Simulating glaciers in the Alps with the Community Ice Sheet Model

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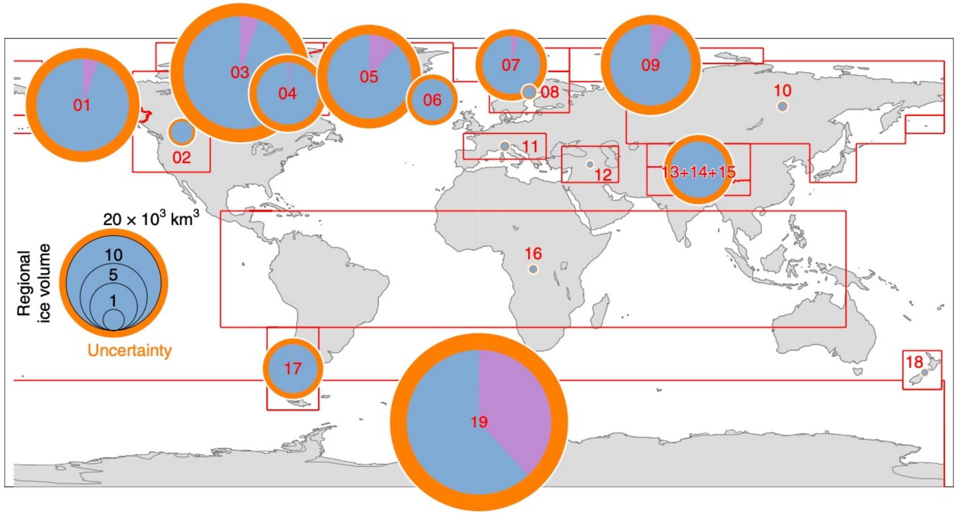
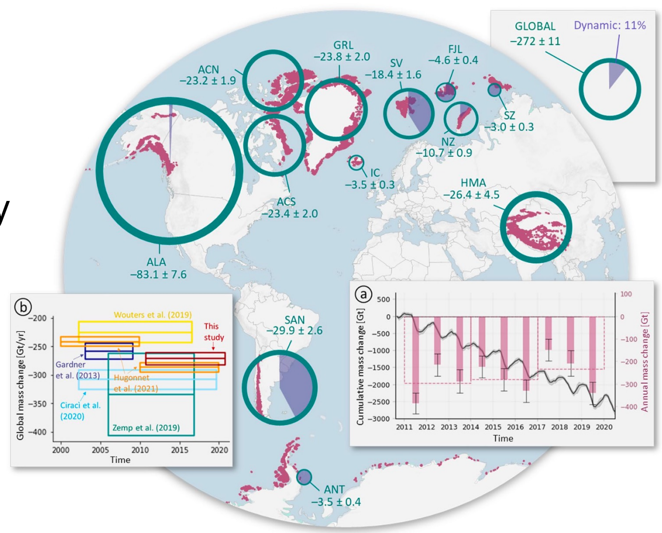
Mountain glaciers



- **~200,000 glaciers** in 19 Randolph Glacier Inventory (RGI) regions
- Total area **~700,000 km^3**
- Volume **~158,000 km^3** (**0.32 m** sea-level equivalent)

Ice volume in RGI regions (Farinotti et al., 2019)

Glacier mass changes from satellite altimetry (Jakob & Gourmelen, 2023)



- 2010–2020: Mass loss **~270 Gt/yr** (2% of total glacier volume)
- ~90% of mass loss is due to atmospheric forcing

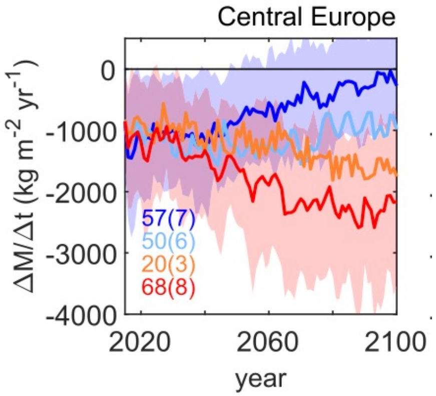
GlacierMIP

Glacier Model Intercomparison Project (2015+): A framework for intercomparison of global-scale glacier mass change models

Phases 1 and 2: Compare century-scale projections driven by GCMs

Marzeion et al. (2020): **Mass loss, 2015–2100**, from 11 glacier models, 10 GCMs, 4 RCPs

