Future sea level projections

Tamsin Edwards
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Ice Flows climate change game puts the fate of Antarctic penguins in your hands

RONNE

FILCHNER

SANAE

FUJI

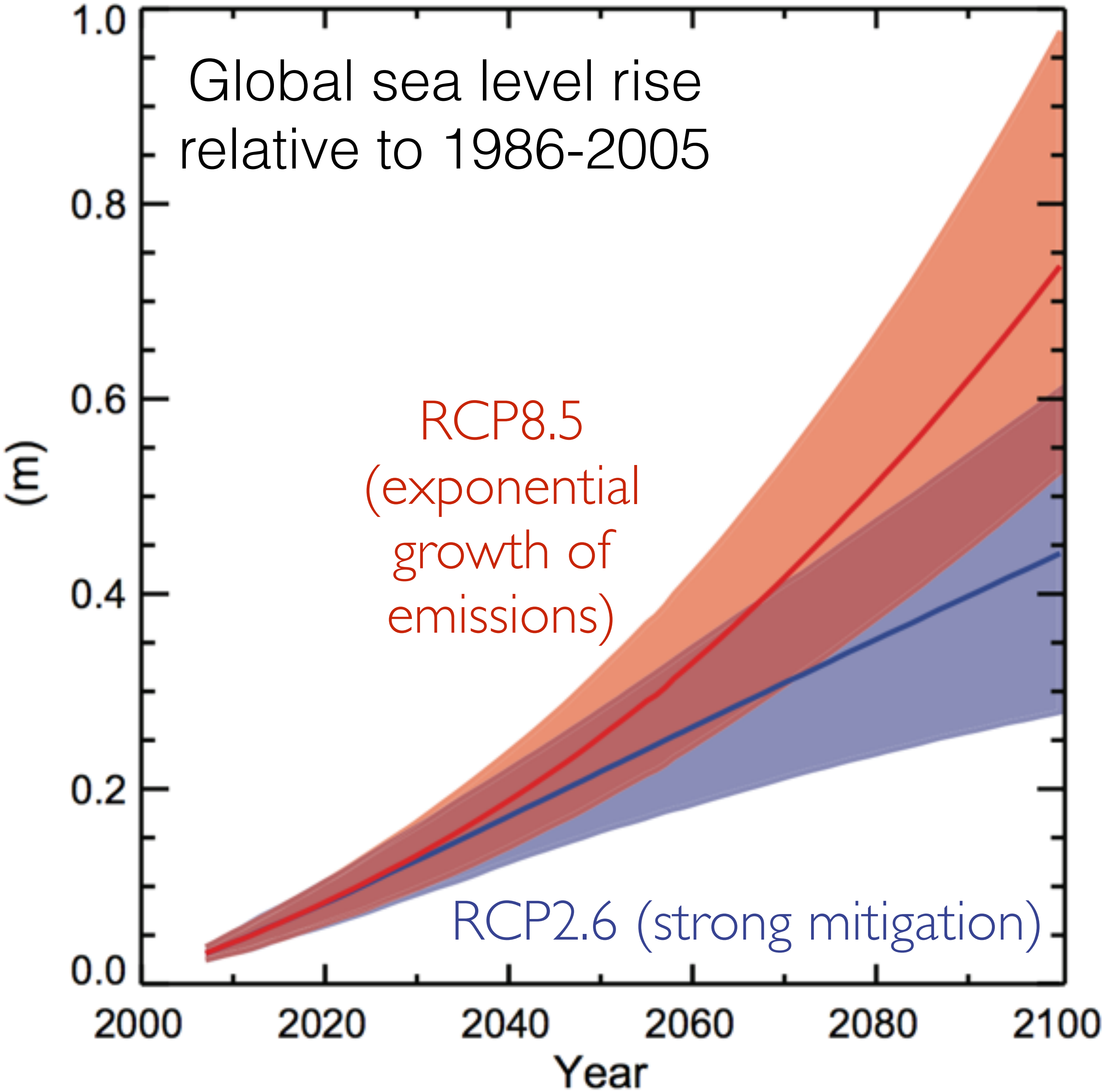
CHILLY

VOSTOK

iceflowsgame.com

Developed by Anne Le Brocq

IPCC projections



Median [≥ 66%]

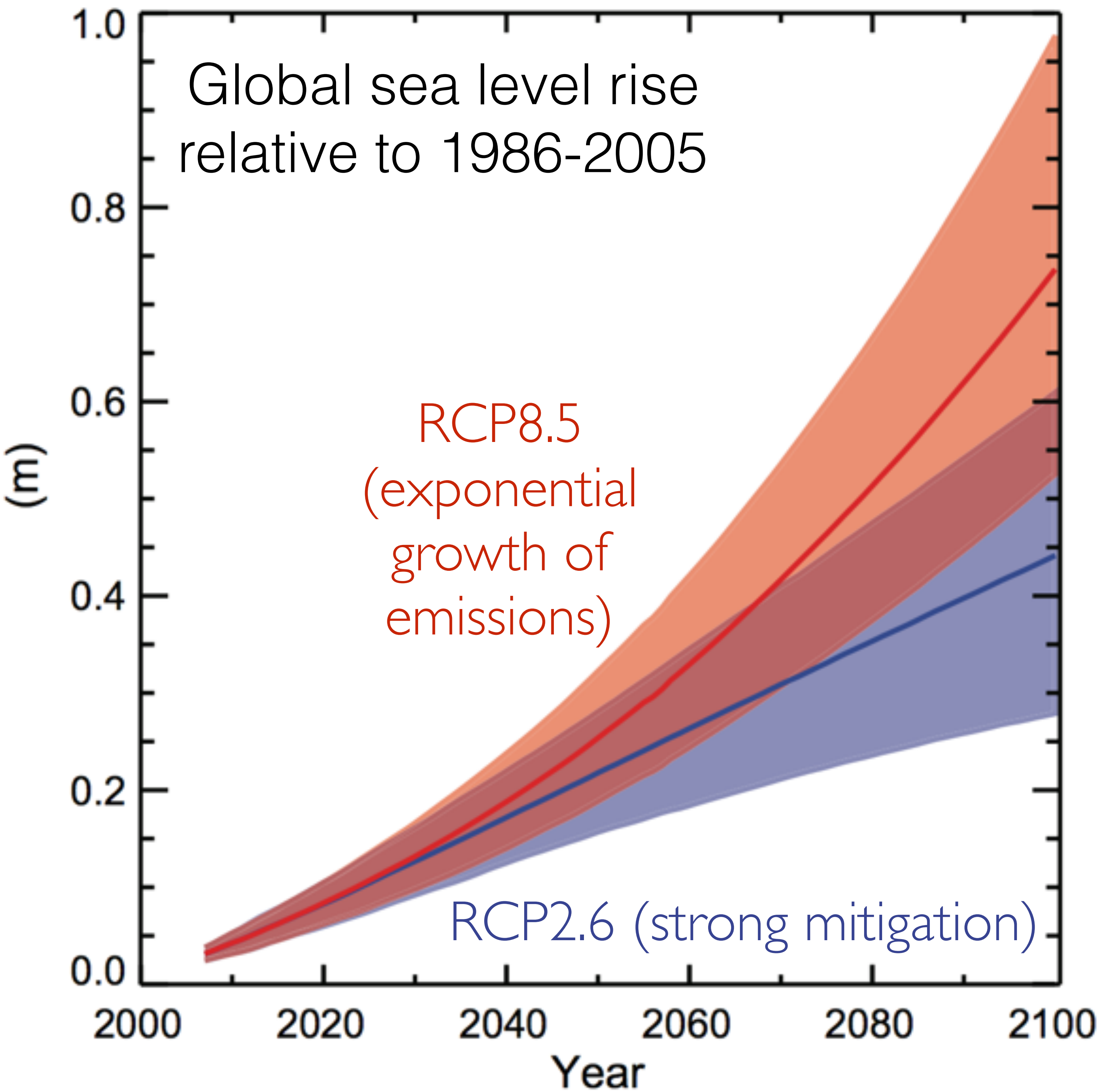
74 [52, 98] cm

44 [28, 61] cm

- Substantial sea level rise no matter what
- Large uncertainties

Adapted from IPCC (2013) Working Group I Summary for Policymakers

IPCC projections



Median [≥ 66%]

74 [52, 98] cm

44 [28, 61] cm

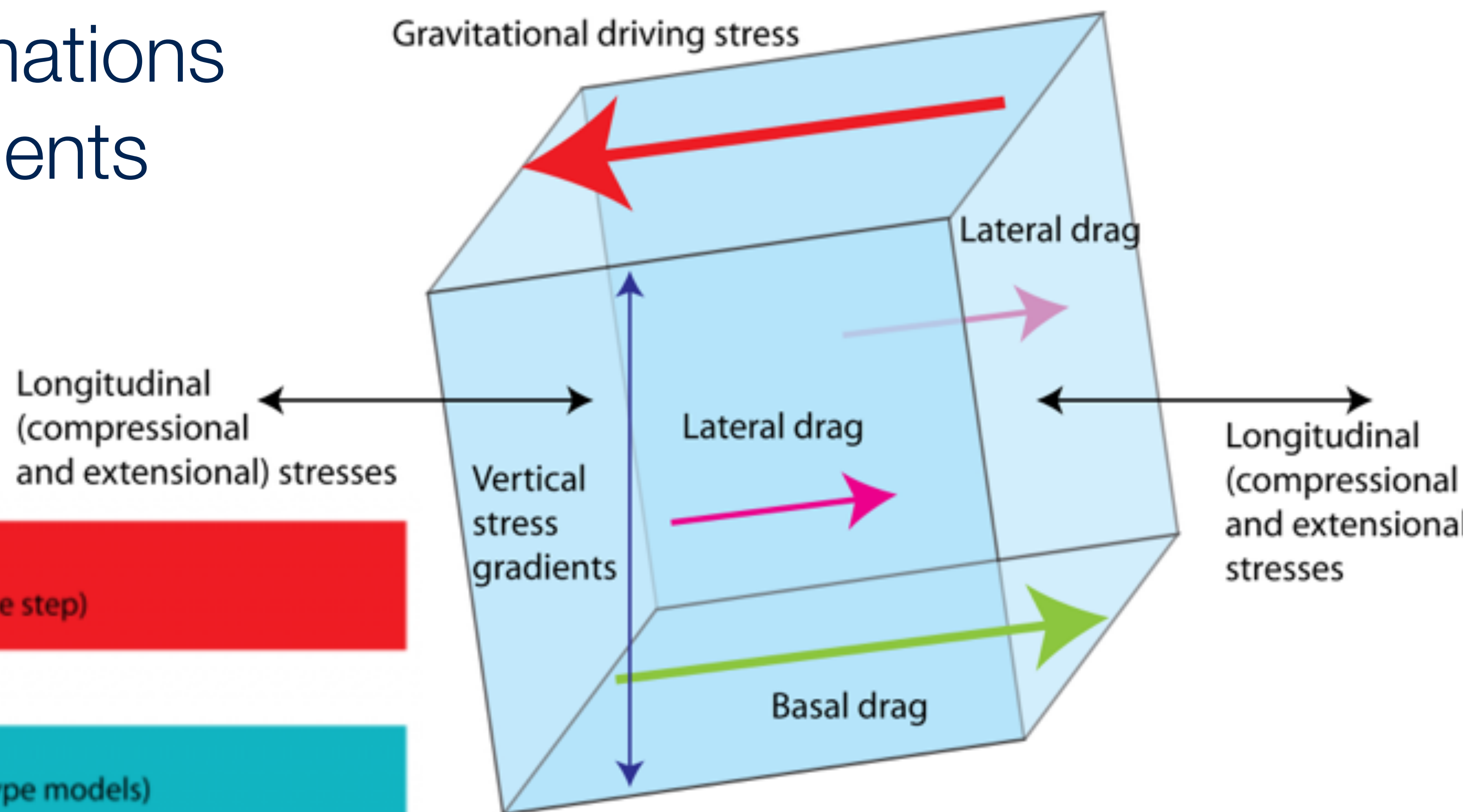
- Substantial sea level rise no matter what
- Large uncertainties
- Ice sheets 1/4 or more
- Antarctica the largest uncertainty: 7 [-1,16 cm]
- Very poorly-constrained upper tail: 50 to 100 cm

Adapted from IPCC (2013) Working Group I Summary for Policymakers

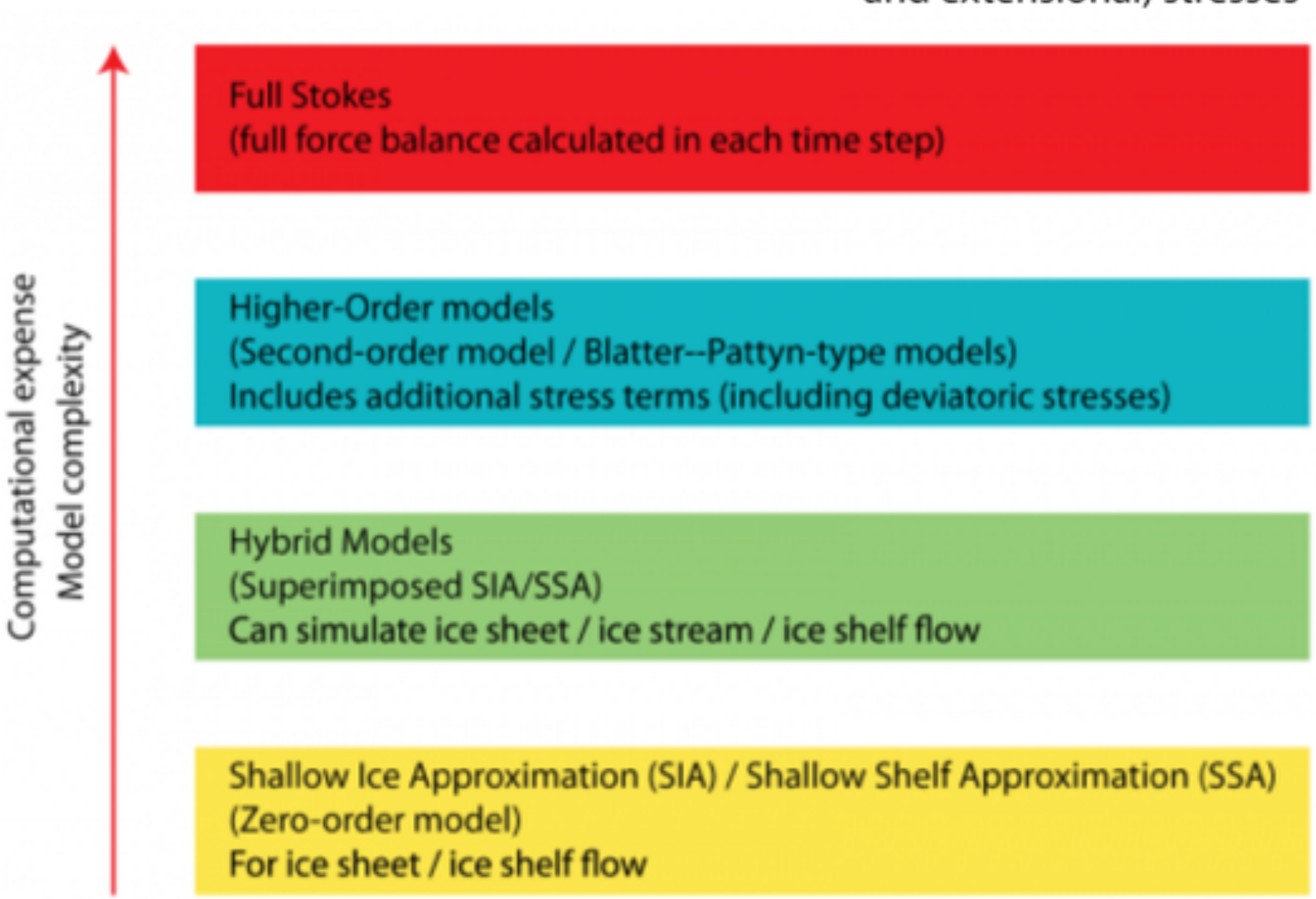
Ice sheet models

- flow of ice under its own weight
- different approximations of stress components

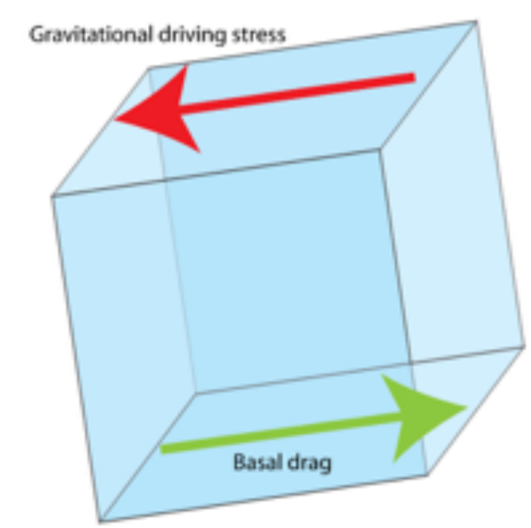
Full Stokes



AntarcticGlaciers.org

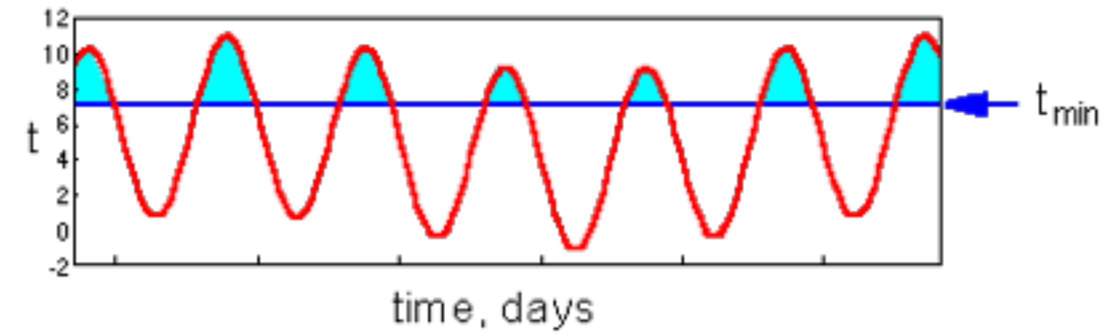


Shallow Ice Approximation



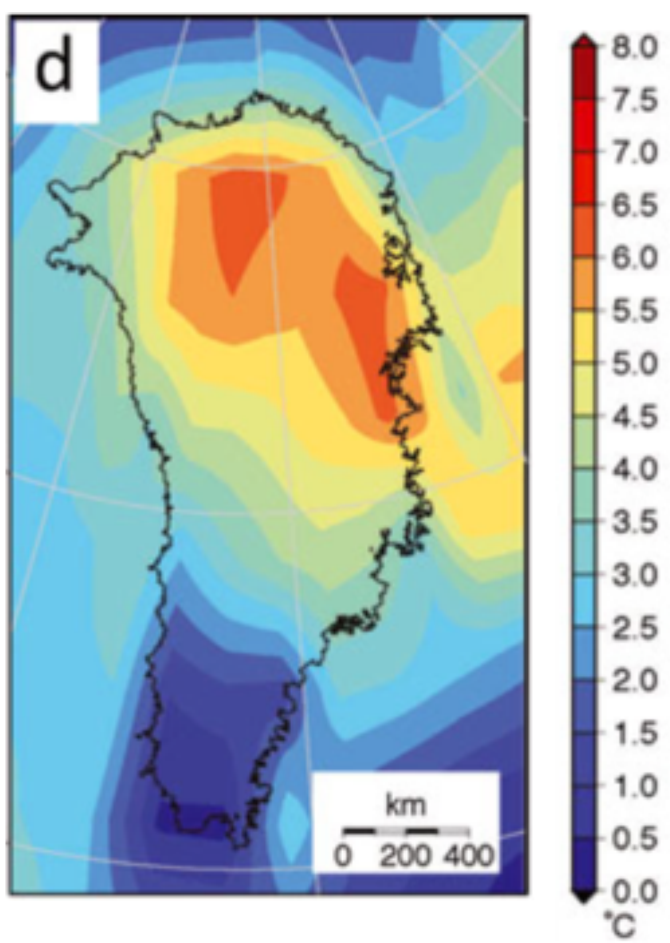
Ice sheet models

- can calculate surface mass balance from atmosphere
  - degree day models
  - energy balance models



