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Projecting the Response of Greenland's Peripheral Glaciers to Future Climate Change: Glacier Losses, Sea Level Impact, Freshwater Contributions, and Peak Water Timing

Muhammad Shafeeque[1,2,3,*], Jan-Hendrik Malles[1,4], Anouk Vlug[1,5], Marco Möller[1,2,6], Ben Marzeion[1,2,*]

[1]Climate Lab, Institute of Geography, University of Bremen, 28359 Bremen Germany
[2]MARUM – Center for Marine Environmental Sciences, University of Bremen, 28359 Bremen Germany
[3]Alfred Wegener Institute for Polar and Marine Research, 27570 Bremerhaven, Germany
[4]Institute of Environmental Physics, University of Bremen, 28359 Bremen Germany
[5]Department of Atmospheric and Cryospheric Sciences, University of Innsbruck, 6020 Innsbruck, Austria
[6]Geodesy and Glaciology, Bavarian Academy of Sciences and Humanities, 80539 Munich, Germany

**Correspondence to*: Muhammad Shafeeque (shafeequ@uni-bremen.de) and Ben Marzeion (ben.marzeion@uni-bremen.de)

Abstract. Greenland's peripheral glaciers are significant contributors to sea level rise and freshwater fluxes, yet their future evolution remains poorly constrained. This study projects the response of these glaciers to future climate change using the Open Global Glacier Model (OGGM) forced by CMIP6 climate data under four emission scenarios. By 2100, the glaciers are projected to lose 19-44 % of their area and 29-52 % of their volume, contributing 10-19 mm to sea level rise. Solid ice discharge is projected to decrease, while freshwater runoff will peak within the 21st century. The runoff composition is projected to change drastically, with shares of glacier ablation decreasing from 92 % in 2021-2030 to 72 % by 2091-2100 and shares of rainfall and snowmelt increasing 8-fold and 15-fold, respectively, suggesting a shift in the hydrological regime. Timing of the maximum runoff varies across scenarios (2050 ± 21 for SSP126; 2082 ± 9 for SSP585) and subregions, with the projected maximum runoff reaching 214-293 Gt/yr, implying significantly increased future freshwater fluxes. These changes will impact fjord water characteristics and coastal hydrography, and potentially influence larger ocean circulation patterns.

Keywords: Climate Change; Greenland's Peripheral Glaciers; Freshwater; Ice Discharge; Sea Level Rise; OGGM; Peak Water

1 Introduction

The Arctic region has experienced a significant increase in air temperatures in recent decades, warming nearly four times faster than the global average (Rantanen et al., 2022). This rapid warming profoundly impacts Greenland's peripheral glaciers, which are either completely detached from the ice sheet or dynamically decoupled (Rastner et al., 2012). These glaciers exhibit accelerated responses to warming compared to the slower-responding ice sheet (Khan et al., 2022; Noel et al., 2017; Larsen et al., 2022; Bolch et al., 2013; Larocca et al., 2023), which are linked to increased surface ablation and solid ice discharge, indicating a high sensitivity to atmospheric warming and oceanic forcing (Bjørk et al., 2017; Liu et al., 2022a; Möller et al., 2024). Greenland's peripheral glaciers account for 8.5-11 % of the global glacier volume outside Antarctica and the Greenland Ice Sheet, and they are significant contributors to current and future sea level rise, presently delivering the second largest contribution (10-13 %) to sea level rise originating from the global glaciers outside the two ice sheets (Hugonnet et al., 2021; Bolch et al., 2013). The peripheral glaciers are equivalent to only ~5 % of the area and less than 1 % of the volume of the Greenland Ice Sheet, yet they contribute 11-20 % of Greenland's total ice mass loss (Hugonnet et al., 2021; Khan et al., 2022; Bollen et al., 2023; Bolch et al., 2013).

Despite their significance, the evolution of these glaciers under future climate scenarios remains insufficiently explored, particularly with respect to a partitioning of freshwater contributions to sea level rise, i.e., solid ice discharge and freshwater runoff. This distinction is critical for predicting changes in fjord water characteristics, sea level, and oceanic circulation (Hopwood et al., 2020; Sugiyama et al., 2021; Edwards et al., 2021; Mankoff et al., 2020; Nowicki et al., 2020). Both solid ice discharge and freshwater runoff (surface melting and rainfall) directly contribute to sea level rise when they enter the ocean (Edwards et al., 2021; Hopwood et al., 2020). However, they differ in timing and spatial distribution of their contributions. When marine-terminating glaciers (excluding floating tongues) calve icebergs into the fjords, these icebergs immediately contribute to sea level rise. As the icebergs drift away from the glacier and gradually melt, they release freshwater over a larger area and longer time scale (Bamber et al., 2018; Davison et al., 2020; Enderlin et al., 2021). Liquid freshwater also directly contributes to rising sea levels when the water enters the ocean. This freshwater input is more concentrated near the glacier terminus and has a more immediate effect on sediment transport, fjord characteristics, and local sea level (Beckmann et al., 2019; Slater et al., 2020). Understanding the dynamics and interplay of solid ice discharge and surface liquid freshwater from peripheral glaciers is crucial for accurately assessing Greenland's overall ice mass losses and their impacts under future climate change.

Existing studies often overlook the impact of future climate change on the individual components of freshwater contributions from these peripheral glaciers and how these changes in magnitude and timing propagate to affect fjord water characteristics, ocean circulation, and sea level rise (Cowton et al., 2015; Hopwood et al., 2020). Solid ice discharge from peripheral glaciers, a significant mass loss process (Bollen et al., 2023; Malles et al., 2023), has received less attention when modeling future climate change scenarios. The composition of future liquid freshwater fluxes from Greenland's periphery, including the relative contributions of ice melt, snowmelt and rainfall, remains poorly quantified (Mernild et al., 2010; Mernild et al., 2013; Mernild et al., 2018). The changes in magnitude and timing of freshwater composition in the surrounding ocean impact the ocean circulation and marine ecosystems (Perner et al., 2019; Bamber et al., 2018; Hopwood et al., 2020; Mankoff et al., 2020; Mathis and Mikolajewicz, 2020; Kanzow et al., 2024). Moreover, the timing of the maximum runoff (called peak water from here on), which has major implications for ocean circulation patterns, fjord ecosystems, and sea level, also requires dedicated projections of freshwater fluxes and timing focused on the peripheral glaciers rather than the whole ice sheet (Oliver et al., 2018; Aschwanden et al., 2019; Bliss et al., 2014). This distinction is important because peripheral glaciers and the Greenland Ice Sheet are likely to exhibit different peak water timing. While the massive ice sheet

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may continue to increase its meltwater contribution well beyond this century, smaller and more climate-sensitive peripheral glaciers are expected to reach peak water earlier. Consequently, some fjords primarily fed by peripheral glaciers may experience peak water within the projection period of this study, while others dominated by ice sheet runoff may not. Previous research suggests that certain glaciers may have already transitioned towards a more cold-based regime (Carrivick et al., 2023), which implies a potential shift in the timing of meltwater release. By focusing on peripheral glaciers, we can better understand and anticipate localized changes in freshwater input to coastal areas, which is crucial for assessing impacts on fjord ecosystems, coastal dynamics, and potentially larger ocean circulation patterns.

This study aims to address these research gaps by investigating how Greenland's peripheral glaciers will evolve under different future climate change scenarios, considering spatial and temporal variability. It employs the Open Global Glacier Model (OGGM) (Maussion et al., 2019), calibrated with recent geodetic mass balance (Hugonnet et al., 2021) and frontal ablation data (Kochtitzky et al., 2022), and is forced using an ensemble of climate projections from CMIP6 (Eyring et al., 2016) under different emission scenarios until 2100. Our modeling results yield projections of future mass loss of Greenland's peripheral glaciers, including the ability to distinguish between mass loss occurring above and below sea level. This distinction allows for more accurate estimations of their contributions to sea level rise, as well as detailed projections of both solid and liquid freshwater contributions. Furthermore, we project the timing and magnitude of peak runoff for these glaciers. Thus, our study also gives insights into the changing composition of projected liquid freshwater runoff, including the relative contributions of different sources such as ice melt, snowmelt, and rainfall, which contributes to enhance our understanding of the evolving hydrological dynamics and their implications in the region.

2 Materials and Methods

2.1 Greenland's Peripheral Glaciers

This study focuses on Greenland's peripheral glaciers that have been classified into three different connectivity levels (CL) by Rastner et al. (2012): completely detached from the ice sheet (CL0), dynamically decoupled (CL1), and dynamically connected to the ice sheet (CL2). In our study, we only consider glaciers of categories CL0 and CL1 (Fig. 1a), as glaciers in category CL2 are usually considered to be part of the ice sheet (Hock et al., 2019; Marzeion et al., 2020). Glacier outlines are taken from the Randolph Glacier Inventory (RGI) version 6.0 (Pfeffer et al., 2014). Deviating from this inventory, we adopted an enhanced subdivision comprising individual drainage basins for the Flade Isblink Ice Cap (RGI ID: RGI60-05.10315) in Northeast Greenland. The new subdivision of Flade Isblink Ice Cap (Fig. 1b) encompasses several marine-terminating basins; however, based on velocity observations, only six of them are active calving basins (Recinos et al., 2021; Möller et al., 2022). This study groups the peripheral glaciers into seven regions: North-East, Central-East, South-East, South-West, Central-West, North-West, and North (Fig. 1).

