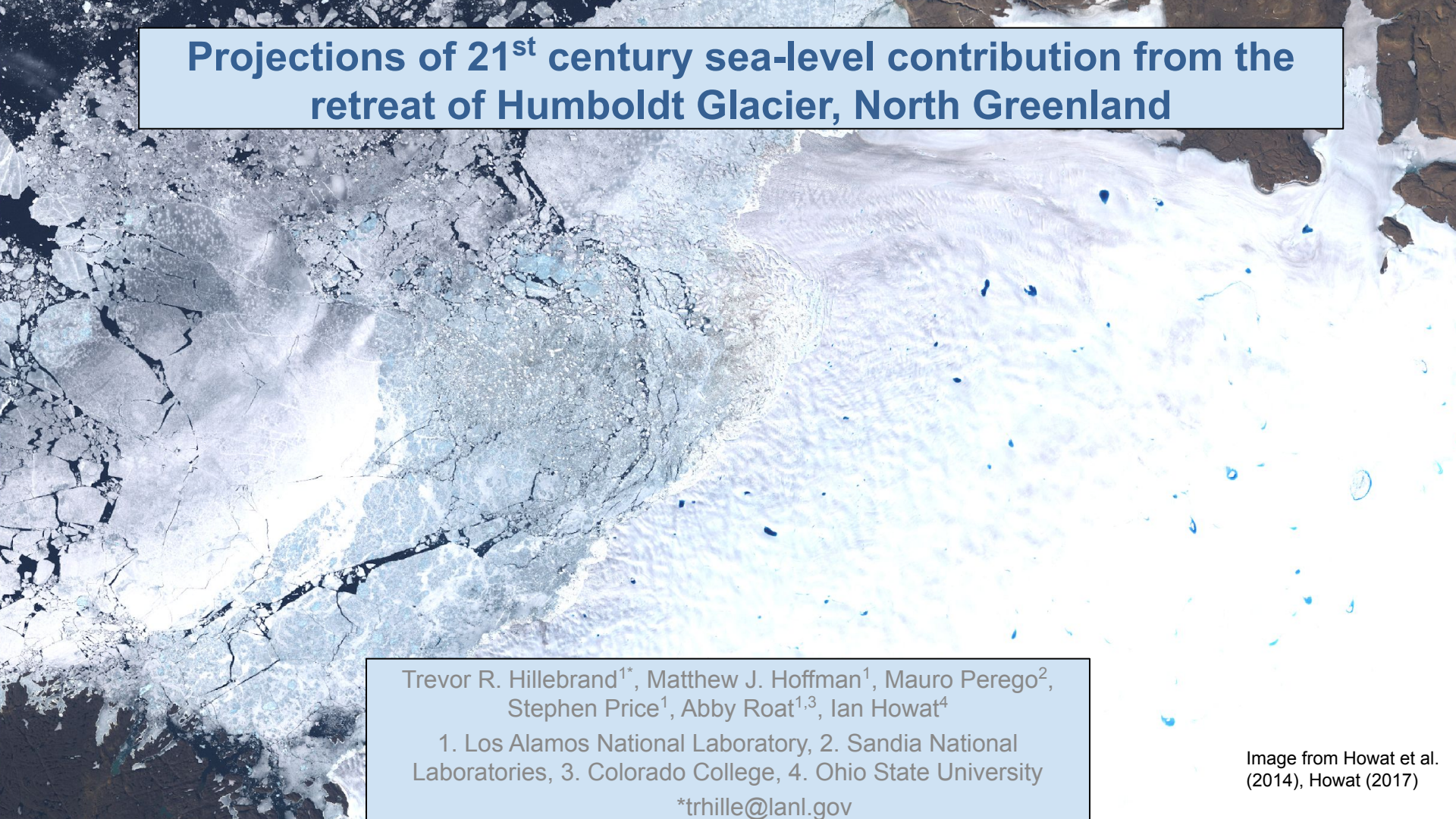




Projections of 21st century sea-level contribution from the retreat of Humboldt Glacier, North Greenland

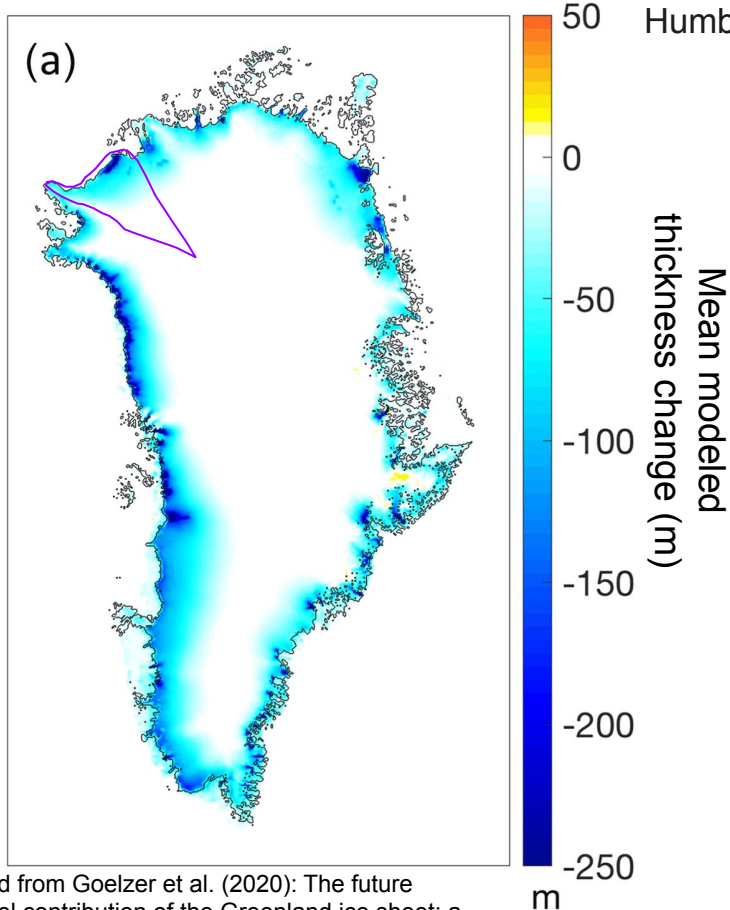
Trevor R. Hillebrand^{1*}, Matthew J. Hoffman¹, Mauro Perego²,
Stephen Price¹, Abby Roat^{1,3}, Ian Howat⁴

1. Los Alamos National Laboratory, 2. Sandia National
Laboratories, 3. Colorado College, 4. Ohio State University

*trhille@lanl.gov

Image from Howat et al.
(2014), Howat (2017)

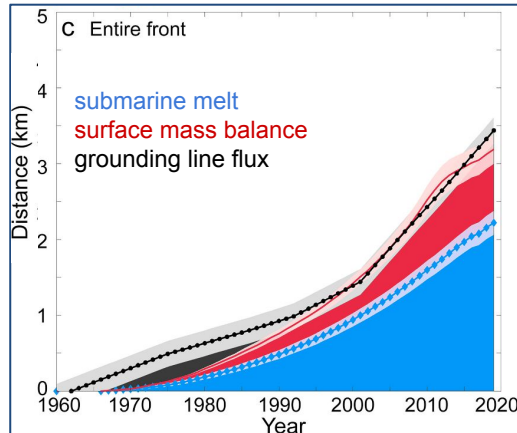
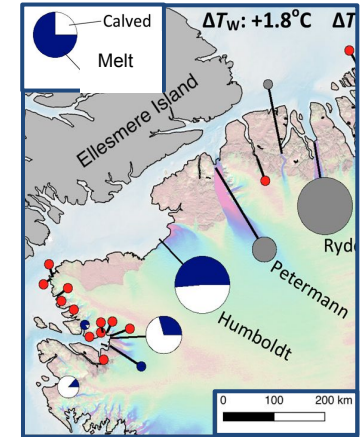
Humboldt Glacier contains ice equivalent to ~ 19 cm global mean sea level rise. Ice sheet models predict significant thinning and retreat of Humboldt Glacier this century.