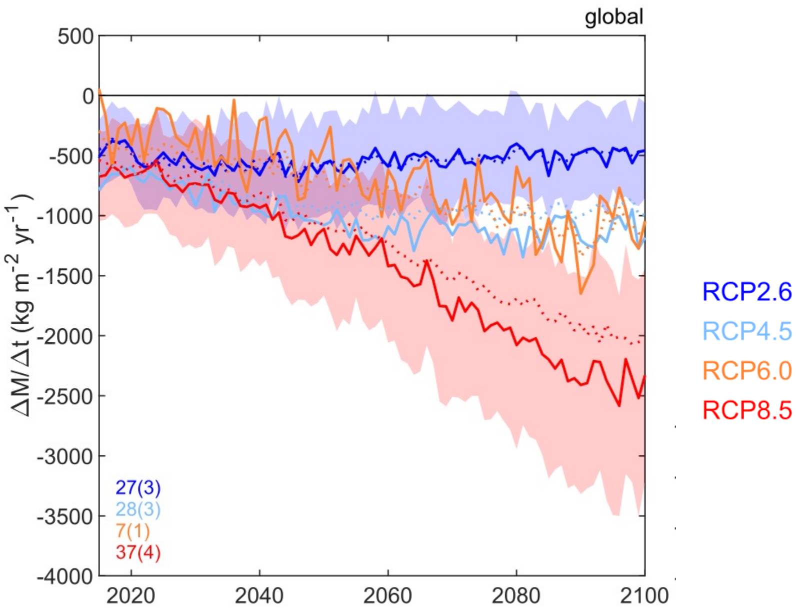
- **RCP2.6**: 79 ± 56 mm SLR (**18%**)
- **RCP8.5**: 159 ± 86 mm SLR **(36%)**



Evolution of SMB, 2015–2100.

Left: European Alps

Right: All glaciers



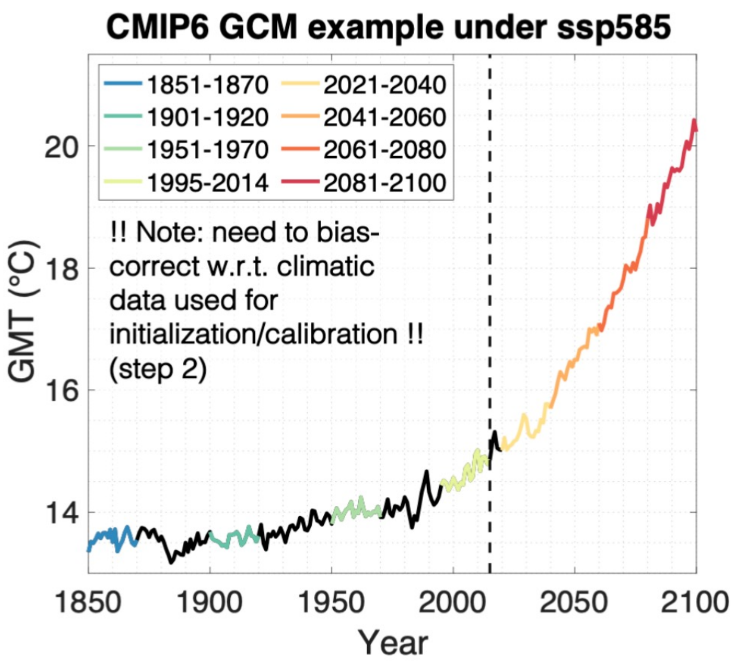
GlacierMIP3

- What would be the **equilibrium volume and area** of all glaciers if global mean temperatures were to stabilize at different temperature levels?
- How much time would the glaciers need to reach their new equilibrium?

Step 1: Use a calibrated model to **simulate the glacier geometry at the RGI date** (c. 2003).