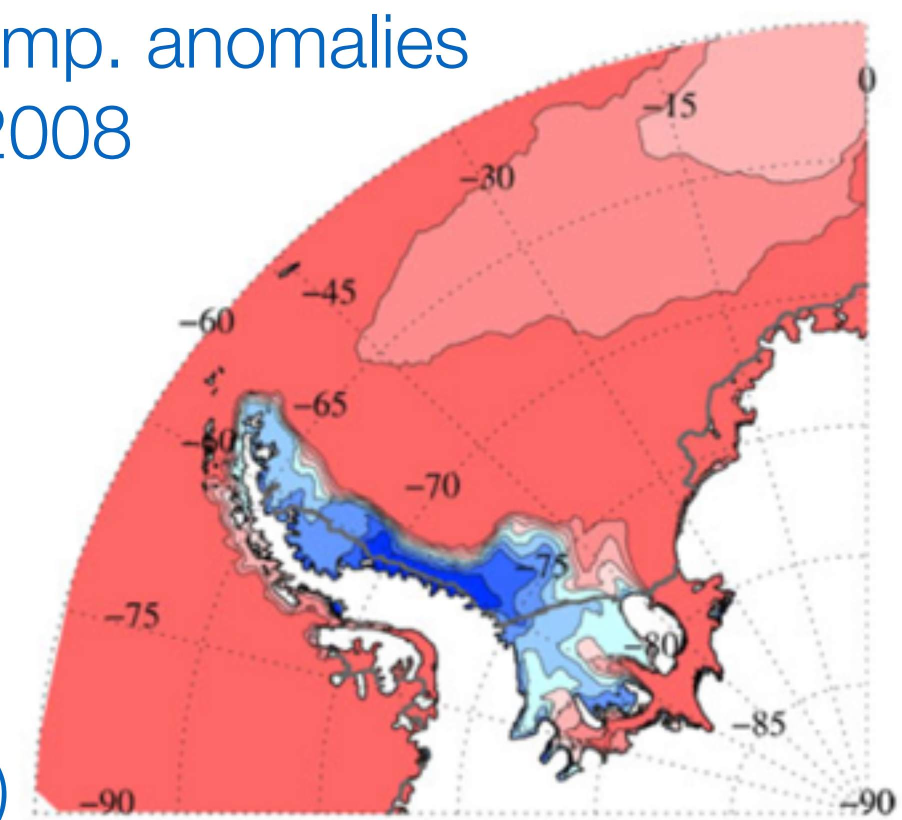
Source: Alexei Sharov

- and/or basal mass balance from ocean
  - melt parameterisation

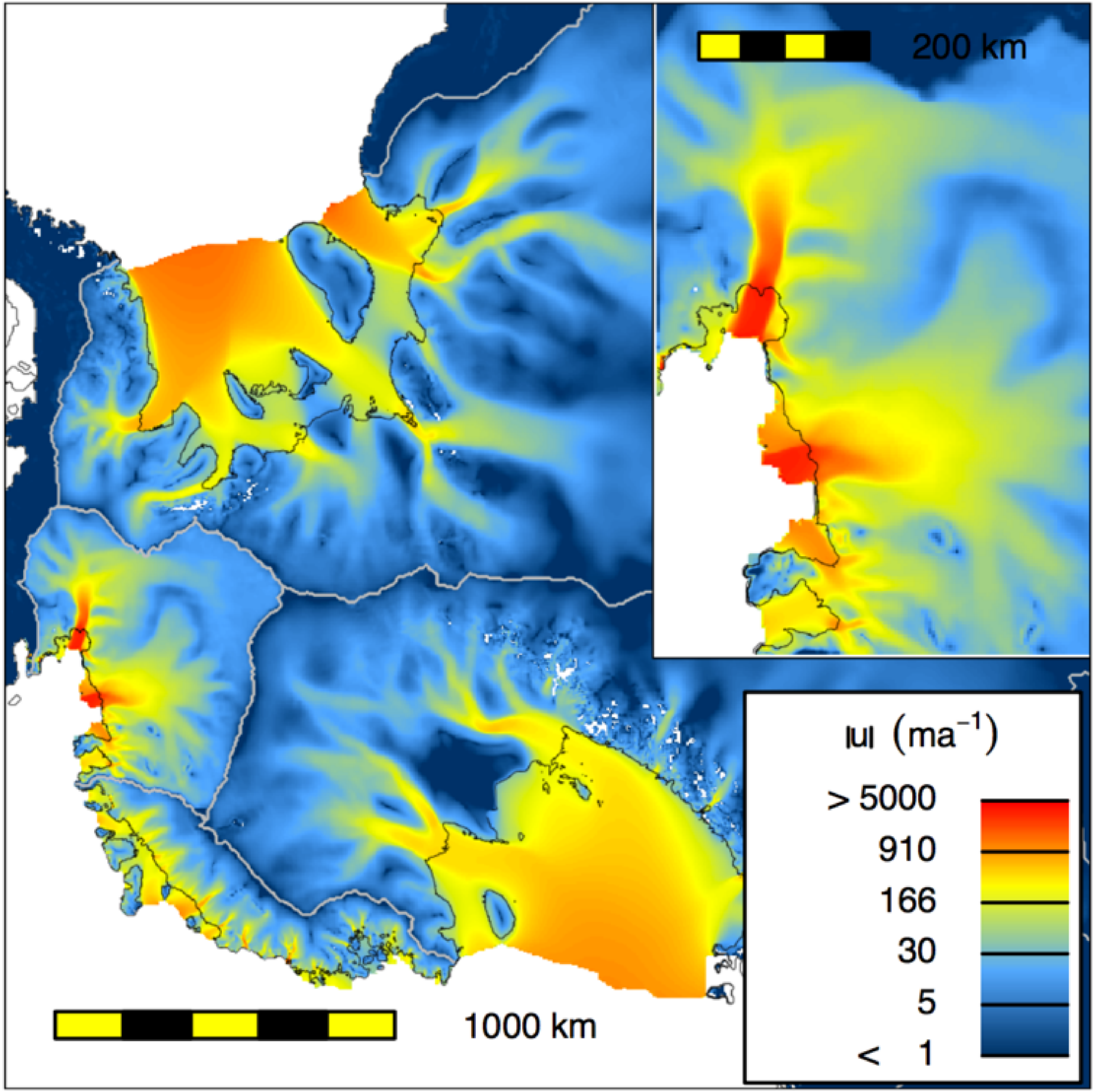


Global climate model summer temp. anomalies for 2091-2100 relative to 1989-2008 under SRES scenario A1B (Goelzer et al., 2013)

Ocean model near-bottom temperatures in 2150 under SRES scenario A1B (Timmerman & Hellmer, 2013)

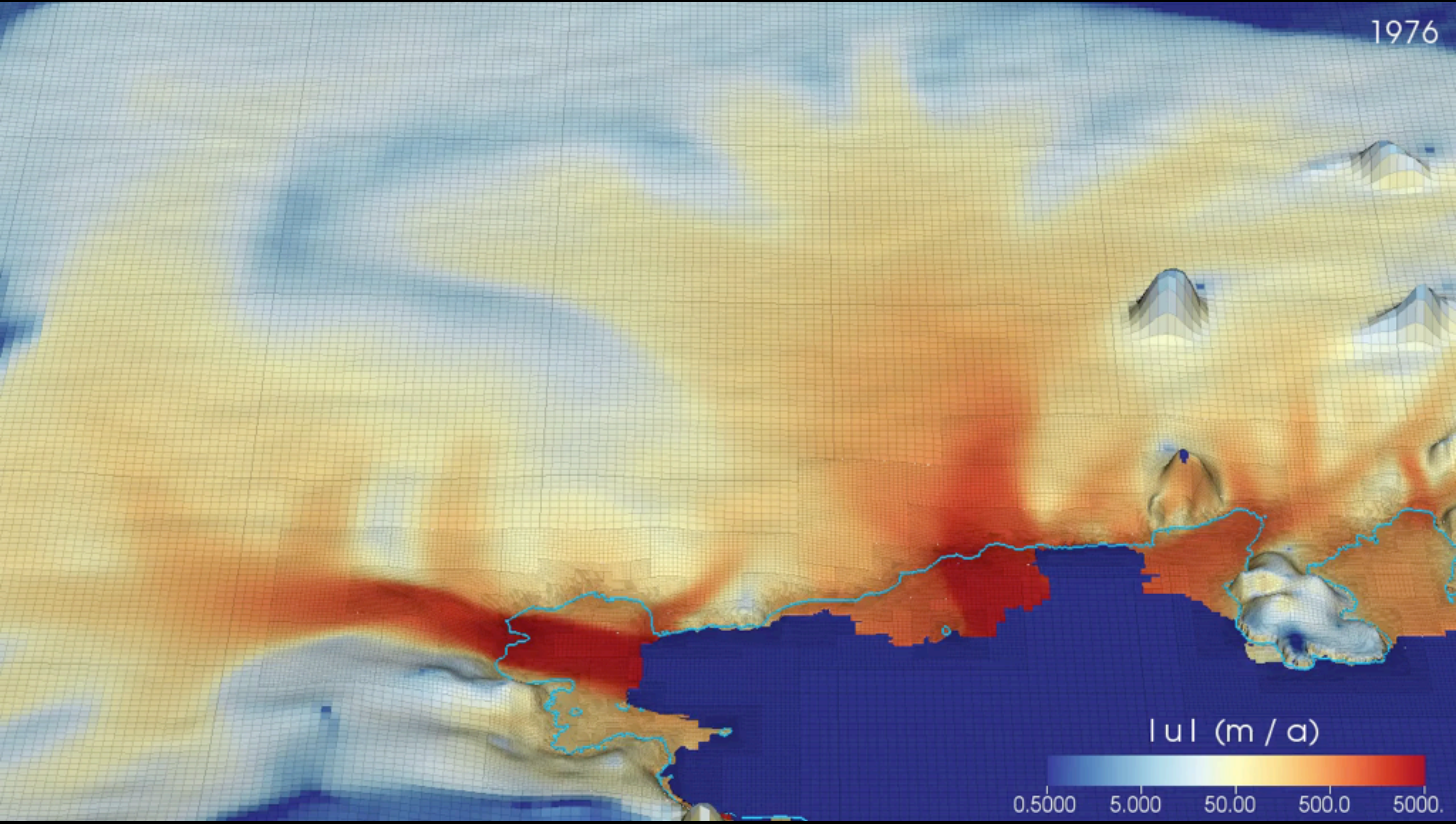


BISICLES



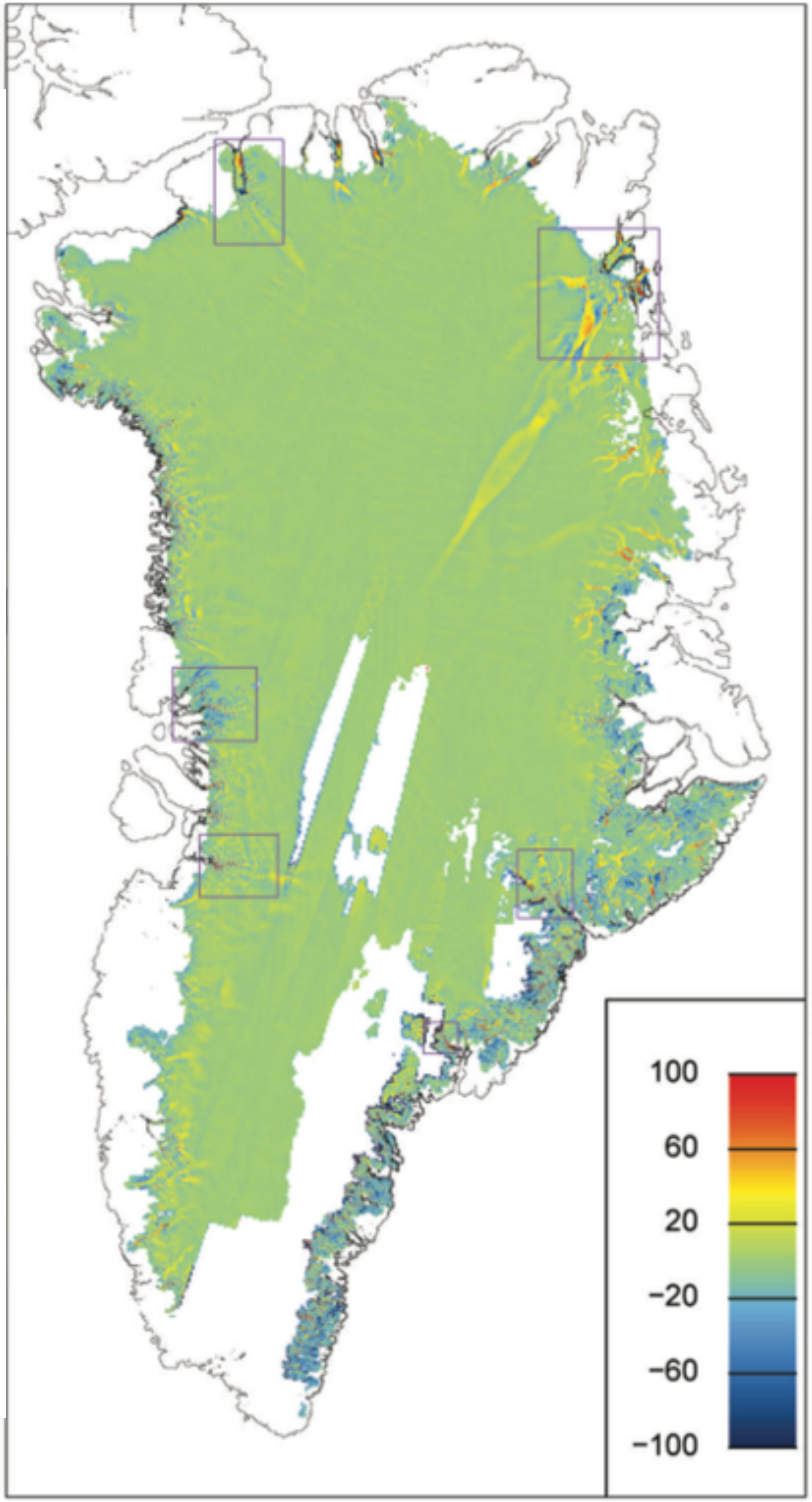
initial ice flow speed (Cornford et al., 2015)

BISICLES



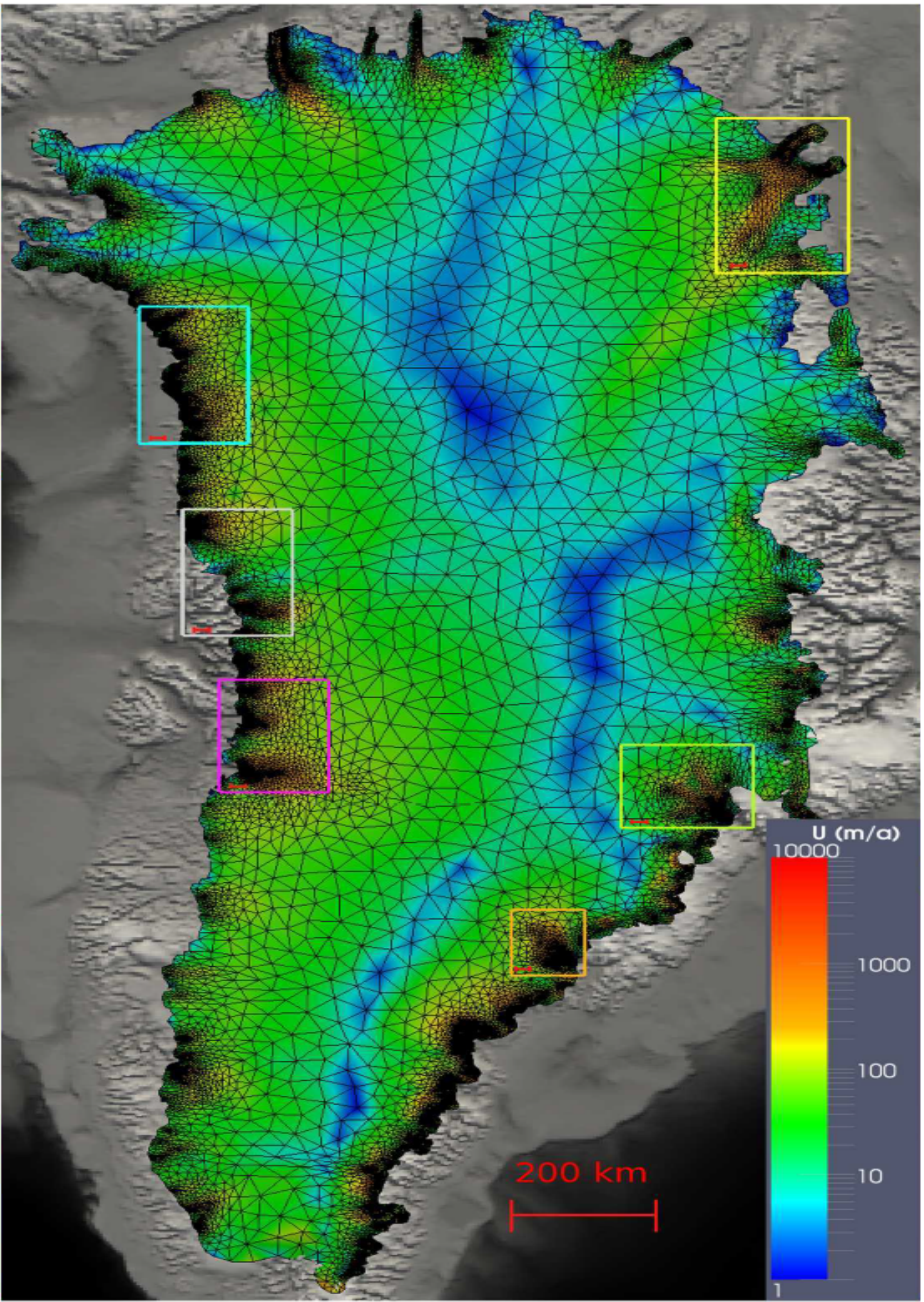
ice flow speed forced by ocean under SRES scenario A1B
(Cornford et al., 2015)

