# Greenland Contribution to Sea Level by 2050: The Role of Meltwater in Shaping the Future Ice Sheet Evolution

Principal Investigator: Helene Seroussi (329); Co-Investigators: Nicole-Jeanne Schlegel (329), Youngmin Choi (329), Alex Gardner (329), Eric Larour (329), Peyman Tavallali (398), Umaa Rebbapragada (398), Amy Braverman (398), Hamed Hamze Bajgiran (California Institute of Technology), Houman Owhadi (California Institute of Technology), Helene Seroussi (Dartmouth College)

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## Objectives & Approach:

The key objective of this project is to **improve understanding of the Greenland Ice Sheet's response to changes in climate on decadal time scales**. We will provide estimates of Greenland's contribution to sea level by 2050 and quantify associated uncertainties.

Our main goals are to:

1) ***Assemble a synthesized dataset of glaciers' observations over the past 35 years***, including measurements of ice elevation, velocities and terminus positions.

2) ***Improve model representation of processes associated with meltwater***, by coupling the Glacier Energy Mass Balance (GEMB) surface model with JPL's Ice Sheet and Sea-level System Model (ISSM). Simulations consider percolation of refreeze of meltwater within snow and firn and its impact on ice dynamics.

3) ***Leverage observations to initialize, constrain, and validate simulations of ice sheet dynamics.*** Simulations will be calibrated over the hindcast period (1985-2017), making use of ISSM's assimilation capabilities and resulting in improved predictive capabilities (2020-2050).

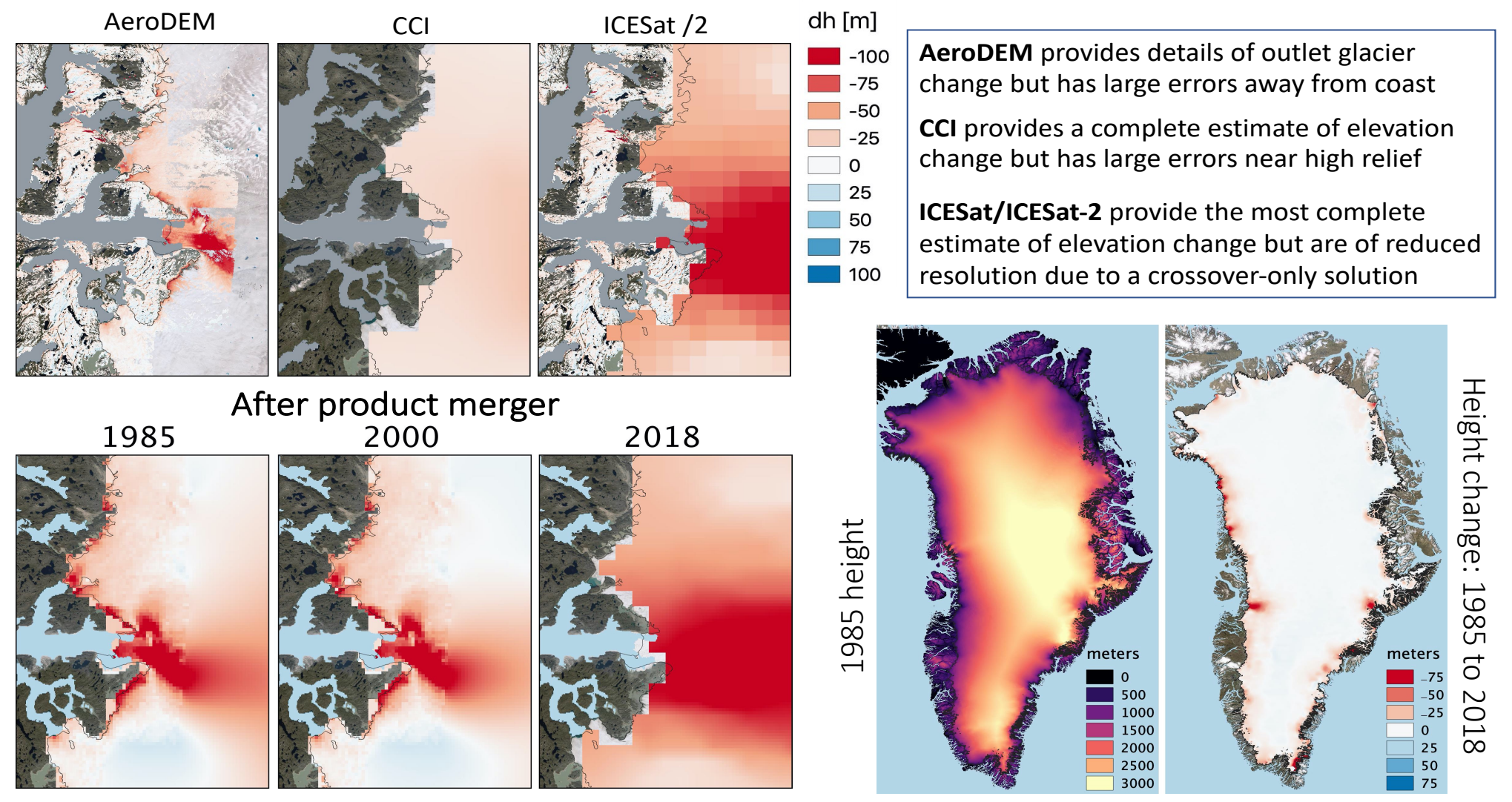
4) ***Develop uncertainty quantification** (UQ) **techniques for systematic analysis of ice sheet model uncertainty***. We will explore alternative UQ techniques, specifically designed for science modelling applications.