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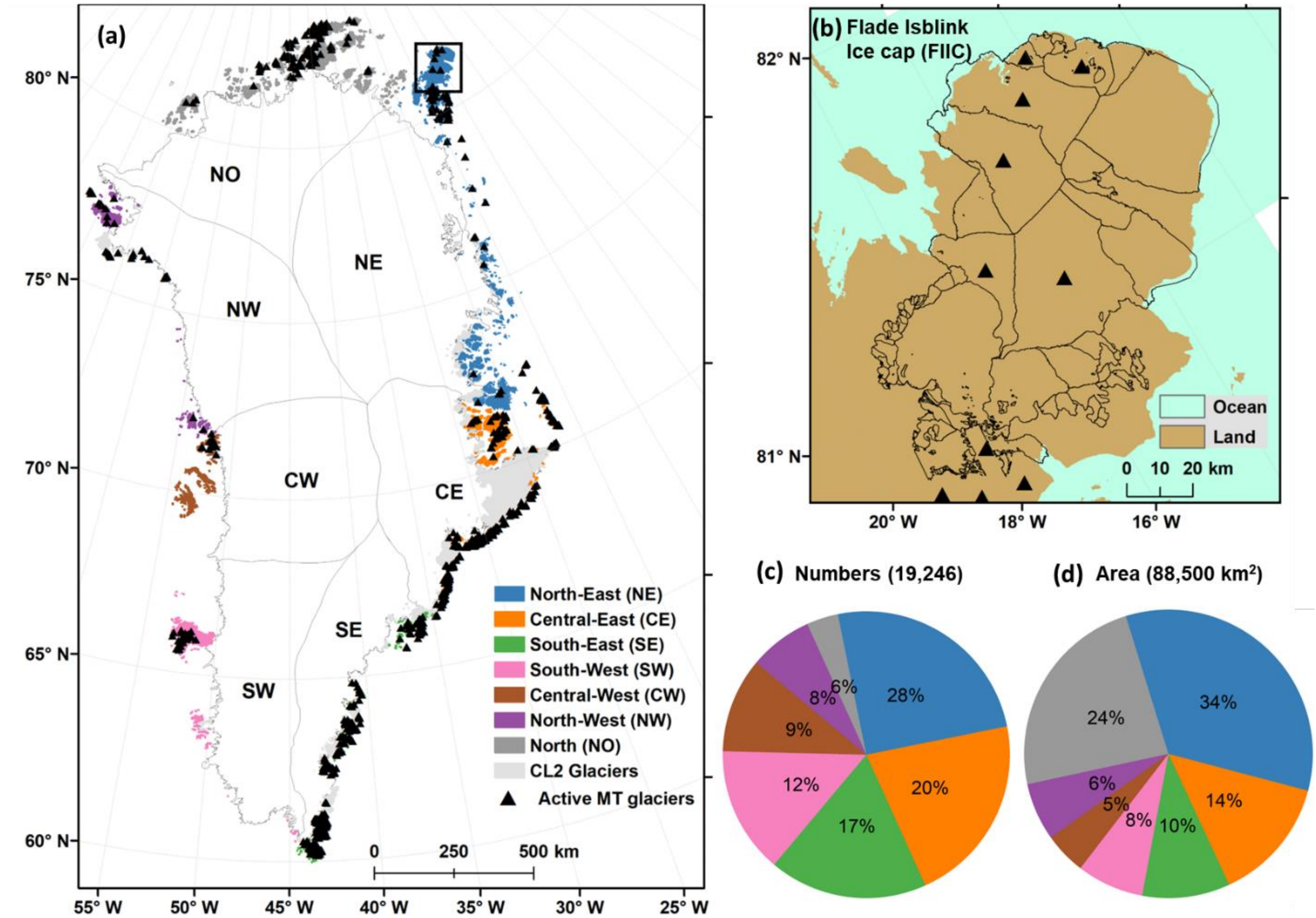

Figure 1: Greenland's Peripheral Glaciers. (a) spatial distribution of considered peripheral glaciers (CL0 & CL1) across the different subregions, excluding peripheral glaciers of CL2, and location of marine-terminating glaciers, (b) new subdivision of Flade Isblink Ice Cap (FIIC) and active marine-terminating glaciers, (c) percentage of glaciers in different subregions, and (d) percentage of glacier area in different subregions of Greenland.

2.2 Data

2.2.1 Historical and Future Climate Data

ERA5 climate data (monthly air temperature and precipitation) (Hersbach et al., 2020) were used as boundary conditions to calibrate the mass balance model. A precipitation correction (with no vertical gradient, but with a multiplicative correction factor; see details in subsection 2.3.1) was applied to the original ERA5 time series. This correction can be seen as accounting for processes like orographic precipitation, avalanches, and wind-blown snow, which are not resolved by the ERA5 data (Maussion et al., 2019).

CMIP6 data for ten GCMs (Table 1) and four Shared Socioeconomic Pathways (SSPs: SSP126, SSP245, SSP370, and SSP585) are used to force the model from 2020 until 2100. Among the selected SSPs, SSP126 represents sustainability (low emissions), SSP245 middle-of-the-road development, SSP370 regional rivalry, and SSP585 fossil-fueled growth (high

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emissions), each offering distinct scenarios for future global socioeconomic development and associated climate challenges (Riahi et al., 2017). The selected GCMs have been employed in several previous studies for similar glacier projections (Edwards et al., 2021; Malles et al., 2023; Rounce et al., 2023; Zekollari et al., 2024), chosen based on their performance in simulating key climatic variables relevant to glacier dynamics and their ability to represent a broad range of potential future climates. Such a standardized selection of GCMs provides consistency and continuity and facilitates the comparison and contrast of results (Hock et al., 2019; Marzeion et al., 2020). This approach ensures a robust and representative sample of climate projections while maintaining comparability with earlier studies. Furthermore, the sample size is large enough to encompass a wide range of potential climatic futures, thus yielding a robust set of scenarios and increasing confidence in the projections. Although CMIP6 models generally do not include dynamic ice sheet components (Eyring et al., 2016; Nowicki et al., 2016), our glacier model OGGM explicitly accounts for ice dynamics. The climate data from these GCMs serves as input for OGGM, rather than directly modeling glacier evolution.

Table 1. Selected GCMs from CMIP6 for future climate change data until 2100.

GCM	Variant	Spatial resolution (°)	Temporal coverage	Reference
BCC-CSM2-MR	r1i1p1f1	1.12	1850-2100	(Xin et al., 2018)
CAMS-CSM1-0	r1i1p1f1	1.12	1850-2100	(Rong, 2019)
FGOALS-f3-L	r1i1p1f1	1.00	1850-2100	(Yu, 2019)
CESM2-WACCM	r1i1p1f1	1.25	1850-2100	(Danabasoglu, 2019)
GFDL-ESM4	r1i1p1f1	1.25	1850-2100	(Horowitz et al., 2018)
INM-CM4-8	r1i1p1f1	2.00	1850-2100	(Volodin et al., 2019a)
INM-CM5-0	r1i1p1f1	2.00	1850-2100	(Volodin et al., 2019b)
MPI-ESM1-2-HR	r1i1p1f1	0.94	1850-2100	(Von Storch et al., 2017)
MRI-ESM2-0	r1i1p1f1	1.12	1850-2100	(Yukimoto et al., 2019)
NorESM2-MM	r1i1p1f1	1.25	1850-2100	(Seland et al., 2020)

The GCM data are bias-corrected using the delta method (Maraun, 2016), which involves employing the relatively high-resolution gridded observations of the ERA5 dataset (Hersbach et al., 2020) as reference climatology and applying only anomalies between the GCMs and the pre-determined reference period (in our case, 1981-2020).

2.2.2 Mass Balance and Frontal Ablation Observations

This study utilizes the mass change estimates for each glacier in the RGI 6.0 during 2000-2020, provided by Hugonnet et al. (2021). However, these mass changes are based on differences in surface elevations derived from digital elevation models (DEMs) between different points in time and do not include any changes occurring below sea level. Thus, when estimating total mass changes and calibrating models of marine-terminating glaciers, it is essential to correct for the mass budget disregarded by not considering changes below sea level.

To obtain frontal ablation estimates, including the mass changes below sea level, which are needed to prevent an erroneous calibration of the surface mass balance model in OGGM, we use the satellite-derived dataset from Kochtitzky et al. (2022). These frontal ablation estimates are used to correct the mass budget for marine-terminating glaciers, ensuring accurate

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calibration of the surface mass balance model. For a detailed description of how this data is incorporated into the calibration process, see Section 2.4.

2.3 Open Global Glacier Model (OGGM)

OGGM is a numerical model framework designed to simulate the evolution of glaciers on a basin to global scale. It is based on a combination of physical and empirical equations that relate glacier mass balance, ice flow, and geometry to environmental variables, such as temperature, precipitation, and topography (Maussion et al., 2019). The basic flowchart of OGGM setup, calibration, and run as used in this study is presented in Fig. 2.

OGGM requires information about the location, area, terminus type, and elevation of each glacier at some point in time (usually the date of data acquisition) within the modeled time interval. These data were taken from RGI 6.0 (Pfeffer et al., 2014). For topographic data, we used the ArcticDEM dataset (Porter et al., 2018) for most of our study's glaciers and the GIMP DEM (Howat et al., 2014) to fill in the gaps. The topographic data is interpolated and resampled to a resolution suitable for the glacier size (Maussion et al., 2019), then smoothed using a Gaussian filter, and finally reprojected centered on the individual glacier using Transverse Mercator map projection.

OGGM uses a flowline model based on shallow Ice Approximation (SIA) to simulate the ice dynamics (Maussion et al., 2019). This flowline considers the width of the glacier, allowing the model to match the observed area-elevation distribution of real glaciers and to parametrize changes in glacier width with thickness changes. This study uses the binned elevation-band flowlines method (Werder et al., 2019). The mean of the slopes within a quantile range is used to calculate the glacier's slope, removing outliers and accurately representing the glacier's main tongue and true length. The downstream lines and bed shape are also calculated to allow the glacier to grow. The dynamical simulations commence from the date of the glacier’s data acquisition in the RGI. The starting date of the simulations may thus vary over a few years between glaciers. The initial geometry comprises the surface area specified by the RGI and the outcome of the ice thickness inversion.