Modified from Goelzer et al. (2020): The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6. [License](#)

Humboldt has lost the largest area of grounded ice in Greenland: $\sim 280 \text{ km}^2$ since 1992 (Wood et al., 2021).

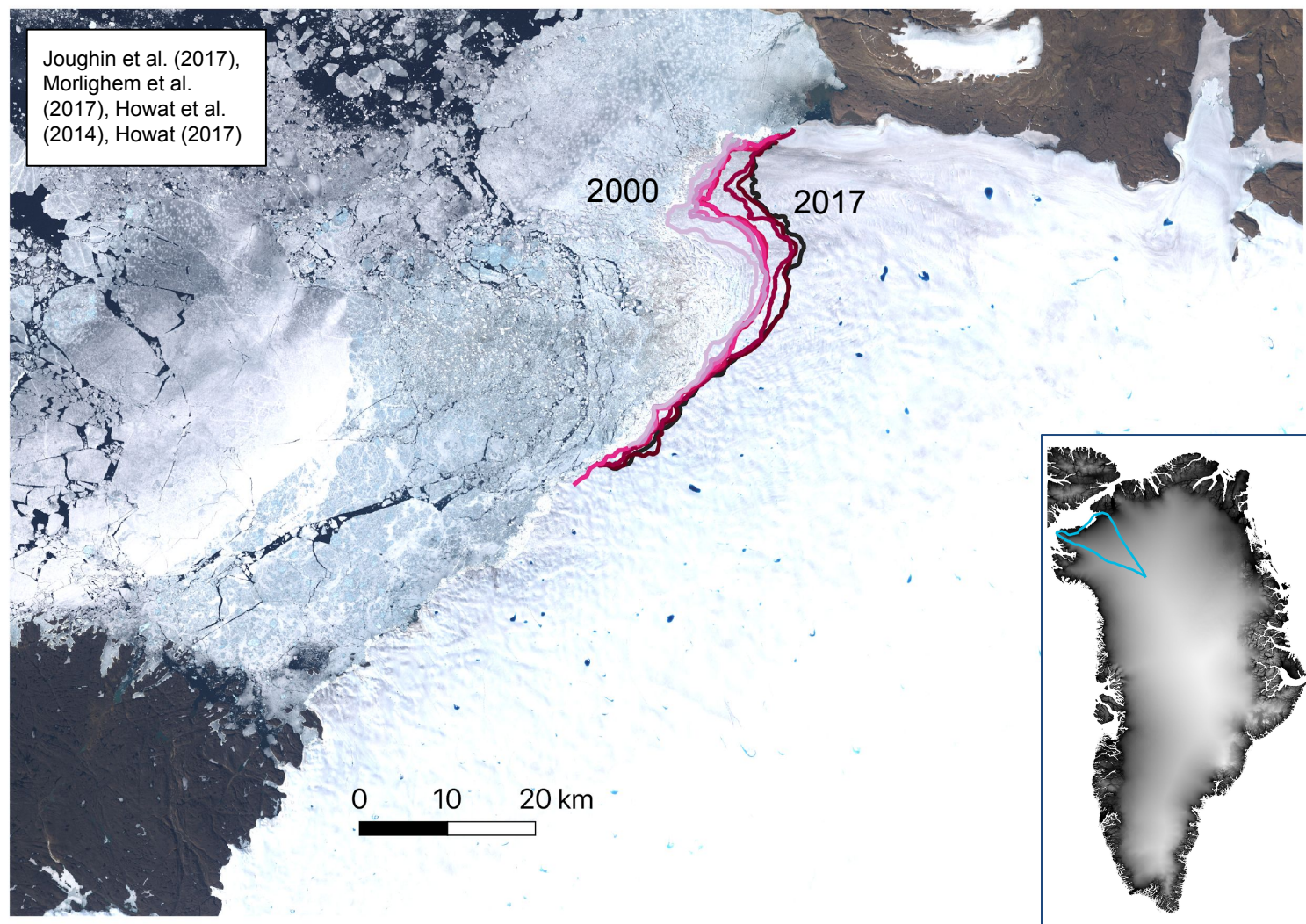
More than half of this is estimated to be from submarine melting.

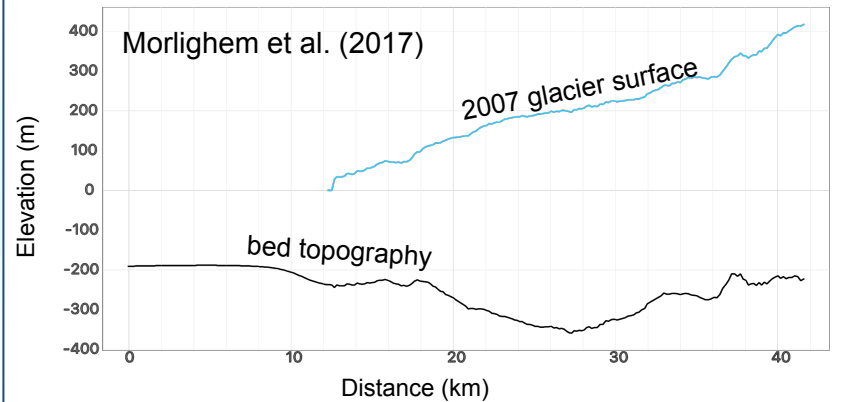
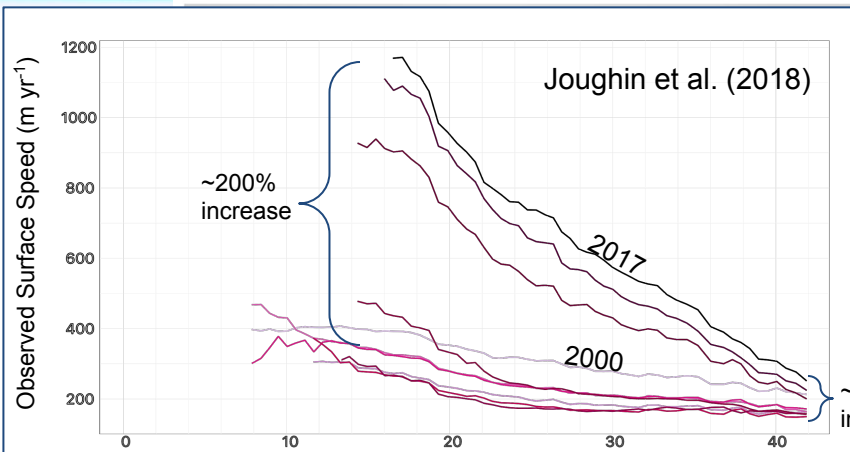


Modified from Wood et al. (2021): Ocean forcing drives glacier retreat in Greenland. [License](#)

Modified from Rignot et al. (2021): Retreat of Humboldt Gletscher, North Greenland, Driven by Undercutting From a Warmer Ocean. [License](#)

Joughin et al. (2017),
Morlighem et al.
(2017), Howat et al.
(2014), Howat (2017)