## Background:

Over the next 30 years, Greenland is expected to experience increasing surface melt, resulting in accelerated ice flow through the modification of the friction at the glacial bed and increased rates of ocean melt the ice fronts. Yet, ice sheet models have crude representation of the physical processes linking meltwater to glacier flow. **Here, we leverage satellite observations acquired over the past 35 year to characterize relevant processes, validate their representation in models, produce calibrated projections of Greenland over the next 30 years, and provide probabilistic uncertainties future scenarios.** Our results will inform future missions by providing key observational requirements needed to better understand and simulate the response of the Greenland Ice Sheet to projected change in atmosphere and ocean.

## Results:

### 1. Observational database



**AeroDEM** provides details of outlet glacier change but has large errors away from coast

**CCI** provides a complete estimate of elevation change but has large errors near high relief

**ICESat/ICESat-2** provide the most complete estimate of elevation change but are of reduced resolution due to a crossover-only solution

**Figure 1.** *Development of a merged, continuous record of elevation change from disparate satellite observations, used to calibrate and evaluate the ice sheet model over the historic period.*

### 2. Surface processes

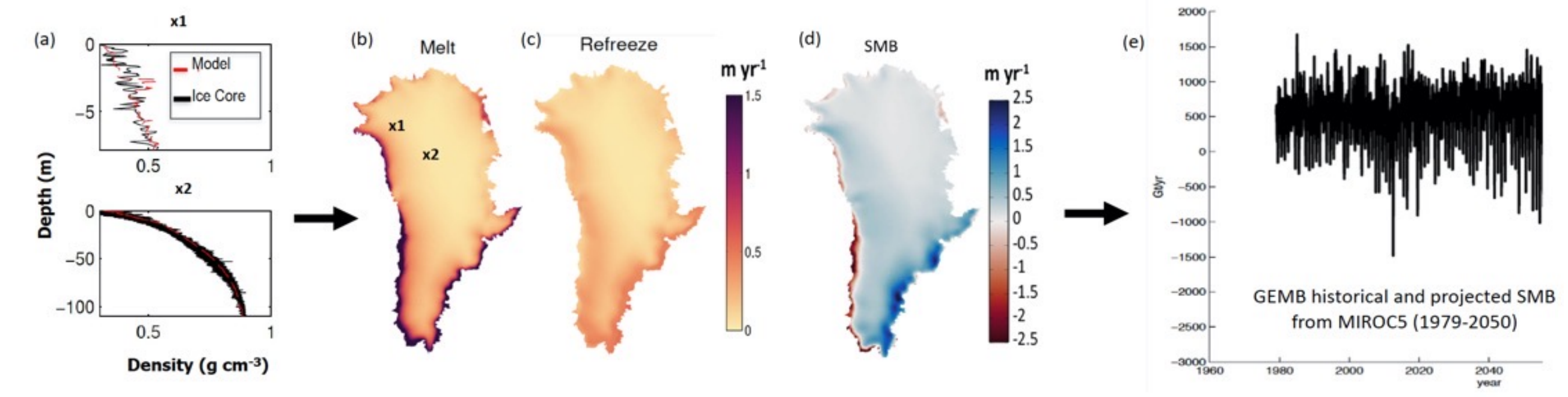
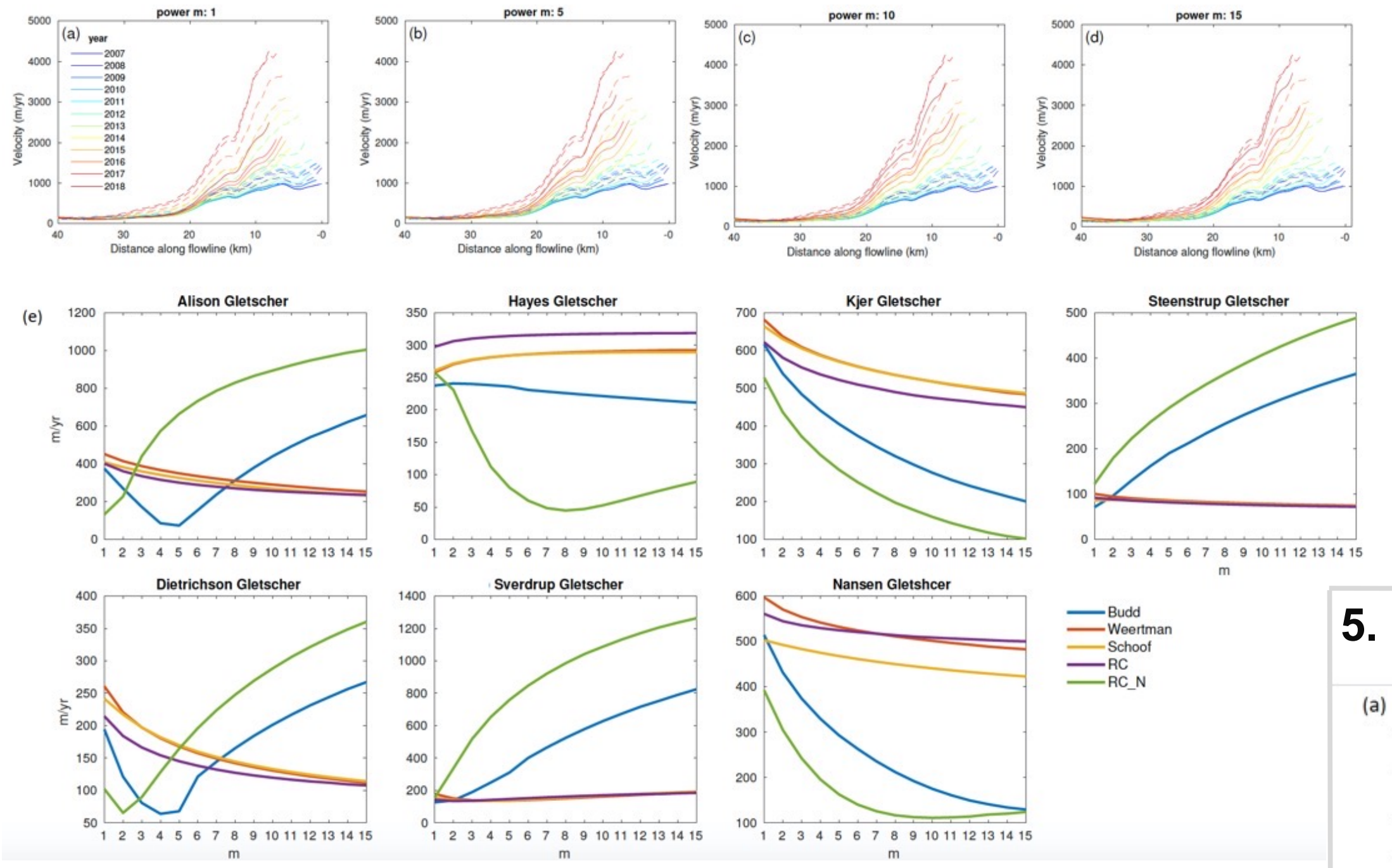


**Figure 2. Calibration of GEMB** *against firn cores (a) and integration of observations, like MODIS data*, **improve model hindcast** *of b) surface melt, c) refreeze, and d) total surface mass balance (SMB), resulting in more reliable ice sheet model forcing and improved confidence in e) projections of surface radiation and mass balance.*

