to the temperature bias and precipitation factor, respectively. GSI_T and GSI_P are calculated annually.

The magnitude and the inter-annual variability of the GSI values per climate attribute represent the influence of the specific attribute on mass balance, representing system response. The larger the GSI, the larger the influence of the attribute on the system. The larger the variability, the less consistent the influence of the climate attribute on the system.

Scenario Projection Approach

For the traditional, top-down, scenario projection approach, we force OGGM with the four CMIP6 SSP scenarios, as represented by four models, outlined in the Section CMIP6 Models. Here, too, we use a fixed geometry, starting from the year 2000, running to 2100. The projections are then superimposed onto the response surface. This is done by calculating the mean annual temperature and annual precipitation

Table 2. Statistics comparing observed and modeled mass balances from the OGGM unperturbed run, for all four glaciers. All values and standard deviations are mean values per glacier

Performance measure	Peyto Glacier	Hintereisferner	Austre Brøggerbreen	Abramov Glacier
MBE (m w.e.)	0.017 ± 0.60	-0.29 ± 0.51	-0.11 ± 0.36	0.057 ± 0.39
MAE (m w.e.)	0.47 ± 0.36	0.46 ± 0.35	0.31 ± 0.19	0.31 ± 0.23
Pearson correlation	0.50	0.80	0.40	0.73−0.11

over 30 years (2010-2040, 2040-2070 and 2070-2100) for each model and scenario (from here on 'model iteration'). The differences between these values and the unperturbed CRU values determine the position on the axes and thus on the response surface.

RESULTS

Unperturbed Run

For the period 1985-2015, we calculate the model performance measures outlined in Table 2. Both individually and averaged over all four glaciers, we see good agreement between modeled and observed mass balances. Averaged over all four glaciers, an MBE of -0.08 ± 0.46 m w.e. and MAE of 0.39 ± 0.28 m w.e. show that overall, the errors are small. They are comparable to the error values Eis and others (2021) found for the validation of their mass balance reconstruction over all reference glaciers. Figure 2 shows that the cumulative mass balances, observed and modeled, match well, though the model slightly underestimates the mass balance, for Hintereisferner and Austre Brøggerbreen in particular. For Abramov glacier, 13 of the 30 observed years are missing, so it is not possible to make a robust judgment of the goodness of fit in terms of cumulative mass balance over the whole period. This is why the years 2011-2015, though observations exist, are removed from the figure. Overall, we are satisfied with the agreement between observed and modelled mass balance, and proceed with the results of this unperturbed run as the 'central square', at temperature bias=0 and precipitation factor=2.5 (standard parameter value).

Scenario-Neutral Approach

As outlined above, we generate response surfaces according to the four steps suggested in Culley and others (2021). Using the defined boundaries of plausible climate change, this results in a response surface over the period 1985-2015 for Peyto Glacier, Hintereisferner, Austre Brøggerbreen and Abramov Glacier, as shown