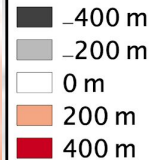




0 10 20 km

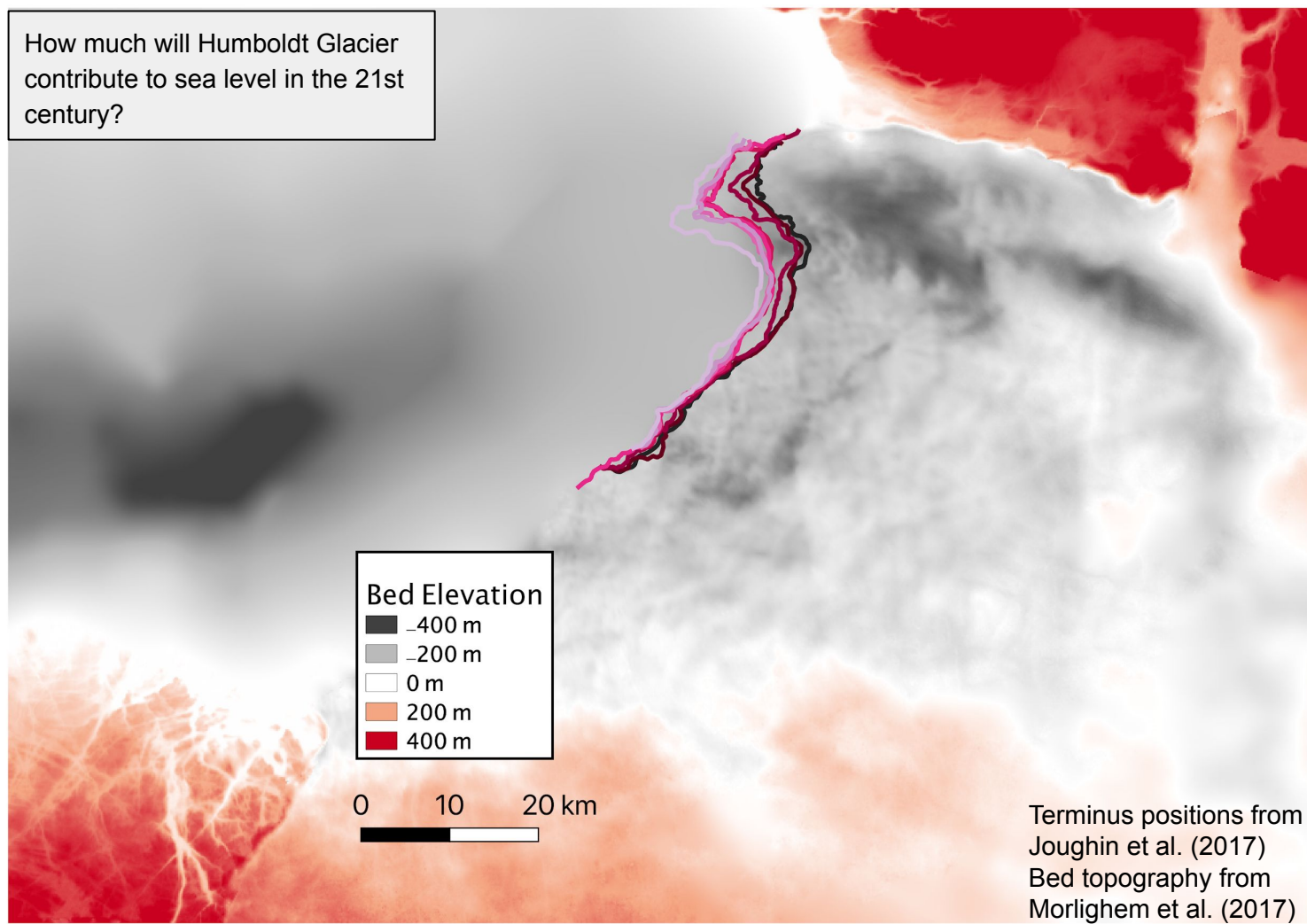


Bed Elevation



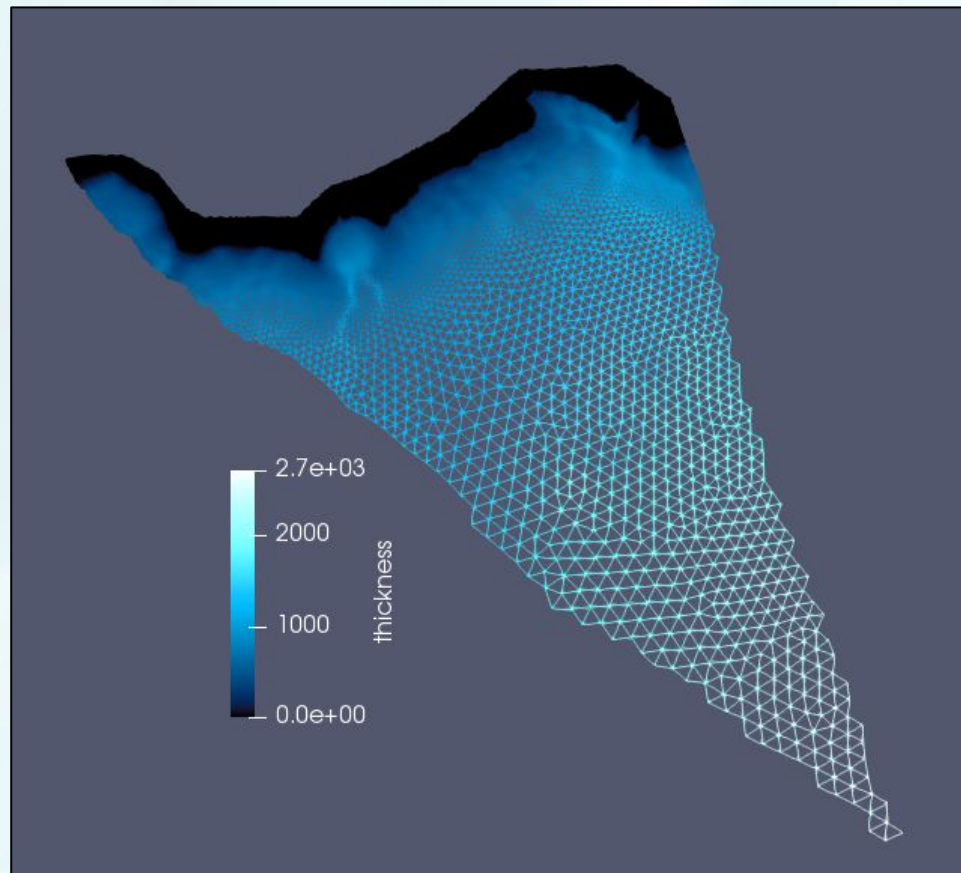
Terminus positions from
Joughin et al. (2017)
Bed topography from
Morlighem et al. (2017)

How much will Humboldt Glacier contribute to sea level in the 21st century?



Model setup

- MPAS-Albany Land Ice (MALI) ice sheet model*
 - Blatter-Pattyn stress balance
 - 3D, finite-element code
 - Ice sheet component of E3SM Earth system model (e3sm.org)
- 1–10km unstructured mesh
 - Regional domain for Humboldt Glacier
 - Fixed velocity boundary conditions
 - ~18,000 cells on 180 CPUs
- RCP 8.5 climate forcings
 - ocean thermal forcing from MIROC5 and HadGEM2
 - MAR3.9 surface mass balance & runoff



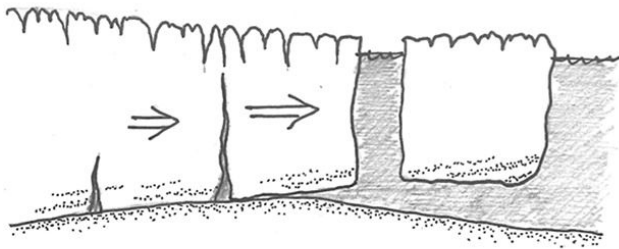
MPAS = Model for Prediction Across Scales

For exhaustive model description, see Hoffman et al. (2018):