**Figure 3. Observational calibration of ISSM results in improved skill in capturing recent ice flow acceleration**. *Top: Observed (dashed) and modeled (solid) velocities for Kjer glacier using a Coulomb (RC_N) friction law and varied friction law exponent,* **m** *(a-d). e) Root Mean Square Error (RMSE) between modeled and observed ice velocity for various sliding laws as a function of* **m** *for 7 different glaciers in Central West Greenland.* **Results vary regionally, but show that accounting for changes in effective pressure** *(i.e., Budd and RC_N)* **better reproduces observations, with more plastic basal conditions (m>7) than commonly assumed in ice sheet models (m=1 or 3).**

### 3. Dynamic modeling of ice sheet flow



### 4. Projection framework

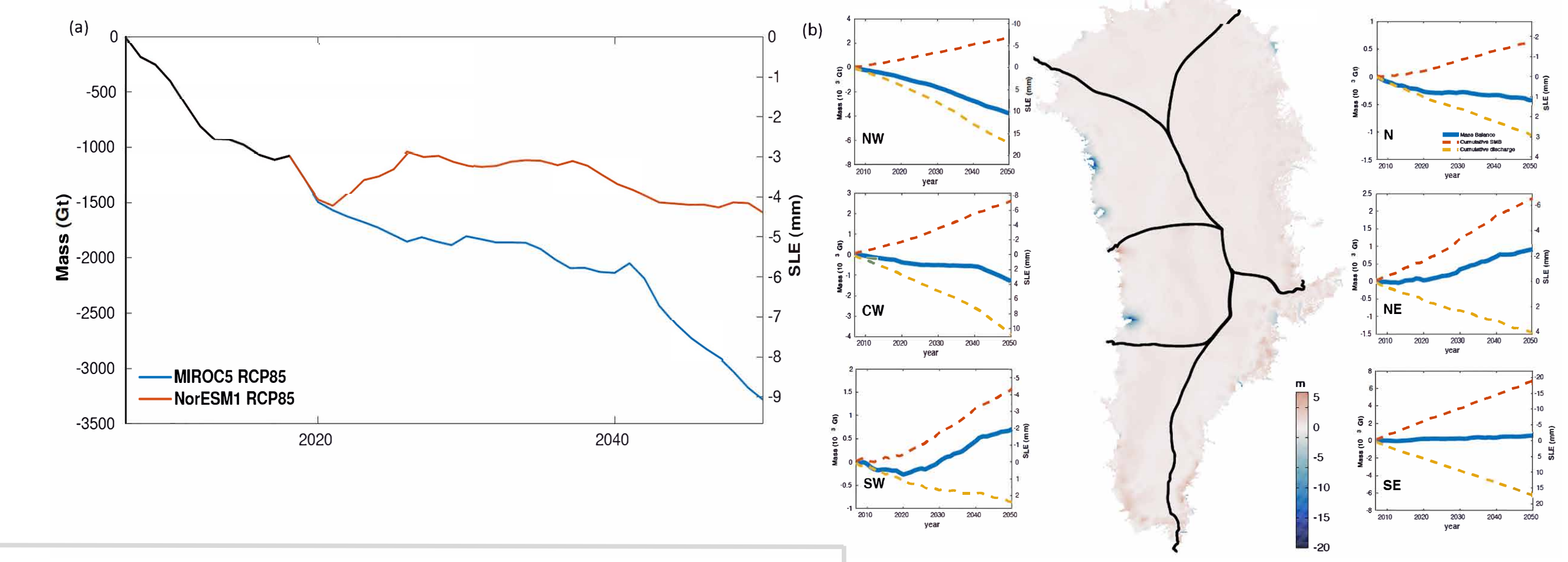


**Figure 4.** *a) Greenland ice mass and sea-level contribution simulated with GEMB SMB and calibrated ISSM through 2050 under RCP8.5. b) Projected ice thickness change with plots of yearly cumulative SMB (red dash), ice discharge (orange dash), and ice mass changes (solid blue) over the same period under MIROC RCP8.5 scenario for six Greenland basins.*