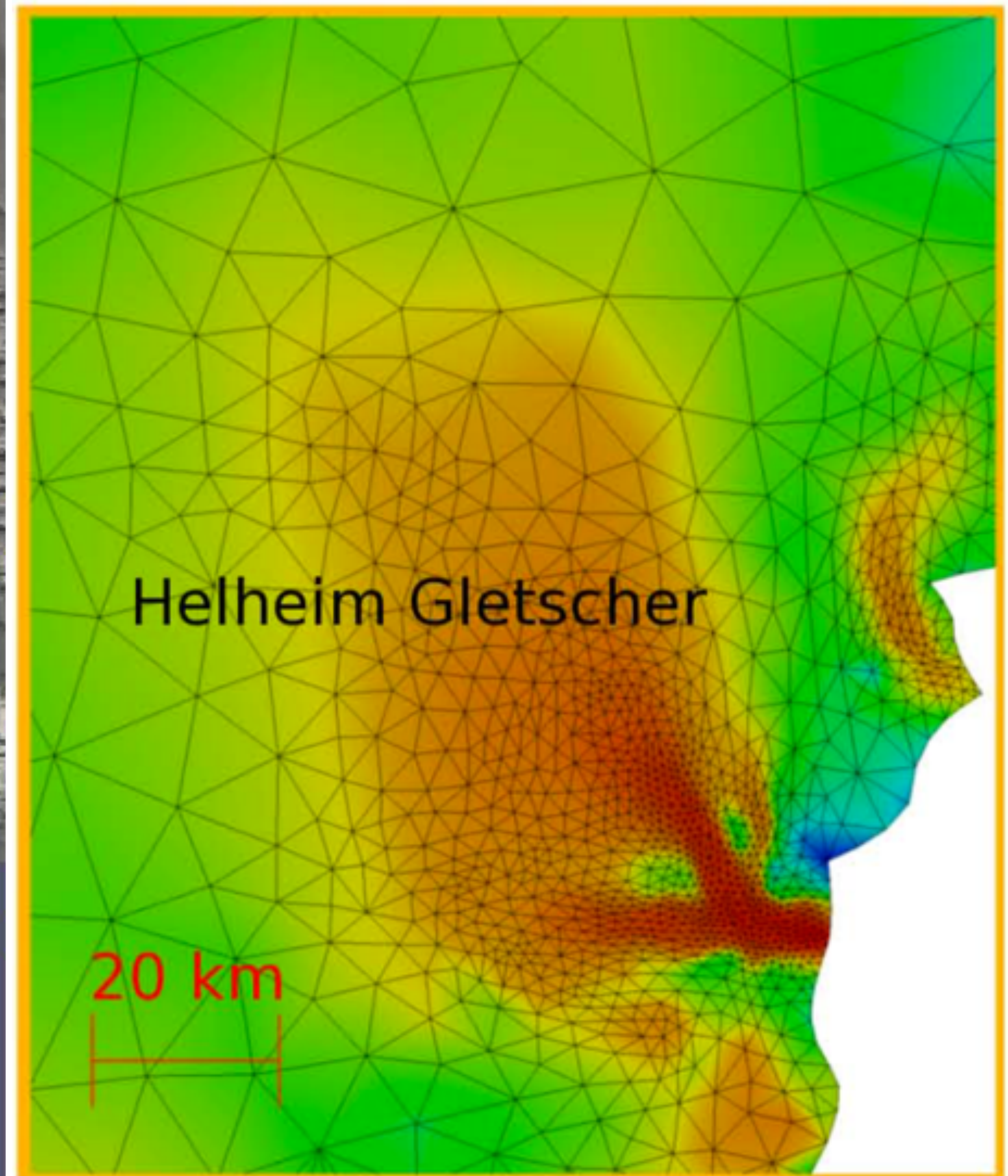
BISICLES



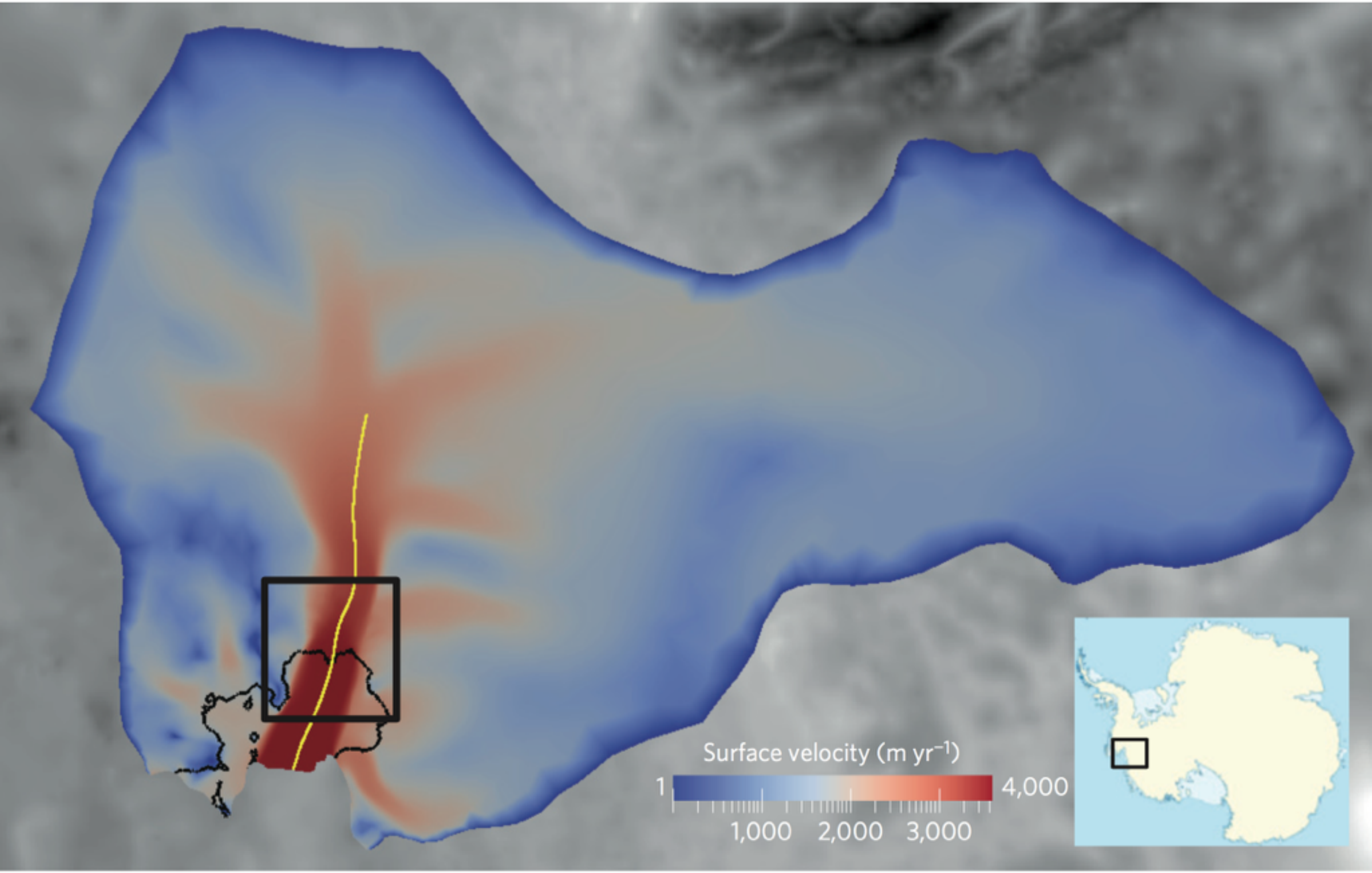
% mismatch between initial ice speed and observations (Lee et al., 2015)

Elmer/Ice





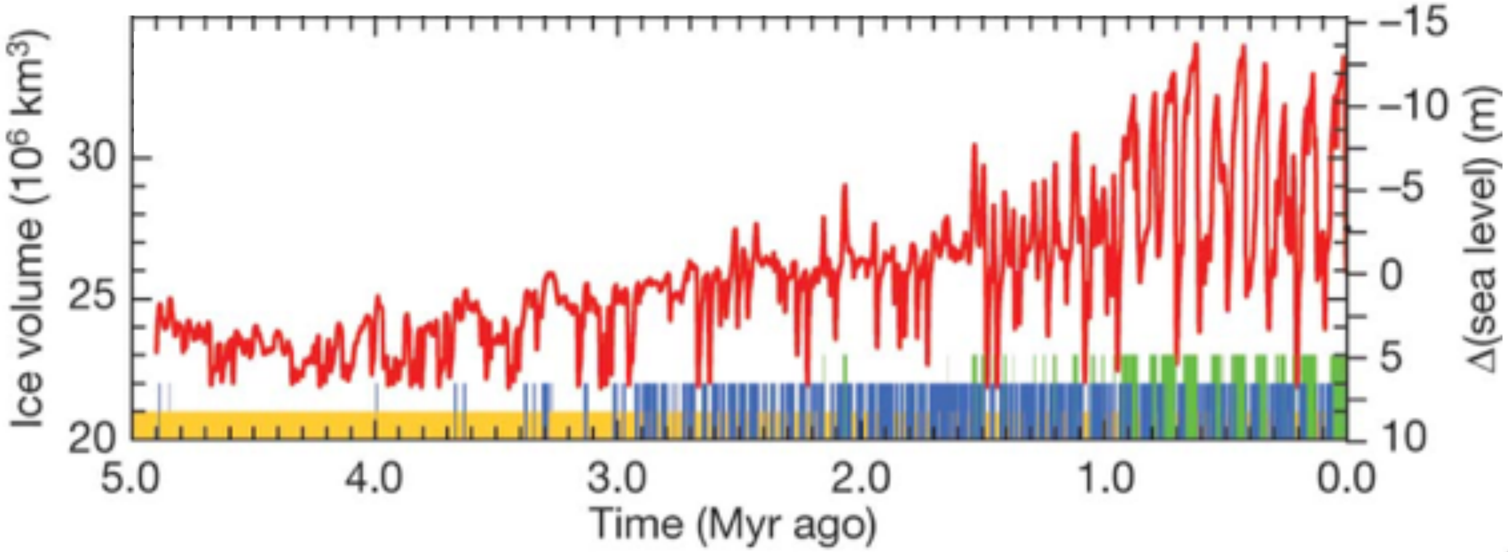
initial surface velocities
(Gillet-Chaulet et al., 2012)



initial surface velocities (Favier et al., 2014)

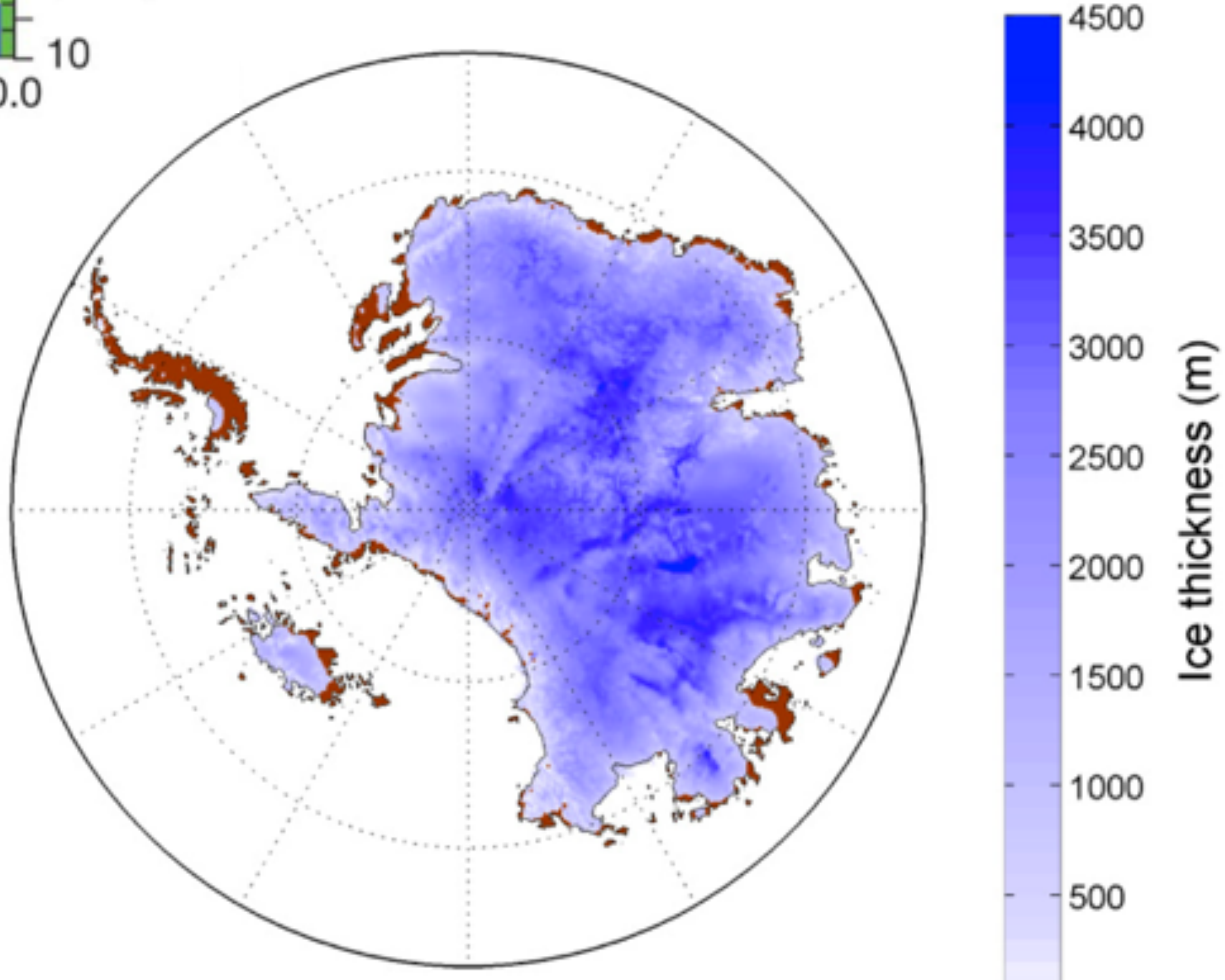
What is an ice sheet model used for?

- Understanding palaeoclimates



Antarctic ice volume and sea level equivalent (Pollard and DeConto, 2009)

Pliocene (3Ma BP)

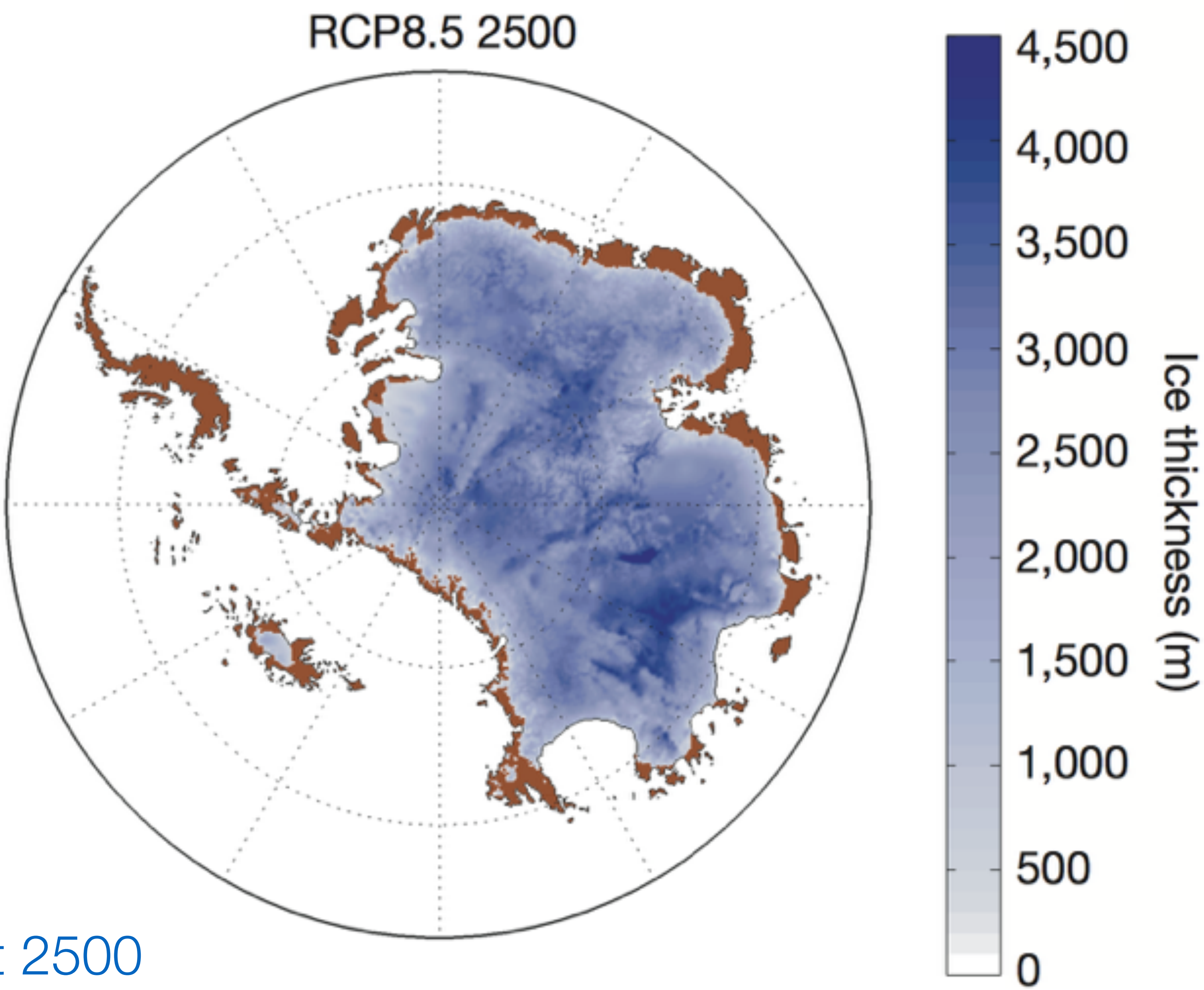


Pliocene ice sheet simulation DeConto and Pollard (2016)

What is an ice sheet model used for?

- Predicting the long-term future

"Antarctica has the potential to contribute …more than 15 m [of sea-level rise] by 2500, if emissions continue unabated. …prolonged ocean warming will delay its recovery for thousands of years."

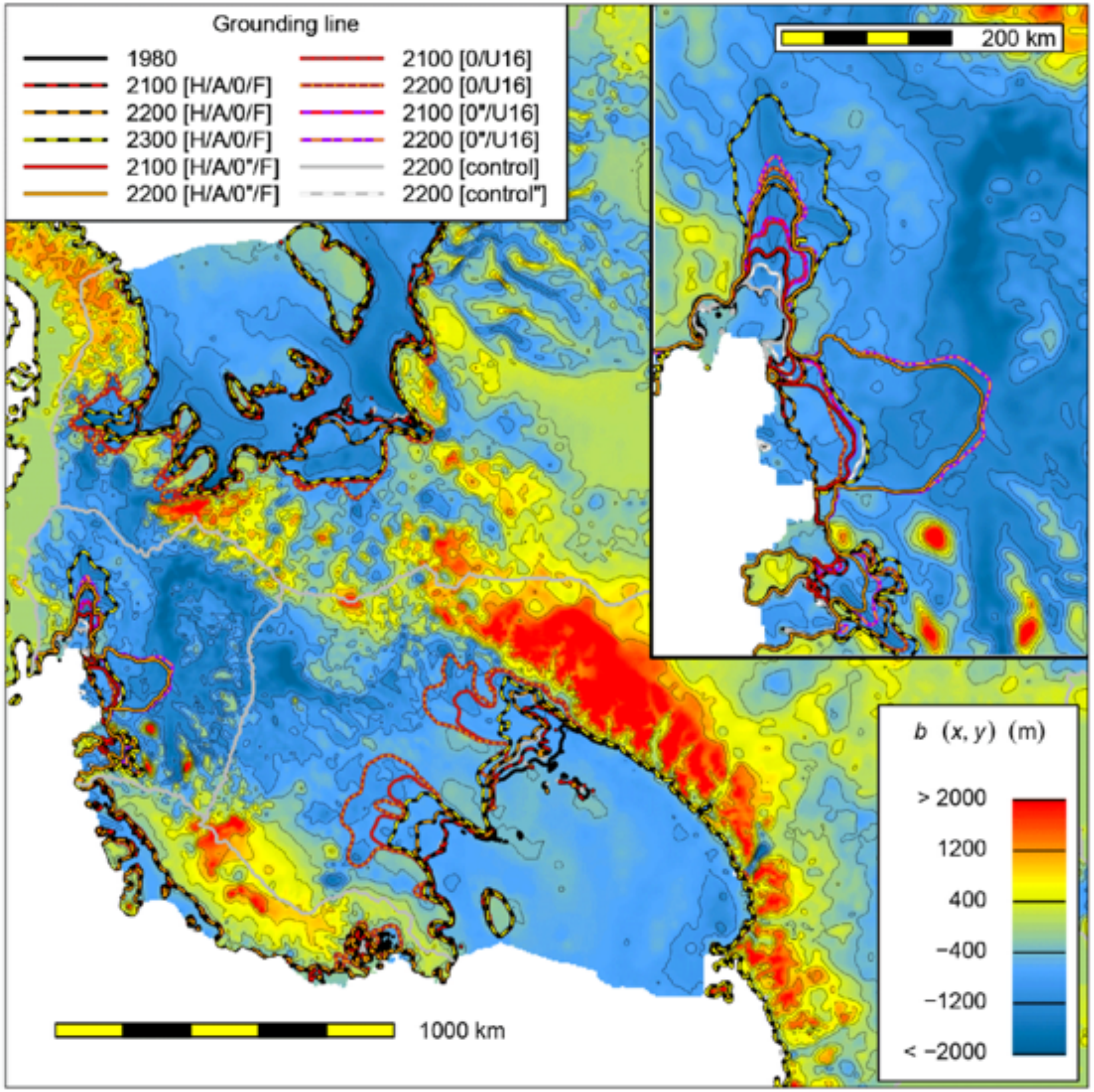


RCP8.5 ice sheet prediction at 2500
DeConto and Pollard (2016)

What is an ice sheet model used for?