Step 2: Bias-correct the prescribed CMIP6 GCMs

Step 3: **Run to equilibrium** (2000–5000 years) for each of 8 repeat periods (4 past, 4 future)



Glacier observations and models

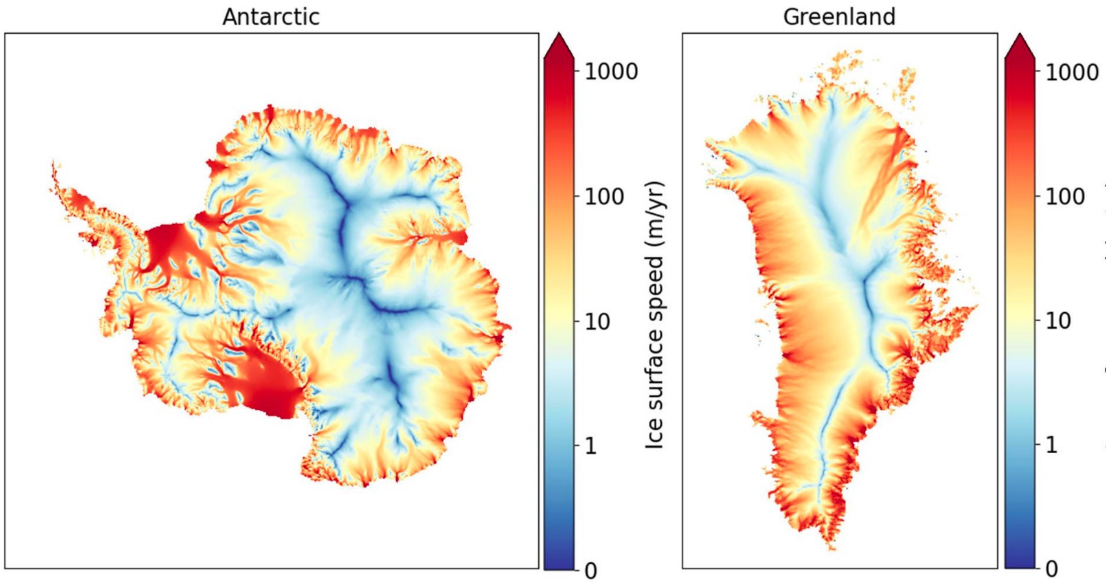
Glaciers areas are well known, but thickness measurements are sparse.

Best thickness estimates are from **Farinotti et al. (2019):** Used 5 models to **invert for ice thickness** based on surface topography and principles of ice flow dynamics.

- All glacier models compute the **surface mass balance** (often with temperature index methods)
- **Geometry change** is computed with methods of different complexity
  - **Volume-area scaling**
  - **Flowline models of ice dynamics**
    - OGGM (Maussion et al., 2019)
    - GloGEMflow (Zekollari et al, 2019)
  - **3D models** (generally for individual glaciers, not regions)

Modeling glaciers with CISM

The Community Ice Sheet Model (CISM) is the dynamic ice sheet component of CESM and has been applied mainly to the Greenland and Antarctic Ice Sheets.



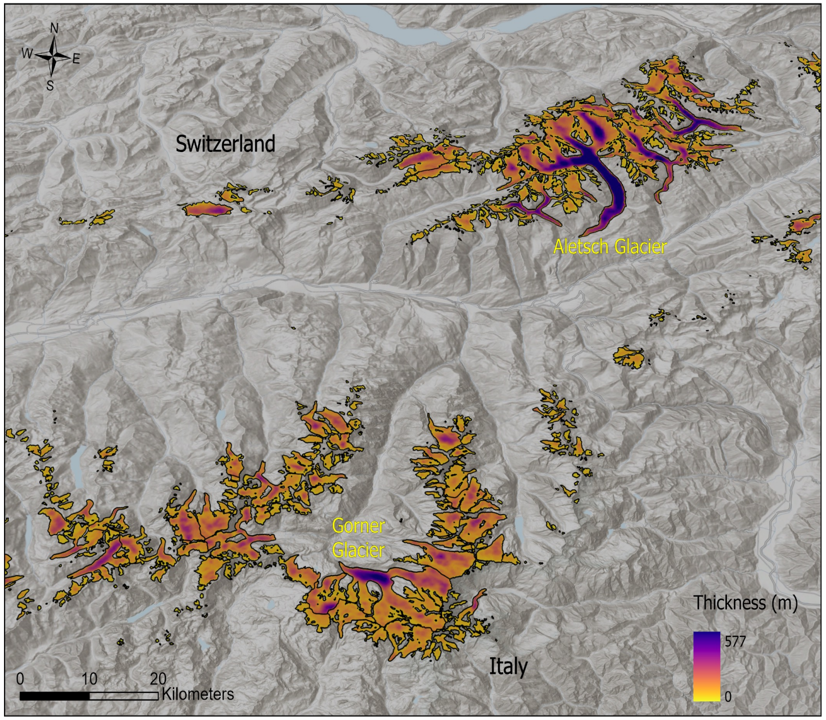
Challenges for glacier modeling:

- **High resolution** (~100–200 m for glaciers, 4 km for ice sheets)
- **Surface mass balance** depends on features below the grid scale of climate models (aspect, orographic forcing, shading)
- Decadal evolution is sensitive to the **initial state**

Modeling glaciers with CISM

European Alps

- 3900 glaciers, ~700 x 450 km domain, 100-m and 200-m grids



- **Glacier outlines** from RGI v6
- Continuous **surface and bed topography** by merging USGS 90 m SRTM DEM and *Farinotti et al. (2019)* glacier-specific surface DEMs and thickness data
- **Atmospheric forcing** (*2m air temperature, total precipitation*) from ISIMIP W5E5 v2, a bias-corrected ERA5 reanalysis dataset.

Glacier mass balance

2-equation calibration scheme:

$$\alpha P_i + \mu (T_i - T_{melt} + \beta) = 0 \qquad (1)$$
$$\alpha P_i' + \mu (T_i' - T_{melt} + \beta) = B_i \qquad (2)$$

Snowfall computed from precip based on temperature (all snow below 0^{o}C, no snow above 2^{o}C)

Eq. (1): **Net zero mass balance** (over the RGI target area for each glacier) for the **baseline climate**, 1979–1988

Eq. (2): Match the **observed mass balance** (Hugonnet et al., 2021) for the **recent climate,** 2000–2019

P = monthly mean precipitation

T = monthly mean surface air temperature (downscaled with lapse rate of 6 K/km)

B = Mass balance

T_{melt} = melting threshold, -1^{o}C

Glacier-specific tuning factors:

μ = SMB factor, mm/yr/deg
α = precipitation correction factor
β = temperature correction factor, usually 0

Glacier dynamics

Depth-integrated higher-order (DIVA) velocity solver

- Includes longitudinal and lateral shear stresses
- Relatively stable at high resolution, unlike SIA (Robinson et al., 2022)

Basal friction:

- **Power law**, $\tau_b = C_p(x, y)\, u^{1/3}$
- **Adjust C_p locally to nudge the ice thickness toward the target value**
- The target value is based on **Farinotti et al. (2019),** corrected for the SMB between the baseline date (1984) and the RGI date (2003)

Glacier advance and retreat

Preserve glacier outlines to the extent possible, allowing modest advance consistent with the cooler baseline climate.

- Each initially glaciated cell has a fixed integer ID (1:3886).
- In **advanced cells**, the ID is given by the adjacent upstream glacier.
- In **retreated cells**, the ID is set to 0 but can return to the initial value.

For advanced cells:

- In the ablation zone (SMB < 0), apply the SMB in full.
- In the accumulation zone (SMB > 0), ignore the SMB.

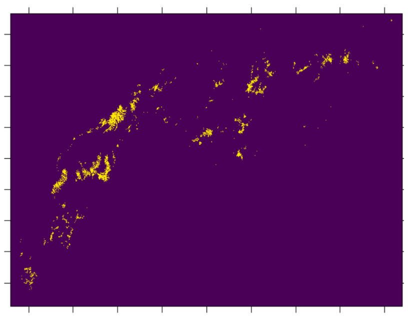
Mont Blanc and Chamonix

Spin-up

Spin up the model for **10,000 years** (8000 with inversion, 2000 without)

Initial A = 2086 km^2, V = 126.6 km^3

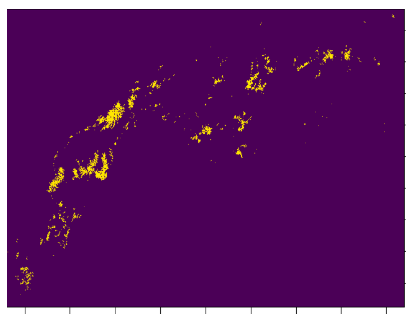
(2003 estimates)