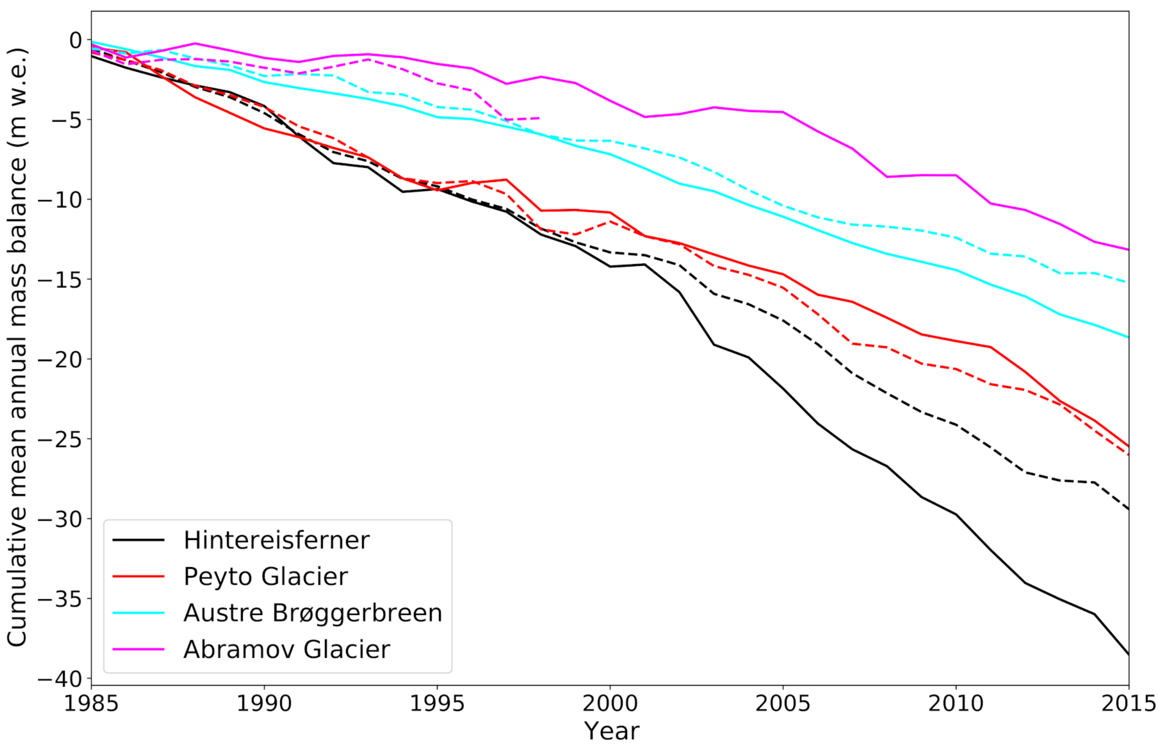

Fig. 2. Cumulative specific mass balance over the period 1985-2015, simulated with OGGM, forced with the unperturbed time series (solid lines), and observed (dashed lines) (WGMS, 2022a)

in figure 3. To assess the influence of seasonality of climate attributes on glacier mass balance, we also generate a "known summer" and "known winter" response surface for each glacier, in which summer and winter, respectively, are kept at their known values from the unperturbed run, and the respective other season is perturbed. The results of this can be seen in figure 4.

Forced with the full unperturbed time series, Hintereisferner responds most sensitively to the changes in climate attributes. Under the baseline, unperturbed climate, mean annual specific mass balance is -1.28 m w.e.. Under the most extreme scenario, with a decrease in precipitation of 20% and temperature increase of 11°C, mean annual mass balance goes down to -22.55 m w.e.. Increases in precipitation markedly affect mass balance in the realm of a temperature bias of -2°C to 2°C, after which precipitation ceases to have an effect. This is likely due to a removal of accumulation from the mass balance equation (Equation 1) entirely, as also winter temperatures are above the threshold at which precipitation falls as snow. For the other glaciers, we see a less extreme response to the changes in climate attributes, though all glaciers follow similar patterns, with an overall higher influence of temperature than precipitation. As Hintereisferner, out of all glaciers show here, has the largest amount of annual precipitation, and the highest sensitivity, this small case study confirms the ideas discussed in Meier (1984); Oerlemans and Fortuin (1992); Oerlemans and Reichert (2000) that sensitivity goes up with precipitation amount, and that generally, glaciers with a higher mass turnover are more sensitive to glaciers in climate.

Besides results for consistently perturbed time series, we also have response surfaces for seasonally perturbed time series, depicted in figure 4. For clarity, we only discuss the two glaciers with the largest differences in seasonal impact: Hintereisferner and Austre Brøggerbreen. The axes here have smaller perturbations, in order to remain within the bounds of plausibility. The highest temperature bias is of 3°C, which is in line with e.g. the exceptionally warm summer of 2022, in the Alps (Cremona and others, 2022). These heat waves caused the mean annual temperature at the Hintereisferner station to rise to -2.3°C at an altitude of 3245 m a.s.l. (Innsbruck University, 2022). The baseline climate mean annual temperature, over 1985-2015, at Hintereisferner was -1.3°C at 2700 m a.s.l.. Adjusted for altitude, using a lapse rate of 6.5°C/km, that would correspond to a temperature difference of 2.2°C, fitting within perturbation limits.