- Predicting the short(ish)-term future

"Given sufficient melt rates, we compute grounding line retreat over hundreds of kilometers in every major ice stream, but the ocean models do not predict such melt rates outside of the Amundsen Sea Embayment until after 2100."



grounding line migration in ocean-forced simulations (Cornford et al., 2015)

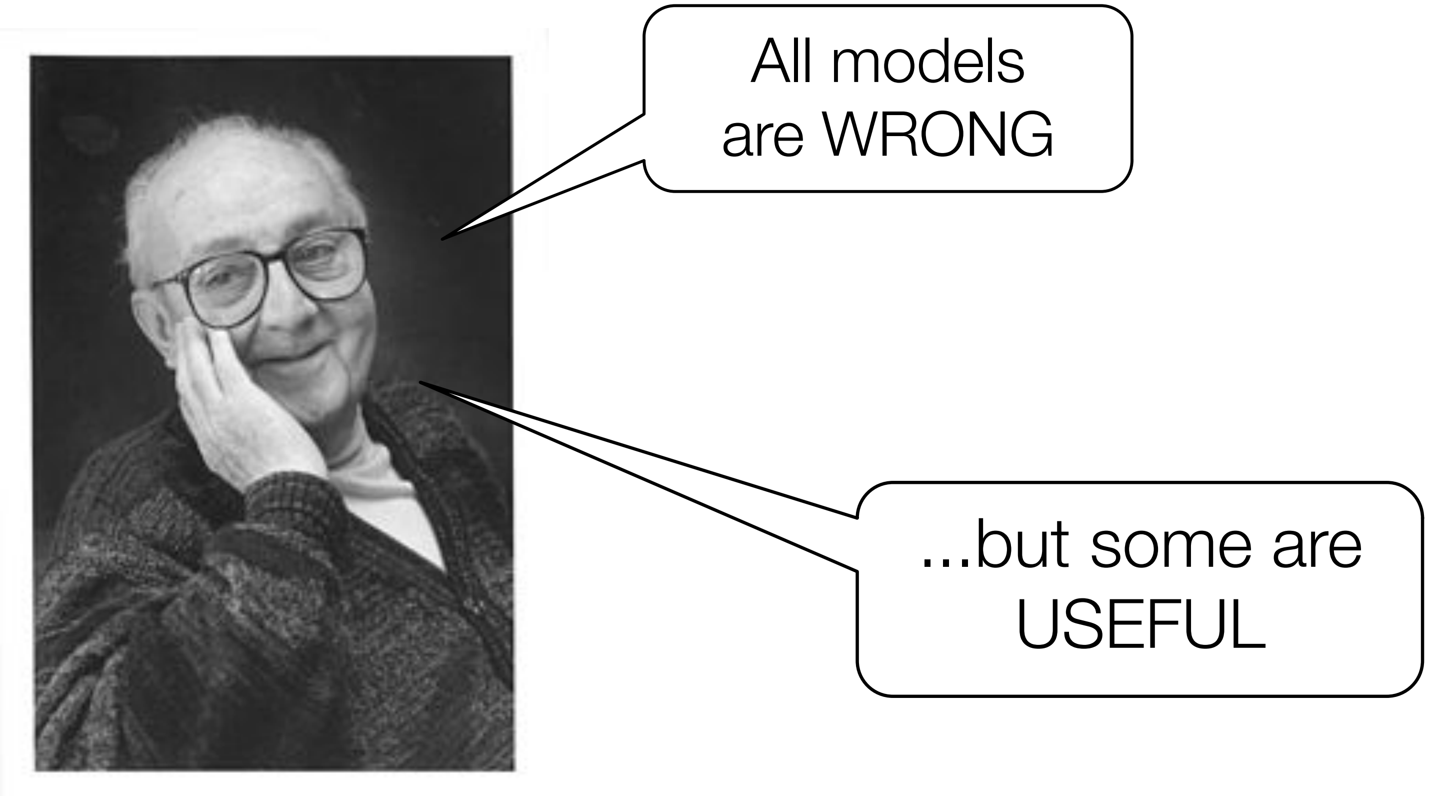
Ice sheet predictions for policymakers

- Ice Sheet Model Intercomparison Project for CMIP6
  - CMIP = Coupled Model Intercomparison Project Phase 6
- IPCC Sixth Assessment Report
  - Published from 2020
- Range of complexities and computational expense
  - Physics: full Stokes, various approximations
  - Spatial resolution and domain
- Standalone and coupled with climate models

ISMIP6 design: Nowicki et al. (2016)

How to use observations with models?

- Combining and comparing observations with models
  - Both are imperfect
  - Different spatial resolution, domains, variables
- To obtain best possible estimates of:
  - system state: past, present and future ice sheet
  - model parameters



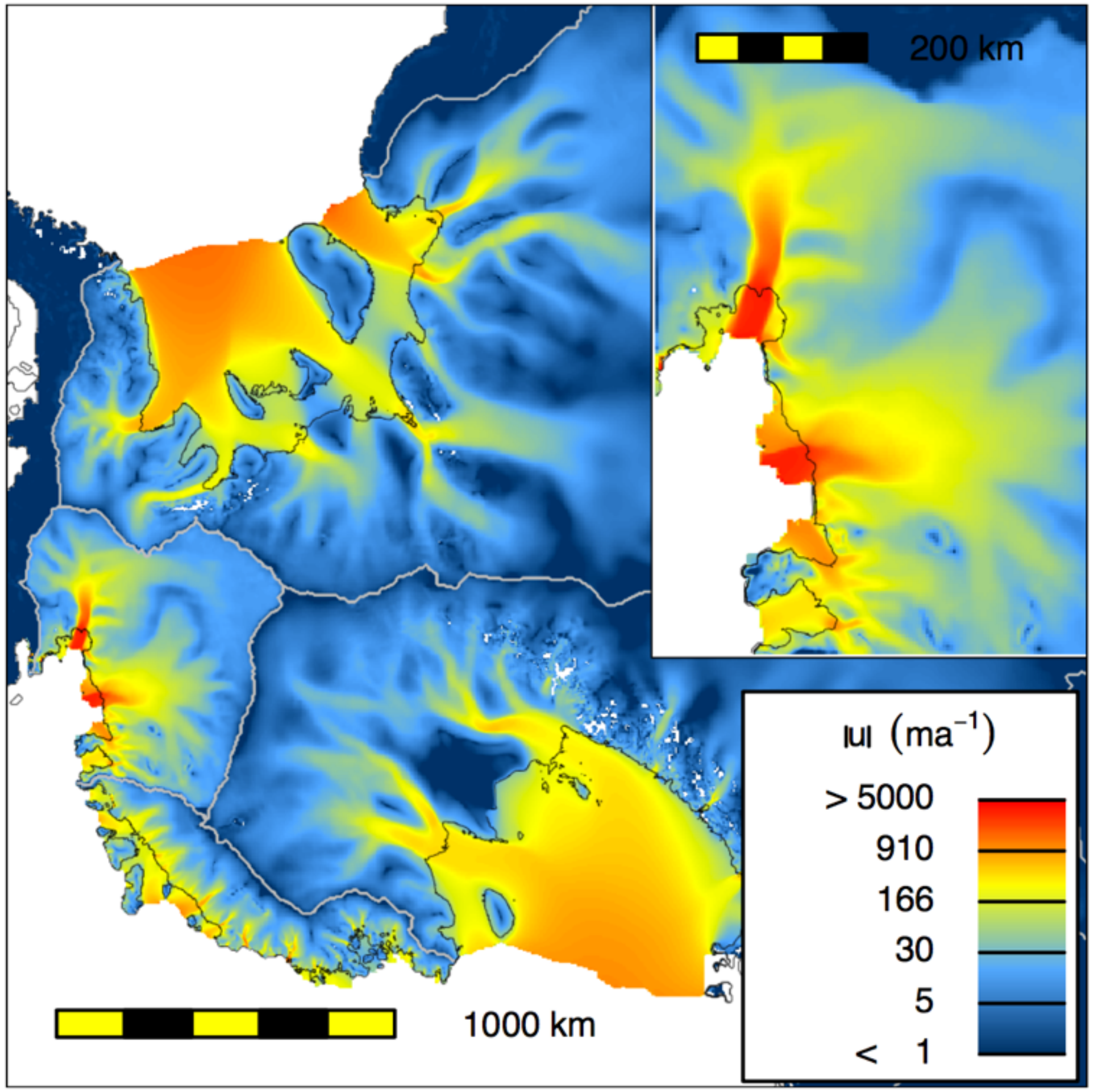
How to use observations with models?

- Formal methods often derived from Bayes Theorem
  1. model simulation(s) of state
  2. compare with observations
  3. update estimate of state and/or parameters

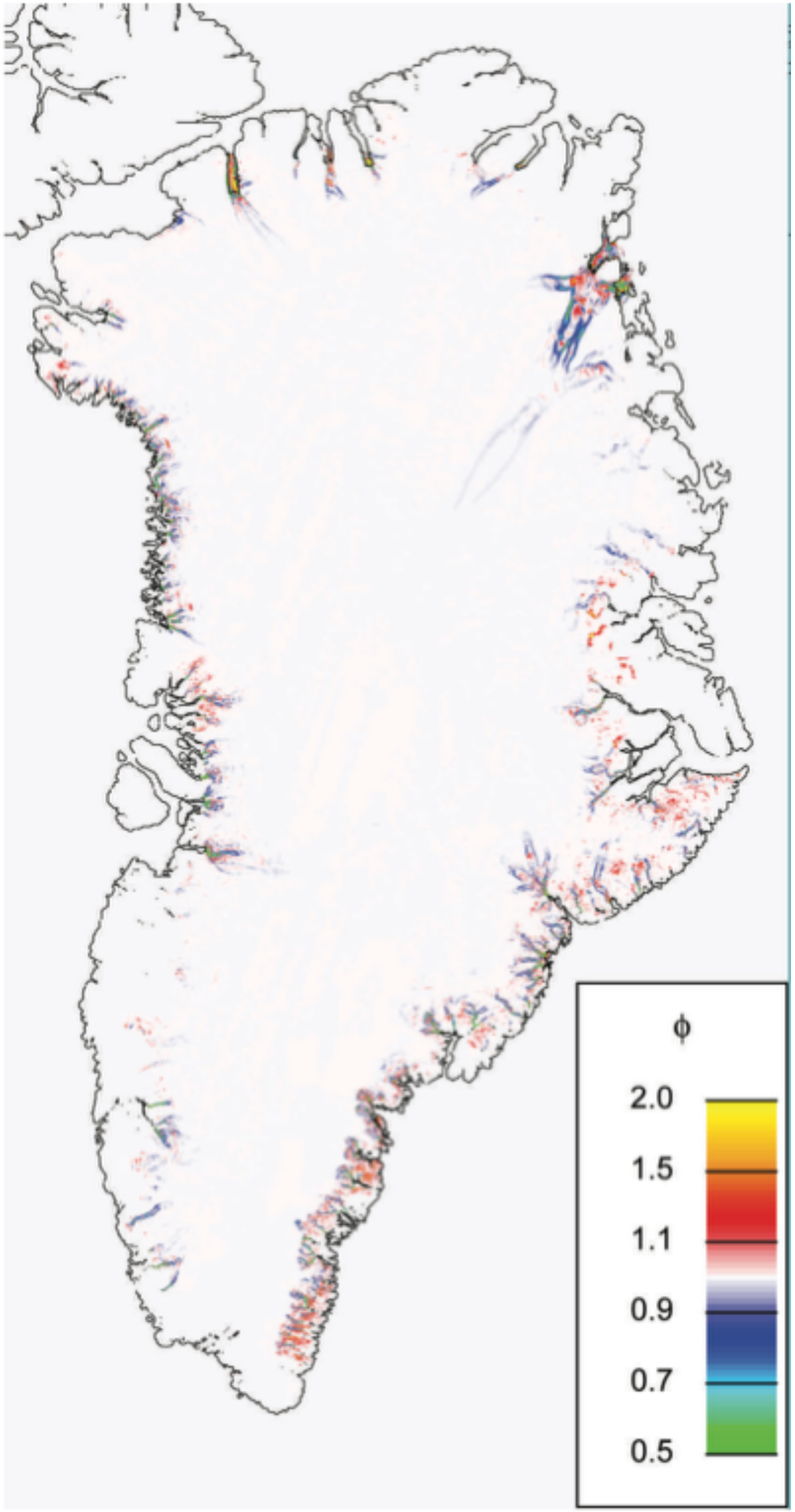
- e.g.
  - Data Assimilation (state) - incorporating obs into simulations
  - Bayesian calibration (parameters) - estimating parameters from obs with Bayesian inference
- Less formal methods also used…
  - 'nudging'
  - 'relaxation'
  - hand tuning

What does an ice sheet model need?

1. Initial state
   - ice sheet geometry
   - ice velocity
   - internal ice temperature
   - basal traction coefficient
   - maybe others, e.g.:
     - enhancement factor
     - effective viscosity, stiffness
     - bedrock topography corrections due to obs uncertainties
     - mass balance corrections to prevent artefacts/drift

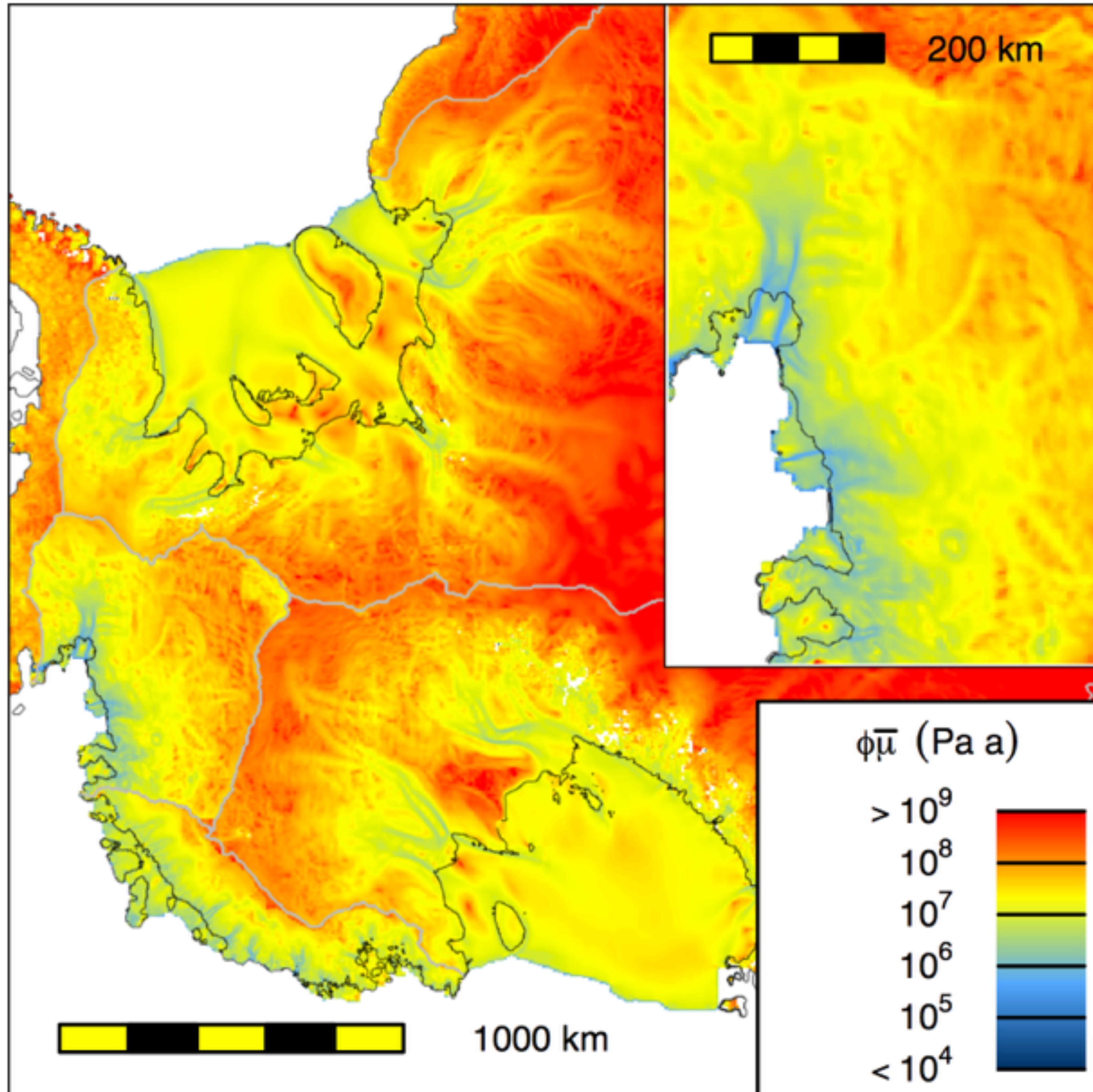


initial ice flow speed again (Cornford et al., 2015)

