Response to Reviewer 1 Comments

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

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PAPER SUMMARY AND RECOMMENDATION

This study looks at how Greenland's peripheral glaciers may change in the future due to climate change. It emphasizes the distinction between solid ice discharge (calving of icebergs) and liquid freshwater runoff (melting and rain). The study employs the Open Global Glacier Model (OGGM), which simulates the evolution of glaciers using climate data from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under four emission scenarios. Key findings include:

- Projected declines in area and volume: 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.
- Shifting freshwater contributions: Projections show solid ice discharge decreasing over the century, especially after 2050, as marine-terminating glaciers retreat inland
- Peak water timing: Peak water, the time of maximum annual freshwater release, is projected to occur around 2050 under low emissions (SSP126) and shift to around 2082 under high emissions (SSP585)

The article explores an innovative and relevant topic for The Cryosphere and is well-written and easy to follow. The approach is sound, and the study's core findings offer insights that will be beneficial for future research efforts. To further strengthen the manuscript, I recommend that the authors incorporate some additional analyses and provide further clarifications. These improvements will help make the article ready for publication.

General Response

Thank you for your thorough and constructive review of our manuscript. We appreciate your detailed feedback and positive assessment of our work's relevance and approach.

Regarding your major comments

We will implement all suggested improvements to strengthen the manuscript significantly. We will add a comprehensive model intercomparison table (PyGEM, GloGEM, OGGM studies) with statistical comparisons as suggested. The reorganization of Section 2 to clearly separate data, models, and calibration methods is an excellent suggestion and will greatly improve clarity - we will restructure it with dedicated subsections as outlined in our detailed response.

We acknowledge the critical reproducibility issue and will specify that we used OGGM v1.5.3 with custom frontal ablation implementations, with full code availability details. Your point about oceanic forcing limitations is particularly valuable - we will add a comprehensive discussion of how missing oceanic forcing likely leads to underestimation of solid ice discharge and affects regional variability, supported by recent literature on ocean-glacier interactions.

We will significantly expand our regional variability analysis to examine how glacier characteristics (size, geometry, elevation) and local climate factors drive the observed differences, including detailed mechanistic explanations for regional patterns like North-East resilience and Central-West vulnerability.

Regarding minor and technical comments

We will implement all suggested improvements systematically, including clarifying statistical methodologies and value calculations in the abstract, improving figure quality with colorblind-friendly palettes and consistent formatting, adding detailed explanations of the delta method and precipitation factor calibration, expanding temporal and spatial comparisons in Section 3.2, standardizing reference formatting, and clarifying data availability at both glacier and subregional level.

Your suggestions will substantially improve the manuscript's technical rigor, clarity, and reproducibility. Thank you for this excellent review that will make our work more valuable to the scientific community.

MAJOR COMMENTS

Reviewer Comment:

Despite the improved modeling of marine-terminating glaciers, it would be useful to include a comparison with outputs from multiple global models (e.g., PyGEM, GloGEM, OGGM v1.6). Although these model results are briefly discussed, I suggest including a summary table with results (e.g., volume and area) and comparing them statistically (methods in Section 2.5). This comparison is valuable given the similarity of the GCMs (L114).

Response: Thank you for this valuable suggestion. We agree that a comprehensive model intercomparison would strengthen our study significantly. We will add a comprehensive comparison table in Section 4.1 that includes modeling results (Kang et al., 2024; Marzeion et al., 2020; Rounce et al., 2023; Schuster et al., 2023; Zekollari et al., 2024).

- Summary of results from GloGEM, PyGEM, and OGGM studies for comparable regions
- Statistical comparison using metrics described in Section 2.5
- Discussion of methodological differences and their implications

Reviewer Comment:

Section 2 could benefit from a clearer separation of data, models, and calibration methods. For instance, the climate section mentions a precipitation factor without explaining its calibration. The

OGGM model section includes all data related to glaciers, so model calibration could be placed in its own subsection under modeling.

Response: Excellent point. The current organization indeed conflates different methodological components, making it difficult to follow.

Proposed Revision: We will restructure Section 2 as follows:

2. Materials and Methods

    2.1 Study Region: Greenland's Peripheral Glaciers

    2.2 Data

        2.2.1 Climate Data (ERA5, CMIP6) and preprocessing

        2.2.2 Glacier Data (RGI, geodetic mass balance, Frontal Ablation Data)

    2.3 Open Global Glacier Model (OGGM)

        2.3.1 Model Framework and Setup

        2.3.2 Mass Balance Model

        2.3.3 Enhanced Marine-Terminating Glacier Module

        2.3.4 Freshwater Runoff and Peak Water Calculations

        2.3.5 Model Calibration

    2.4 Statistical Analysis

Precipitation Factor Explanation: We will add a detailed explanation in 2.3.5 that the precipitation factor (fp = 1.6) is a global multiplicative correction applied to ERA5 precipitation, calibrated to account for orographic precipitation, avalanches, and wind-blown snow that are not resolved in reanalysis data.

Reviewer Comment:

Reproducibility: There is no mention of the version of OGGM used in this study. According to the documentation, the most recent version was not used due to issues with the proposed frontier ablation (https://tutorials.oggm.org/stable/notebooks/tutorials/kcalving_parameterization.html). It would be helpful to specify the version used.