As can be seen from the response surfaces in figure 4, there are marked differences in the responses of Austre Brøggerbreen and Hintereisferner to seasonal perturbations. When the summer season is unperturbed, mass balance is only dependent on precipitation for Austre Brøggerbreen, while for Hintereisferner, temperature remains influential. When winter is unperturbed, precipitation is of little importance for both glaciers, and differences in mass balance are mostly due to temperature changes. The differing responses of the glaciers are likely due to their location, and how much precipitation falls as snow. For Austre Brøggerbreen, winter precipitation almost solely falls as snow. Perturbations within the boundaries shown here would not affect this (figure 4 a). For Hintereisferner however, these increases in temperature would affect the fraction of winter precipitation that falls as snow, impacting accumulation and thus mass balance through both temperature and precipitation (figure 4 c). In summer, temperature changes mainly have an effect on melt, and, of secondary importance, on the state of precipitation. For both glaciers, mass balance almost exclusively changes with temperature, affecting the amount of melt. Precipitation has little to no influence, likely due to little of summer precipitation falling as snow at these temperatures. The results discussed here are in line with Oerlemans and Reichert (2000), who observe similar results when comparing Nigardsbreen (Norway) and Franz-Josef glacier (New Zealand), which have comparable differences in their precipitation patterns. Oerlemans and Reichert (2000) do note the importance of Hintereisferner summer precipitation for its mass balance, which we do not observe in our response surfaces.

Glacier sensitivity index

The GSI results overlap with and complement the visual results in the response surfaces. For Hintereisferner, GSI_T varies between 1.12 m w.e.$^{\circ}$C^{-1} and 1.96 m w.e. $^{\circ}$C^{-1}, while for Austre Brøggerbreen, GSI_T varies between 0.32 m w.e. $^{\circ}$C^{-1} and 0.56 m w.e. $^{\circ}$C^{-1}. For Peyto and Abramov glacier respectively, GSI_T values vary between 0.56 m w.e. $^{\circ}$C^{-1} and 0.81 m w.e. $^{\circ}$C^{-1}, and 0.41 w.e. $^{\circ}$C^{-1} and 0.62 m w.e. $^{\circ}$C^{-1}. The magnitude indicates the largest influence of temperature on mass balance for Hintereisferner, as is also visible in figure 3.

For precipitation, the influence is more difficult to quantify in a sensitivity characteristic, because it is very dependent on the temperature whether precipitation affects mass balance. At low temperatures, when precipitation falls as snow and adds to accumulation, the amount of annual precipitation matters. As an example, for Hintereisferner, GSI_P ranges between -0.8 m w.e. and 2.1 m w.e. at temperature bias ranges -2 to 3°C. At higher temperature biases, GSI_P reaches values as low as -22.2 m w.e.. For Austre Brøggerbreen, these ranges lie between -0.7 and 0.6 m w.e. at temperature bias -2 to 3°C, and go up to -4.11 m w.e. at a temperature bias of 11°C. This is consistent with the visual results of the response surfaces, where mass balance varies with precipitation in the left columns, at lower temperature biases,

