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Mass Balance Sensitivity and Future Projections of Rabots Glaciär, Sweden

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Abstract: Glacier mass balance is heavily influenced by climate, with responses of individual glaciers to various climate parameters varying greatly. In northern Sweden, Rabots Glaciär's mass balance has decreased since it started being monitored in 1982. To relate Rabots Glaciär's mass balance to changes in climate, the sensitivity to a range of parameters is computed. Through linear regression of mass balance with temperature, precipitation, humidity, wind speed and incoming radiation the climate sensitivity is established and projections for future summer mass balance are made. Summer mass balance is primarily sensitive to temperature at −0.31 m w.e. per °C change, while winter mass balance is mainly sensitive to precipitation at 0.94 m w.e. per % change. An estimate using summer temperature sensitivity projects a dramatic decrease in summer mass balance to −3.89 m w.e. for the 2091–2100 period under climate scenario RCP8.5. With large increases in temperature anticipated for the next century, more complex modelling studies of the relationship between climate and glacier mass balance is key to understanding the future development of Rabots Glaciär.

Keywords: glacier mass balance; climate sensitivity; mass balance prediction; Rabots Glaciär

Citation: Taveirne, M.; Ekemar, L.; González Sánchez, B.; Axelsson, J.; Zhang, Q. Mass Balance Sensitivity and Future Projections of Rabots Glaciär, Sweden. *Climate* **2021**, *9*, 126. https://doi.org/10.3390/cli9080126

Academic Editor: Salvatore Magazù

Received: 5 July 2021
Accepted: 4 August 2021
Published: 6 August 2021

1. Introduction

Glaciers, such as Rabots Glaciär, are one of the most sensitive indicators of the impacts of anthropogenic climate change [1] and are constantly adapting to meteorological fluctuations. The resilience and the recovery rate of a glacier affects the response to these fluctuations [2]. The ongoing anthropogenic global warming complicates the resilience of glaciers, and their retreat inhibits an important role regarding the rise of the global sea level [3]. The retreat of glaciers also has a great impact on the hydrological cycle, the flora, fauna and human communities adjacent to alpine and arctic environments [2]. Thus, glaciers are not only studied as part of climate reconstruction modelling but also for predicting future behaviour to climate change

A particularly useful way of studying the changes in glaciers is by measuring the mass balance and their climate sensitivity. The glacier mass balance is defined as the sum of the ablation and accumulation at a specific point, thus representing the amount of water stored or released. Techniques such as remote sensing or direct measurements on the surface of the glacier are used to measure the glacier's mass balance [4]. A negative mass balance means that the glacier is shrinking due to melt water discharge, and a positive balance means that the mass is increasing [5]. Changes in the mass of the glacier are likely to affect the ice-albedo feedback loop, since a decrease of white or light surfaces might contribute to an increased air temperature and vice versa [6]. Climate sensitivity indicates how changes in climate parameters affect the mass balance. These parameters can include temperature, precipitation, wind speed, humidity, and solar radiation [7]. Temperature, solar radiation, wind speed and humidity impact the melt rate of the glacier, while precipitation and humidity impact the accumulation of snow, and wind can redistribute freshly fallen snow [8].

Several Swedish glaciers have been the object of study for several decades due to their mass loss and the retreat of paleo-ice sheets through time. Rabots Glaciär, which is the focus of this study, is far less extensively researched than its neighbour Storglaciären. The earlier research provided by Bolin Centre Database mainly focused on either glacier inventory [9] or calculating response rates with past climate changes [3,10]. Rabots Glaciär and Storglaciären have shown a non-synchronised response to recent climate change which has occurred since the beginning of the 20th century [11]. Both glaciers reached their maximum around the year 1916, and shortly thereafter started to retreat as a consequence of a 1 °C temperature increase approximately in the 1910–1930 period [3]. Storglaciären reached an equilibrium in the 1980s, but the response of Rabots Glaciär lagged behind and was still adjusting to the new climate with a slower but longer ongoing retreat rate than Storglaciären [11]. The reason for the different behaviours and sensitivities of the glaciers can be correlated to geometrical differences [10]. Furthermore, the rate of the volume loss of the glacier between 2003–2011 has increased significantly compared to the earlier studied periods of 1959–1980, 1980–1989, and 1989–2003. This is assumed to be a continued reaction to the earlier 1 °C temperature increase in combination with recent temperature changes connected to global warming [3].