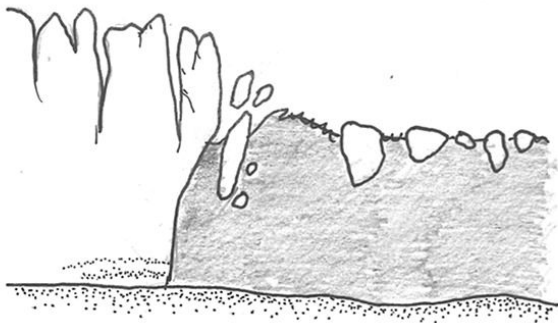
MPAS-Albany Land Ice (MALI): a variable-resolution ice sheet model for Earth system modeling using Voronoi grids

Iceberg calving

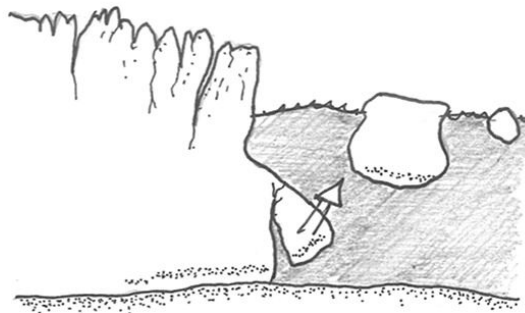
A: Longitudinal extension



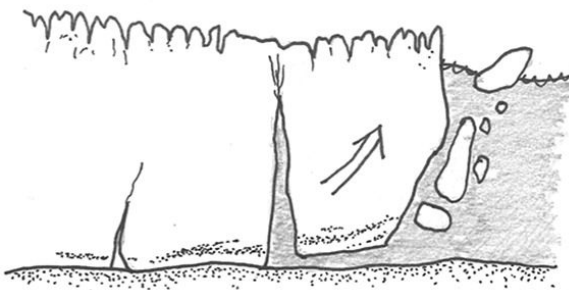
B: Melt-undercutting



C: Buoyant calving - ice foot



D: Buoyant calving - full thickness



von Mises stress calving
(Morlighem et al., 2016):

$$c = ||\mathbf{v}|| \sigma / \sigma_{\max}$$

c = Calving rate

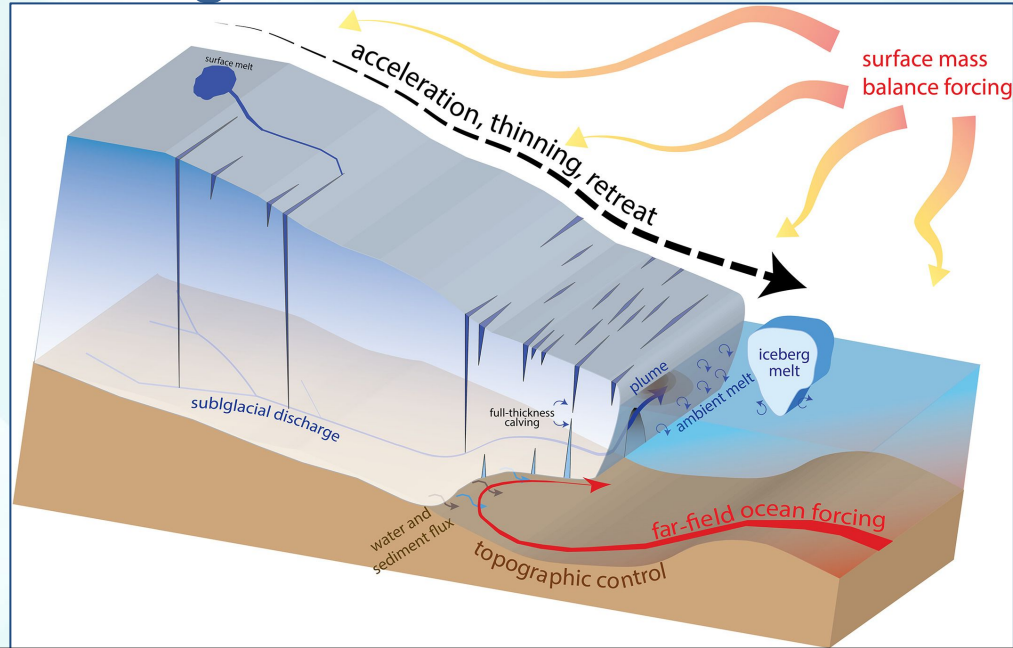
v = ice velocity

σ = von Mises stress $\propto$
(viscosity) $\times$ (strain
rate) $^{1/3}$

$\sigma_{\max}$ = threshold stress

Submarine melting

Surface melting is assumed to drain to bed and into ocean, where it participates in melting the glacier terminus.



$$\text{Submarine melt} \propto (\text{water depth}) \times (\text{subglacial discharge})^{0.39} \times (\text{ocean temperature})^{1.18}$$

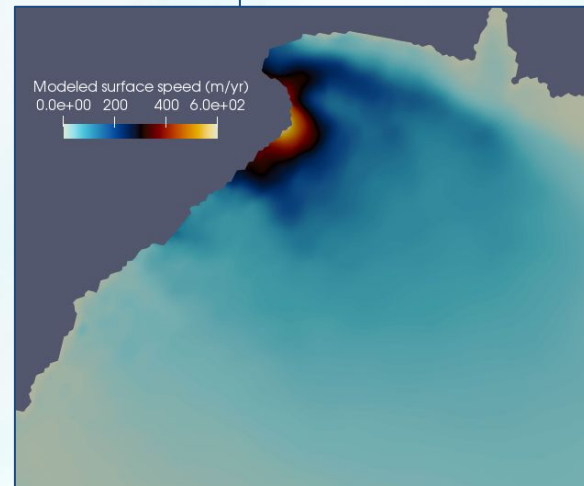
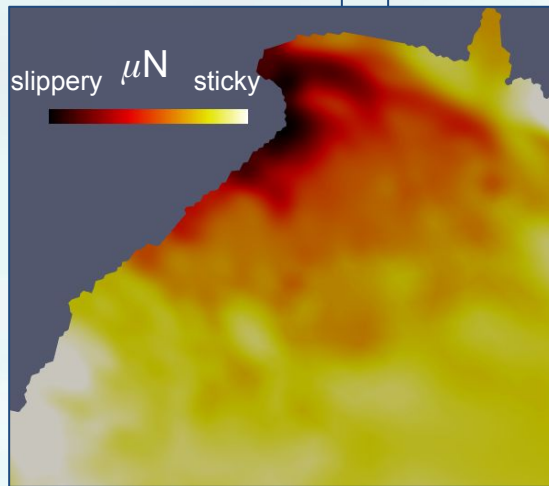
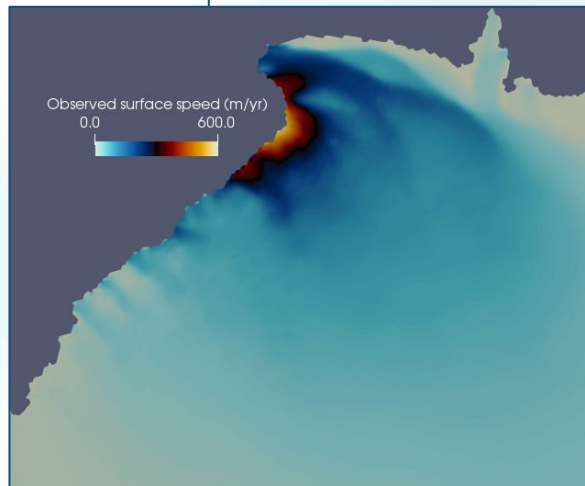
Basal friction optimization for initial condition at 2007