Initial glaciated region

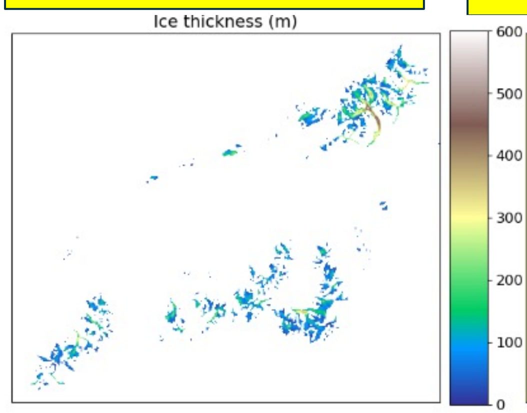
Final A = 2501 km^2, V = 138.0 km^3

(1980s climate)

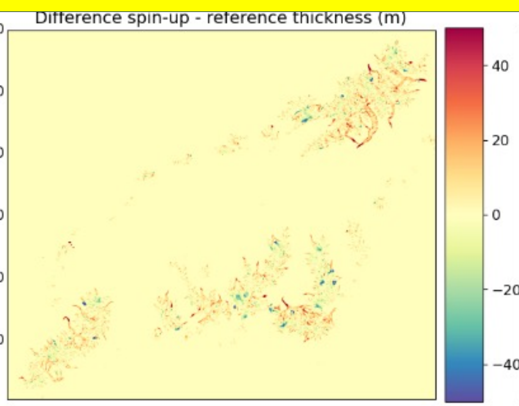


Final glaciated region

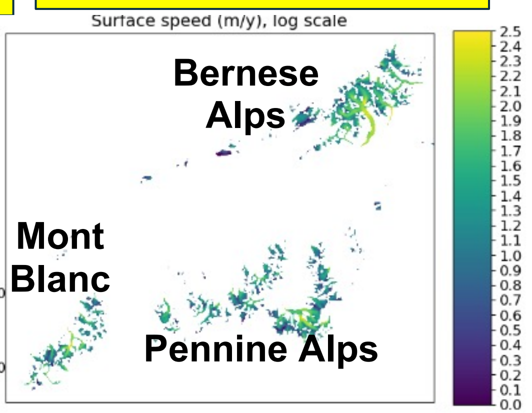
Initial thickness (m)



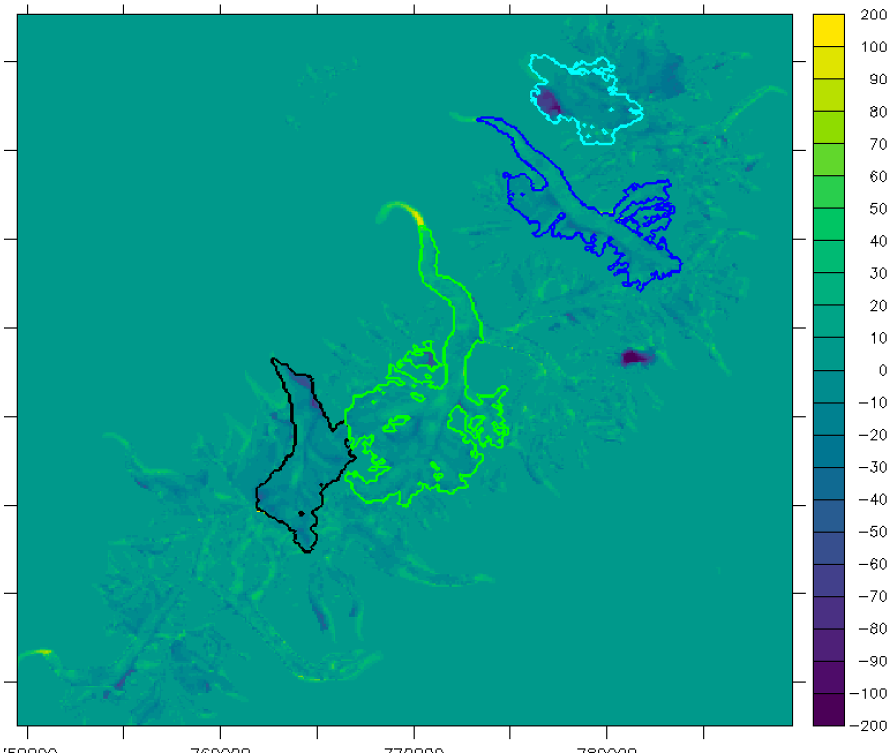
Final minus initial thickness



Surface speed (m/yr)