Response: Thank you for highlighting this critical reproducibility issue. Based on our research:

We used OGGM v1.5.3 with custom implementations for frontal ablation based on Malles et al. (2023). The reason we did not use OGGM v1.6+ is indeed the frontal ablation implementation issues mentioned in the tutorials. We implemented the enhanced frontal ablation parameterization (https://github.com/MuhammadShafeeque/Enhanced-Modeling-Marine-Terminating-

Glaciers/tree/Shafeeque) on OGGM v1.5.3, which provides the stable foundation needed for our Greenland-wide study.

Proposed Addition: We will:

- Specify OGGM version (v1.5.3)
- Update code and data availability statement with specific version information

Reviewer Comment:

Oceanic Forcing: The study frequently notes the lack of oceanic forcing in the OGGM model, but the potential implications of this limitation are not discussed. I recommend that the authors explore how incorporating oceanic forcing might affect their projections, particularly for solid ice discharge and regional variability. Could the current projections underestimate or overestimate the actual contribution?

Response: This is an excellent point that deserves detailed discussion. Our research reveals this is a significant limitation with important implications.

Key Implications of Missing Oceanic Forcing:

1. **Solid Ice Discharge Underestimation:** Studies show that oceanic forcing strongly controls marine-terminating glacier behavior (Bjørk et al., 2017; Chudley et al., 2023). Our projections likely underestimate:
    - Calving rates in warming ocean conditions
    - Regional variability in glacier response
    - Acceleration of retreat for glaciers experiencing warm water intrusion
2. **Regional Bias Implications:**
    - North-East region glaciers, which show resilience in our study, may be more vulnerable to oceanic warming
    - Our consistent solid ice discharge trends across emission scenarios may be unrealistic
    - The slight increase we project for North-East ice discharge contradicts observed decreasing trends linked to oceanic forcing

Literature Evidence:

- Möller et al. (2024): Demonstrated heterogeneous impacts of ocean thermal forcing on Greenland peripheral glaciers
- Wood et al. (2021): Showed ocean forcing drives glacier retreat in Greenland
- Slater et al. (2020): Highlighted importance of submarine melting for tidewater glaciers

Proposed Addition to Discussion (Section 4.4): We will add a comprehensive subsection discussing:

- Quantitative estimates of potential underestimation based on literature
- Regional implications for each subregion

Reviewer Comment:

Regional Variability: The study mentions significant regional variability in projected glacier loss, sea level rise contributions, and freshwater runoff. I encourage the authors to expand their analysis of these regional differences, examining how factors such as glacier size, geometry, elevation, and local climate contribute to the observed variability.

Response: We agree that our current analysis of regional variability is too superficial. The regional differences we observe reflect complex interactions that deserve detailed investigation. Combining responses to similar comments from Reviewer 2, we outline here the changes we envision.

Enhanced Regional Analysis Plan:

1. **Glacier Characteristics Analysis:**
   - Size distribution analysis by region
   - Elevation range and hypsometry comparison
   - Marine vs. land-terminating glacier ratios
   - Geometric properties (length, width, slope)
2. **Climate Drivers:**
   - Regional temperature and precipitation trends
   - Elevation-dependent warming patterns
   - Seasonal cycle variations
3. **Specific Regional Insights to Add:**
   - **North-East Resilience:** High snowfall rates, resistant geometry, delayed oceanic forcing response
   - **Central-West Vulnerability:** Low elevation, high surface melt sensitivity
   - **Flade Isblink Stability:** Large ice cap dynamics, multiple outlet glaciers

Proposed New Analysis: We will add detailed figures/tables/supplementary material showing:

- Regional glacier characteristic distributions
- Climate forcing variations by region

- Correlation analysis between glacier properties and projected changes
- Discussion of physical mechanisms driving regional differences

Reviewer Comment:

Figures Quality: Please check the quality of the figures, particularly Figures 3 and 4. It is unclear whether the glaciers are represented as points, polygons, or grid interpolations. Additionally, several panels show mismatched axis ranges, which makes the analysis difficult to interpret. Consider using color palettes that are more accessible for colorblind readers (e.g., ColorBrewer palettes: https://www.datanovia.com/en/blog/the-a-z-of-rcolorbrewer-palette).

Response: Thank you for these important technical comments. We acknowledge the figure quality issues. We'll update figures by combining your suggestions with Reviewer 2's.

Specific Improvements Planned:

- **Figure 3 & 4 Clarifications:**
  - Clarify that glaciers are represented as polygons from RGI outlines
  - Add clear legends explaining data representation
  - Standardize axis ranges across panels for comparison
  - Add clear methodological note about LOESS smoothing and mean statistics
- **Colorblind-Friendly Palettes:**
  - Replace current color schemes with perceptually uniform palettes that are accessible for the most common forms of colorblindness (Viridis, Plasma, or similar)
  - Ensure sufficient contrast ratios
- **Layout Consistency:**
  - Standardize font sizes across all figures
  - Align subplot dimensions and spacing
  - Consistent ordering of regions between different figure panels
  - Improve label placement to avoid overlaps

Reviewer Comment:

Precipitation Factor Calibration: The manuscript does not explain how the precipitation factor is calibrated, which is important for analyzing freshwater contributions. Please consider adding a table listing all parameters, their values, and any calibrations involved (Section 2.4).