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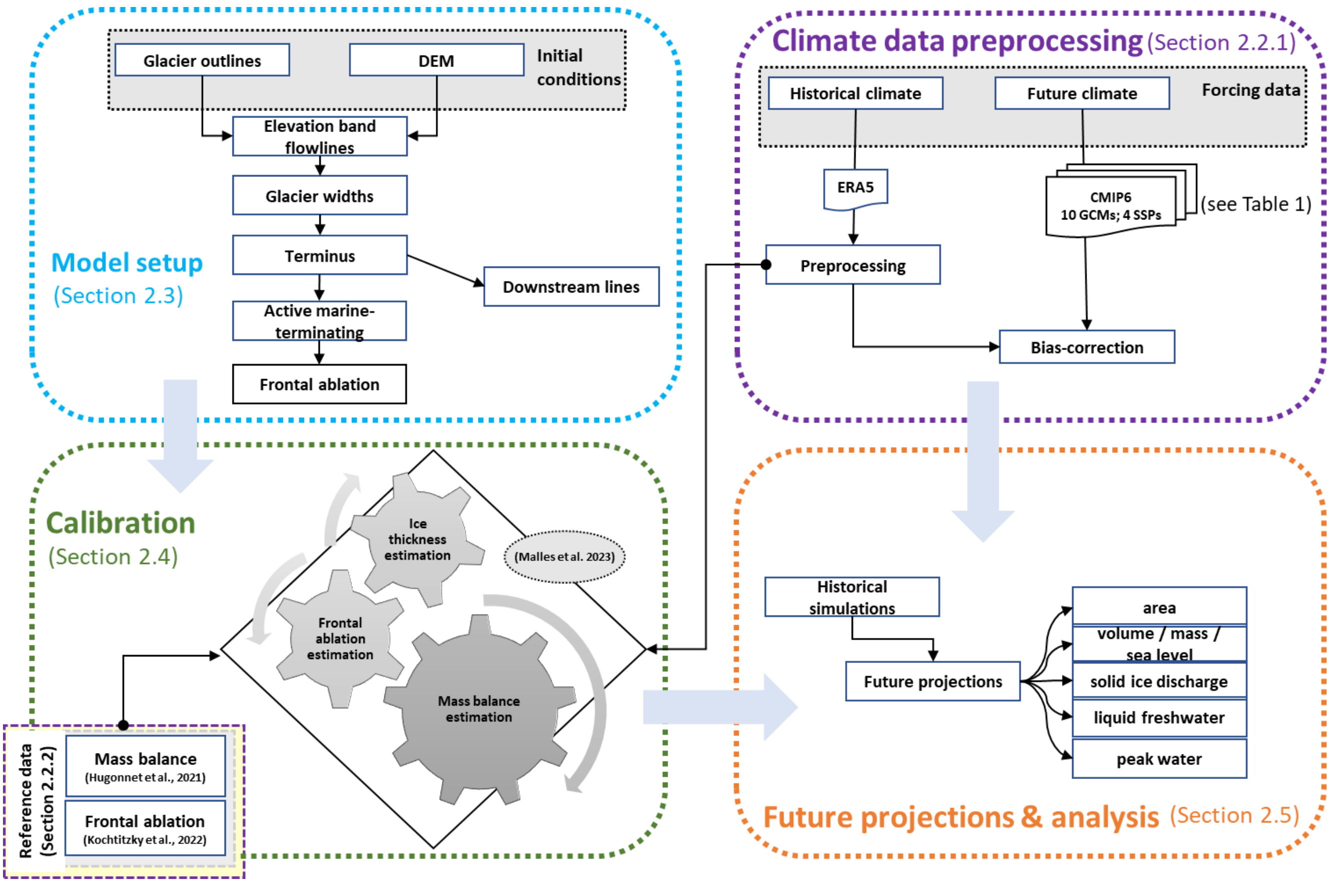

Figure 2: Workflow chart of Open Global Glacier Model (OGGM).

2.3.1 Mass Balance Model

The climate data is interpolated to the glacier location to compute the glacier's monthly surface mass balance. The air temperature data is corrected using a lapse rate calculated based on the gridded climate dataset. This calculation is performed at each grid point along the flowline of the glacier. The solid precipitation is calculated using a threshold air temperature. Specifically, all precipitation is considered solid when the air temperature is below 0°C. All precipitation is considered liquid when the air temperature is above 2°C. For temperatures between 0°C and 2°C, a linear interpolation between solid and liquid precipitation is applied. The monthly surface mass balance of a glacier, pertaining to the grid point i located at elevation z_i, is computed for every grid point along the flowline.

$$m_i(z) = f_P P_i^{solid}(z) - \mu max(T_i^m(z), 0), \quad (1)$$

where $m_i(z)$ is monthly surface mass balance for grid point i (in mm w.e.); f_P is precipitation factor; $P_i^{solid}(z)$ is solid precipitation (in mm w.e.); μ is air temperature sensitivity (in mm w.e. K^{-1}); $T_i^m(z)$ is the air temperature above the threshold

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for ice melt at the glacier surface (in K). We applied a global f_P = 1.6, consistent with the default-OGGM v1.4 setup (Oggm-Documentation, 2024). The parameter μ is a calibrated individually for every glacier, as detailed in section 2.4.

2.3.2 Enhanced Modeling of Marine-Terminating Glaciers

Accurately modeling marine-terminating glaciers is crucial for understanding their dynamics and predicting their response to climate change. In this study, we apply an enhanced approach by incorporating a module that accounts for hydrostatic pressure balance, enabling the shallow ice approximation for marine-terminating glaciers with terminal cliffs (Malles et al., 2023). In the enhanced parametrization, the sliding velocity calculation was also updated to take the water depth of the glacier's bed into account. The sliding velocity calculation considers the height above buoyancy, calculated as the difference between ice thickness and the ratio of ice and ocean water densities multiplied by water depth. OGGM was updated for consistency in the dynamical model core and ice thickness inversion, incorporating height above buoyancy and frontal ablation parameterization. The same frontal ablation parameterization is applied in the dynamical model, ensuring a consistent ice thickness inversion solution for all glaciers. The parameterized frontal ablation flux is subtracted from the flux through the grounding line in every time step. When the accumulated difference is sufficiently positive/negative, the glacier can advance/retreat into the next grid cell. If the thickness of one or more grid cells falls below flotation in a specific time step, the part of this volume that is contained in grid cells beyond the one adjacent to the last grid cell above flotation is removed and added to the frontal ablation output variable (i.e., the formation of ice shelves is suppressed).

Frontal ablation (Q_f) in marine-terminating glaciers is determined by employing the calculation method proposed by Oerlemans and Nick (2005):

$$Q_f = kdhw, \tag{2}$$

Where k, d, h, and w are water-depth sensitivity parameter (in yr^{-1}), water depth (in m), ice thickness (in m), and width at the glacier front (in m), respectively. An iterative procedure is employed to find a value for the water-depth sensitivity parameter that produces a frontal ablation estimate within the uncertainty bounds of the data used. This value is used in ice thickness inversion and a subsequent historical dynamical run. The mass loss through frontal ablation is considered as solid ice discharge. For a more detailed description of this process, including its implementation in OGGM, readers are referred to Malles et al. (2023).

2.3.3 Freshwater Runoff and Peak Water

All the runoff generated through surface melt processes and direct rain is considered as liquid freshwater runoff. The total annual freshwater runoff from the glacier was calculated by summing the components of off-glacier snowmelt, on-glacier melt, on-glacier liquid precipitation, and off-glacier liquid precipitation.

$$TR = \sum GR_{i,s,r} + SR + RR, \tag{3}$$

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Where *TR* is total liquid freshwater runoff, $GR_{i,s,r}$ denotes the sum of runoff from glacier ice (GR_i), snow (GR_s), and rain (GR_r), *SR* is snowmelt off-glacier, and *RR* is rain runoff off-glacier. *SR* and *RR* are the freshwater runoff components from the deglaciated areas within the RGI boundaries, where the glacier has retreated or disappeared over time. Although the glaciers have retreated from these areas, they still contribute to the total freshwater runoff due to initial boundary constraints and are therefore included in the calculation.

"Peak water" is defined as the moment in time when the amount of annual freshwater released from a glacier reaches its highest level and begins to decrease. As a glacier shrinks, more annual meltwater is released until a maximum is reached. Peak water is determined after applying an 11-year rolling mean to the total liquid freshwater runoff time series to reduce short-term variability and highlight long-term trends.

2.4 Model Calibration

In previous versions of OGGM, spatial interpolation was used in the calibration process of the surface mass balance model due to the lack of observational data. However, we are now able to calibrate on a glacier-by-glacier basis using geodetic mass balance (Hugonnet et al., 2021) and frontal ablation data, including volume changes below sea level (Kochtitzky et al., 2022). We use the following equation after Malles et al. (2023) for calibration:

$$\mu = \left(f_p P_{solid} - \frac{\Delta M_{awl} + C + f_{bwl} \Delta M_f}{A_{rgi}}\right) \frac{1}{T_m}, \quad (4)$$

Where ΔM_{awl} is observed annual volume change above sea level of a glacier (Gt/yr) as given by Hugonnet et al. (2021), C is observed annual frontal ablation rate of a glacier as given by Kochtitzky et al. (2022) (Gt/yr), ΔM_f is observed annual volume retreat due to area changes in the terminus region of a glacier (Gt/yr), as given by Kochtitzky et al. (2022), f_{bwl} is an assumed fraction of ΔM_f occurring below the waterline, A_{RGI} is glacier surface area of a glacier as given by the RGI 6.0 (km^2), T_m is annually accumulated air temperature above the threshold for ice melt (-1 °C) at the glacier surface (K). For a comprehensive description of the calibration process, readers are referred to Malles et al. (2023).

2.5 Future Projections and Analysis

Finally, future glacier area, volume, mass loss, sea level rise, solid ice, freshwater runoff contributions, and peak water were projected from 2020 to 2100 for all peripheral glaciers in Greenland. We employed several tests to analyze the data and assess the statistical significance of our findings. One-way Analysis of Variance (ANOVA) was used to compare means across multiple groups (e.g., emission scenarios) for normally distributed data (Fisher, 1992). Two-way ANOVA examined the effects of two independent variables (e.g., region and emission scenario) on a dependent variable, as well as their potential interaction. The F-statistic in ANOVA, representing the ratio of between-group variability (variation between sample means) to within-group variability (variation between sample means), was used to quantify the significance of differences. For non-normally distributed data, we used the Kruskal-Wallis test, a non-parametric alternative to one-way ANOVA (Kruskal and Wallis, 1952). Following significant results, Tukey's Honestly Significant Difference (HSD) test was

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applied for post-hoc pairwise comparisons (Tukey, 1949). These methods assessed differences in glacier area retreat, volume loss, sea level rise contributions, freshwater runoff, and peak water timing across emission scenarios and regions. The choice of test depended on data characteristics and comparison specifics.

3 Results

3.1 Projected Glacier Area Retreat, Volume Loss, and Sea Level Rise Contributions

Our projections suggest notable declines in area and volume of glaciers along the periphery of Greenland by the year 2100 across all evaluated emission scenarios (see Figs. 3 and 4). A one-way ANOVA test revealed significant differences in area retreat among SSP scenarios ($F(3,36) = 19.65$, $p<0.001$), indicating the varied impacts of emission levels on the spatial changes of Greenland's peripheral glaciers.