Projections of future climate show a continued warming in the Alpine environment of Sweden. Using a climate ensemble, the Swedish Meteorology and Hydrology Institute (SMHI) have estimated an increase in annual mean temperature that varies between 3 °C in case of RCP4.5 and 7 °C in case of RCP8.5 compared to the mean temperature of the years 1961–2001 [12]. There are no studies yet that examine the strength of the impact temperature changes may have on Rabots Glaciär. There is little published research regarding Rabots Glaciär, with the most recent article published by the previously mentioned Brugger and Pankratz [3]. Studies by Hock et al. [13] based on climate scenario RCA3 using a zero-dimensional temperature-index climate model, does however, project that Storglaciärens cumulative mass balance will continuously decrease until the year 2100.

With this information in mind, the aim of this study is to quantify the climate sensitivity of Rabots Glaciär's mass balance and use this sensitivity to create a projection of future mass balance. The sensitivity represents the mass change caused by variations in climatic parameters. Climate sensitivity can be calculated in two ways: as an energy flux, or as a glacier mass balance variation [7], the latter of which will be used in this paper. Once the climate sensitivity of Rabots Glaciär is established, the relationship between mass balance and climate will be computed in a simple linear regression model to indicate the mass balance's response to future climate change.

2. Materials and Methods

2.1. Study Area

The study area is located in the north of Sweden at the Kebnekaise massif. The focus is on Rabots Glaciär, located in the northwest area with an extension of ~4 km^2, approximately 4.5 km west of Tarfala Research Station (Figure 1). Rabots Glaciär is a polythermal glacier [14] without subglacial overdeepenings, which reached its maximum in 1916 and started to retreat afterwards [10].

The average ice depth of Rabots Glaciär is 84 m, with a maximum of 175 m. The glacier is situated between 1060 and 1920 m.a.s.l. [10]. The mass balance of Rabots Glaciär is measured through stake observation in summer, and through density measurements of the glacier ice combined with snow depth probings in winter [15]. Rabots Glaciär's mass balance has been recorded since 1982, with data available until the end of 2011 (data missing for 2002, 2004 and 2007). Figure 2 shows that the mass balance, measured in m w.e. (meters water equivalent), has decreased substantially over the course of the monitoring period. The response rate to climatic changes for Rabots Glaciär is, however, described as slow in comparison to Storglaciären. This is assumed to be caused by Rabots Glaciär's thick ice sheet and the absence of steep slopes [14].

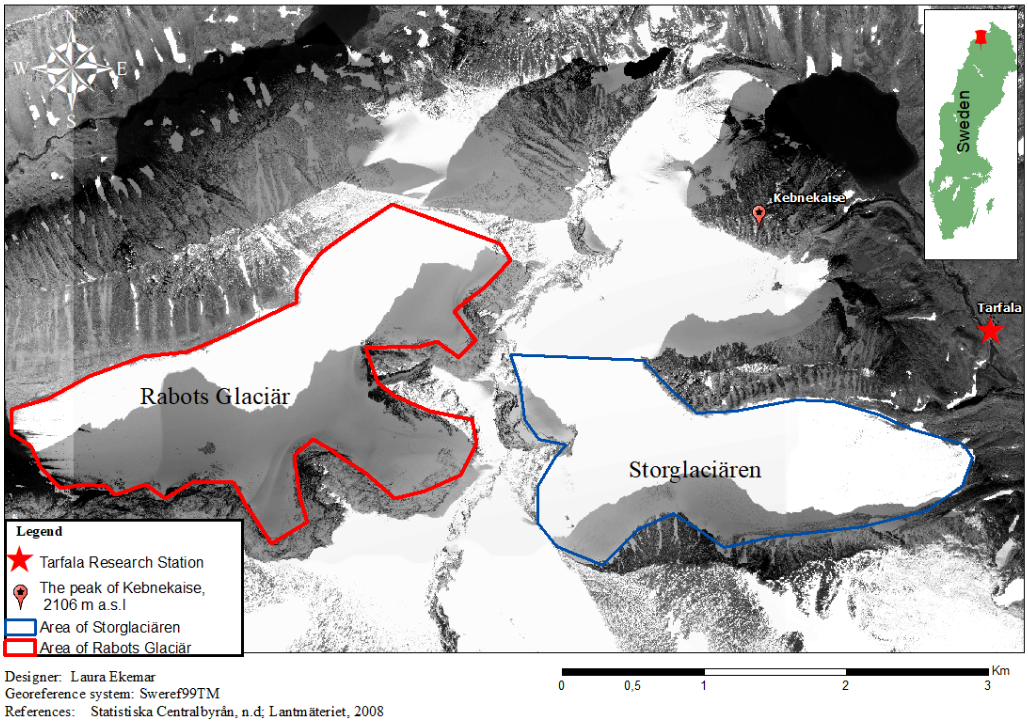

Figure 1. Map of the study area "Rabots Glaciär" in relation to Storglaciären, the peak of Kebnekaise and the Tarfala Research Station.