Response: This is a crucial methodological detail that we did not explain sufficiently. The precipitation factor (fp = 1.6) was not calibrated in this study, but rather adopted from the standard OGGM v1.4 framework, originally calibrated by Maussion et al. (2019) against WGMS reference glaciers. Their cross-validation results are available at this link (https://cluster.klima.uni-bremen.de/~oggm/ref_mb_params/oggm_v1.4/crossval.html). This global constant accounts for orographic precipitation enhancement, snow redistribution, avalanche accumulation, and systematic ERA5 underestimation. Our calibration focused solely on the temperature sensitivity parameter (μ), which we calibrated individually per glacier using geodetic mass balance and frontal ablation observations (previous Section 2.4). The key distinction is that fp = 1.6 represents a pre-determined global value from the OGGM framework, while μ was individually calibrated as this study's primary methodological contribution. We will add a clarifying table listing all parameters, their values, and calibration methods to make this distinction clearer for readers.

MINOR COMMENTS

Reviewer Comment:

Abstract: Clarify how the values (e.g., 19-44%) were calculated—are they multi-model means or medians for extreme scenarios?

Response: These values represent the range between SSP126 (low end) and SSP585 (high end) scenarios, with each value being the ensemble mean ± 1 standard deviation across 10 GCMs.

Proposed Clarification: "By 2100, the glaciers are projected to lose 19±6% (SSP126) to 44±15% (SSP585) of their area and 29±6% (SSP126) to 52±14% (SSP585) of their volume (ensemble mean ± 1 standard deviation across 10 GCMs), contributing 10±2 to 19±5 mm to sea level rise."

Reviewer Comment:

Fig. 1. Define "MT glaciers" and consider adjusting the size or transparency of the triangles for better clarity.

Response: Proposed Revisions: We'll define "MT" as "Marine-Terminating" in figure caption and reduce triangle size and add transparency (alpha = 0.7).

Reviewer Comment:

Fig 1c: Change "Numbers" to "Number of glaciers" and verify the caption.

Response: Will change to "Number of glaciers" and verify the caption.

Reviewer Comment:

L125: Please elaborate on the delta method and explain how anomalies are calculated.

Response:

Detailed Explanation to Add (or supplementary material):

The CMIP6 temperature and precipitation data are downscaled to the baseline climate ERA5, that has been used for calibrating OGGM. A variation of the delta method (e.g. Ramírez Villegas and Jarvis (2010)) is being used for this procedure, whereby the precipitation is scaled and scaled temperature anomalies are applied to the 1981-2020 CE baseline climatology. This procedure is applied on a month-by-month basis.

For temperature:

$$T_{corrected} = T_{ERA5} + scf \times \left(T_{GCM} - \overline{T_{GCM\,(1981-2020)}}\right)$$

Where $scf = \frac{std\left(T_{ERA5\,(1981-2020)}\right)}{std\left(T_{GCM\,(1981-2020)}\right)}$

For precipitation: $P_{corrected} = P_{ERA5} \times \left(\frac{P_{GCM}}{\overline{P_{GCM\,(1981-2020)}}}\right)$

Reviewer Comment:

L234: Could one variable be analyzed using different methods? Please clarify.

Response: We will clarify that different statistical tests were selected based on data distribution characteristics:

- Parametric tests (ANOVA, t-tests) for normally distributed data
- Non-parametric tests (Kruskal-Wallis) for non-normal distributions
- Post-hoc tests (Tukey's HSD) following significant omnibus tests

Reviewer Comment:

Fig 3: Was smoothing applied to the confidence intervals? Consider sharing the vertical axis across subplots to increase the size of the lower subplots. This applies to subsequent figures as well.

Response: Yes, LOESS smoothing was applied to both means and confidence intervals. We will:

- Clearly state this in the caption
- Implement shared y-axis across subplots and resize for better readability

Reviewer Comment:

Section 3.2: The section heading suggests a comparison, but there is little temporal and spatial comparison between variables. Please expand this comparison.

Response: We will add explicit comparisons:

- Temporal evolution of solid vs. liquid contributions
- Regional patterns in the transition from solid to liquid dominance
- Quantitative analysis of the timing differences
- Cross-regional comparison of freshwater composition changes

Reviewer Comment:

References: Some references are listed with full journal titles, while others use abbreviations. Please ensure consistency throughout the reference list.

Response: We will standardize all references consistently throughout based on the journal's format.

Reviewer Comment:

Data: Clarify whether the data on Zenodo is available at the subregional scale or glacier-ID scale.

Response: We will clarify that the Zenodo data includes both:

- Glacier-ID scale results for individual glaciers
- Subregional aggregated time series
- Metadata describing data structure and variables

We believe these revisions will significantly strengthen the manuscript and address all reviewer concerns comprehensively. Thank you again for the thorough and constructive review.

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