Under the low-emission scenario (SSP126), glacier area shows a relatively steady annual decrease of 0.18 ± 0.03 % yr^{-1} (mean ± 1 SD), in contrast to the high-emission scenario (SSP585), which exhibits a more pronounced annual decline of 0.43 ± 0.08 % yr^{-1} (Fig. 3b). Additionally, a trend towards increasing standard deviation over time across all scenarios (one-way ANOVA, $p < 0.001$) indicates growing variability in the projections of the remaining glacier area, reflecting increased uncertainty as the century progresses. Projections suggest a decrease in total glacier area by 19 ± 6 % under SSP126 and 44 ± 15 % under SSP585.

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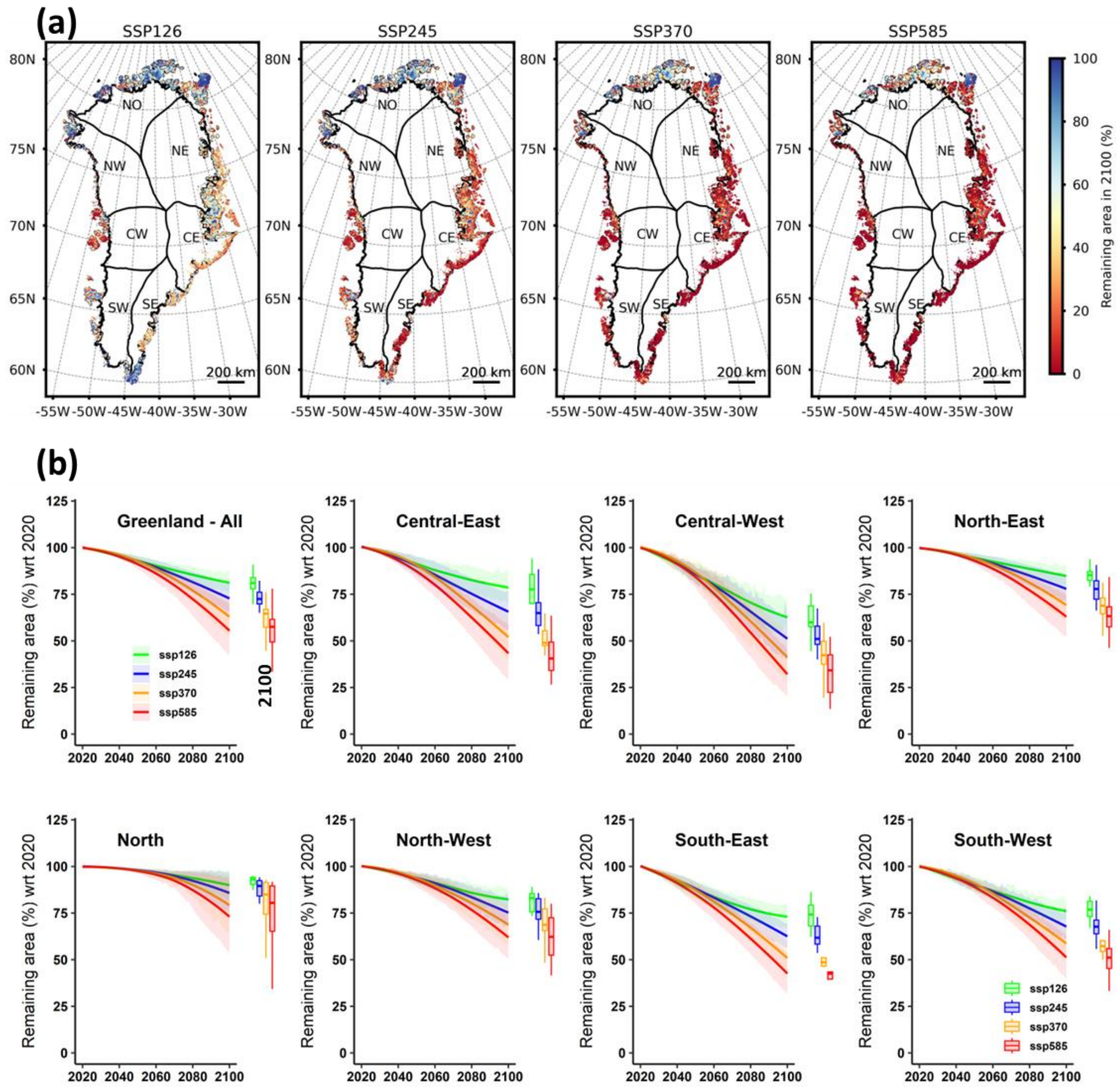

Figure 3: (a) Spatial distribution of projected remaining glacier area in 2100 compared to 2020 under different emission scenarios (mean of 10 GCMs). (b) Projected remaining glacier area from 2020 to 2100 (mean ± 1SD). The solid lines and shaded areas (mean ± 1SD) are plotted using the locally estimated scatterplot smoothing (LOESS) regression method. The box plots represent the statistics of the remaining area in 2100 compared to 2020 under 4 SSPs (10 GCMs).

Similarly, glacier volume is expected to decrease by 29 ± 6 % under SSP126 and 52 ± 14 % under SSP585, with a significant regional variability (Fig. 4). For instance, the Central-West subregion is projected to experience the most severe volume loss,

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which is statistically higher than other regions ($p < 0.05$, Tukey's Honestly Significant Difference (HSD) Test). Conversely, the North-East region shows the lowest projected loss (Fig. 4b). A two-way ANOVA confirms that both the subregion ($F (6,72) = 62.34$, $p < 0.001$) and SSP scenario ($F (3,72) = 118.79$, $p < 0.001$) have a significant impact on the projected glacier volume loss, independent of each other. However, no interaction effect was observed between region and SSP ($p = 0.085$), indicating that the impact of SSP on projected total volume loss does not significantly differ across regions and vice versa.

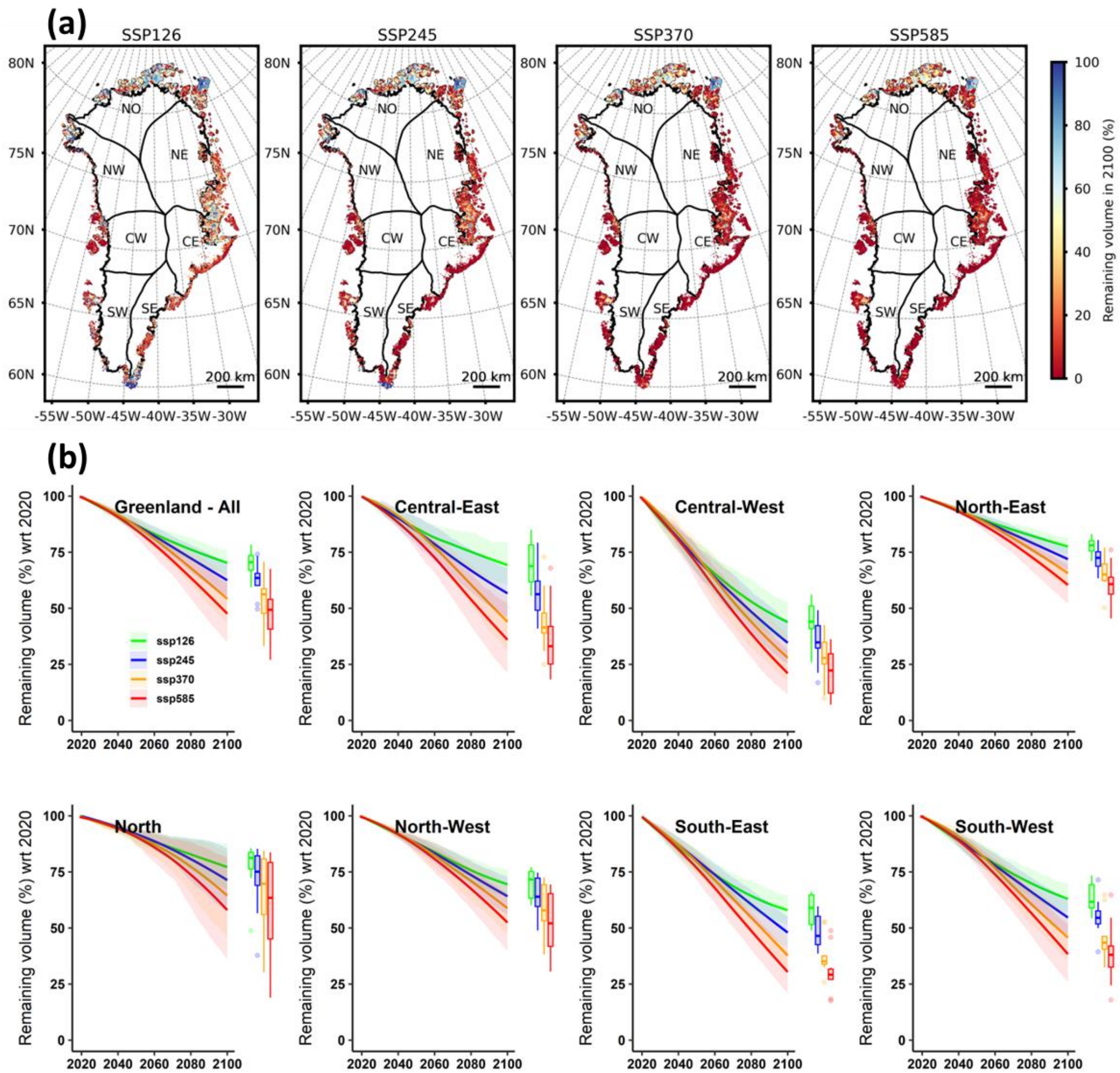

Figure 4: (a) Spatial distribution of projected remaining glacier volume in 2100 compared to 2020 under different emission scenarios (mean of 10 GCMs). (b) Projected remaining glacier volume from 2020 to 2100 (mean ± 1SD). The solid lines and shaded

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areas (mean ± 1SD) are plotted using the locally estimated scatterplot smoothing (LOESS) regression method. The box plots represent the statistics of the remaining area in 2100 compared to 2020 under 4 SSPs (10 GCMs).