Assume basal friction law of the form $\tau_b = \mu N u^{1/m}$
For $m = 1/3$, find μ to minimize:

$$J(\mu) = \int_{\Omega} \frac{1}{\sigma^2} |u - u^{obs}|^2 ds + R(\mu)$$

velocity mismatch regularization

Forward model



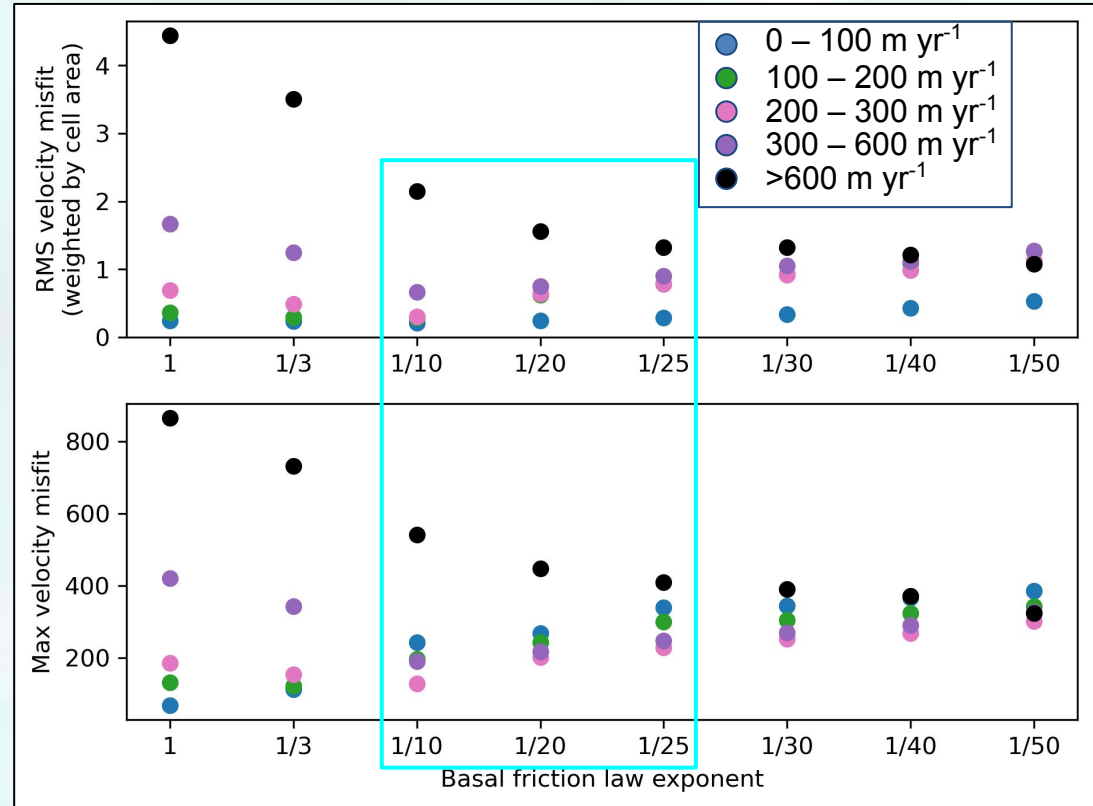
N is effective pressure from ocean connection assumption

μ is friction parameter

u is basal speed

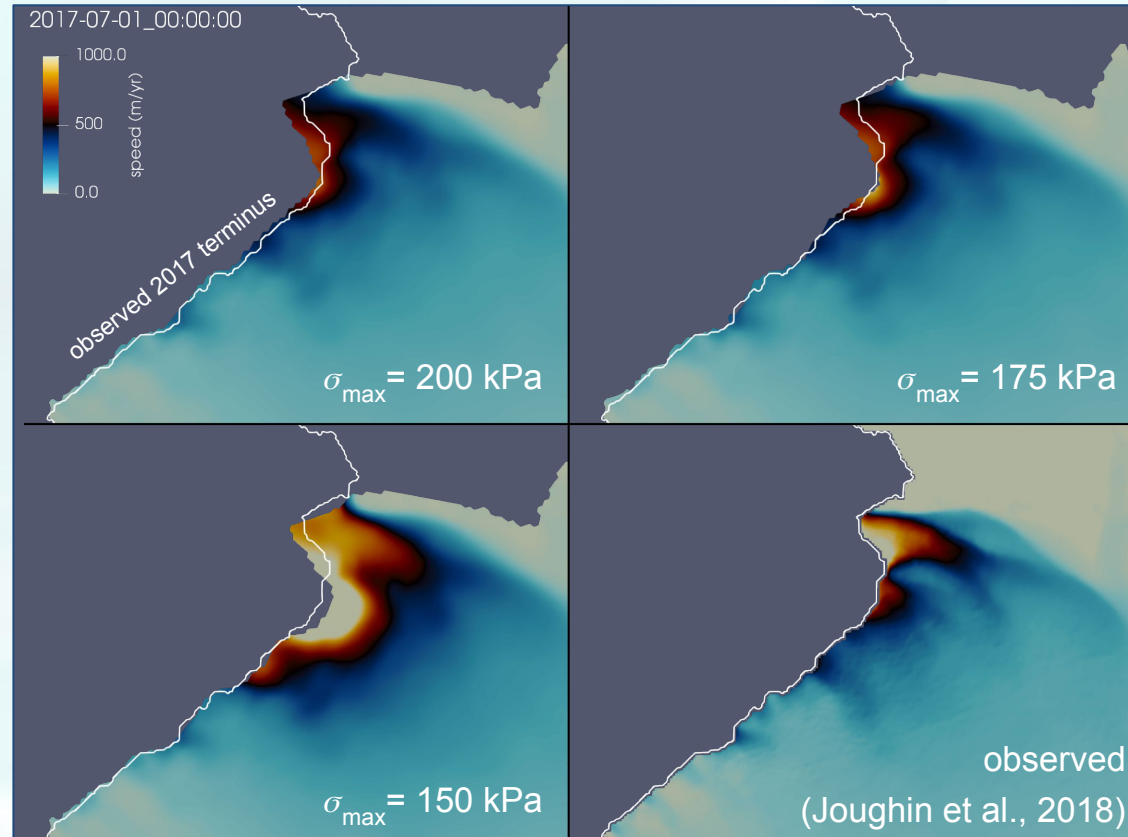
After optimizing friction parameter μ , we tune the power-law exponent

- Scale friction parameter for new exponent: $\mu_m = \mu_{\text{opt}} u^{1/3 - 1/m}$
- Set of forward runs from 2007–2017:
 - Impose retreat rate to match observed 2017 terminus position.
 - Use exponents of 1, 1/3, 1/10, 1/20, 1/25, 1/30, 1/40, 1/50
- Determine best exponent value(s) by comparing modeled and observed velocities at 2017
- We choose exponents of 1/10 – 1/25 as the best trade-off between matching fast-moving and slow-moving areas.