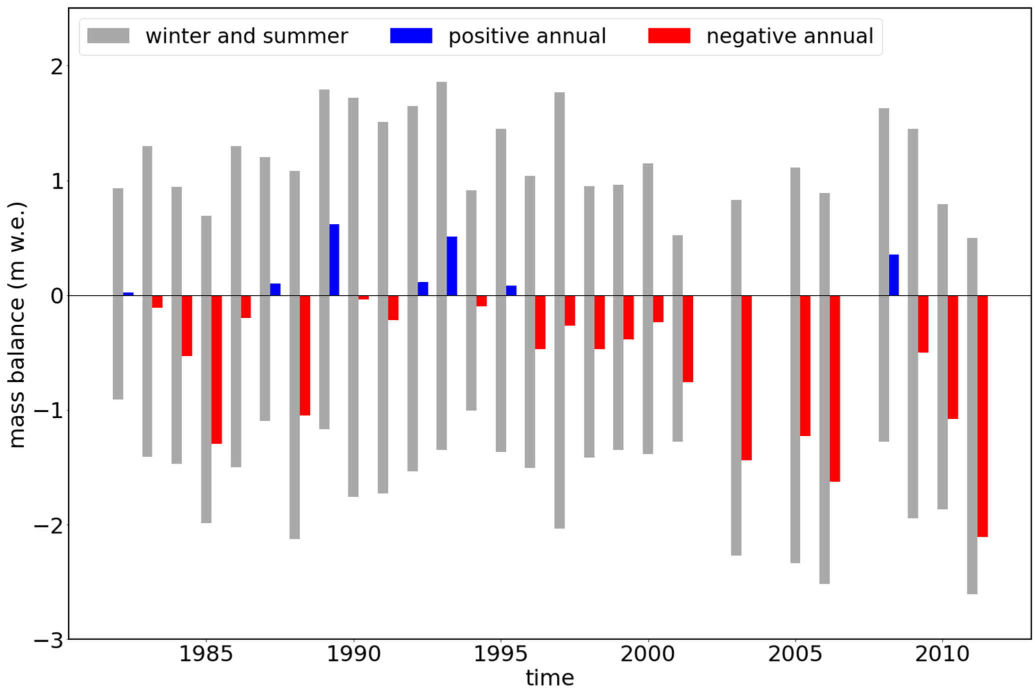

Figure 2. Mass balance of Rabots Glaciär between 1982 and 2011, including both summer and winter mass balance for each year, as well as annual mass balance.

2.2. Mass-Balance Sensitivity Computation

Sensitivity is an important aspect of mass balance as it allows for understanding of how a glacier will respond to changes in those parameters that affect the mass balance. Climate sensitivity parameters include temperature, wind speed, total incoming radiation at the surface, humidity and precipitation. To obtain the sensitivity to climate parameters in Rabots Glaciär, past data of mass balance has been retrieved from the Bolin Centre Tarfala database [16]. The net annual mass balance is established as the total of summer and winter mass balance. Summer mass balance is surveyed in September, encompassing the period from April to September, and winter mass balance is surveyed in April, encompassing the period between October and march [17]. The changes in mass balance were correlated with climate data from the same time period as the mass balance data set. The mass balance changes in response to 1 °C increase in temperature, or 1% increase in humidity, wind speed, precipitation, and incoming radiation were quantified. The climate data were also collected from the Bolin Centre Tarfala database [18]. The air temperatures between the years 1967–1987 were measured with a Pt100 platinum resistance thermometer, placed in a radiation screen where every minute was recorded by chart recorders. Observations from July 1989 and forward are based on digital logger stations. The first digital logger station installed was a MP100 temperature/humidity sensor in a multi-plate radiation shield. The Swedish Meteorological and Hydrological Institute installed another automatic weather station in 1995 near the original one, and it is used to fill in gaps in the data series [19].

The mass balance sensitivity was computed through establishing a linear regression model between mass balance and each climatic parameter. The significance of the linear regression was assessed through use of the *p*-value and the proportion of variance (R-squared). The *p*-value expresses whether there is a statistically significant correlation and should ideally be lower than 0.05. The R-squared shows how much of the variation in mass balance is explained by changes in climate parameters. Following a format by Che et al. [7], climate sensitivity is expressed as a change in mass balance per % variation in each parameter, to make climate parameters with varying units, such as °C and mm, comparable. Thus, the sensitivity per single unit of a climate parameter, expressed for example in m w.e./°C, was divided by the average of that climate parameter over the study period to obtain a sensitivity expressed in m w.e./%. The data were analysed on three timescales. To explore the general behaviour of the glacier, an annual mass balance sensitivity was calculated. Specific sensitivities for summer and winter mass balance were computed to determine the influence of the different parameters during the melt season and outside of the melt season. The sensitivities and their statistical significance were plotted in Python.