The losses in glacier volume translate to a contribution to sea level rise of 10 ± 2 mm under SSP126 and 19 ± 5 mm under SSP585, with substantial regional variability (Fig. 5a). For all SSPs, sea level rise (SLR) shows significant positive trends over 2021 to 2100: SSP126 (0.10 ± 0.01 mm/yr), SSP245 (0.13 ± 0.02 mm/yr), SSP370 (0.16 ± 0.03 mm/yr), and SSP585 (0.19 ± 0.04 mm/yr) (Fig. 5a). The North-East subregion is found to exhibit the strongest increase in SLR contribution (0.092 ± 0.027 mm/yr^2) and the highest mean SLR contribution by 2100 across all SSPs. Under SSP585, it is projected to contribute 37 % of the total SLR, see Fig. 5b). In contrast, the Central-West subregion is suggested to have the weakest increase (0.0082 ± 0.0015 mm/yr^2) and the lowest projected SLR contribution (3 %) under SSP585.

A one-way ANOVA highlighted significant differences in mean SLR contributions between subregions for each SSP ($p<0.001$). Additionally, two-way ANOVA analysis underscored the significant interaction between subregions and emission scenarios on end-of-century area, volume losses, and SLR contributions ($p<0.001$), demonstrating the compound influence of local environmental factors and global emission trajectories on the dynamics of glacier evolution. These findings indicate that SLR from Greenland's peripheral glaciers is set to substantially increase through the 21st century under all SSPs.

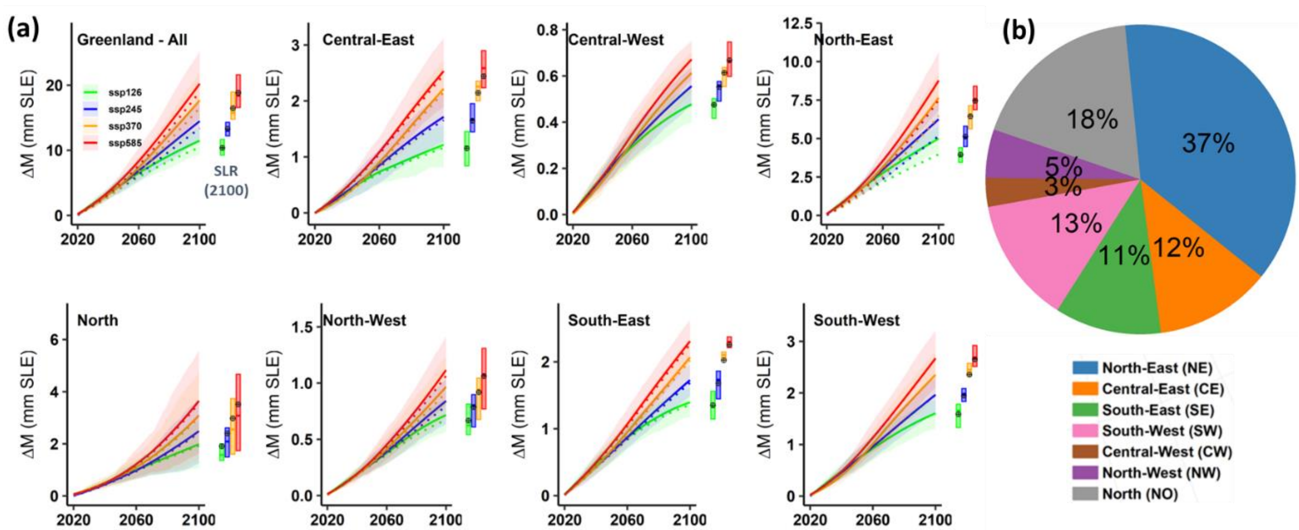

Figure 5: (a) Solid lines represent the projected cumulative mass change in mm Sea Level Equivalent (mm SLE) in different subregions from 2020 to 2100 (mean ± 1SD; 10 GCMs). The dotted lines represent sea level rise (mm SLE), considering mass change below sea level. The solid lines and shaded areas (mean ± 1SD for total mass loss) and dotted lines (sea level rise) are plotted using the locally estimated scatterplot smoothing (LOESS) regression method. The interquartile ranges (boxplots) represent the statistics for the cumulative sea level rise contributions from different subregions for the year 2100. (b) Percent contributions in sea level rise from each subregion by 2100 under SSP585 (mean of 10 GCMs).

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3.2 Freshwater Contributions: Solid Ice Discharge vs Liquid Freshwater Runoff

Our projections reveal significant but contrasting trends in both solid ice discharge and liquid freshwater runoff from Greenland's peripheral glaciers over the 21st century, influenced by climate change and emission scenarios.

Solid ice discharge shows an average of 3.0 ± 0.7 Gt/yr from 2020 to 2100 under the high-emission SSP585 scenario, with a notable decrease post-2050 attributed to the diminishing extent of marine-terminating glaciers (Fig. 6). Accordingly, the solid ice discharge exhibits a declining trend under all scenarios, with substantial interannual variability. For example, under SSP126, the solid ice discharge decreases at a rate of -0.011 Gt/yr², a statistically significant trend mirrored across other scenarios: SSP245 (-0.014 Gt/yr²), SSP370 (-0.017 Gt/yr²), and SSP585 (-0.018 Gt/yr²). These trends were supported by a two-way ANOVA, which highlighted a significant year-on-year reduction in solid ice discharge ($p<0.001$) across all scenarios.

In terms of regional ice discharge, most areas exhibit declining trends, except for the North-East, which shows a marginal increase from 1.05-1.06 Gt/yr in 2021-2030 to 1.15-1.23 Gt/yr by 2091-2100 under low and high emission scenarios. Two-way ANOVA tests confirm significant differences ($p<0.001$) in ice discharge between the period I (2021-2030) and period II (2091-2100) of projections. However, no significant differences are found among emission scenarios ($p>0.05$) or in the interaction between scenarios and selected decades ($p>0.05$). It is important to note that our model does not account for ocean temperature changes, which may affect solid ice discharge projections.

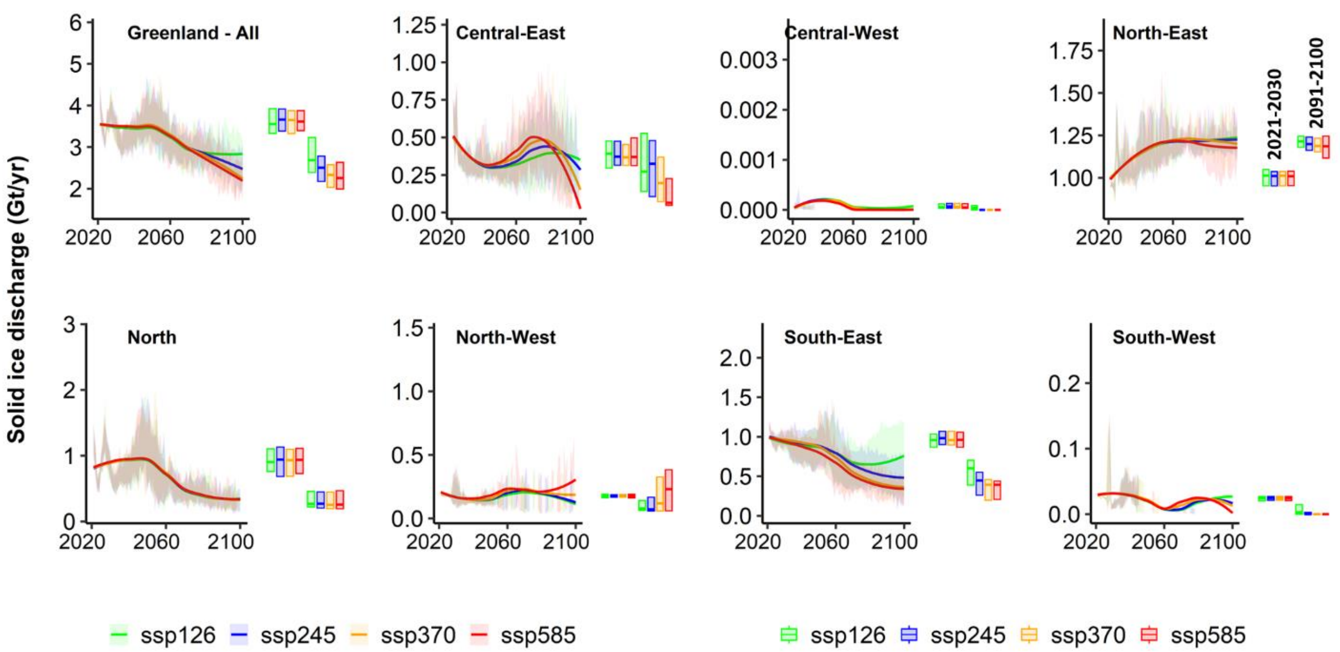

Figure 6: Solid ice discharge in different subregions from 2020 to 2100. The first set of interquartile ranges (boxplots) represents the average solid ice discharge over 2021-2030, and the second set represents the average over 2091-2100 under different emission scenarios.

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Conversely, projections for liquid freshwater runoff indicate a significant increase over the century, with annual averages ranging from 138 ± 12 Gt/yr under SSP126 to 184 ± 27 Gt/yr under SSP585 (Fig. 7a). Freshwater runoff increases under SSP585 from 145 ± 27 Gt/yr to 216 ± 46 Gt/yr, whereas it decreases under SSP126 from 145 ± 25 Gt/yr to 120 Gt/yr by 2100 compared to 2020. The North-East subregion emerges as the dominant contributor, accounting for 35 % of the total runoff over 2020-2100 under SSP585. This contribution is contrasted sharply by the Central-West region, which contributes only 3 % of the total annual freshwater runoff (Fig. 7b). These regional differences in runoff contributions are influenced by variations in glacier number, area, and ice volume among subregions (Fig. 1c-d).

The composition of freshwater runoff is also expected to shift markedly over the century. Under SSP585, the proportion of glacier meltwater in total runoff is projected to decrease from 92 % in 2021-2030 to 72 % by 2091-2100. Meanwhile, contributions from off-glacier rainfall and snowmelt are expected to increase from less than 1 % to 8 % (~ 8-fold) and from 1 % to 15 % (~15-fold), respectively (Fig. 7c-d). The seasonal distribution of freshwater runoff components is also projected to change significantly (Fig. 7e-f). In 2021-2030, glacier melt dominates runoff from May to September, peaking in July. By 2091-2100, while glacier melt still peaks in July, its contribution is notably reduced. Snowmelt shows a marked increase, especially in May-June, while rainfall contributions increase throughout the year especially during summer months.