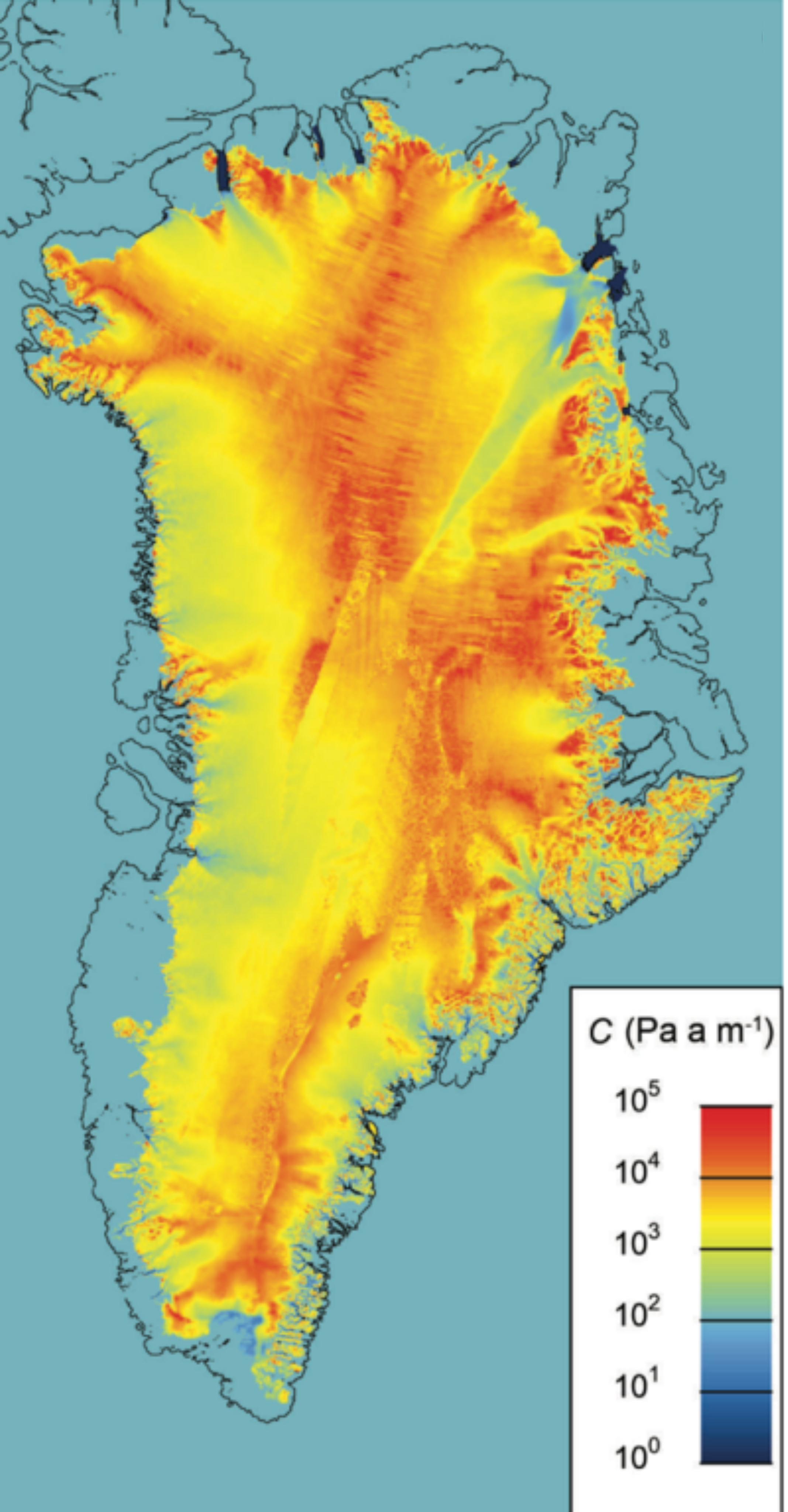


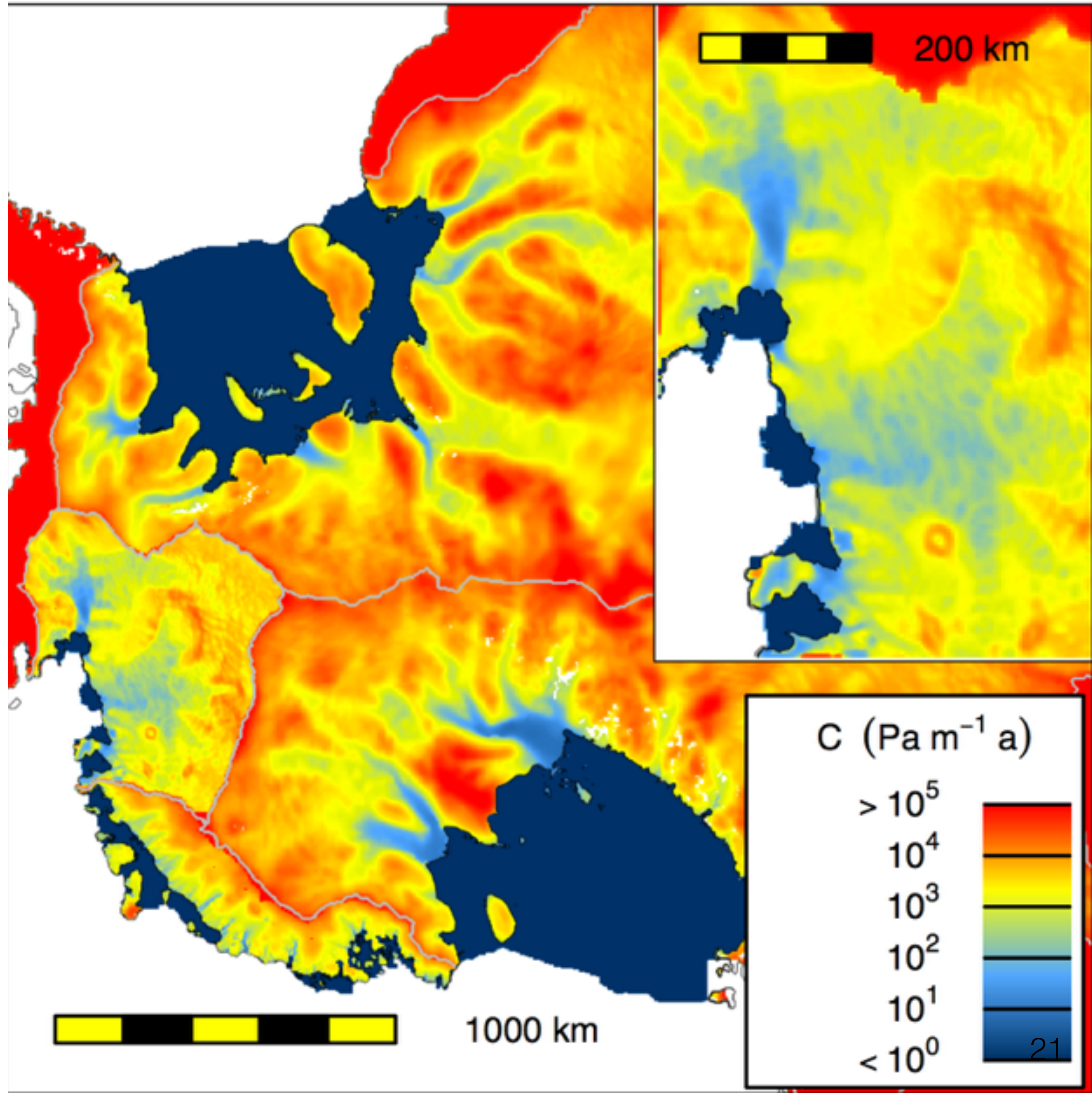
integrated effective viscosity
(Lee et al., 2015)

average effective viscosity
(Cornford et al., 2015)

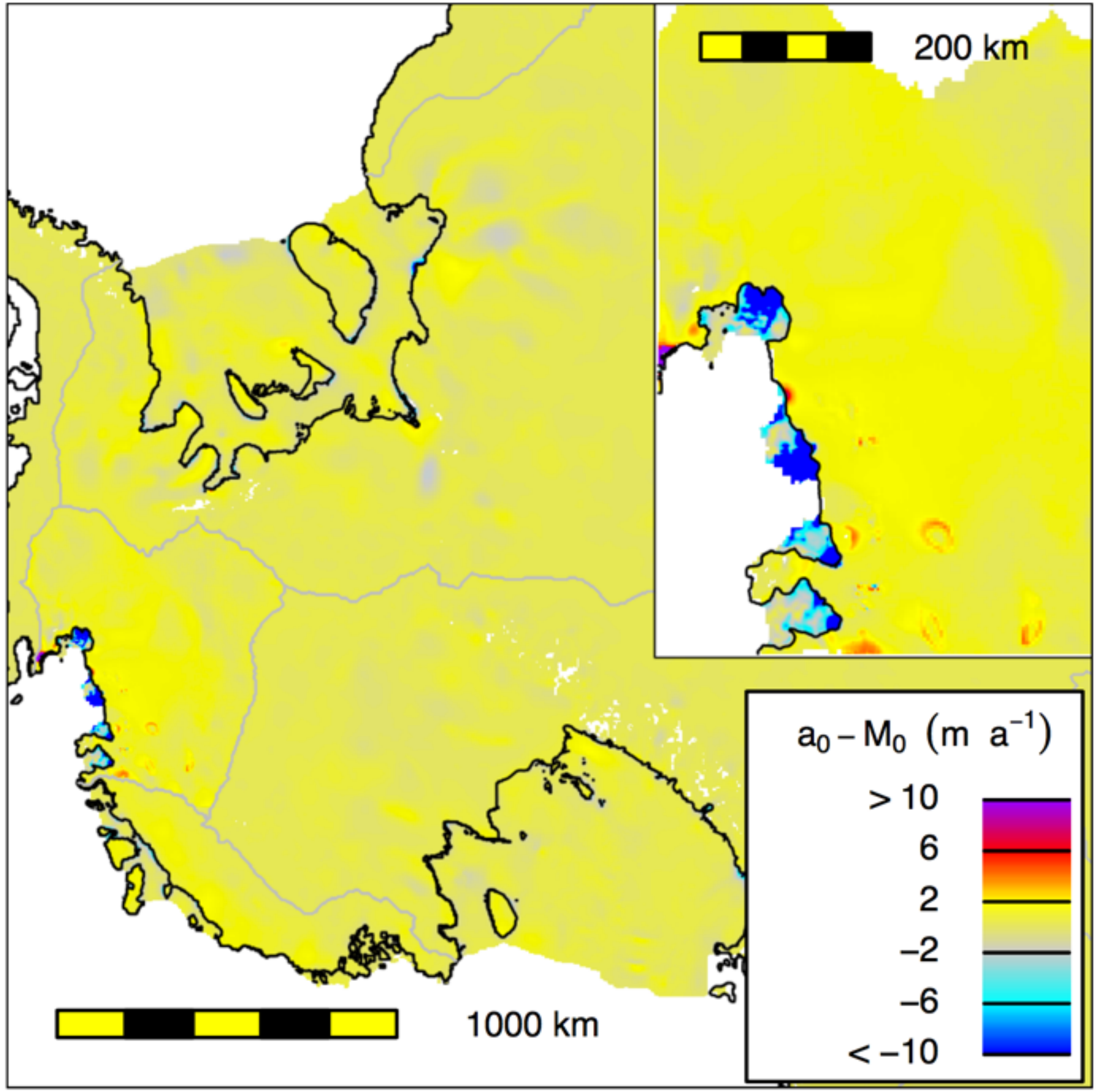


basal traction coefficient
(Lee et al., 2015; Cornford et al., 2015)





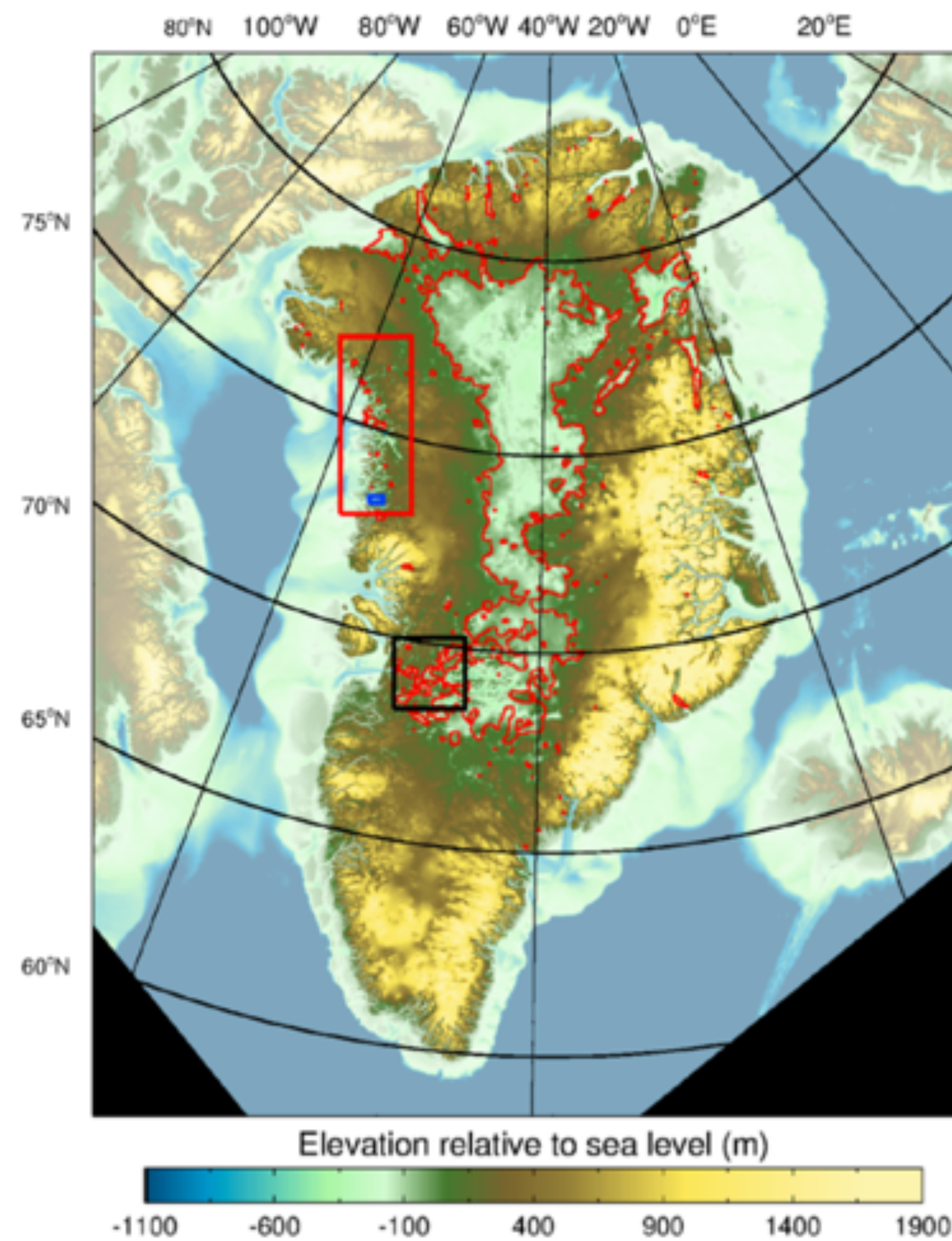
synthetic mass balance
(Cornford et al., 2015)

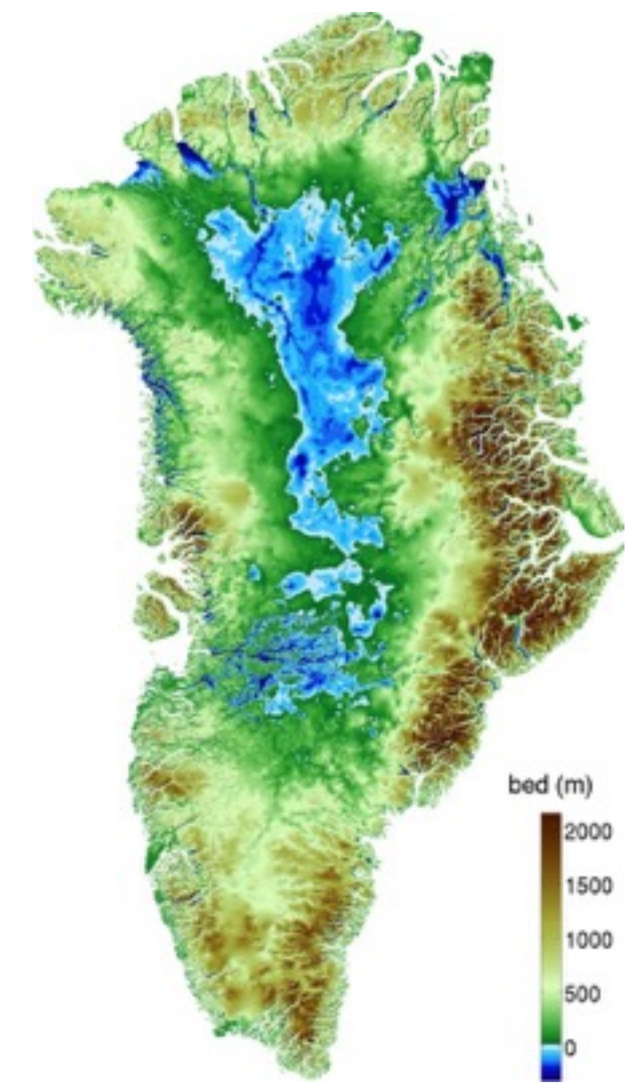


What does an ice sheet model need?

2. Boundary conditions

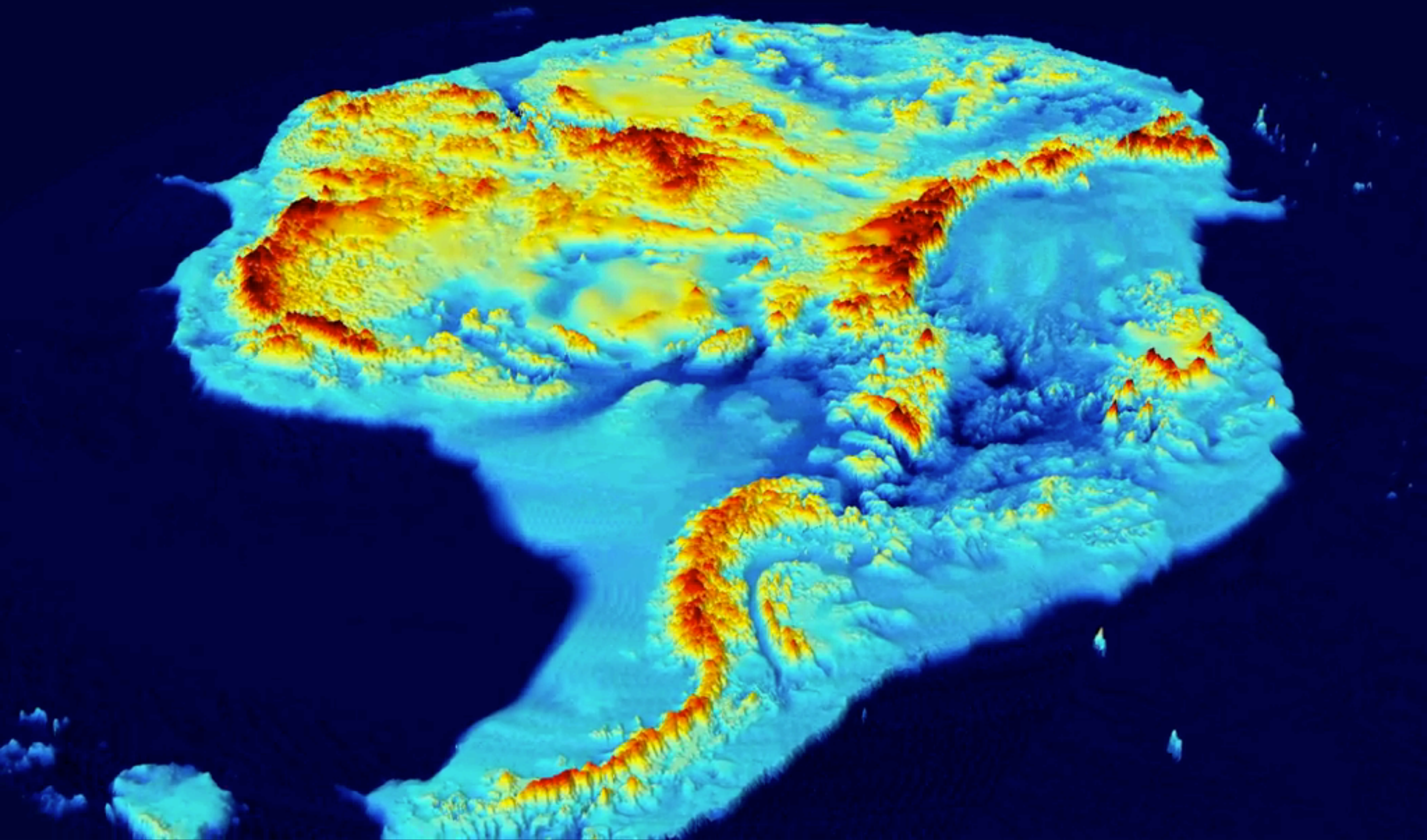
- bedrock topography, geothermal heat flux