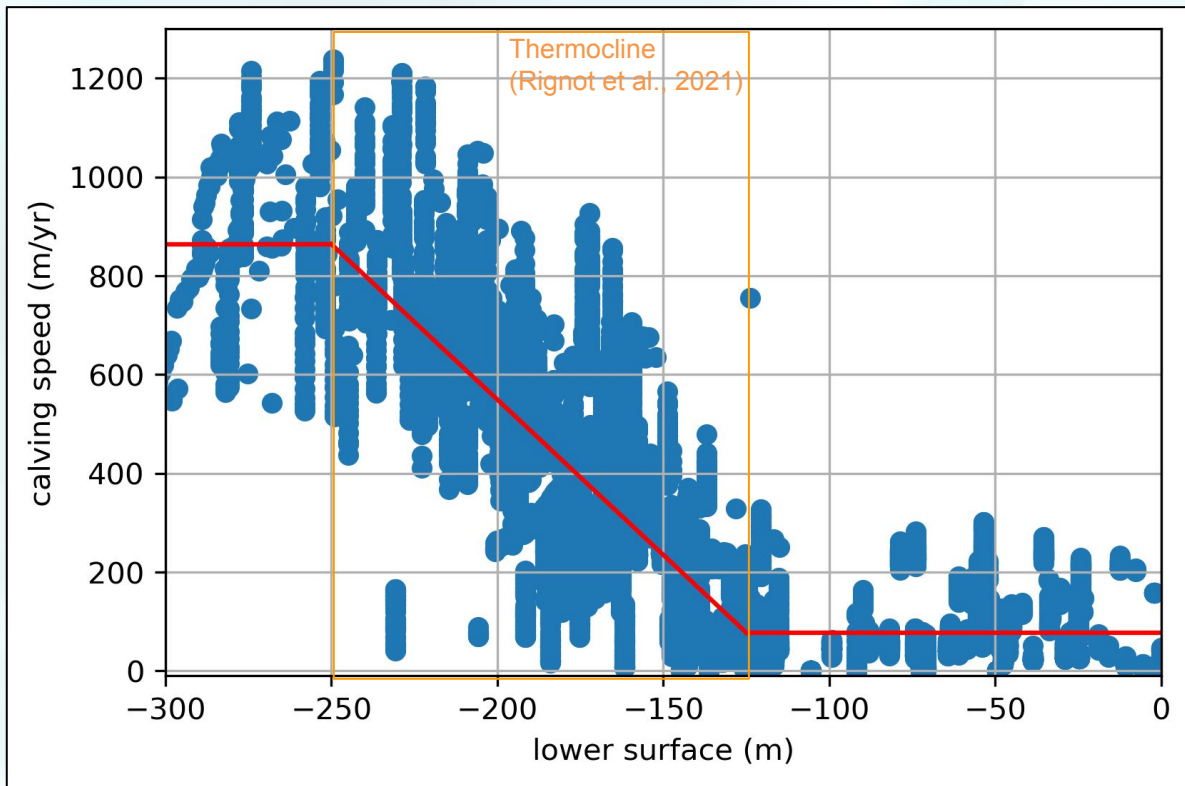
We then tune the von Mises stress calving law to match observed terminus and velocity from 2017–2018

- $c = |v|/\sigma_{\max}$ (Morlighem et al., 2016)
 - c = calving rate
 - v = ice velocity
 - σ = von Mises stress
 - $\sigma_{\max}$ = threshold von Mises stress necessary for retreat
- Tensile strength of ice varies from 700–3100 kPa (Petrovic, 2003)
- Choi et al. (2021) found it necessary to use $\sigma_{\max}$ as low as 150 kPa to match observations.
- We find $\sigma_{\max} \leq 200$ kPa necessary to initiate retreat, but have to impose a limit on calving rate of 3 km/yr (Choi et al., 2018) to avoid a non-physical positive feedback between ice velocity and calving rate.
- We choose $\sigma_{\max} = 200$ kPa for forward runs. This underestimates the observed speed-up, but also avoids overestimating in other areas.

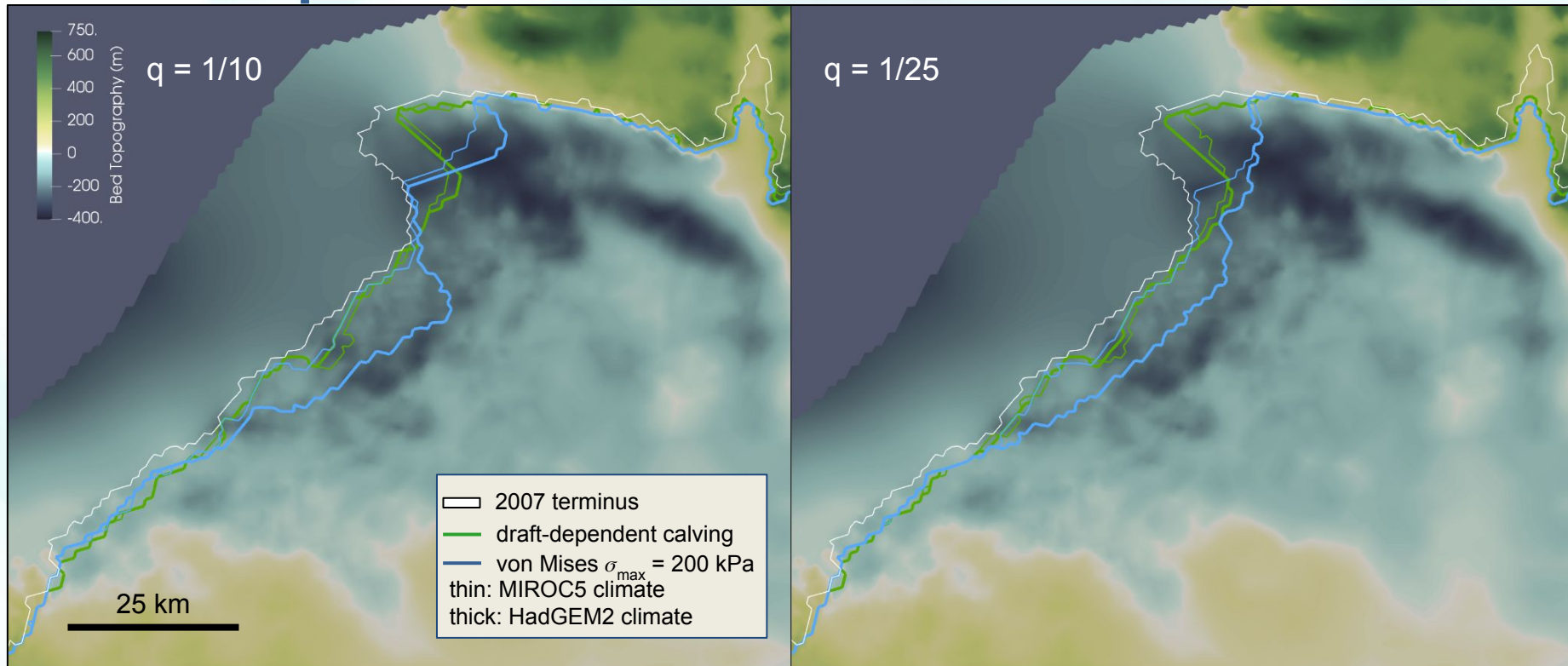


A draft-dependent calving relationship

- To avoid the non-physical feedback between ice velocity and calving velocity, we propose an empirical calving relationship.
- Calculate required calving rate from retreat rate - melt rate for each basal friction law/climate forcing pair
- Calculate best-fit line between ice bottom and calving speed for depths between 125 and 250 m. Use constant values above and below.
- We use this relationship in a set of forward runs. These are more faithful to observations than the runs with von Mises calving, but have a narrower range of variability.