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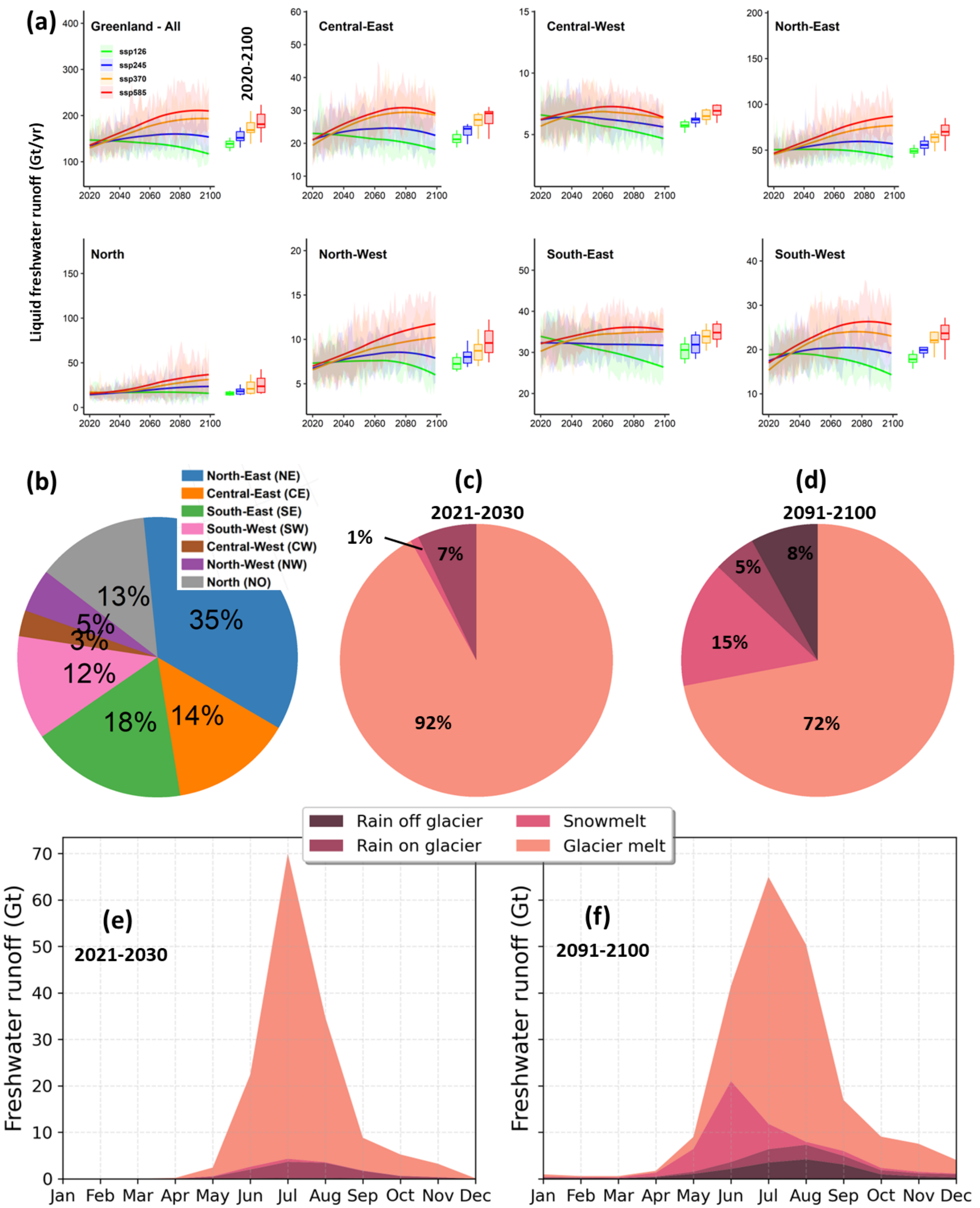

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Figure 7: (a) freshwater runoff (Gt/yr) from different subregions under four emission scenarios (10 GCMs) from 2020-2099. The box plots represent the statistics of average freshwater runoff from 2020-2099. (b) percent freshwater runoff contributions from different subregions under SSP585. (c-d) Average percent contributions of runoff components to total freshwater runoff during 2021-2030 and 2091-2100 under SSP585. (e-f) Seasonal distribution of freshwater runoff components for the same periods under SSP585.

3.3 Peak Water Timing and Magnitude

The timing and magnitude of peak water runoff from Greenland's peripheral glaciers are significantly influenced by varying emission scenarios, demonstrating notable spatial and temporal variability (Fig. 8).

For Greenland peripheral glaciers, peak water runoff is projected to occur around the year 2050 ± 21 under the low-emission SSP126 and around 2082 ± 9 under the high-emission SSP585 scenario (Fig. 8a). The shift of nearly 30 years is statistically significant (Kruskal-Wallis $p < 0.05$), indicating a strong influence of emission scenarios on the hydrological responses of the glaciers. The maximum runoff at these peak times is expected to be 214 ± 21 Gt/yr under SSP126 and 293 ± 61 Gt/yr under SSP585 (Fig. 8b), underscoring the increased runoff associated with higher emissions.

Subregional analysis reveals that southern regions such as South-East and South-West are expected to experience earlier peak waters, with median timings around 2038 (± 17 years) and 2035 (± 10 years) under SSP126, respectively. Conversely, northern and central subregions show a delayed response; for instance, the North-East and North regions are projected to reach their peak around 2053 (± 22 years) and 2055 (± 25 years) under SSP126, shifting to 2080 (± 19 years) and 2086 (± 13 years) under SSP585 (Fig. 8a). Despite these apparent differences in timing across subregions, statistical analysis using the Kruskal-Wallis test indicates that these variations are not statistically significant ($p > 0.05$), suggesting that while regional differences exist, they do not diverge significantly under different scenarios.

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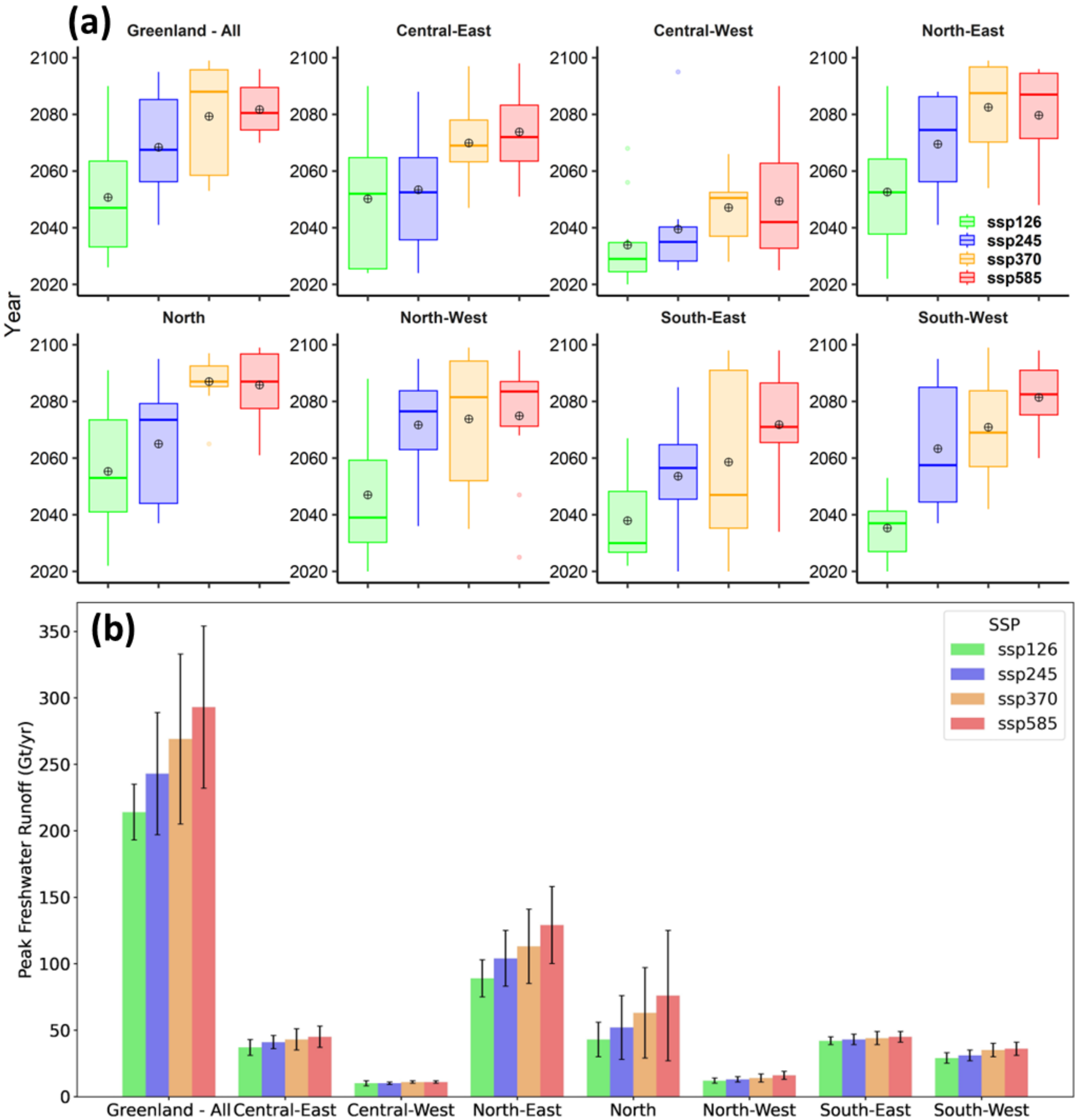

340 **Figure 8: (a) Box plots representing statistics of peak water year under different emission scenarios in subregions. (b) Mean maximum freshwater runoff (Gt/yr) at peak water year (mean ± 1SD for 10 GCMs).**

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4 Discussion

4.1 Increasing Glacier Mass Losses and Contribution to Sea Level Rise

Our projections indicate substantial losses in both area and volume of Greenland's peripheral glaciers by 2100, highlighting their high sensitivity to climatic changes. Under the high-emission scenario (SSP585), glacier area and volume are expected to decline by up to 44 % and 52 %, respectively, by 2100 (Figs. 3 & 4). These losses align with existing models predicting accelerated glacier retreat and mass loss (up to 50 % by 2100) in response to warming air temperatures (Hock et al., 2019; Marzeion et al., 2020; Rounce et al., 2023). Discrepancies across these studies can be attributed to the use of different climate forcings, initial conditions, and the representation of ice flow dynamics in different glacier models (Zekollari et al., 2022; Marzeion et al., 2020). The variability in our projections across different emission scenarios underscores the potential impact of climate mitigation efforts on the fate of these glaciers (Fox-Kemper et al., 2023).