2.3. Future Projections of Mass Balance

Predicting the future mass balance due to changes in climatic parameters improves understanding of the possible impacts of the different climate scenarios described by the Intergovernmental Panel on Climate Change (IPCC) [20]. The projected temperature change data used in this study are collected as an ensemble of 8 GCM models, displayed in Table 1, downscaled by the regional climate model RCA4 at 0.44° resolution from the Rossby Centre of the Swedish Meteorological and Hydrological Institute for the European domain, EURO-CORDEX, within the CORDEX project. The CORDEX initiative aims to generate regional projections of climate change up until the year 2100, motivated by the timeline of the 5th Assessment Report from IPCC. The EURO-CORDEX RGM simulations consists of the general CORDEX resolution of 0.44 degree (EUR-44, ~50 km) and a high resolution of 0.11 degree (EUR-11, ~12.5 km) [21]. The future predictions of Rabots Glaciär's mass balance are based on temperature changes during the summer months in case of the actualization the emission scenarios RCP4.5 and RCP8.5. Under the intermediate emission scenario RCP4.5, the global mean surface temperature increases by 1.1 °C to 2.6 °C by the year 2100; while under the high emission scenario RCP8.5 the global mean surface temperature increases by 2.6 °C to 4.8 °C [22]. The data was extracted for Rabots glacier at

67°55′ N, 18°29′ E in the summer months of June, July, and August. The scenarios were chosen to illustrate both the minimum and maximum impact climate change could attain.

Table 1. The GCM models used to obtain temperature predictions.

Model Name	Modelling Centre	Reference
CanESM2	Canadian Centre for Climate Modelling and Analysis	Chylek et al., 2011 [23]
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	Voldoire et al., 2012 [24]
CSIRO-Mk3.6	CSIRO and Queensland Climate Change Centre of Excellence (QCCCE)	Jeffrey et al., 2011 [25]
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	Dunne et al., 2012 [26]
IPSL-CM5A-MR	Institut Pierre-Simon Laplace	Dufresne et al., 2013 [20]
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Watanabe et al., 2011 [27]
MPI-ESM-LR	Max Planck Institute for Meteorology	Popke et al., 2013 [28]
NorESM1-M	Norwegian Climate Centre	Bentsen et al., 2013 [29]

The change in mass-balance was calculated with a zero-dimensional temperature regression model, which was based on the model provided as an equation by Hock et al. [13]. They found that mass balance was modelled more accurately by simple temperature index models than by energy-balance models. The equation they used was Equation (1):

$$b_s = \alpha_s \sum_{i=t_1}^{t_2} T_i + \beta_s \tag{1}$$

where b_s is equal to projected summer mass balance. α_s and β_s are obtained from the linear regression of observed summer mass-balance (b_s) and the positive degree day sum (ΣT_i), which is the sum of temperatures over 0 °C. Based on the results of high summer mass balance sensitivity to average summer temperature in this paper, the summer mass balance was predicted using average summer temperature instead of the positive degree sum. Thus, the equation used was Equation (2):

$$b_s = \alpha_s T_i + \beta_s \tag{2}$$

where b_s remains the projected summer mass balance, and α_s and β_s are obtained through linear regression of observed summer mass balance of Rabots Glaciär and observed average summer temperature. The parameter T_i is the yearly predicted mean summer temperature from the model ensemble, calculated as the change relative to the mean state of 1981–2010.

2.4. Validation

We use the climate simulations for the historical period 1982–2011 to validate the mass balance method by comparing with the observed mass balance in the same period. The simulated temperature data were applied into Equation (2) to obtain the sensitivity value of summer mass balance to temperature. The modelled summer mass balance for 1982–2011 falls within the range of summer mass balance values observed over this period (Figure 3).

The modelled summer mass balance exhibits considerably less interannual variability than the observations due to the simple statistical model used. The modelled summer mass balance shows a slight downward trend as expected for the warming trend in 1982–2011.