Mont Blanc Massif

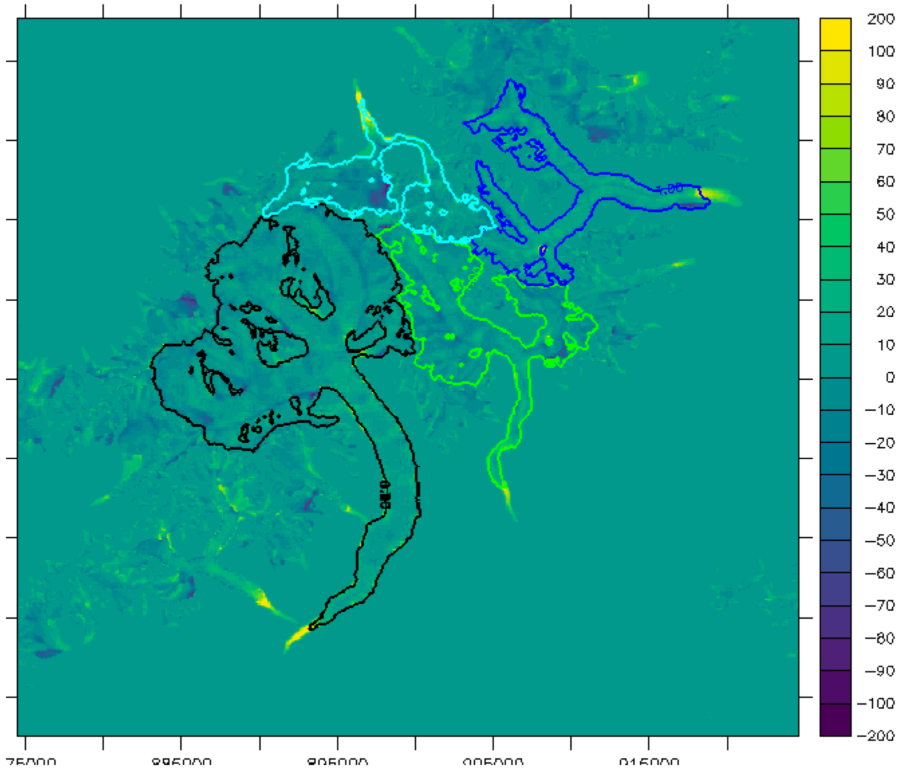


Spun-up minus initial ice thickness

Lower left to upper right: Bossons, Mer de Glace, Argentière, Trient

Mont Blanc and Mer de Glace

Bernese Alps



Spun-up minus initial ice thickness

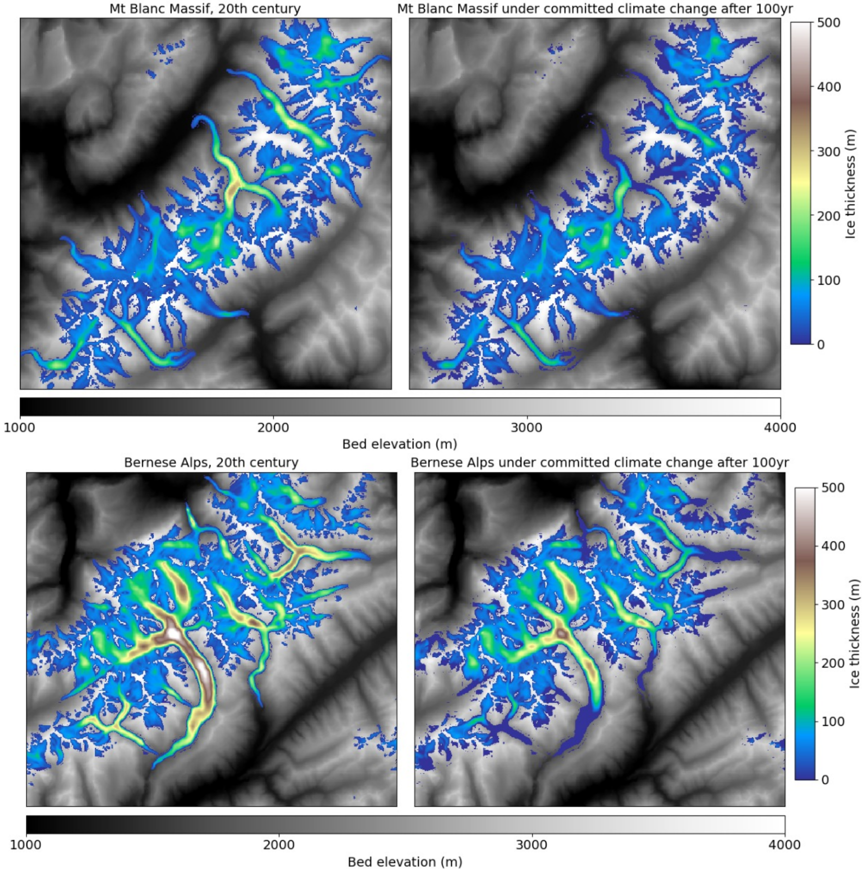
Clockwise from lower left: Greater Aletsch, Fiescher, Unteraar, Lower Grindelwald