The projected glacier losses from Greenland's peripheral glaciers translate into a SLR contribution of ~19 ± 5 mm by the end of the 21st century under SSP585 (Fig. 5). The projected SLR is consistent with recent projections for Greenland's peripheral glaciers (Edwards et al., 2021; Marzeion et al., 2020). This contribution is significant when considering Greenland's total SLR contribution (Aschwanden et al., 2021; Grinsted et al., 2022). Goelzer et al. (2020) estimated a mean SLR contribution of 90 ± 50 mm from the Greenland Ice Sheet alone under RCP8.5, suggesting that peripheral glaciers represent a substantial additional contribution to Greenland's total ice loss.

The regional variability in projected glacier losses (Figs. 3 & 4) reflects the complex interplay between localized climatic conditions, topography, and glacier dynamics (King et al., 2020; Wood et al., 2021). For instance, the resilience of North-East glaciers is attributed to high snowfall rates and resistant glacier geometry (Bevis et al., 2019), while Central-West glaciers are prone to surface melt and dynamic destabilization (Vijay et al., 2019; Cowton et al., 2018). This is also evident in decreasing ice discharge rates over recent years that oppose increasing ocean thermal forcing (Möller et al., 2024). This regional heterogeneity in glacier response aligns with observations of historical glacier changes across Greenland (Khan et al., 2022; Mouginot et al., 2019) and underscores the importance of considering local factors in future projections.

Furthermore, the projected glacier losses (Figs. 3 & 4) markedly affect other interconnected processes beyond direct SLR, including freshwater contributions, primarily through alterations in surface meltwater (Fig. 7) and solid ice discharge (Fig. 6). As land-terminating glaciers retreat, a decrease in glacier coverage will shift the relative contribution of rainfall, snowmelt, and ice melt (Fig. 7c-d) and alter freshwater fluxes to coastal hydrography, removing critical buffers against extreme summer discharge (Huber et al., 2020; Khan et al., 2022; Straneo et al., 2022; Bliss et al., 2014). Similarly, the reduction in the number of calving fronts of marine-terminating glaciers (Malles et al., 2023) will lead to reduced solid ice flux into fjords.

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4.2 Changing Dynamics of Freshwater Contributions

The divergent trends in solid ice discharge (Fig. 6) and liquid freshwater runoff (Fig. 7) from Greenland's peripheral glaciers elucidate the shifting dynamics of these glaciers in response to climatic changes. The projected decrease in solid ice discharge across all emission scenarios (-0.011 to -0.018 Gt/yr²), which occurs sharply after 2050, is consistent with other projections (Malles et al., 2023) and historical trends (Kochtitzky and Copland, 2022), suggesting a gradual transition from calving-dominated to surface melt-dominated systems as marine-terminating glaciers retreat inland. The statistically significant negative trends of solid ice discharge under all scenarios, with no substantial differences among SSPs (Fig. 6), reflect the dominant role of climatic changes relative to variations in emissions scenarios for this century (Oerlemans et al., 2022; Slater et al., 2019). Our projections of consistent solid ice discharge trends across emission scenarios should be interpreted cautiously, as they do not account for oceanic forcing. Several previous findings show that Greenland's marine-terminating peripheral glacier response is more sensitive to warming compared to land-terminating glaciers (Hill et al., 2017; Liu et al., 2022b).

The contrasting slight increase in solid ice discharge projected for the North-East subregion (Fig. 6) can be attributed to its more extensive coverage of marine-terminating glaciers (Kochtitzky and Copland, 2022) and probably to a delayed response to recent climate and ocean forcing, as decreasing ice discharge has been observed over the first two decades of the 21st century in this subregion (Möller et al., 2024). The larger number and area of marine-terminating glaciers in this subregion provide a greater source for calving fluxes, even when considering the projected overall glacier retreat and thinning in this region (Morlighem et al., 2019).

The significant increase in liquid freshwater runoff (61 Gt/yr under SSP5858 from 2020 to 2100, see Fig. 7a), driven by enhanced surface melting under higher air temperature regimes, is consistent with findings of accelerated mass loss from Greenland's periphery (Marzeion et al., 2020; Rounce et al., 2023). The projected 46 ± 27 Gt/yr higher freshwater runoff from Greenland peripheral glaciers by 2100 under SSP585 compared to SSP126 (Fig. 7a) indicates severe impacts of warmer climate under high emissions.

The strong regional variations observed in the freshwater runoff projections, with 35 % of liquid runoff originating from the North-East glaciers by 2100 (Fig. 7b), align with the heterogeneous influence of localized climatic, glacier-characteristic (numbers, sizes, and types) and topographic factors (Bevis et al., 2019; Khazendar et al., 2019; Wood et al., 2021). Localized climatic factors, such as variations in air temperature and precipitation patterns, can significantly impact glacier mass balance and runoff (Noël et al., 2018). Additionally, topographic factors, including elevation, slope, and aspect, influence the exposure of glaciers to solar radiation and the distribution of snow accumulation, which in turn affect glacier ablation and runoff (Huss et al., 2017).

Our results indicate significant changes in the composition of freshwater runoff over the century, with a decreasing proportion of glacier meltwater and increasing contributions from rainfall (8-fold) and snowmelt (15-fold) in total runoff (Fig. 7c-d). The seasonal analysis (Fig. 7e-f) further illustrates this shift, showing a reduced glacier melt season and increased contributions from snowmelt earlier and rainfall throughout the year by 2091-2100. This shift in runoff composition is consistent with projected trends across the Arctic region (Bintanja and Andry, 2017; Bintanja and Selten, 2014; Bliss et al., 2014; Vihma et al., 2016) and reflects the combined effects of glacier retreat and broader Arctic amplification (Smith et al., 2019; Nowicki et al., 2016; Jones et al., 2016; Box et al., 2019), including rising temperatures and changes in precipitation patterns.

The projected timing of peak water runoff from Greenland's peripheral glaciers (Fig. 8) varies significantly across emission scenarios, providing insights into the future evolution of Greenland's peripheral glaciers. The earlier peak water timing (2050s) under low-emission scenarios compared to high-emission scenarios (2080s) highlights the potential opportunity for adaptation. The nearly 30-year difference (Fig. 8a) in projected peak water timing between scenarios emphasizes the capacity of glaciers to potentially regain a new equilibrium, smooth their freshwater runoff, and preserve their buffering capacities under lower emission scenarios, thus delaying the impacts of climate change. However, under high emission scenarios, glaciers continue to contribute higher meltwater until exhausted and eventually lose all mass and become unable to support freshwater runoff. These findings are consistent with the patterns observed by Bliss et al. (2014) for Greenland's peripheral glaciers. They noted significant increases in annual runoff during the 21st century, which aligns with our projection of higher runoff and delayed peak water timing under high-emission scenarios.

The subregional differences in timing of peak water (Fig. 8b), although not statistically significant, suggest that local factors such as glacier size, elevation, climate, and oceanic feedback may influence the peripheral glaciers' response to warming (Solomon et al., 2021). This aligns with the findings of Bliss et al. (2014) that runoff trends can vary significantly based on glacier size and elevation, even within the same region. Their study found that in the Greenland periphery, smaller glaciers tended to have more positive runoff trends, while larger glaciers showed both positive and negative trends depending on their elevation. This aspect is consistent with our projections of continued high meltwater contribution under high emission scenarios until glaciers approach exhaustion.

4.3 Implications for Fjords, Ecosystems, and Ocean Dynamics

The projected changes in freshwater contributions from Greenland's peripheral glaciers have significant implications across multiple spatial scales, from local fjord systems to global ocean circulation patterns.

On the local scale, the alterations in the timing, magnitude, and composition of freshwater input are likely to impact fjord circulation and ecosystems. The decreased solid ice discharge (Fig. 6) and increased liquid runoff (Fig. 7a), coupled with changes in runoff composition (Fig. 7c-d), will modify the seasonality and stratification patterns of fjord waters (Arp et al., 2020; Bliss et al., 2014; Bacon et al., 2015; Le Bras et al., 2018). For instance, in Godthåbsfjord, Southwest Greenland, Mortensen et al. (2013) observed that increased freshwater input enhanced estuarine circulation and altered water properties, subsequently affecting ecosystem productivity. Similarly, in Young Sound, Northeast Greenland, Sejr et al. (2017) found that changes in freshwater runoff led to stronger stratification and altered nutrient availability, impacting the fjord's ecosystem dynamics.

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The composition and seasonality of freshwater runoff are projected to shift markedly over the century (Fig. 7c-f). This seasonal shift in runoff sources could lead to earlier and potentially more variable freshwater inputs to coastal waters (Rennermalm et al., 2013; Van As et al., 2017). The projected increase in spring snowmelt could result in earlier stratification of fjord waters, while the more distributed summer rainfall could lead to more frequent pulses of freshwater input throughout the season. This change in the temporal distribution of freshwater input could have significant implications for fjord stratification, nutrient cycling, and ecosystem dynamics (Hopwood et al., 2020; Holding et al., 2019; Sejr et al., 2022). For instance, changes in the timing of peak freshwater input could affect the marine organisms adopted to stable conditions, including spring phytoplankton bloom, with cascading effects through the marine food web (Oksman et al., 2022; Juul-Pedersen et al., 2015).

Moreover, the expected decrease in solid ice discharge may reduce the influx of terrestrial nutrients typically associated with glacial flour, potentially altering the nutrient dynamics in fjord ecosystems (Meire et al., 2016; Meire et al., 2023; Meire et al., 2017). The projected changes in freshwater contributions, both in terms of volume and composition, will likely have cascading effects on fisheries and other industries that rely on freshwater resources (Holding et al., 2019; Boberg et al., 2018; Hopwood et al., 2020). Our projections of future freshwater contributions and peak water timing provide critical data for understanding and anticipating the impacts of climate change on Greenland's fjord ecosystems and coastal dynamics at the local scale.