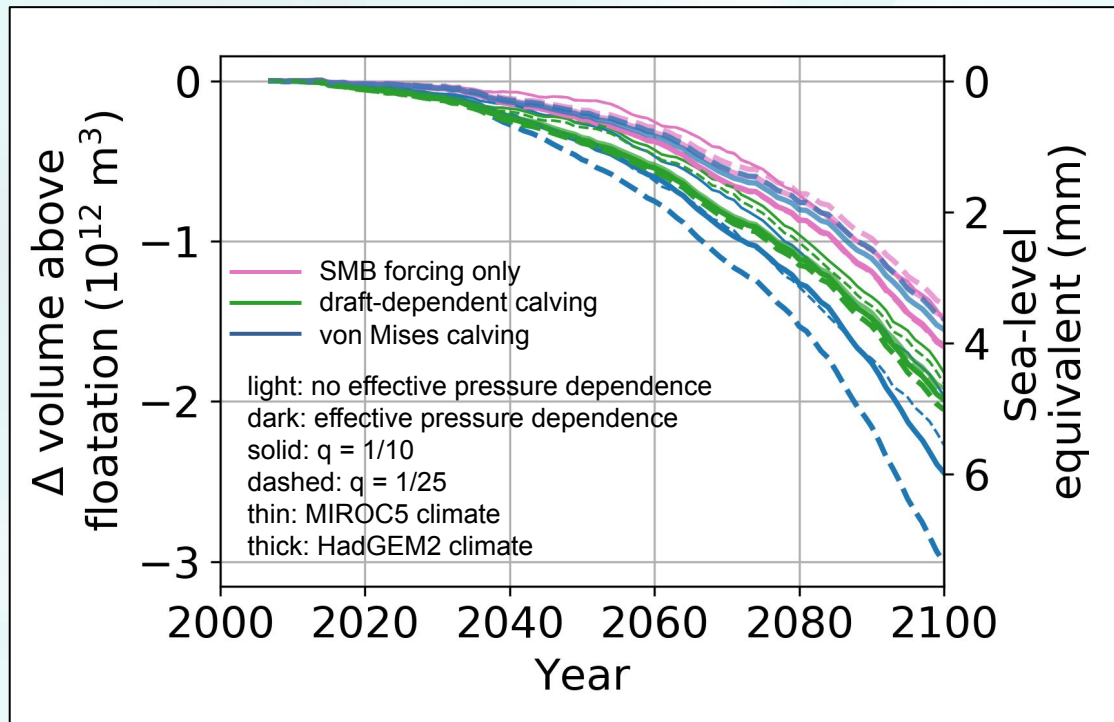
Terminus positions at 2100



The empirical draft-dependent calving law leads to similar amounts of retreat for all cases, while von Mises stress calving law leads to widely different retreat between the pairs of basal friction law exponents (q) and climate forcings.

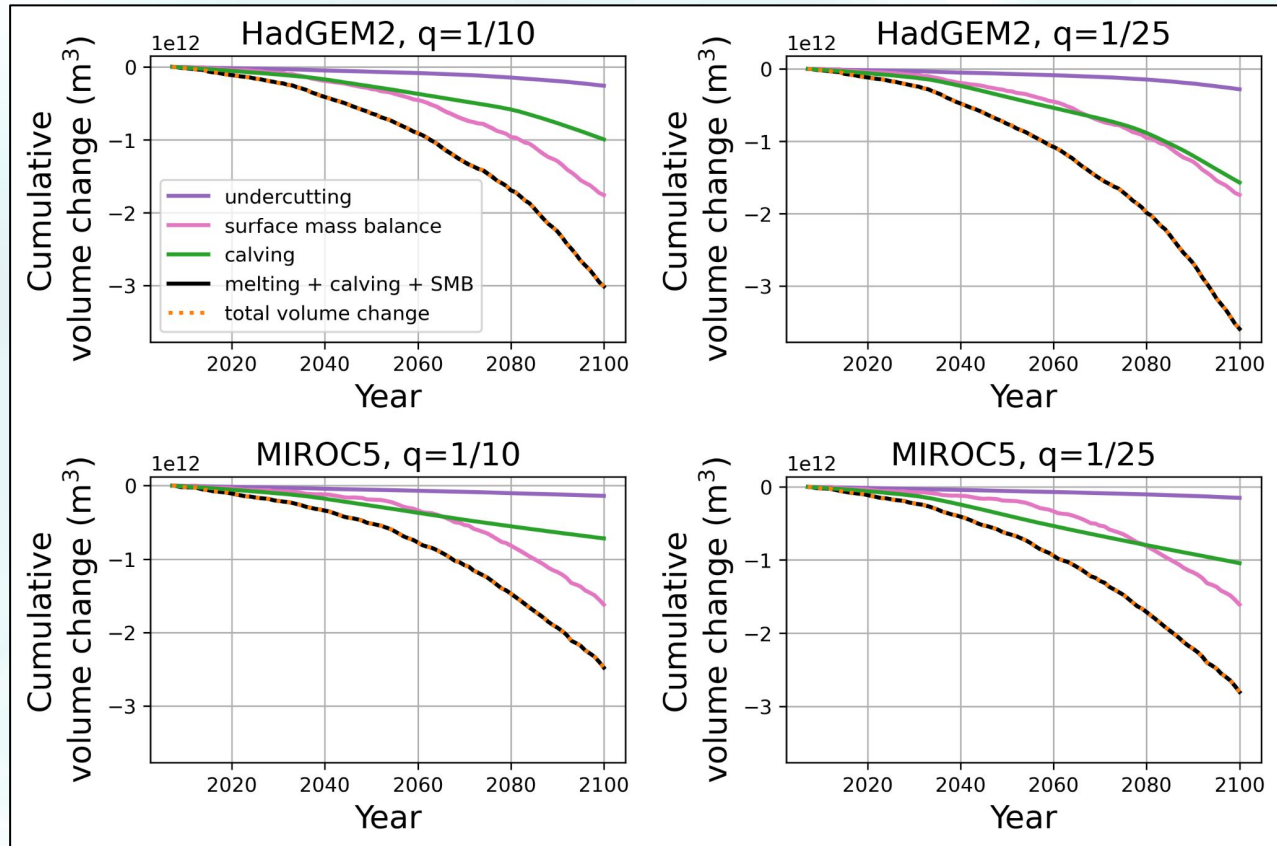
Projections of volume change and sea-level contribution

- 3.5 – 7.5 mm sea-level rise by 2100
- Choices of calving parameterization and basal friction law exponent (q) result in wide range of SLR.
- Surface mass balance forcing (and ice dynamical response) contributes >50% of SLR by 2100.
- Including effective pressure in the basal friction law increases SLR by 50–100% (compare dark and light curves).