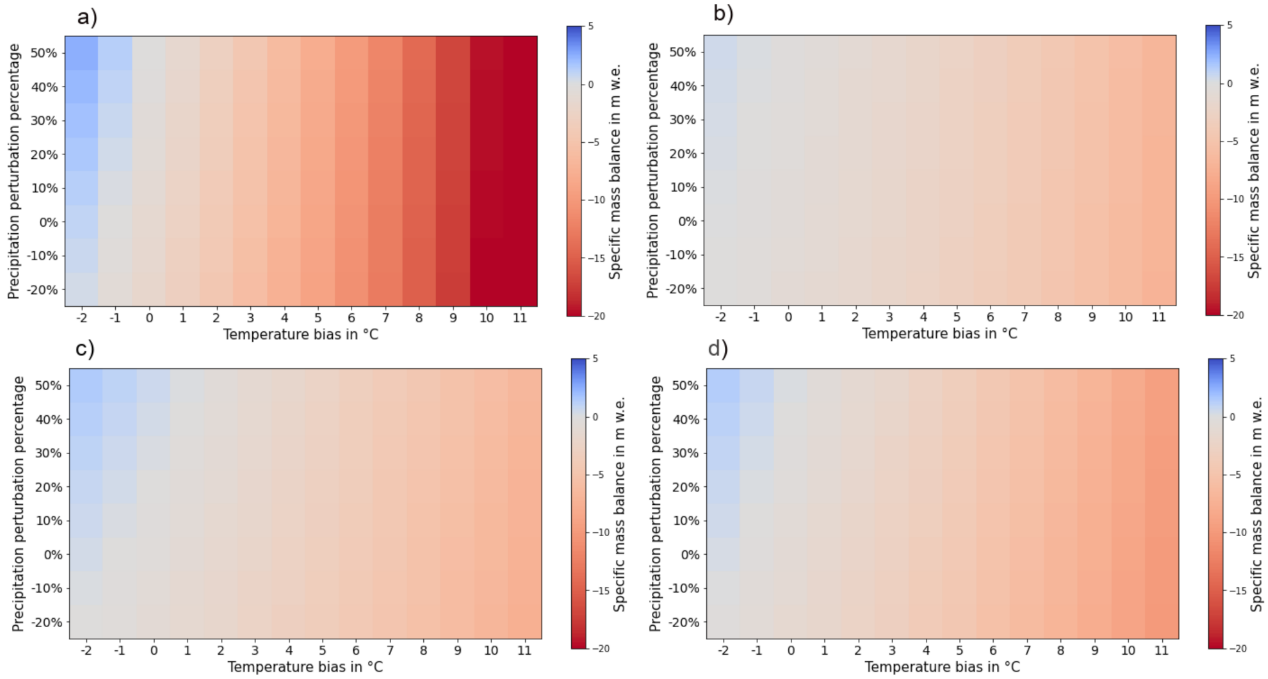

Fig. 3. Response surfaces for a) Hintereisferner, b) Austre Brøggerbreen, c) Abramov Glacier and d) Peyto Glacier, resulting from the fully perturbed time period 1985-2015. Mass balance values represent the annual mean over the 30-year time period. For comparison purposes, the color bars are unified and the transition blue-orange is centered at 0 m w.e.

and remains more consistent as the temperature bias increases.

Scenario projections

For all four glacier, we calculate the development of their mass balance under the four SSPs, with the models described in Section CMIP6 Models. The results are superimposed onto the response surfaces, as a means to estimate the impact of the given climate change projection, as also seen in e.g. Kay and others (2014) and Culley and others (2021). First, two example results are given here, in figure 5, for glaciers Austre Brøggerbreen and Hintereisferner, and time slice 2070-2100. On the response surface, we observe clear differences between the different models in their manifestation of the SSPs. For both glaciers, EC-Earth 3 has the largest increase in temperature and precipitation from the baseline climate, while FGOALS 3 projects the lowest increases in temperature, and a decrease in precipitation rather than an increase. NorESM2 and MPI-ESM1 show similar responses, with little change in precipitation. For Austre Brøggerbreen, we see that the EC-Earth 3 SSP126 scenario indicates a larger increase in temperature than