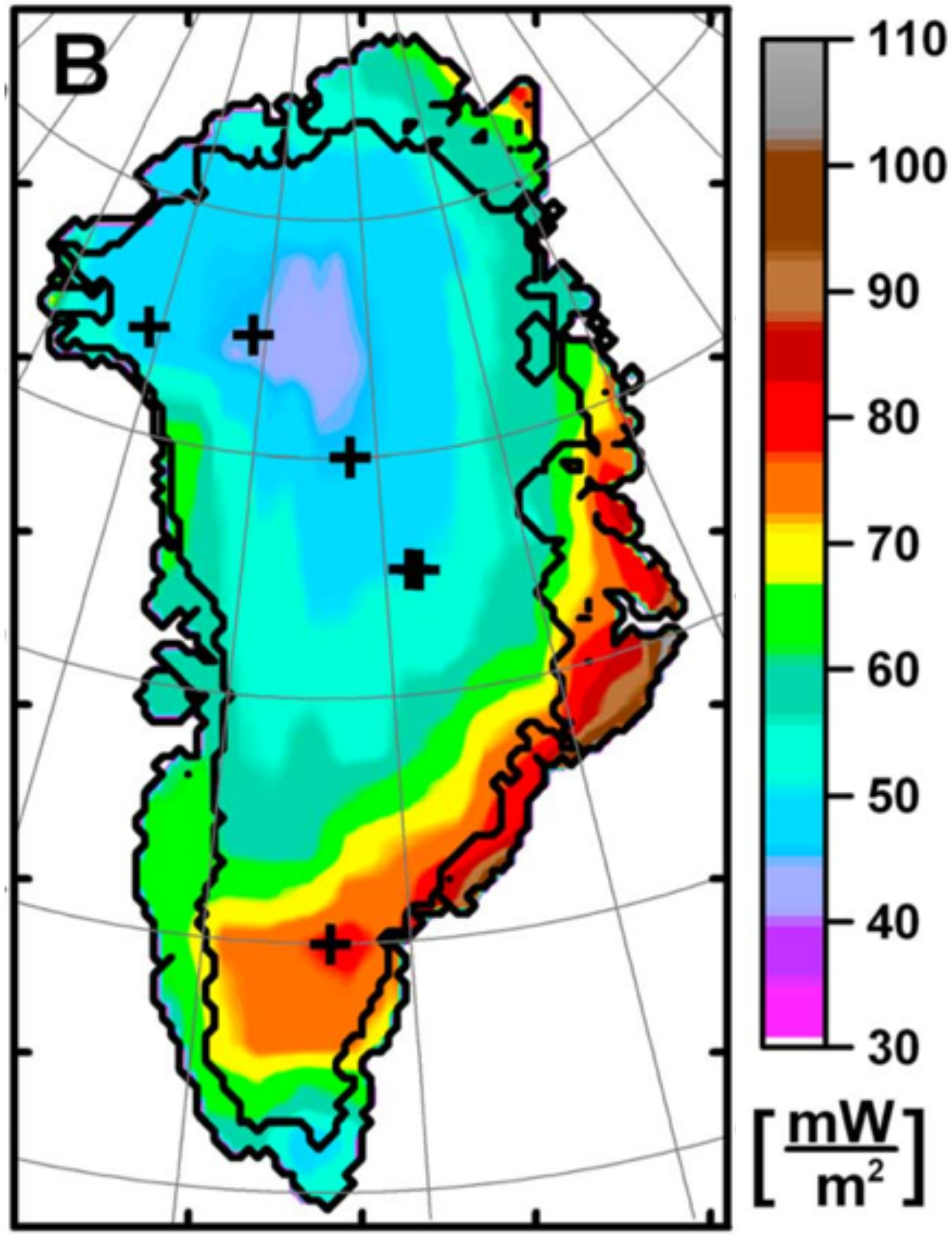


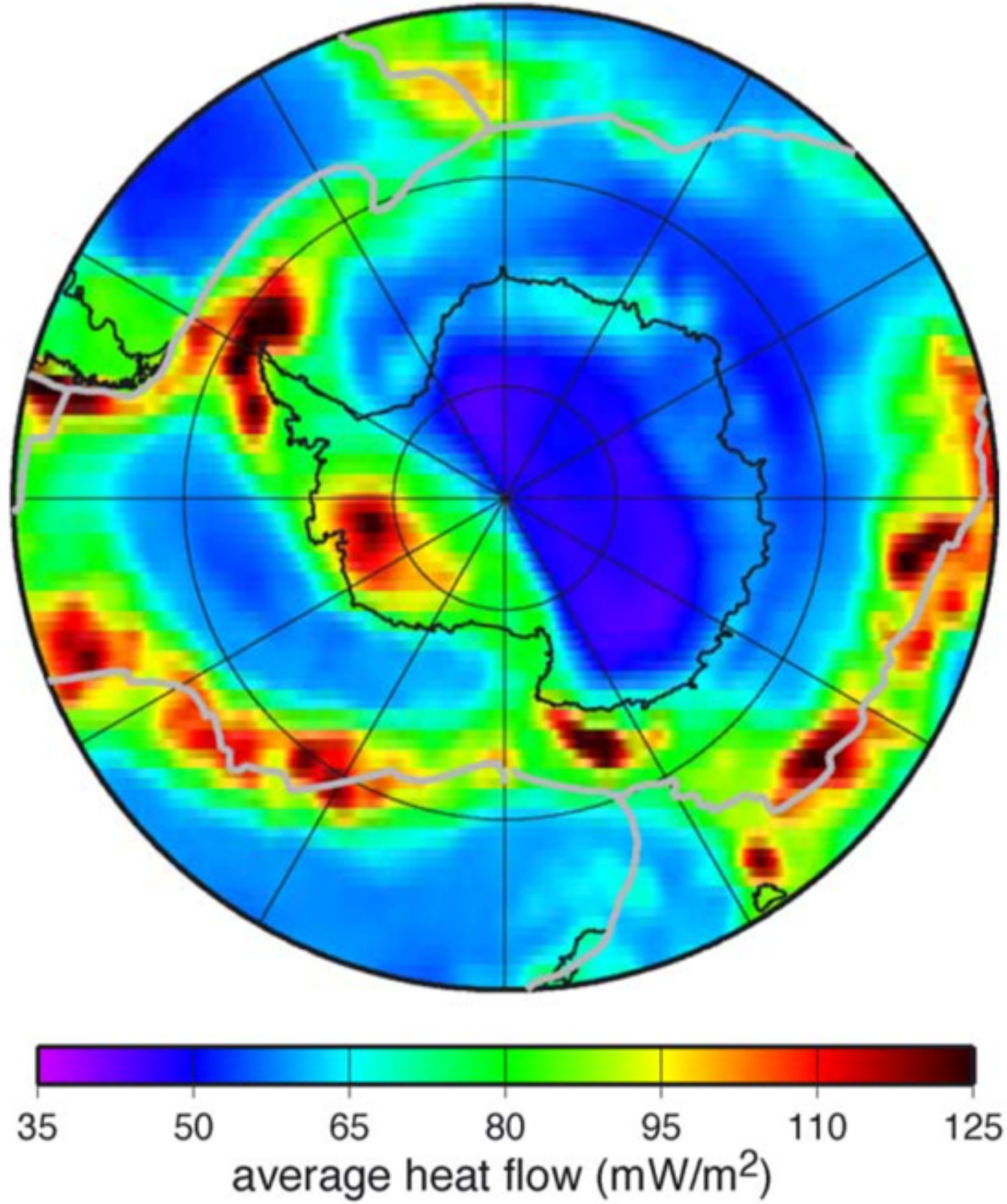


bedrock elevation (Bamber et al., 2013; Morlighem et al., 2014)

bedrock elevation: BEDMAP2
(Fretwell et al., 2013)







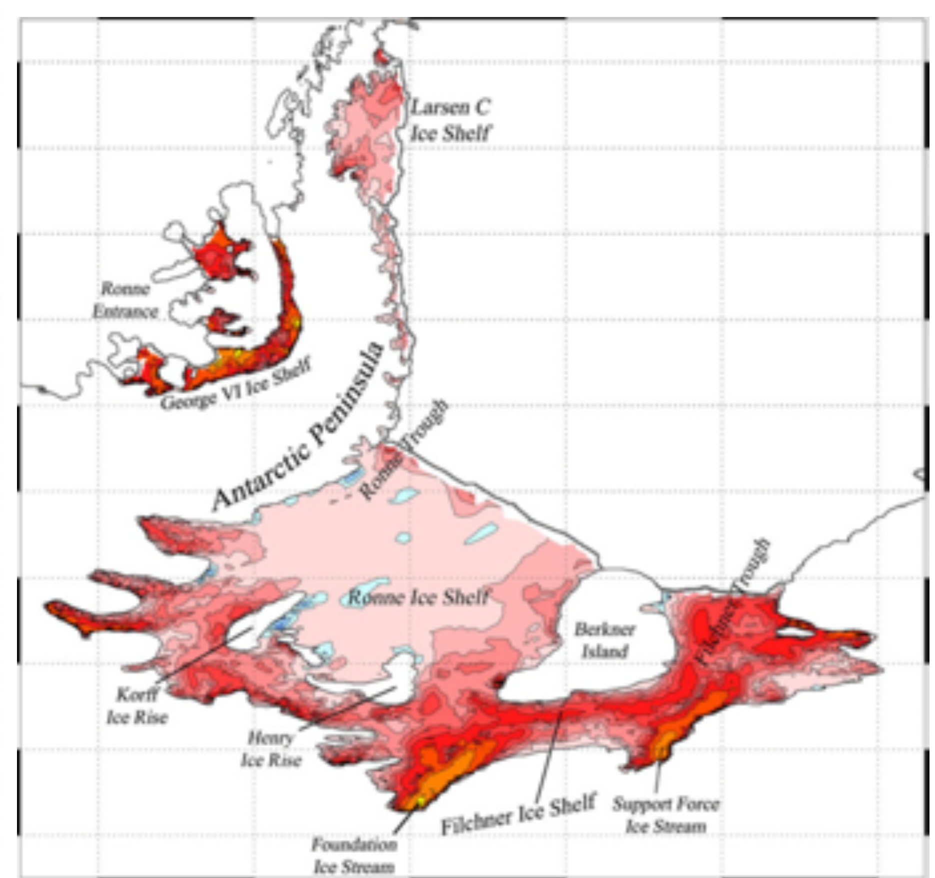
geothermal heat flux
(Shapiro et al., 2004;
Rogozhina et al., 2012)

What does an ice sheet model need?

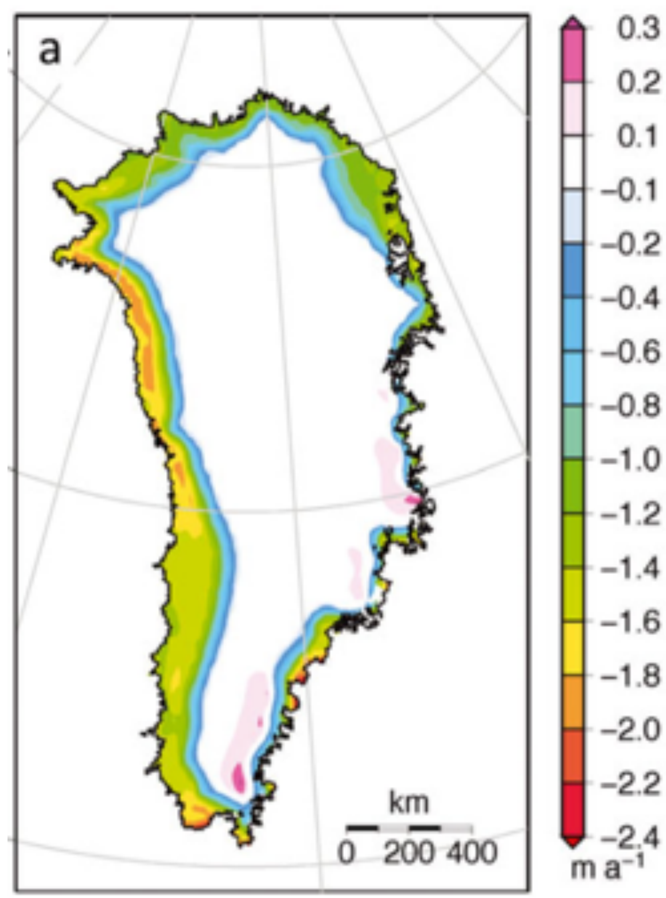
3. Climate forcing or mass balance
   - atmosphere:
     - temperature & precipitation, or
     - surface mass balance (SMB)
   - ocean
     - temperature, or
     - basal melting

- observations
- climate models
- ice cores
- schematic

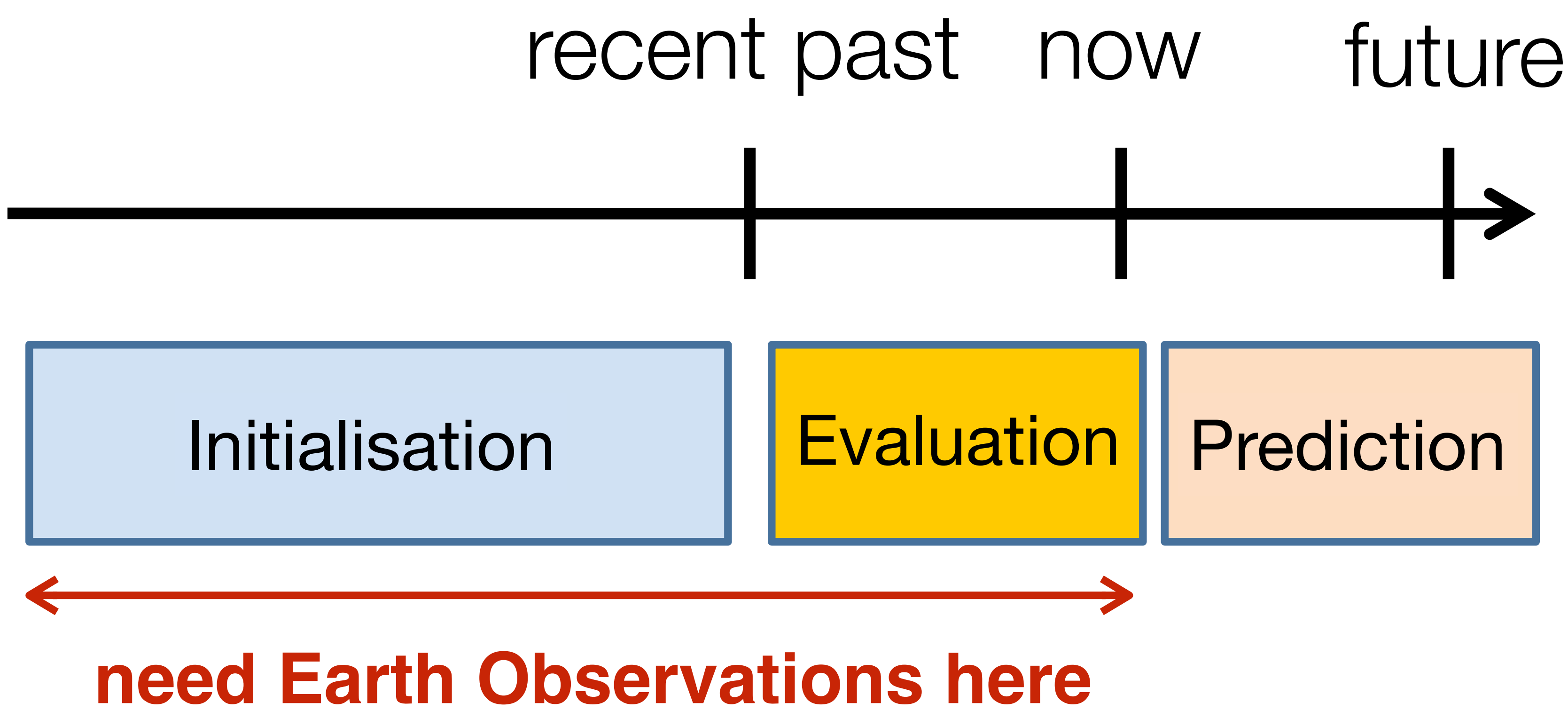
Basal melt rates in 2140-2149 under SRES scenario A1B (Timmerman & Hellmer, 2013)



Regional climate model SMB anomalies for 2091-2100 relative to 1989-2008 under SRES scenario A1B (Goelzer et al., 2013)



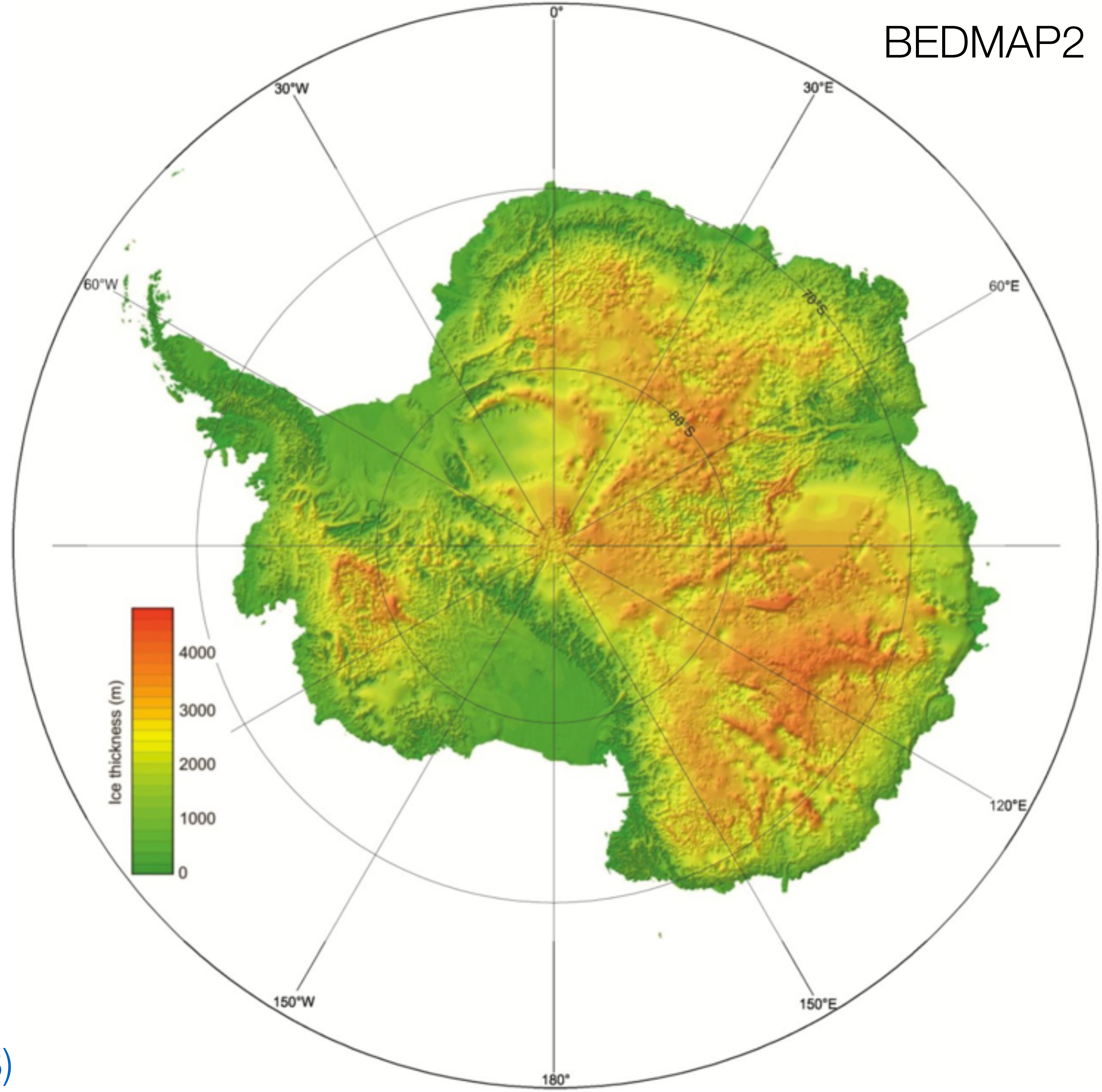
Earth Observations



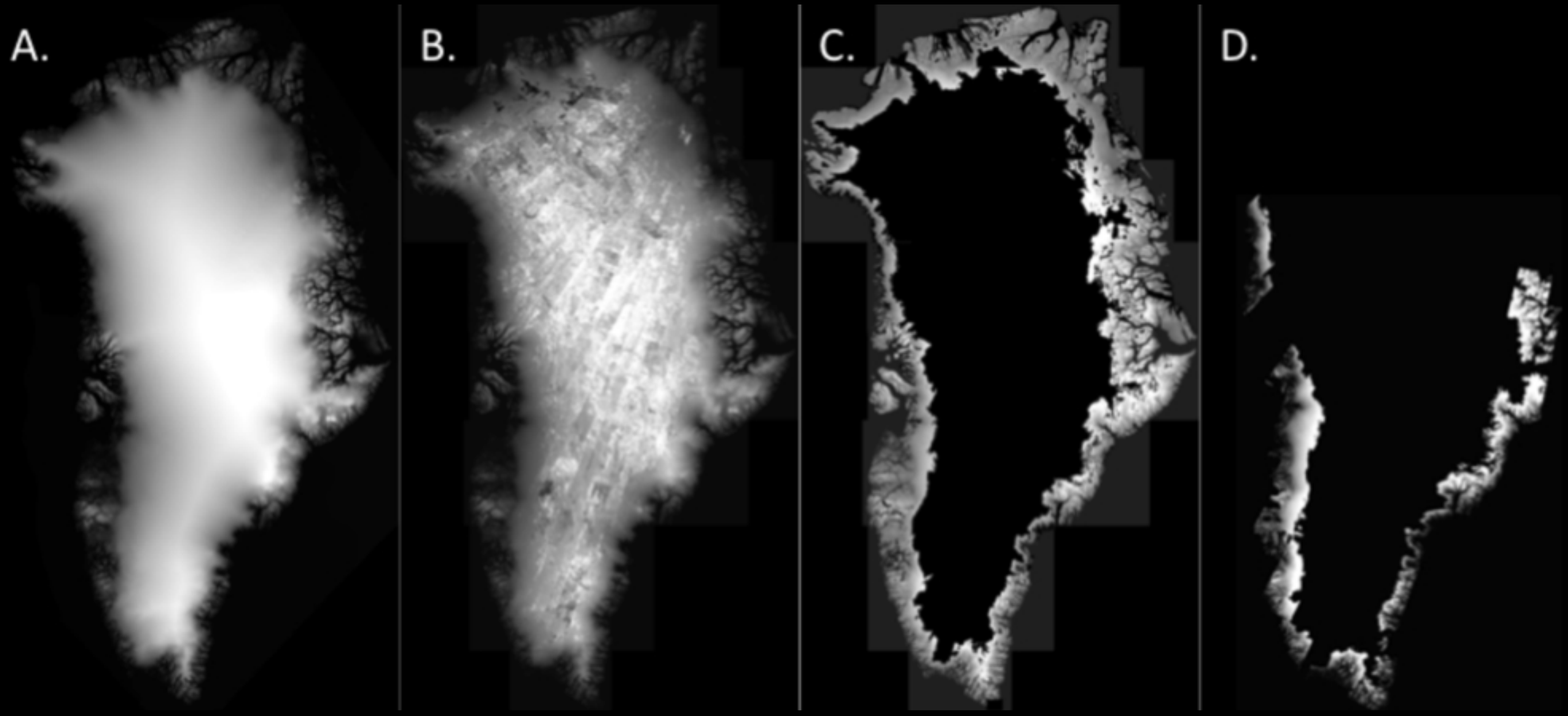
Initialising an ice sheet model

- Need to find self-consistent values for ice sheet state
  - geometry, flow, ice temperature, basal traction coefficient, …
- Consistent with observations and reconstructions
  - EO: geometry, elevation changes, velocities
  - recent climate, reconstructed palaeoclimate
- Even though both are imperfect
- Data assimilation of various kinds, e.g.:
  - tuning and inverse methods to estimate basal traction coefficient from surface or balance velocities
  - setting geometry equal to observed, then allowing model to ‘relax’ to quasi-equilibrium state