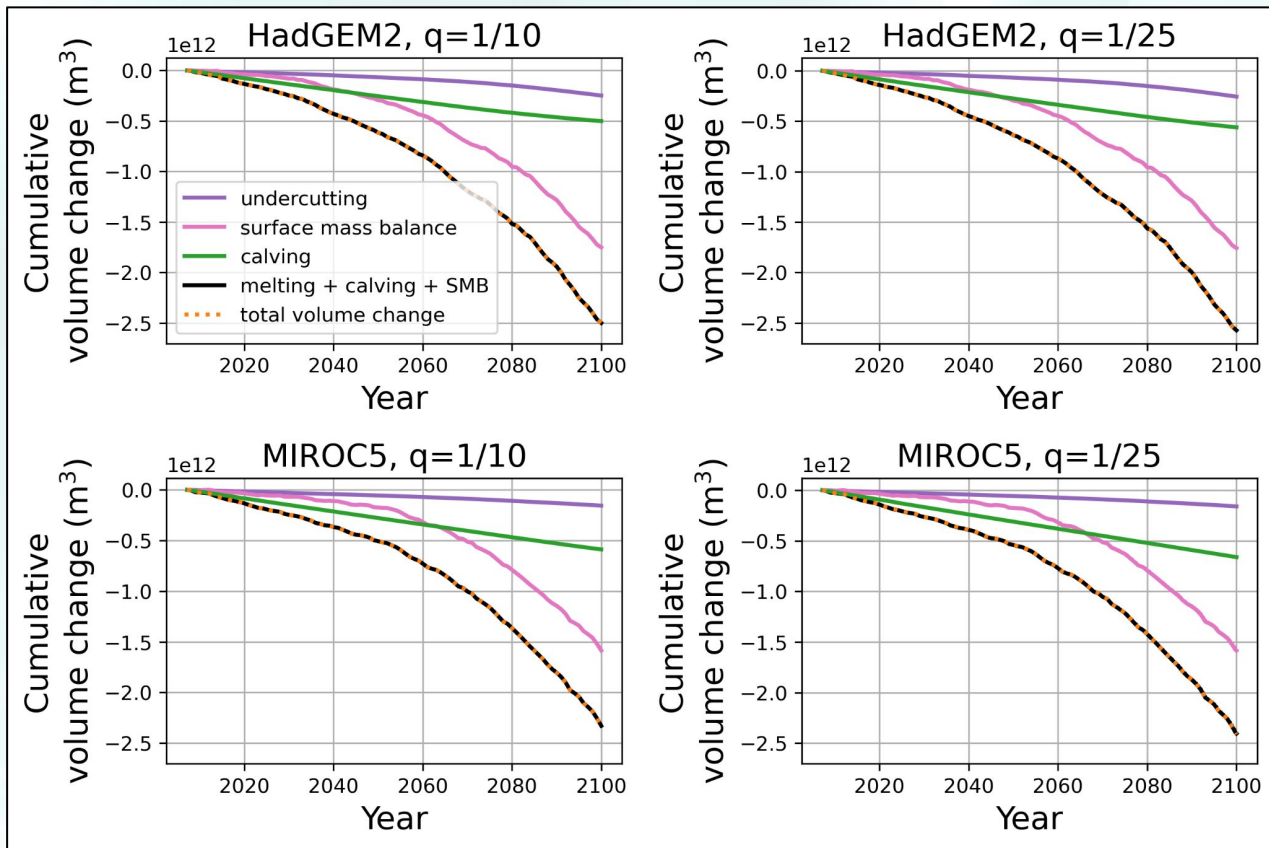
Mass budgets: von Mises calving

- Surface mass balance is the dominant term in mass budget, but calving is nearly equal in one climate/basal friction scenario.
- Calving mass flux is sensitive to both climate forcing and basal friction law exponent (q).

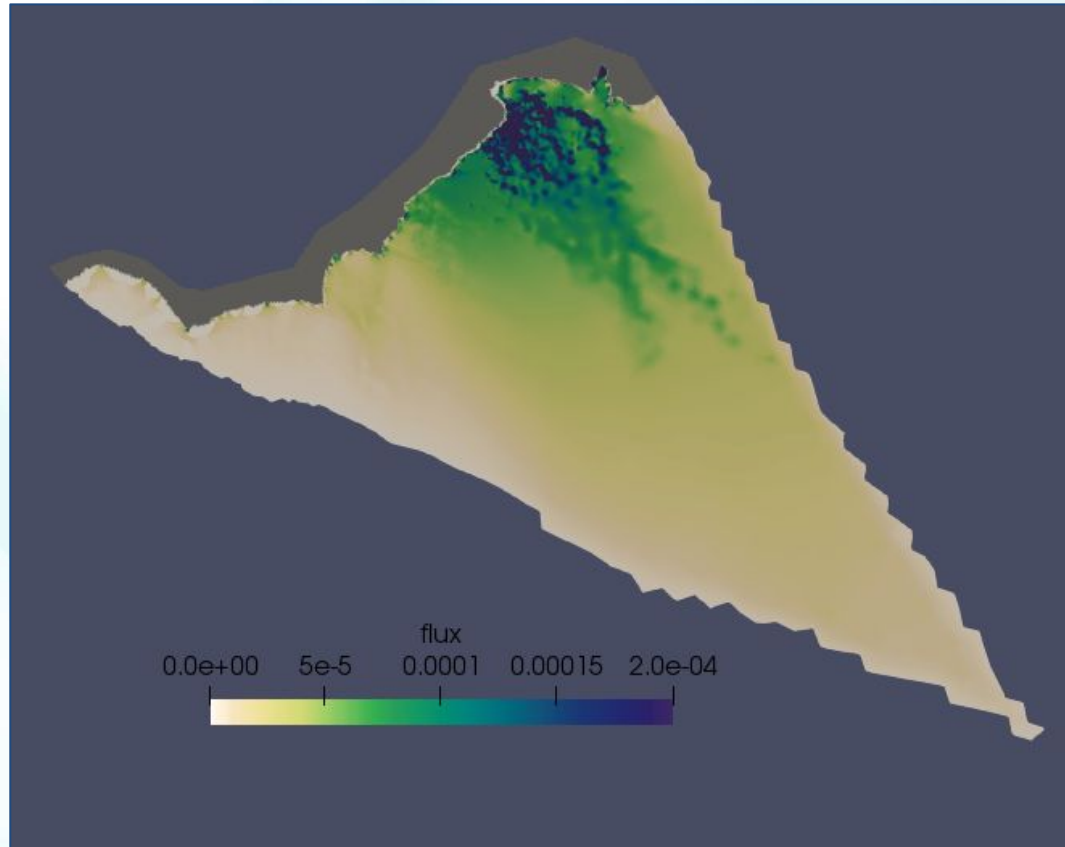


Mass budgets: draft-dependent calving

- Surface mass balance even more dominant.
- Calving is fairly insensitive to climate forcing and basal friction law exponent (q).

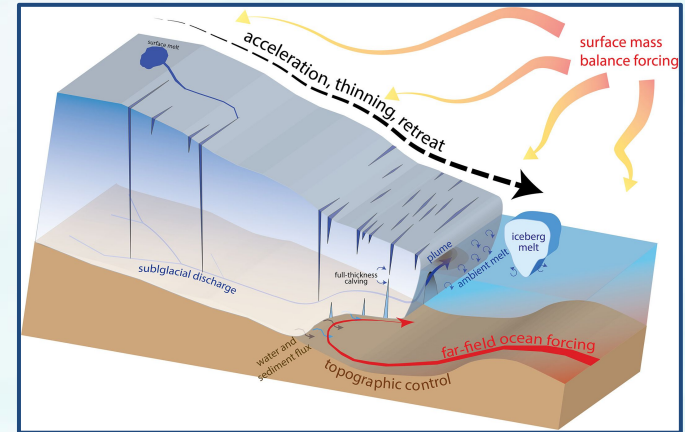


Subglacial hydrology



Model of coupled channelized and distributed subglacial hydrologic systems, using 30 years of daily surface runoff forcing from RACMO2.3p2 (Noël et al., 2019).

Surface runoff is assumed to drain to the glacier bed through crevasses and moulins.



Subglacial hydrology



Results from a 30-run subglacial hydrology run forced with RACMO2.3p2 runoff (Noël et al., 2019) indicate that the ocean connection assumption yields summer-like effective pressure patterns near the terminus. Most of the year, effective pressure should be relatively higher near the terminus than we use here.

Work by Abby Roat (Colorado College & LANL)

Summary

- 1) Our model experiments predict 4–7.5 mm sea-level rise from Humboldt Glacier by 2100 with RCP8.5 forcing.
 - a) ISMIP6 multi-model ensemble predicts total GIS contribution of 90 ± 50 mm by 2100 (Goelzer et al., 2020).
- 2) A plastic, effective pressure-dependent basal friction law is required to qualitatively reproduce observed speed-up, but still falls short.
- 3) Choice of basal friction law and calving parameterization leads to wide range of sea-level rise predictions by 2100.
 - a) Including effective pressure in basal friction law increases sea-level contribution 50–100% by 2100.
 - b) The strong dependence of SLR projections on the choice of calving and basal friction laws has important implications for whole ice-sheet projections aiming to capture the impacts of outlet glacier dynamics.
- 4) Mass loss dominated by surface mass balance.
- 5) Forthcoming:
 - a) Further refinement of tuning to observations
 - b) Forcing with wider range of available climate forcings
 - c) Incorporate effective pressure from subglacial hydrology modeling

Acknowledgements

Funding:

DOE Office of Science:

- Scientific Discovery Through Advanced Computing
- Probabilistic Sea Level Projections from Ice Sheet and Earth System Models

Computing:

- DOE National Energy Research Supercomputing Center
- LANL Institutional Computing: Reducing uncertainties in 21st century sea-level rise through improved modeling of the ice sheet basal interface

Brice Noël provided RACMO2.3p2 output for subglacial hydrology modeling.

Sophie Nowicki provided access to ISMIP6 climate forcings.

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