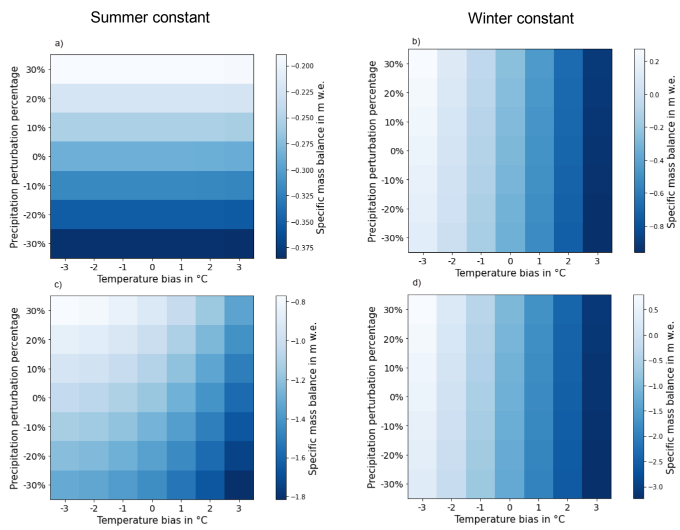

Fig. 4. Response surfaces for Austre Brøggerbreen (a and b) and Hintereisferner (c and d),resulting from the seasonally perturbed time period 1985-2015. The word 'constant' at top of the figure refers to a perturbation of 0 for that season in all years. Mass balance values represent the annual mean over the 30-year time period. The summer contribution to mass balance for 'summer constant' is -1.07 m w.e. for Austre Brøggerbreen (a) and -3.84 m w.e. for Hintereisferner (c). For 'winter constant', the winter contributions to mass balance are 0.49 m w.e. (b) and 1.49 m w.e. (d). For clear contrast of the colors, and thus of the differences per season and glacier, the color scales are not unified, so please note.

all, more extreme, SSPs in the other models. This shows the high potential uncertainty in the use of climate change projections, when applied to glacier mass balance.

Because of the realization that by 2070-2100, the present-day geometry used in our OGGM runs would no longer be representative of the glacier state, we present a more zoomed-in response surface in figure 6. Overlaid here are the SSPs as represented by the four GCMS, for the time period 2010-2040. As the differences between the baseline climate and SSP climates are smaller here for temperature, but larger for precipitation, the axes are adapted to focus on this range. We see that over this period, the projections have diverged much less than for 2070-2100, but the differences between models remain.

DISCUSSION

The methods applied here depart from the conventionally used top-down approach of modelling glacier response to pre-defined climate change scenarios. The aim was to apply a scenario-neutral approach in glaciology, expanding their use to this research field. We endeavor to show the overall and seasonal sensitivity of four different glaciers to changes in precipitation and temperature, as well as use this approach as a framework in which to analyze pre-defined climate change scenarios. Especially the simplicity and two-folded type of result - visually in response surfaces and quantified in the GSI - form the method's strength. However, there are significant limitations as well, pertaining to the use of a fixed geometry, only four glaciers, and the generation of the perturbed time series.

Sensitivity

Overall, the use of this scenario neutral approach can provide a comprehensive overview of a glacier's sensitivity to temperature and precipitation. As we see above, the response surfaces clearly exhibit the high sensitivity of the Hintereisferner, especially to temperature changes, compared to the other three glaciers in our study. The same is conveyed through the Hintereisferner having the highest GSI_T (1.12 m w.e./°C - 1.96 m w.e./°C). The numbers for the GSI_T are in line with the observed temperature sensitivity for the glacier calculated by Fischer (2010) after 1979, which ranges between 0.38 m w.e./°C and 1.54 mm w.e./°C.

This type of sensitivity analysis is more difficult to reach through the use of top-down methods with scenario projections, as they are highly uncertain and do not cover the total range of plausible changes in climate, especially on smaller scales, such as the glacier or basin scale. Neither are pre-defined projections