Jungfrau and Greater Aletsch Glacier

Committed glacier loss

In a highly optimistic scenario—no warming compared to 2000–2019—the Alps will lose 63% of their 1980s volume.

- Most of the volume loss is in the first 100 years.



Mont Blanc

Left: 1984
Right: 2084

Bernese Alps

Left: 1984
Right: 2084

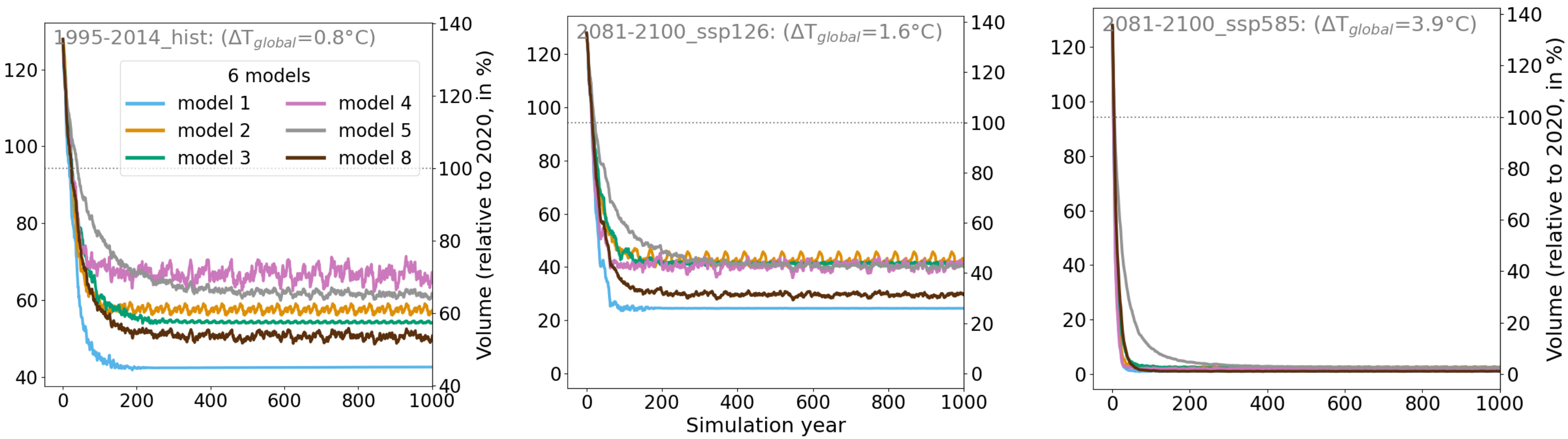
CISM vs. other GlacierMIP3 models

CISM sensitivity is on the high end compared to other GlacierMIP3 models

- 1995–2014: Median loss ~40%, CISM loss ~50%
- ssp1-2.6: Median loss ~ 60%, CISM loss ~70%
- ssp5-8.5: Near-total loss for all models

GlacierMIP3 results from Lilian Schuster

Bias-corrected GFDL forcing, relative to 2020 volume (CISM = model 8)



1995–2014 | ssp1-2.6 | ssp5-8.5

Future work

- Understand why CISM is more sensitive than other GlacierMIP3 models for the Alps
  - Related to 3D geometry and elevation/temperature feedbacks?
- Extend to other glacier regions (High Mountain Asia in progress)
  - Add support for marine-terminating glaciers
- Incorporate dynamic glaciers in CESM
  - Move away from glacier-specific tuning factors, perhaps using the CLM hillslope scheme (elevation- and aspect-dependent)

Thank you!