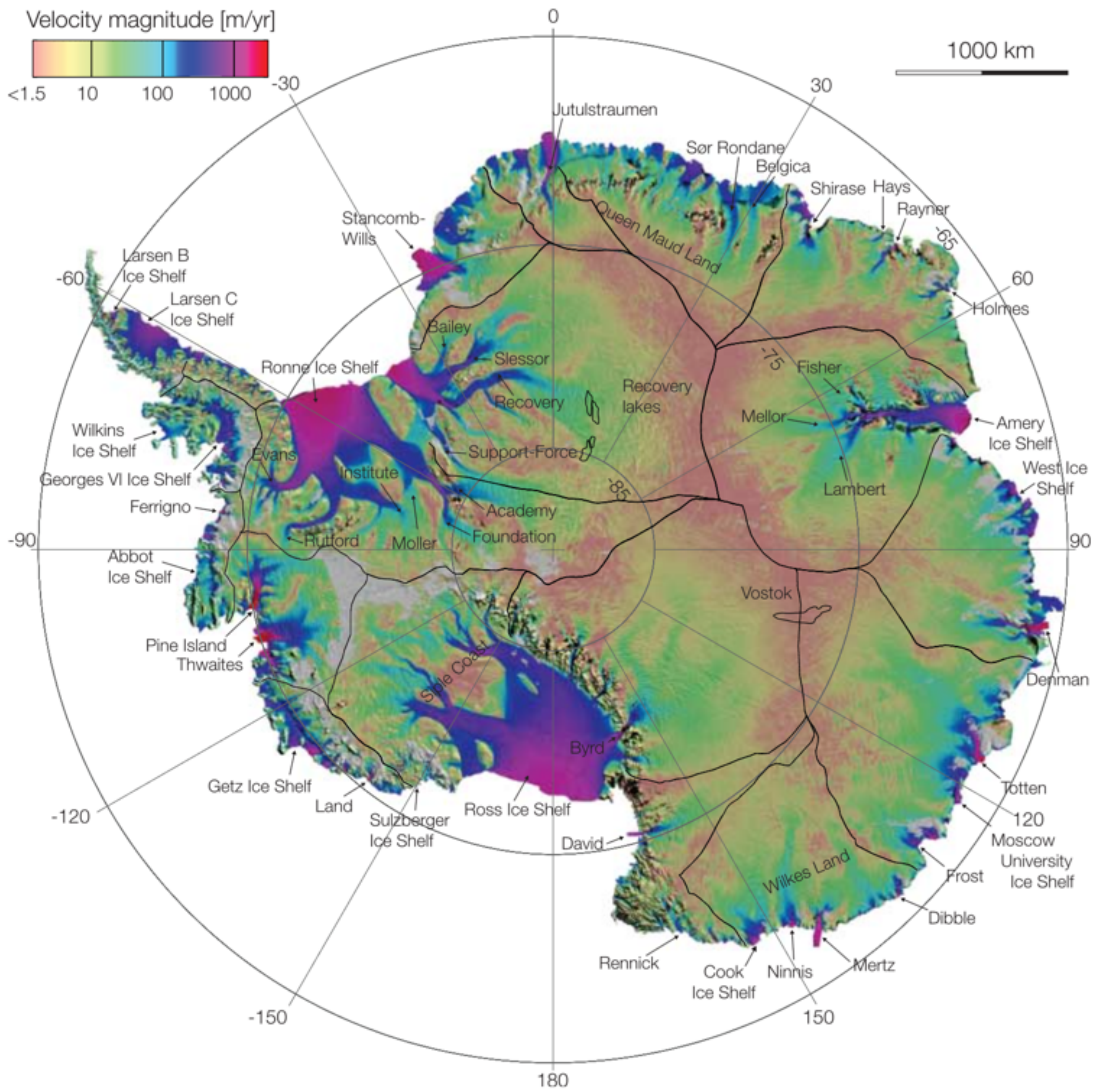
BEDMAP2



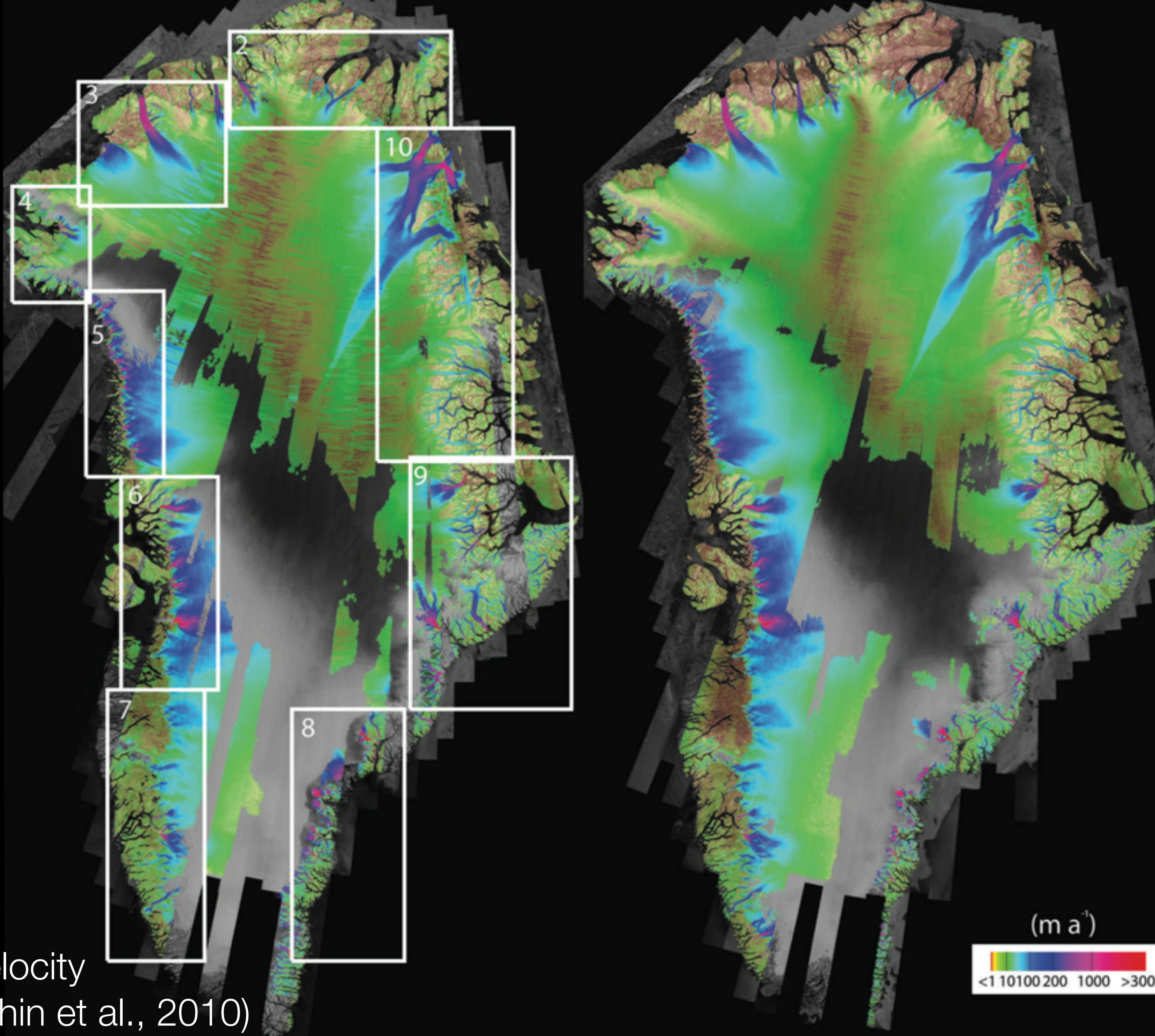
ice thickness
(Fretwell et al., 2013)



surface elevation
(Howat et al., 2014)



ice velocity
(Rignot et al., 2011)



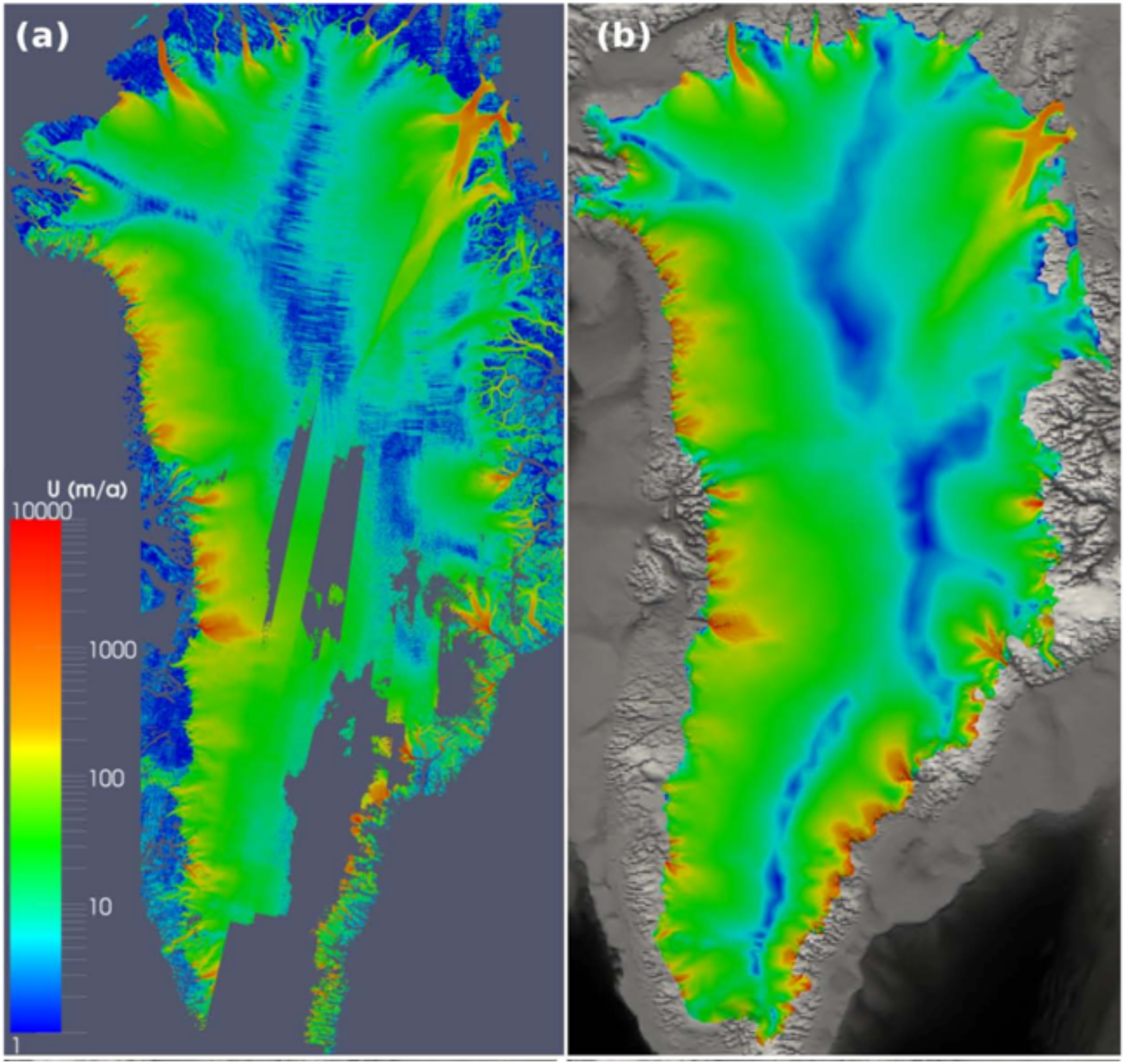
ice velocity
(Joughin et al., 2010)

Estimating basal traction coefficient

minimise mismatch between modelled and observed velocities

e.g. cost function

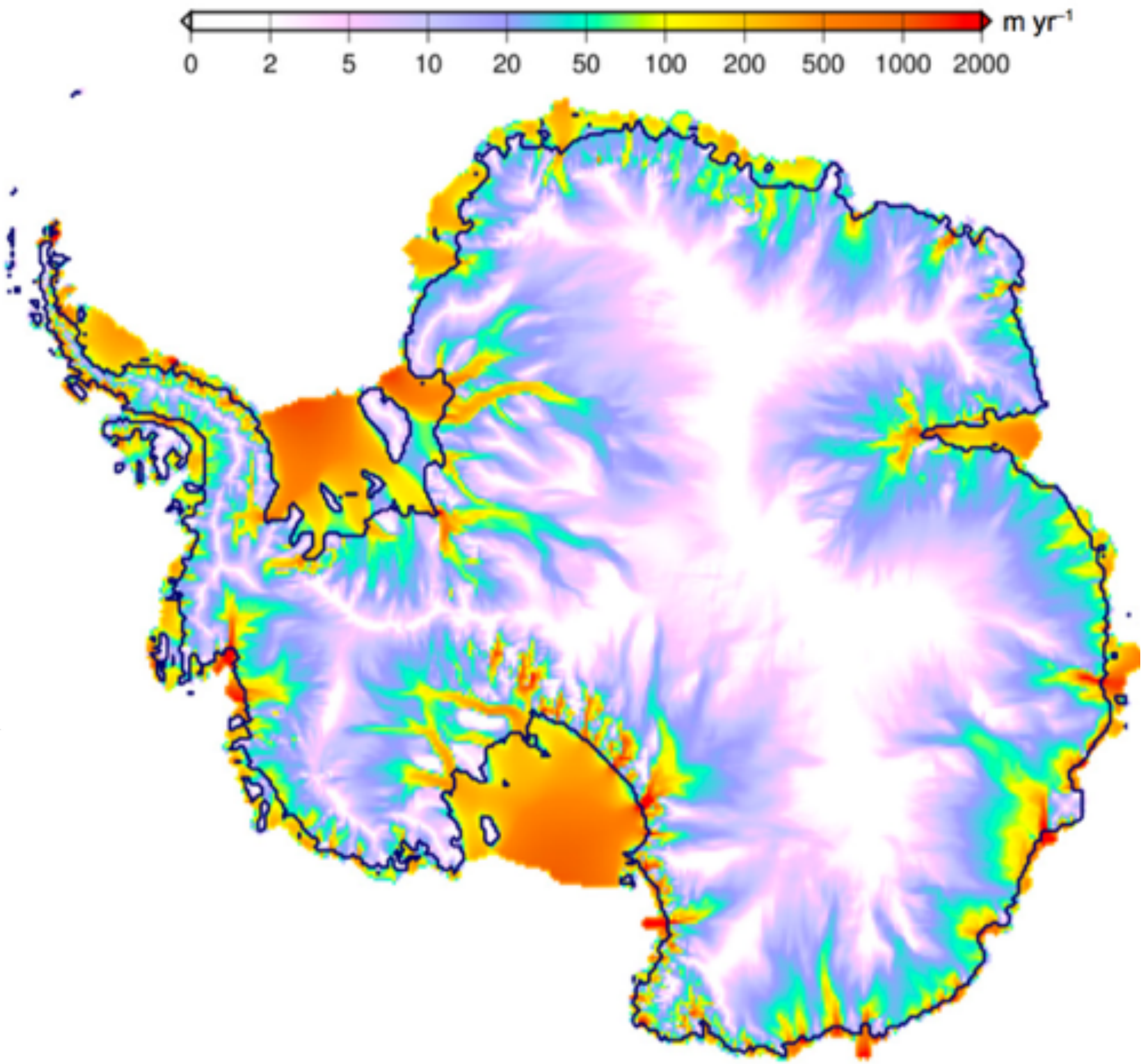
$$J_o = \int_{\Gamma_s} \frac{1}{2} \left(|\boldsymbol{u}_H| - |\boldsymbol{u}_H^{\mathrm{obs}}| \right)^2 \mathrm{d}\Gamma,$$



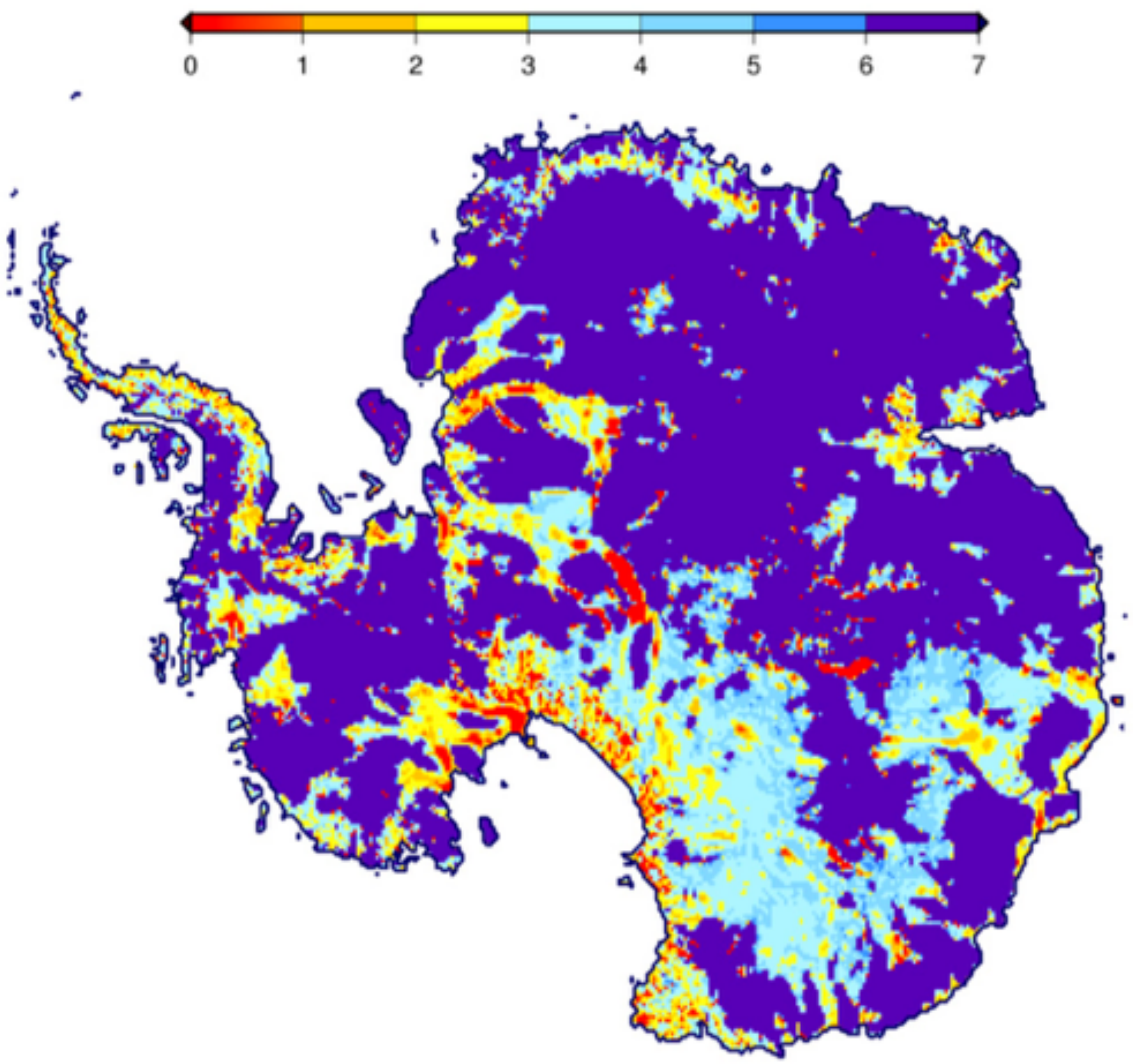
observed and initial model surface velocities (Gillet-Chaulet et al., 2012)

Estimating basal traction coefficient

inversion gives estimate of basal traction coefficient



initial average velocities
(Ritz et al., 2015)



initial log(effective basal traction coeff.)