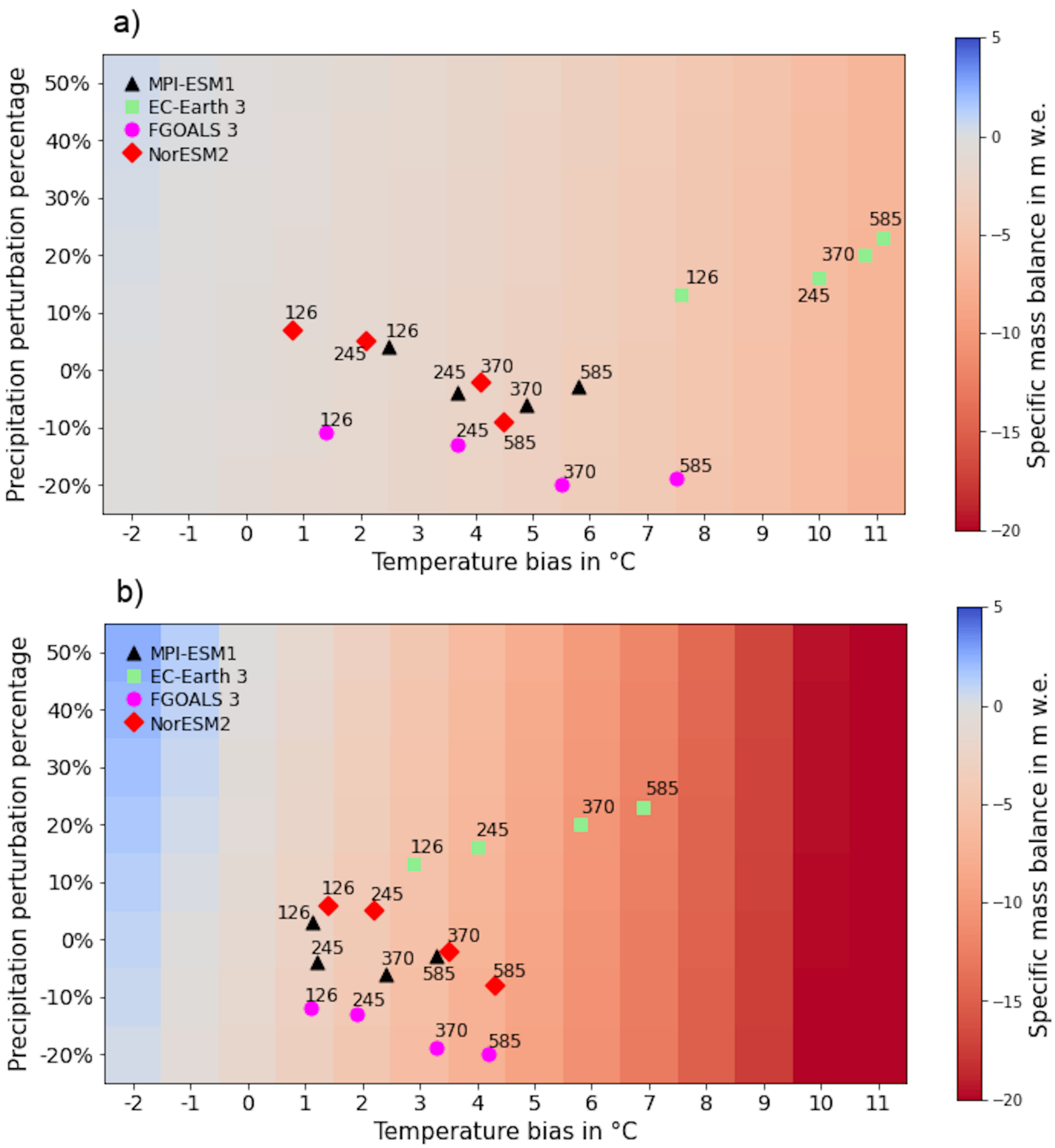

Fig. 5. Response surfaces for Austre Brøggerbreen (a) and Hintereisferner (b), with the SSPs for all models overlaid, averaged over the period 2070-2100