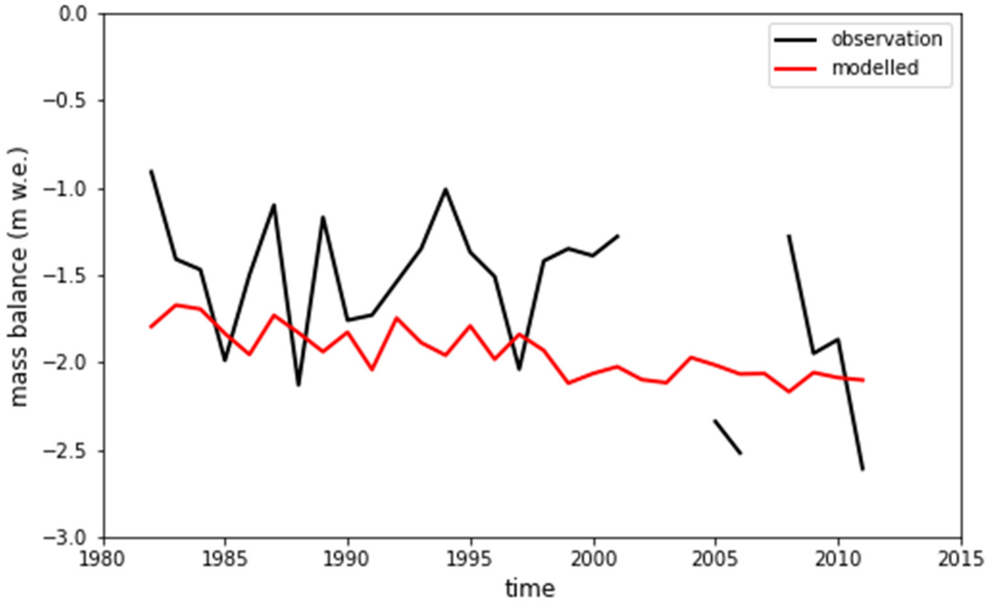

Figure 3. Comparison of summer mass balance observations with the summer mass balance calculated from the modelled temperatures for the period 1982–2011.

3. Results

3.1. Sensitivity

The climate sensitivity shows how different parameters affect the mass balance of Rabots Glaciär. Annual sensitivity values show a more general trend, while summer and winter sensitivities are more specifically centred around seasons of ablation and accumulation.

3.1.1. Annual Mass Balance Sensitivity

Figure 4 shows that an increase of 1 °C in mean temperature impacts the annual mass balance with a decrease of 0.25 m w.e., which is equivalent to a −0.67 m w.e./% mass balance change. In the figure, the R-squared value of the correlation of mass balance with each climatic parameter is displayed at the end of the bar. Mass balance sensitivity to wind speed is −0.19 m w.e./%. The sensitivity values for wind speed, humidity, and temperature are negative, which associates them with melting, whereas the precipitation and incoming radiation sensitivity values are positive, which associates them with accumulation.

Although annual mass balance is most sensitive to temperature and wind speed, neither of these are associated with p-values below 0.05. In fact, none of the correlations between annual mass balance and climate parameters have a p-value that indicates statistical significance. Figure 4 shows that the R-squared values of the correlations are generally low, all remaining well below 0.30. Thus, summer and winter mass balance climate sensitivity are computed separately in order to obtain more meaningful correlations.