### 5. Estimation of uncertainties

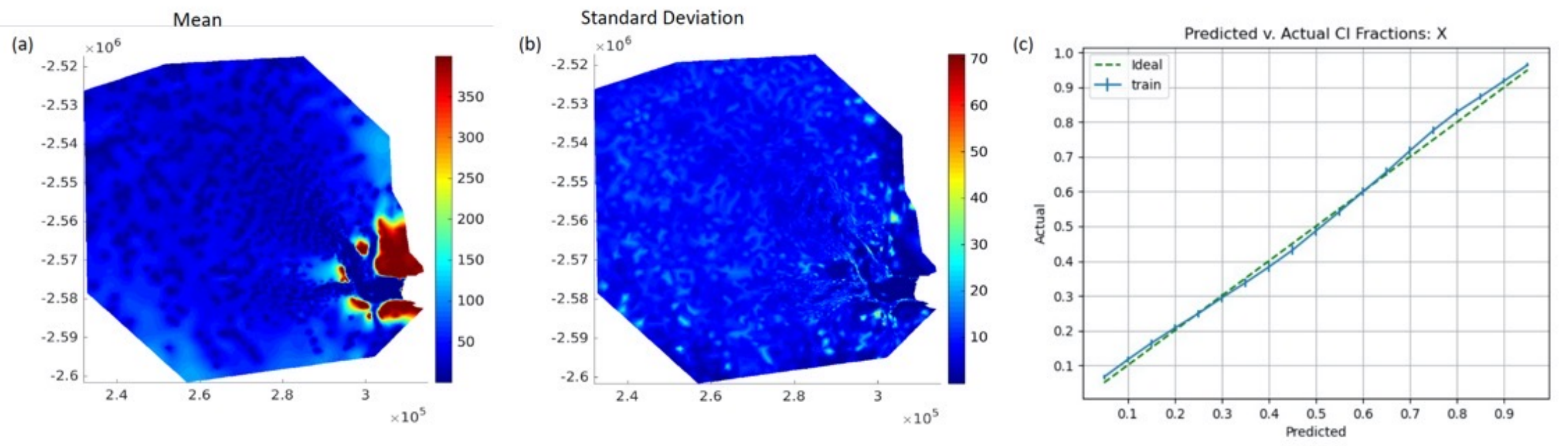


**Figure 5.** *UQ of basal friction using a novel game theoretic approach (DTUQ4) has been evaluated against a Bayesian approach. a) Mean and b) standard deviation of basal friction in Helheim Glacier using DTUQ4. c) Evaluation of our Bayesian approach, showing the fraction of velocities falling inside predicted confidence intervals.*

## Significance:

Earth 2050 is a JPL/Caltech initiative to improve our understanding of fundamental climate science questions. **Here we address the stability of the Greenland Ice Sheet and its contribution to sea-level rise by 2050, with an effort to consolidate the link between JPL expertise on ice observations and modeling, and to initiate new collaborations between JPL and campus in UQ analysis.** This project uniquely focuses on the evolution of Greenland until 2050, an important time scale for observing, understanding and predicting its evolution and contribution to sea level. By informing our numerical model simulations with observations, we can improve model hindcasts of ice flow and better assess simulation error. Since the dimensionality of the model parameter space is large (thousands to hundreds-of-thousands of parameters), development and use of novel UQ methods, like those based on the game theoretic approach, opens the door to more robust estimates, including distribution of worst-case scenarios.

## Publications:

V.C. Tsai, L.C. Smith, A.S. Gardner, H. Seroussi H (2021). "A unified model for transient subglacial water pressure and basal sliding". Journal of Glaciology 1–11. https://doi.org/10.1017/jog.2021.103

H.H. Bajgiran, P.B. Franch, H. Owhadi, C. Scovel, M. Shirdel, M. Stanley, and P. Tavallali (2021). "Uncertainty Quantification of the 4th kind; optimal posterior accuracy-uncertainty tradeoff with the minimum enclosing ball", https://arxiv.org/abs/2108.10517.

A. Gardner, N.-J. Schlegel, E. Larour et al., 2021, "Glacier Energy and Mass Balance (GEMB) v1: A model of firn processes for cryosphere research", Geosci. Model Dev., in prep.

A. Feldman, P. Tavallali, U.D. Rebbapragada, H. Owhadi, H. Seroussi, N.-J. Schlegel, Y. Choi, et al., "Using Bayesian Inference to Quantify Uncertainty in Glacier Ice Frictions and Velocities", in prep.

Y. Choi, H. Seroussi, A. S. Gardner, & N.-J. Schlegel, "Impact of basal friction law on the dynamics of northwest Greenland", in prep.

**National Aeronautics and Space Administration**

**Jet Propulsion Laboratory**
California Institute of Technology
Pasadena, California

**www.nasa.gov**

**PI/Task Mgr Contact**
**Email: schlegel@jpl.nasa.gov**

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