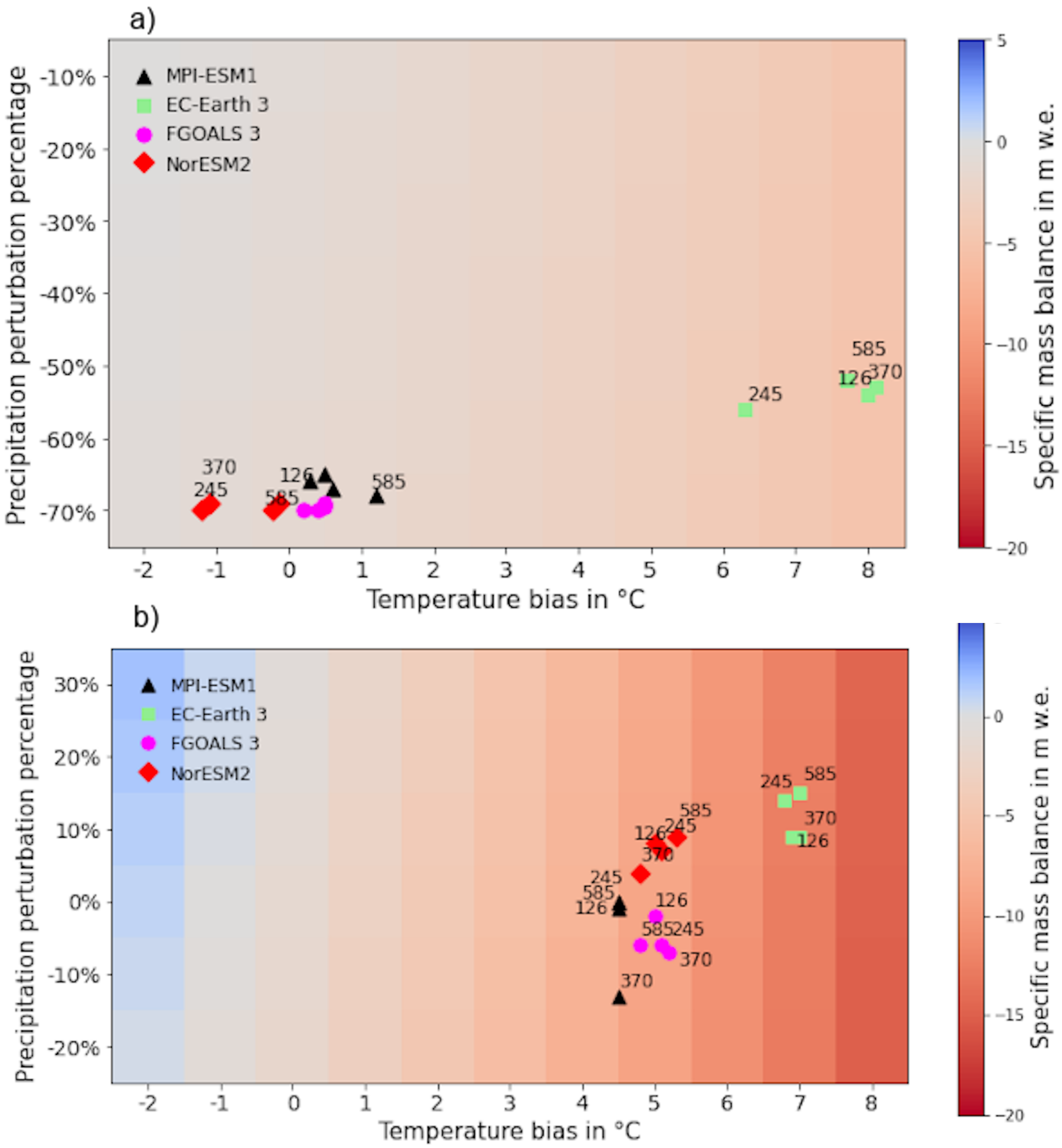

Fig. 6. Response surfaces for Austre Brøggerbreen (a) and Hintereisferner (b), with the SSPs for all models overlaid, averaged over the period 2010-2040. Note the difference in precipitation axes for the two glaciers. For Austre Brøggerbreen, the differences between several SSPs for models MPI-ESM1 and FGOALS 3 are so small that they are not labeled, for legibility purposes

well suited for direct glacier comparison, as the changes in climate differ per glacier. Through response surfaces and GSI, glacier response to the same range of plausible changes in temperature and precipitation can be compared in a computationally inexpensive way.

Seasonal response

In terms of seasonal sensitivity, the scenario neutral approach is especially useful in determining the impact of climate characteristics per season. By keeping one season unperturbed, the impact of perturbations in the other can be isolated. By keeping perturbation ranges the same, comparisons of responses can be made between glaciers. As done here, for two glaciers, it provides insight into the differing importance of single seasons and climate characteristics per glacier. This knowledge can be applied to uncertainty analysis in studies of these glaciers, and judging the importance of said uncertainties, in discussing reliability of observation or model results.