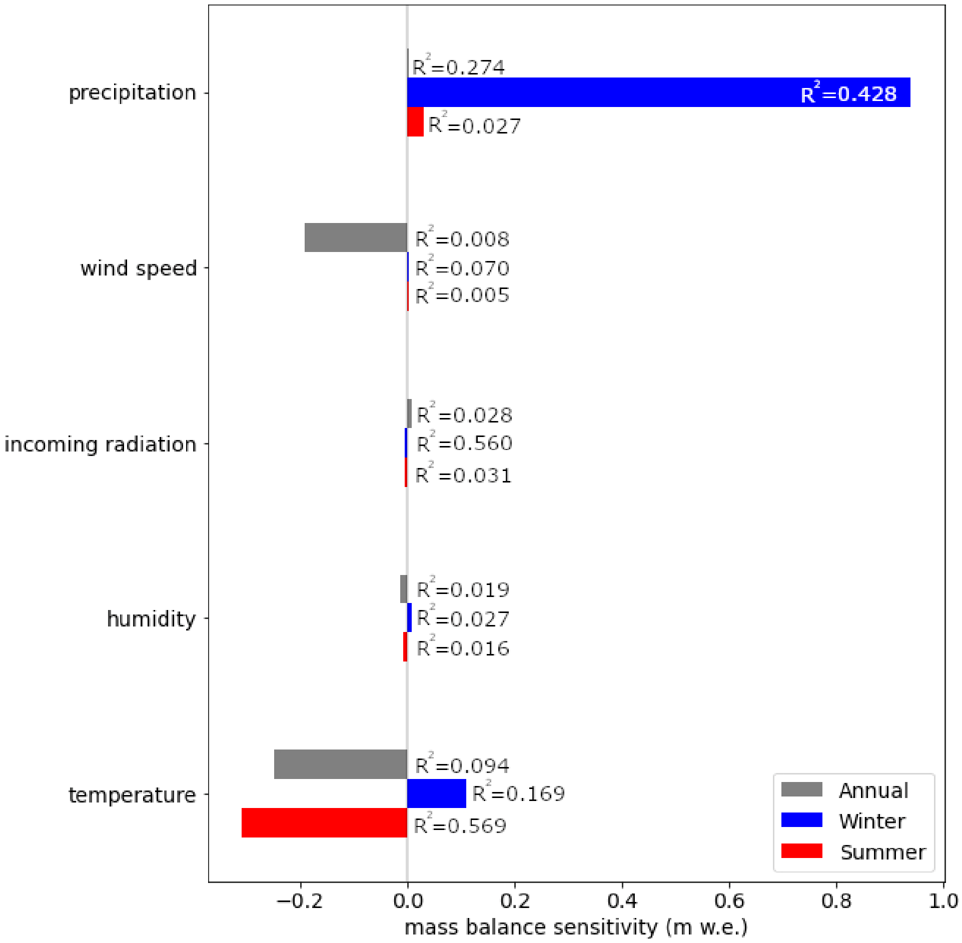

Figure 4. Annual, summer and winter mass balance sensitivity to a percentage change in climatic parameters and their R-squared value (value close to each bar).

3.1.2. Summer Mass Balance Sensitivity

Figure 4 shows that the summer mass balance of Rabots Glaciär is most sensitive to changes in temperature, with a mass balance change of −0.31 m w.e./°C (equivalent to a−0.84 m w.e./% temperature sensitivity). Mass balance sensitivity to other climatic parameters is much lower, with a mass balance change of 0.031 m w.e./% precipitation increase, and even lower sensitivities to wind speed, incoming radiation and humidity.

The summer mass balance sensitivity is statistically significant only for the parameter of temperature, with a *p*-value of 0.000 and an R-squared value of 0.569. This is illustrated in Figure 4, where temperature is shown to have the highest explanatory power over variations in summer mass balance.

3.1.3. Winter Mass Balance Sensitivity

In contrast to the summer mass balance, the winter mass balance is more sensitive to changes in precipitation, shown in Figure 4. For each percentage increase in winter precipitation, there is a 0.94 m w.e. winter mass balance increase. The winter mass balance sensitivity to temperature is 0.11 m w.e./°C (or 0.30 m w.e./%), and thus much lower than the summer mass balance sensitivity to temperature. Winter mass balance sensitivities to humidity, incoming radiation and wind speed are all below 0.01 m w.e./%. The winter mass balance sensitivity to incoming radiation is the only negative sensitivity, such that a radiation increase is correlated with a glacier mass decrease. This is, however, the opposite for temperature.

For winter mass balance sensitivity, the following parameters presented statistical significance: temperature, with a *p*-value of 0.033 and an R-squared of 0.169; incoming radiation, which has a *p*-value of 0.022 and an R-squared of 0.560; and precipitation, with a *p*-value of 0.021 and an R-squared of 0.428. The R-squared values show that, although all three are statistically significant, both precipitation and incoming radiation have a much higher explanatory power over winter mass balance variations than temperature.

3.2. Summer Mass Balance Prediction

During summer, Rabots Glaciär's mass balance is most sensitive to temperature, and in winter it is most sensitive to precipitation. On an annual basis, however, the mass balance is much more sensitive to changes in temperature than precipitation, with a sensitivity of −0.67 m w.e./% for temperature, and 0.0021 m w.e./% for precipitation (shown in Figure 5). Thus, for future changes in the mass balance of Rabots Glaciär, the increase in temperature can be seen as the most important factor to consider. This is supported by previous studies of future glacier mass balance, which regard temperature changes as the main climate parameter to include [13]. Considering the importance of temperature in changing mass balance, predictions of future mass balance are based on the relationship between temperature and mass balance, established through linear regression. Mass balance predictions are limited to summer mass balance, as summer mass balance variation is well explained by summer temperatures (R-squared of 57%).