On a regional scale, the cumulative effect of increased freshwater input from peripheral glaciers could significantly impact coastal and shelf seas around Greenland. Our projections of maximum runoff (214-293 Gt/yr at peak water, Fig. 8) represent a substantial increase in freshwater flux to the ocean. This additional freshwater could enhance stratification in shelf seas, potentially affecting deep water formation processes. Böning et al. (2016) demonstrated that enhanced freshwater flux from Greenland could lead to reduced convection in the Labrador Sea, a key region for deep water formation in the North Atlantic.

The spatial variability in freshwater contributions, with the North-East region projected to account for 35 % of total runoff by 2100 under SSP585 (Fig. 7b), suggests that regional impacts may be unevenly distributed. This could lead to localized changes in coastal currents and potentially influence larger circulation patterns in the North Atlantic. For example, Luo et al. (2016) showed that meltwater from southern Greenland can be rapidly transported along the coast, potentially impacting the East Greenland Current and, subsequently, the North Atlantic subpolar gyre.

On a global scale, the altered freshwater input from Greenland's peripheral glaciers, combined with changes from the Greenland Ice Sheet, could have far-reaching consequences for ocean circulation patterns. Of particular concern is the potential impact on the Atlantic Meridional Overturning Circulation (AMOC). While our study focuses on peripheral glaciers, the projected freshwater contributions should be considered in the context of total freshwater flux from Greenland (Bamber et al., 2018). Several researchers suggested that increased freshwater input from Greenland could lead to potentially disrupt the AMOC, with potential implications for global climate (Böning et al., 2016; Oliver et al., 2018; Yang et al., 2016;

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Bakker et al., 2016; Carmack et al., 2016). Our findings provide understanding and can help quantify the impacts of the future evolution of Greenland's Peripheral Glaciers and their role in the broader climate system.

4.4 Uncertainties, Limitations, and Future Research Priorities

This study provides important insights into the potential future changes in Greenland's peripheral glaciers, yet it is crucial to acknowledge some key uncertainties and limitations. The uncertainties in the projected results, represented as standard deviations, primarily arise from uncertainties in future climatic forcing based on the GCMs. These uncertainties are greater for high-emission scenarios, particularly in projections of glacier losses (±6 % for SSP126 versus ±15 % for SSP585, Fig. 3-4), sea level rise (±2 mm versus ±5 mm, Fig. 5), and freshwater contributions (±12 Gt/yr versus ±27 Gt/yr, Fig. 7), but are lower for peak water timing (±21 years versus ±9 years, Fig. 8). Additionally, these uncertainties vary across different regions. Scenario uncertainty, which reflects different future socio-economic pathways, becomes increasingly significant in the latter half of the 21st century, consistent with the findings of Marzeion et al. (2020).

Although CMIP6 models generally do not include dynamic ice sheet components, our glacier model OGGM explicitly accounts for glacier ice dynamics. Incorporating glacier ice dynamics is crucial as it allows us to capture important feedbacks and interactions that static ice sheet models cannot. However, uncertainties in CMIP6 climate projections propagate through OGGM, including the effect that neglecting a dynamically evolving ice sheet might have on the regional climate, affecting our glacier evolution simulations. The projected glacier area retreat significantly impacts freshwater runoff components and solid ice discharge, with CMIP uncertainties in temperature and precipitation directly influencing these projections. This glacier area loss largely drives the shift from glacier melt-dominant runoff to increased rainfall and snowmelt contributions, but the magnitude and timing of this shift are subject to CMIP-derived uncertainties. Glacier losses are further amplified by changes in surface properties like albedo, creating a positive feedback loop (Clark et al., 1999), which can either amplify or mitigate CMIP uncertainties. These dynamic processes are particularly important for Greenland's peripheral glaciers, where changes in ice extent can significantly alter local and regional climate patterns, affecting precipitation and temperature regimes (Beghin et al., 2015). While OGGM's ability to simulate these dynamics provides a more comprehensive picture of potential future scenarios, it is important to note that the model's outputs inherit and potentially compound the uncertainties in the CMIP6 climate projections.

When comparing our results to other global glacier studies, we find that our projections for Greenland's peripheral glaciers align well with the ranges reported in recent literature. For example, our projected glacier area losses (up to 44 %) and mass loss (up to 52 %) by 2100 are consistent with Marzeion et al. (2020) and Hock et al. (2019), who projected global glacier area and mass losses of up to ~43 % and ~50 %, respectively, under high-emission scenarios. Our estimates of sea level rise contribution (10-19 mm) also fall within the range of these studies. In a recent study, Zekollari et al. (2024) employed a different modeling approach, using a temperature-index model coupled with an ice dynamics model calibrated for glacier-specific and regional mass balance observations, yet arrived at comparable projections (47 % to 52 % volume loss by 2100) for Greenland's peripheral glaciers. This consistency across different modeling approaches and studies lends credibility to

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our findings. While OGGM captures general trends effectively and its performance in the GlacierMIP ensemble is robust, the model is still subject to uncertainties related to its structure and the resolution of climate forcings.

The current study relies on statistically downscaled GCM data, which may not fully capture important local-scale atmospheric processes over the complex topography of the Greenland periphery that can influence glacier mass balance (Noël et al., 2016; Lewis et al., 2019). Using higher-resolution regional climate models and observational data would potentially improve the accuracy of the projections.

Additionally, this study only considers atmospheric forcing at the glacier surfaces and does not incorporate oceanic forcing. The latter has been demonstrated to be a key control on the behavior of Greenland's peripheral glaciers (Bjørk et al., 2017; Chudley et al., 2023; Möller et al., 2024) through enhanced terminus melt, undercutting, calving, and iceberg melting (Cowton et al., 2015; Davison et al., 2022; Davison et al., 2020; Morlighem et al., 2019; Malles et al., 2023). The projected changes in freshwater contributions from both liquid and solid components may have the potential to alter oceanic forcing on local to regional scales, subsequently also impacting ice discharge from Greenland's peripheral glaciers (Möller et al., 2024; Solomon et al., 2021; Lenaerts et al., 2015; Benn et al., 2017). Developing approaches to account for oceanic forcing in OGGM could thus provide important insights into glacier-ocean interactions and feedback and may improve projection reliability. First approaches to couple glacier models with ocean circulation models have already been presented (Slater et al., 2020; Gladstone et al., 2021; Cook et al., 2021), but substantial development is still required.

At present, OGGM shows limitations regarding model structure and initialization. It simplifies critical processes and does, e.g., not explicitly account for refreezing processes, which are known to contribute substantially to future mass balance trajectories of Arctic glaciers (Möller and Schneider, 2015). Using more sophisticated energy balance-based ablation schemes (Gardner et al., 2023; Rounce et al., 2023; Zekollari et al., 2022) in OGGM could improve the representation of the surface mass balance, but comes at the costs of substantially increased demands on quantity and quality of atmospheric data. Better constraints on parameters like initial glacier size, which can vary between data sources (Citterio and Ahlstrøm, 2013; Rastner et al., 2012; Pedersen et al., 2013), could also reduce uncertainties. Furthermore, the lack of observations near glacier calving fronts limits constraints on frontal ablation, an important process for mass loss (Schaffer et al., 2020).

Key priorities for future research should focus on addressing these limitations by using higher resolution atmospheric and oceanic forcing, initializing models with the best available data sets on glacier geometry and dynamics (Ultee and Bassis, 2020; Kochtitzky and Copland, 2022; Recinos et al., 2023), incorporating more complete representations of surface and submarine melt processes, and coupling glacier models with ocean circulation (Zhao et al., 2021; Quiquet et al., 2021; Malles et al., 2024). Detailed observational data sets from satellite and field studies will be critical for validating and improving models (Gardner et al., 2019; Porter et al., 2018). As models continue to advance, improved partitioning of the processes driving peripheral glacier mass loss will support more robust projections of sea level rise and freshwater contributions to the oceans.

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5 Conclusion

This study provides a comprehensive assessment of the future evolution of Greenland's peripheral glaciers under different climate change scenarios. Our projections indicate substantial glacier area (44 ± 15 %) and volume losses (52 ± 14 %), contributing approximately 19 ± 5 mm to global sea level rise by 2100 under the high emission scenario (SSP585). These glacier losses cause a significant shift in freshwater contributions, with solid ice discharge decreasing and liquid freshwater runoff increasing (until peak water) during the 21st century. Importantly, runoff composition undergoes significant changes, with glacier melt contribution decreasing from 92% to 72%, while rainfall and snowmelt increase 8-fold and 15-fold, respectively, indicating a shift in the hydrological regime. Our projections reveal variable peak water timing across emission scenarios and regions, occurring between the 2050s (SSP126) and 2080s (SSP585) for all Greenland peripheral glaciers. This variable peak water timing leads to divergent glacier futures: lower emissions may allow glaciers to reach a new equilibrium, while high emissions could result in complete glacier loss and drive toward the end of glacier-fed runoff.

These projected changes in freshwater contributions from Greenland's peripheral glaciers are likely to have far-reaching implications. On the local scale, we expect significant impacts on fjord circulation, ecosystem productivity, and coastal environments. Regionally, these changes may affect ocean stratification and coastal currents. On a global scale, the altered freshwater input could potentially contribute to changes in large-scale ocean circulation patterns, with potential implications for the ocean system and global climate.

Our projections indicate a significant difference of up to 9 mm in sea level rise between low and high emission scenarios from Greenland peripheral glaciers alone, suggesting effective greenhouse gas emission controls are crucial for minimizing climate change impacts.

A key limitation in the current projections is the lack of incorporation of oceanic forcing in OGGM, which might impact the behavior of marine-terminating glaciers. Future research might focus on reducing the resulting uncertainties by incorporating glacier-ocean interactions into a coupled modeling architecture.

Data and code availability

The data from this study can be accessed at https://doi.org/10.5281/zenodo.12737991. The OGGM codes are available at https://github.com/OGGM/oggm. The sources of the datasets used in this study are given in the references provided throughout the text.

Author contributions

M.S., M.M., and B.M. were responsible for the conceptualization of the study. M.S. developed the methodology, carried out all analysis and visualization, and wrote the original draft of the manuscript. J.-H.M. and A.V. assisted in enhanced modeling and calibration of marine-terminating glaciers. All authors contributed to the manuscript by reviewing and editing the original draft.

Competing interests

Some authors are members of the editorial board of the journal The Cryosphere.

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