A limitation here is that of course, climate change is not limited to one season only, and the resulting mass balances cannot be taken as true results for seasonal climate change perturbations. However, when a season is known through observations, such as precipitation and temperature from glacier weather stations, response surfaces can be used to provide the likely boundaries of the annual balance. As continuous mass balance observations are only available for very few glaciers (Landmann and others, 2021), these boundaries can provide an intermediate step of knowledge, before annual mass balance is observed or modelled. The model would be forced with the known winter season values, an average of previous summer values, and plausible summer perturbations. Especially if the known season is out of the ordinary, e.g. especially dry, this can provide valuable knowledge for the annual mass balance range to follow. One example of this could be for the current winter, 2022-2023, the first three months of which are strongly below the 2012-2022 accumulation average for Swiss glaciers (Switzerland, 2022).

Scenario projections

The main goal of superimposing scenario projections onto the scenario-neutral response surfaces is to gauge their time line and the differences between projections and models. In the examples here, they provide clear indications of model differences and ranges of glacier response. Especially on shorter time scales, such as the decadal scale, where fixed geometry mass balance still matches observed balances well (van der Laan and others, 2022), these overlays can provide a useful first step for dynamical modelling studies, as they can be done before running the impact model. This type of rapid assessment is generally considered the greatest asset of scenario neutral approaches in climate change studies (Prudhomme and others, 2010; Kay and others, 2014)

Limitations and outlook

Finally, while scenario neutral approaches can be useful, there are important limitations to the interpretation of their results, especially considering we only study four glaciers here. The most limiting factor here, for both the GSI and response surfaces from this study, is the difference between mass balance response here, and mass balance response in reality, the latter under changing glacier geometry. Especially on larger time scales, mass balances under severe changes in climate will develop in line with both climate and the glacier's changes in area, volume and altitude. That is why the response surfaces here cannot be interpreted as the full, true glacier response to climate change. If a scenario neutral approach were to be applied in dynamical glacier modelling, other response variables than mass balance become available: volume, area and runoff. Two consistent response variables would be volume and area, rather than runoff, as the latter two is subject to a peak, referred to as peak water, and then decreases as the glacier shrinks (Förster and van der Laan, 2022; Huss and Hock, 2018). This feature could also be utilized, identifying under which different combinations of temperature and precipitation perturbation peak water would arise. The overlaying of scenario projection time slices then gives information on timing of these peak water conditions, and with that give a critical system threshold for communities downstream. This would be one way of making scenario neutral approaches useful for management purposes, as is already the case for flood management (Kay and others, 2014).

The outlook for future application of scenario neutral approaches in OGGM could lie in running the dynamical model, but the main priority of this method will lie in sensitivity studies, rapid comparison of glaciers and educational purposes. The latter will mainly be done in the interactive module of OGGM Edu (OGGM, 2022), an educational platform by the OGGM consortium (Maussion and others, 2019). Through the response surfaces, glacier sensitivity to climate change can be illustrated, in addition to OGGM Edu applications such as the mass balance simulator. The method can easily be extended from the four glaciers presented here, to all land-terminating glaciers listed in the RGI, which should be done as a pilot with all 279 land-terminating reference glaciers, before implementing this on a larger scale.

CONCLUSION

Overall, we conclude that scenario neutral approaches are very suitable to the modelling of glacier mass balance, due to precipitation and temperature being its main drivers. The method yields visual output that is easily understood, also by non-experts in the field of glaciology, and a quantification in the form of the GSI. Both these results make it easy to rapidly compare the sensitivity of glaciers to changes in climate, as well as the seasonal importance of precipitation and temperature. The method confirming long-standing ideas in glaciology, such as the relationship between sensitivity and precipitation and temperature (Meier, 1984; Oerlemans and Fortuin, 1992), shows consistency, while adding new features, such as response surfaces providing boundaries to a range of future mass balances. This can be especially valuable when only one season is known. Overlaying scenario projections can also deliver an additional step of knowledge, in which the response surface becomes the framework in which to compare time lines of projections and differences between models and scenarios. While there are limits to their interpretation, mainly due to using a fixed geometry in this study, scenario neutral approaches are an additional, easy, and useful facet to sensitivity studies in particular, and mass balance modelling studies as a whole.

[Scenario-neutral Mass Balance Modelling]A scenario-Neutral Approach to Climate Change in Glacier Mass Balance Modelling [van der Laan]Larissa van der Laan, Kim Cholibois, Ayscha El Menuawy and Kristian Förster

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