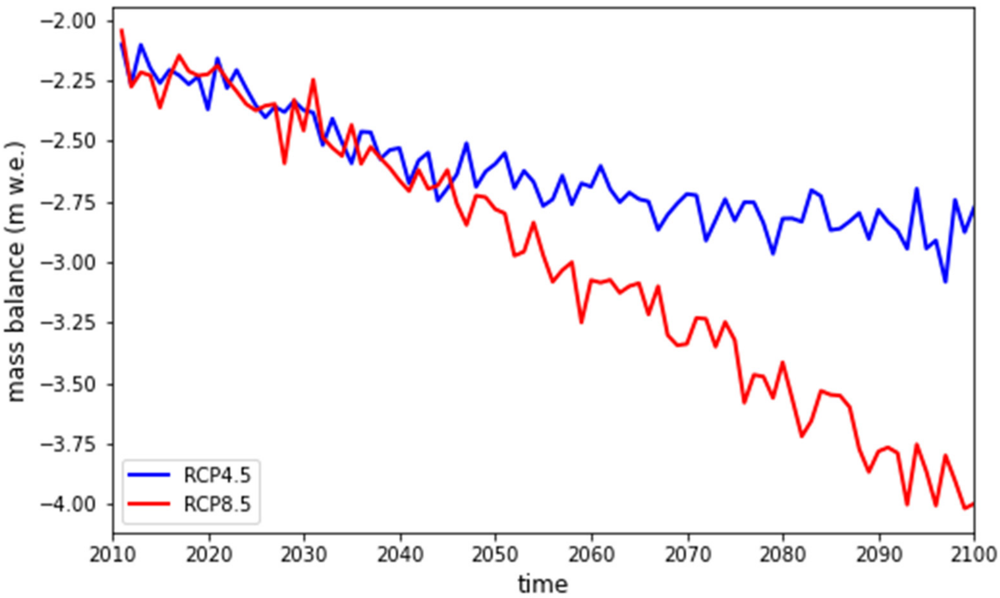

Figure 5. Predicted summer mass balance until the end of the century under the RCP4.5 and RCP8.5 climate scenarios.

The summer mass balance projection under both climate scenarios RCP4.5 and RCP8.5 is shown in Figure 5. The RCP4.5 projection shows a negative trend in mass balance until around 2080, after which the mass balance seems to stabilise. The mean summer mass balance is projected to be −2.87 m w.e. for the 2091–2100 period. The projection under RCP8.5 consists of a continuous decrease in mass balance over the period 2010–2100. The projected mean summer mass balance for 2091–2100 is −3.89 m w.e., which is over twice as large as the observed mean summer mass balance of −1.64 m w.e. over the period of 1982–2011.

4. Discussion

Overall, temperature and precipitation are the most influential climate parameters driving Rabots Glaciär's mass balance. The sensitivities are only statistically significant when summer and winter mass balance are considered separately. Summer mass balance is mainly dictated by summer temperature, with an increase in temperature causing intensified ablation. Winter mass balance is mostly regulated by winter precipitation [13]. While precipitation can potentially lower the summer albedo and cause increased melt, there is no statistically significant relationship between summer mass balance and summer precipitation. The relationship between winter incoming solar radiation and winter mass balance is statistically significant. The effect of incoming solar radiation on winter mass balance is small, as reflected in the relatively low sensitivity value. However, the summer incoming solar radiation shows no significant relationship with summer mass balance, despite temperature, which is connected to incoming radiation, having a significant effect. A more complex model of mass balance sensitivity to climate parameters would be needed to clarify whether the statistically insignificant parameters have an effect that is not captured in a simple statistical analysis.

The geometry of the glacier can possibly affect the mass balance sensitivity, since the response to temperature changes of both Rabots Glaciär and Storglaciären have occurred at different rates [10]. The sensitivity in this paper is based only on Rabots Glaciär's past mass balance response to climatic changes and is thus specific to the glacier. Other glaciers may be affected by increased air temperatures more or less strongly. Furthermore, static factors such as aspect, bed surface slope, and especially altitude are also influential on the mass balance of individual glaciers [30]. As these factors do not change over time, however, a mass balance sensitivity to these cannot be computed for an individual glacier.

While the separation of mass balance into seasons makes for more significant sensitivity values, other studies of mass balance climate sensitivity often do not include this seasonal separation. Thus, to make a valid comparison, the annual sensitivity values need to be used. Rabots Glaciär's annual temperature sensitivity of –0.25 m w.e./°C is lower than five Swiss glaciers, which have temperature sensitivities between −0.7 and −0.9 m w.e./°C [31]. Rabots Glaciär 's temperature sensitivity is also much lower than the highly sensitive Brewster Glacier in New Zealand, which has an annual temperature sensitivity of −2.0 m w.e./°C [32]. The annual temperature sensitivity of Rabots Glaciär falls within the range of annual temperature sensitivities found in the Arctic, as this spans from –0.2 to –2.0 m w.e./°C [33]. Out of the Arctic glaciers studied, maritime glaciers have higher sensitivity values, while more continental glaciers, such as Rabots Glaciär, have lower annual temperature sensitivities. Thus, the comparatively low annual temperature sensitivity of Rabots Glaciär is likely heavily influenced by its continentality.

While mass balance is closely linked to climate, there are other factors that are not included in this sensitivity analysis. Mass balance is heavily impacted by albedo changes, but as albedo is not widely monitored, it cannot easily be used as a driving factor in future projections of mass balance [34]. It is also important to emphasise the effect warming air temperatures can have, specifically in the form of an ice-albedo feedback loop. Melt seasons that start earlier and last for longer, combined with shorter winters, mean that changes in the surface albedo could be a driving factor of increasing local air temperature. Other climate feedbacks caused by changes in precipitation and cloud cover may also affect the temperature but cannot be considered in a simple linear regression.

Hock et al. [13] present a clear decrease in the cumulative mass balance until the year 2100 of the neighbouring glacier Storglaciären. This indicates the same tendencies as the results of this paper's linear regression projection. However, it is important to note that Hock et al. [13] based their projections of future mass balance on RCA3, the previous version of the regional climate model used here. The climate forcing used in the RCA3 model is the B2 emission scenario, which is a climate scenario from earlier versions of the IPCC than the one used here. This scenario involves an increase in carbon emissions over the next century which is lower than that in RCP8.5 but does not include the emission decrease of RCP4.5 [35]. Therefore, the projected future changes in mass balance of the two glaciers cannot be compared directly. Based on the RCP4.5, an initial steep decrease in the mass balance will occur, which will approach stabilization by the end of the century. The projected increased air temperature under climate scenario RCP8.5 will likely contribute to a continuously decreasing mass balance of Rabots Glaciär. By the end of the century, the summer mass loss could be over twice as large as during the recent past. Both scenarios fit well with predictions for mass loss at neighbouring Storglaciären [13]. To improve future projections of mass balance, a division of glacier models into altitude bands could be included, as sensitivity is strongly correlated with altitude [31].

5. Conclusions

In the recent past, Rabots Glaciär has exhibited a negative trend in mass balance, with a large decrease in the years 2000–2011 compared to earlier time periods. Through linear regression of mass balance with temperature, precipitation, humidity, wind speed and incoming radiation, we quantified the climate sensitivity of Rabots Glaciär's mass balance between 1982–2011. The climate sensitivity values show that the main effect on summer mass balance is produced by changes in temperature, with a sensitivity of -0.31m w.e/°C. In winter, precipitation is the main driver with a sensitivity of 0.94 m w.e./% change. Furthermore, projections for future summer mass balance were made based on an ensemble of regional climate models for RCP4.5 and RCP 8.5. Under the milder IPCC scenario (RCP4.5), the projected summer mass balance is –2.9 m w.e. for 2091–2100. Under the most extreme scenario (RCP8.5), the summer mass balance is projected to decrease to approximately –3.9 m w.e. in 2091–2100. This future prediction shows a clear effect of climate change in the sensitive glacial environment. Warming will affect valley glaciers worldwide, which creates a need for further research to fully understand glacier mass balance variations.

Author Contributions: Conceptualization and methodology—M.T., L.E., B.G.S. and J.A.; Data curation—L.E. and J.A.; Formal analysis—M.T.; Visualization—M.T. and B.G.S.; Supervision—J.A., Q.Z.; Writing (original draft)—M.T., L.E. and B.G.S.; Writing (review and editing)—M.T., L.E., B.G.S., J.A. and Q.Z. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge financial support from the Swedish Research Council (Vetenskapsrådet; grant nos. 2013-06476 and 2017-04232).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analysed in this study. The mass balance data can be found here: https://bolin.su.se/data/tarfala/rabot.php (accessed 3 December 2020), and the past climate data can be found here: https://bolin.su.se/data/tarfala/climate.php (accessed 4 December 2020).

Acknowledgments: We want to thank the Bolin Centre for the available climate and glacial data regarding Rabots Glaciär. Data of future climate and temperatures were retrieved from the Swedish Meteorology and Hydrology institute which made it possible to perform this study. We are also grateful to Josefine Axelsson and the people who provided valuable input to our work: Ellen Berntell, Peter Jansson, Fredrik Östlund, Beatrice Varpula and Qiong Zhang. The computations were enabled by resources provided by the Swedish National Infrastructure for Computing (SNIC) at the National Supercomputer Centre (NSC), partially funded by the Swedish Research Council through grant agreement no. 2018-05973. We acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups (listed in Table 1 of this paper) for producing and making available their model output. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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