Large initialisation uncertainties

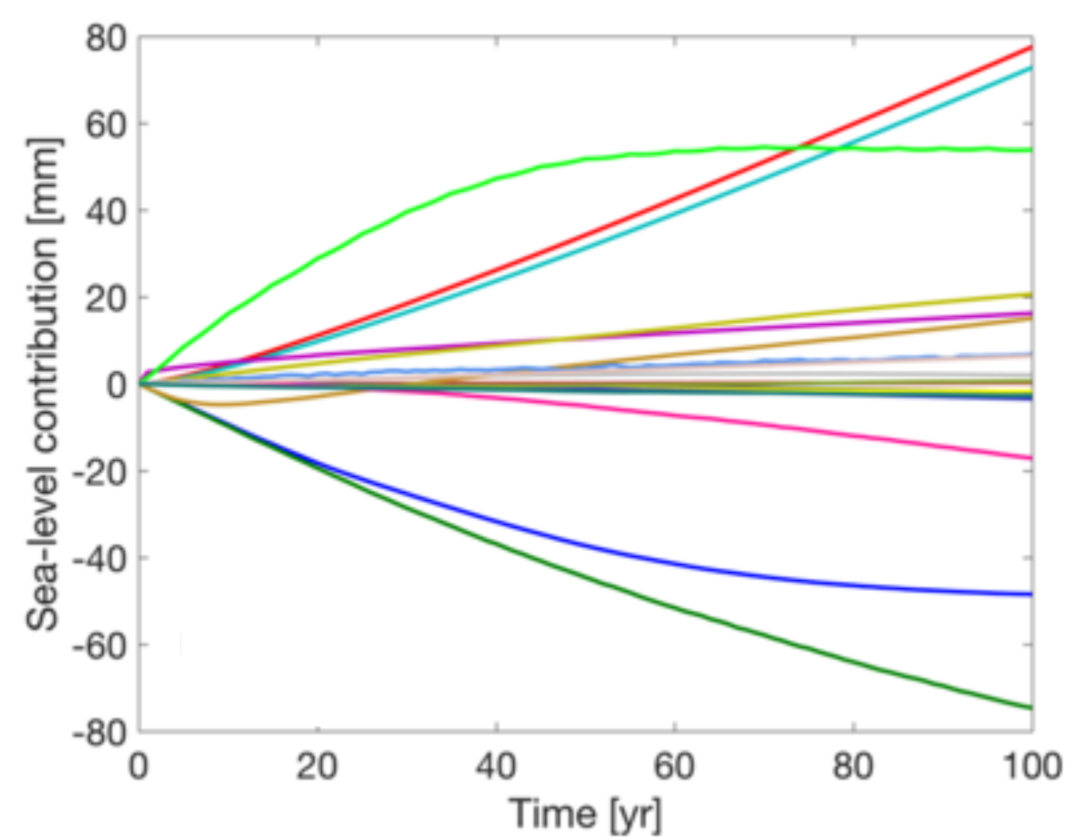
- Different methods
  - formal vs ad-hoc
  - free vs fixed geometry spin-up
  - glacial-interglacial cycle(s) vs recent climatology
  - mass balance corrections vs subtracting drift from predictions
- Different datasets and time periods
  - sometimes multiple variants
  - mismatches in time coverage
  - definition of "recent" climatology
- Different model structures
  - derive different initial states even if same method and data

	CISM	Elmer/Ice	GISM-HO	GISM-SIA	GRISLI	MPAS
DERIVATION OF ICE TEMPERATURE						
Spin-up simulation	Quasi-SS; fixed geom. (B13)	One g–ig cycle with SICOPOLIS (G97)	Two g–ig cycles; IT rescaled to obs. thick.	Two g–ig cycles; IT rescaled to obs. thick.	Quasi-SS; fixed geom. (B13)	Quasi-SS; fixed geom. (B13)
Spin-up SAT	E09, constant	E09, constant	Two g–ig cycles, evolving	Two g–ig cycles, evolving	E09, constant	E09, constant
BASAL DRAG CALIBRATION						
Method	Tuning	Control	n/a	n/a	Iterative inverse	Tuning
Target velocities	Balance	Surface	n/a	n/a	Surface	Balance
INITIALISATION						
Relaxation	n/a	55 years	1000 years (restrictions)	1000 years (restrictions)	200 years	n/a
Drift	Synthetic	Control	Synthetic	Synthetic	Control	Synthetic
Climate SMB Dates	ERA-I MAR 1989–2008	ERA-I MAR 1989–2008	ERA-40 PDD 1960–1990	ERA-40 PDD 1960–1990	ERA-I MAR 1989–2008	ERA-I MAR 1989–2008

initialisation methods in ice2sea project Edwards et al., 2014)

How much does it matter?

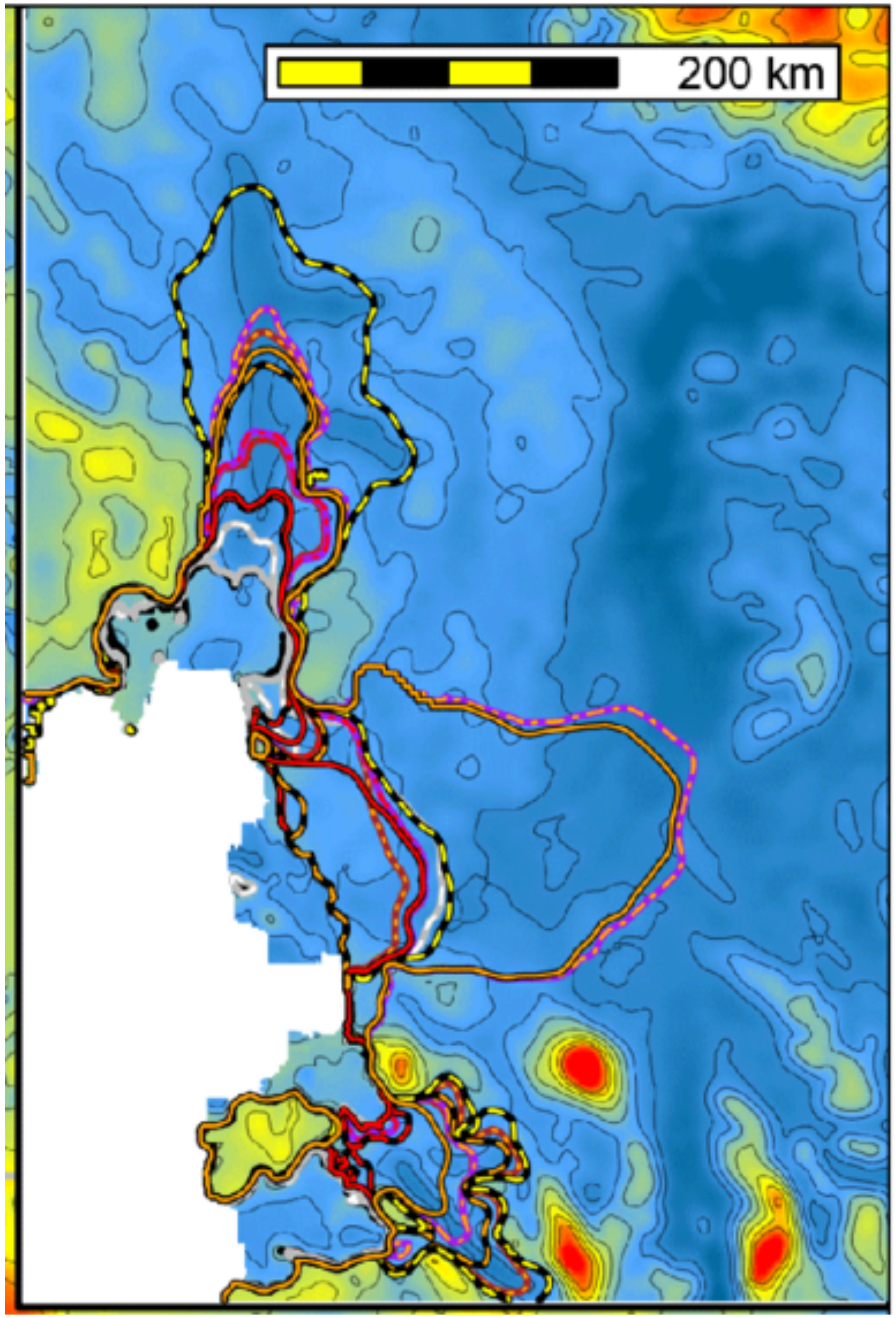
- Short-term ice sheet prediction like weather not climate
  - ice sheet responds on centennial timescales
  - decadal-century scale response depends strongly on initial state
- Drift if no mass balance corrections
  - subtract from predictions
- More important than ever
  - robust decadal-century scale predictions for adaptation



Greenland model drift
(Goelzer et al., 2016, EGU abstract)

How much does it matter?

- Initial accumulation from:
  - regional climate model
  - initialisation: mass balance corrections inferred for this climate

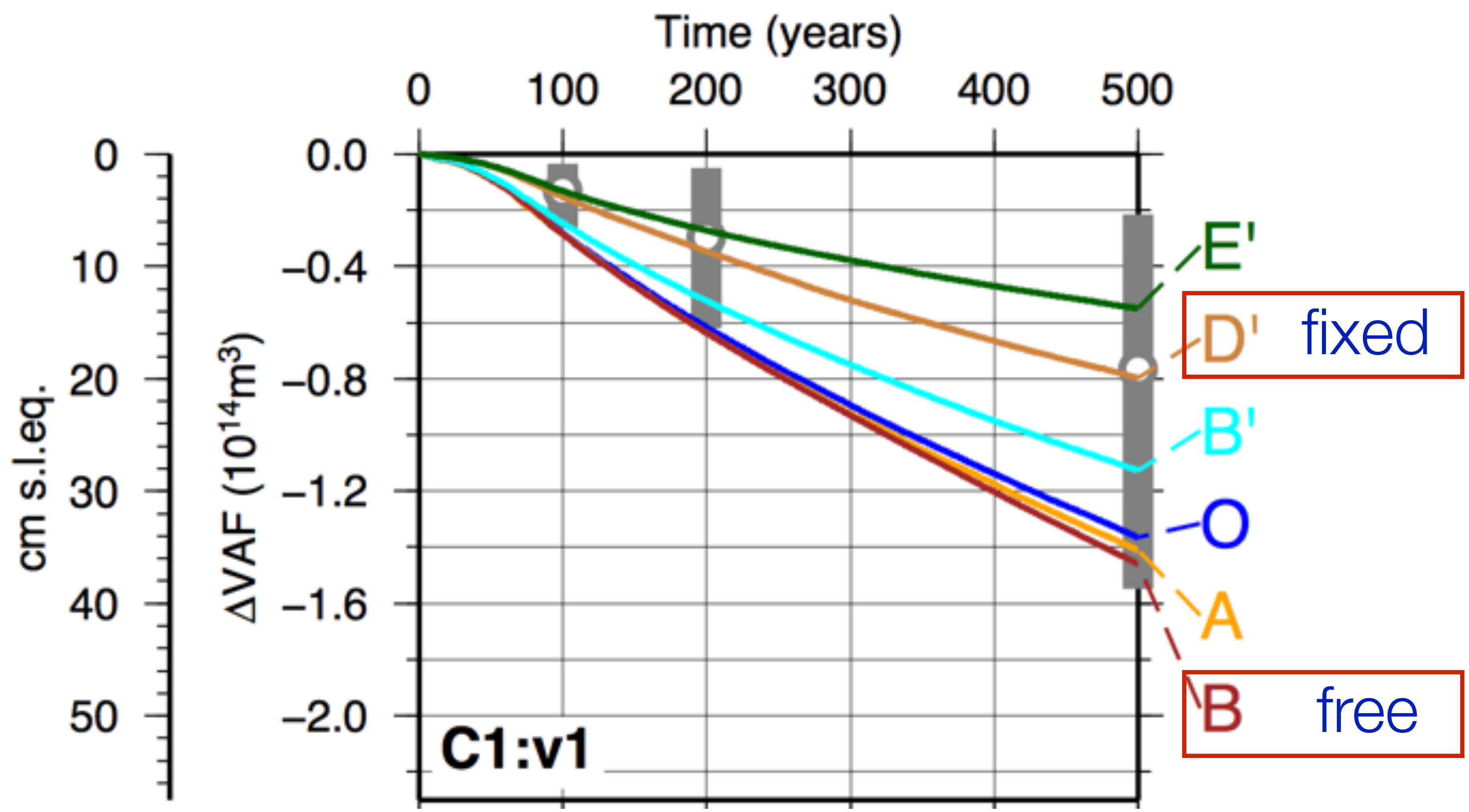


"Within the Amundsen Sea Embayment the largest single source of variability is the onset of sustained retreat in Thwaites Glacier, which can triple the rate of eustatic sea level rise….depends strongly on its initial state"

Cornford et al. (2015)

How much does it matter?

- Greenland ice sheet
  - 500 years of A1B scenario
- glacial-interglacial cycle spin-up
  - fix geometry to observed or allow to evolve freely?



grey = SeaRISE ensemble range

Saito et al. (2016)

initMIP

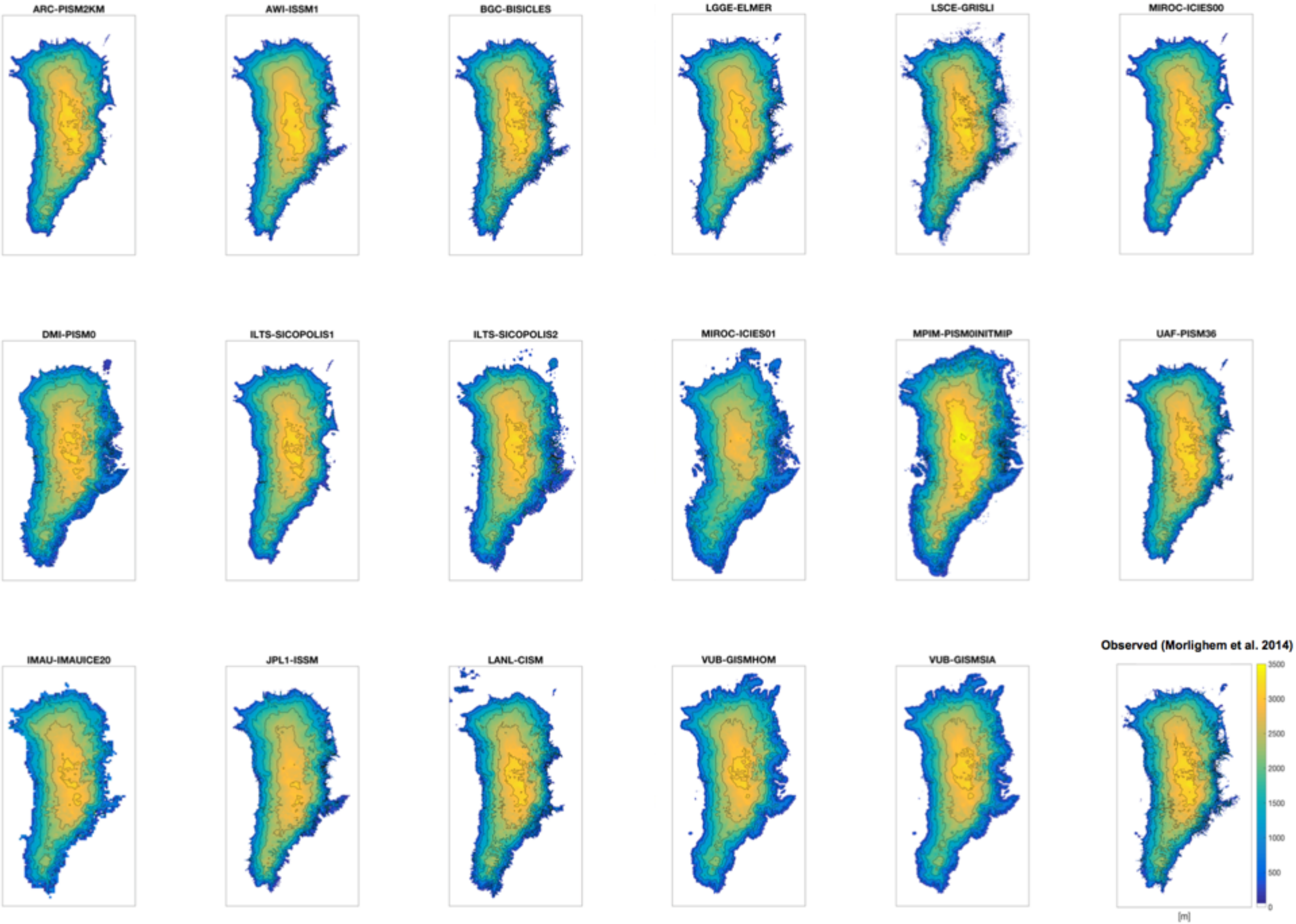
initMIP Goals

- Compare and evaluate the initialisation methods used in the ice sheet modelling community
- Estimate uncertainty associated with initialisation
- Get the ice sheet modelling community started with ISMIP6 activities

ISMIP6
Ice Sheet Model Intercomparison Project for CMIP6

- "Requirements"
  - Participants can and are encouraged to contribute with different… initialisation methods
  - The choice of model input data is unconstrained to allow participants the use of their preferred model setup without modification.
  - The specific year of initialization (between 1950 and 2014) is equally unconstrained

See ISMIP6 wiki for more details



initial ice thickness
(Goelzer et al., 2016, EGU abstract)

evaluating an ice sheet model

Evaluating an ice sheet model

- Important!
    - tests model adequacy
    - can quantify model uncertainty
- Not much formal statistical inference out there
    - only arbitrary comparisons e.g. RMSE
- Calibrating models in statistical framework
    - use ensemble of simulations with different input values and fields
    - compare with observations
    - update knowledge about good/bad parameter values
- Ad-hoc methods also used

Model calibration statistical frameworks

- History matching
  - rule out poor versions of model to give confidence intervals
- Bayesian calibration
  - highest weights to best versions to give probability distributions

What if:
obs = dog
model = cats?

- Strengths and weaknesses
  - HM: “this model can’t simulate dogs”
  - BC: “here is the cat that looks most like a dog”
    “…but here is my uncertainty about that answer”

History matching: Pine Island Glacier

1. model ensemble

5000 simulations
varying 7 parameters

2. observations

grounding line
thickness
velocity

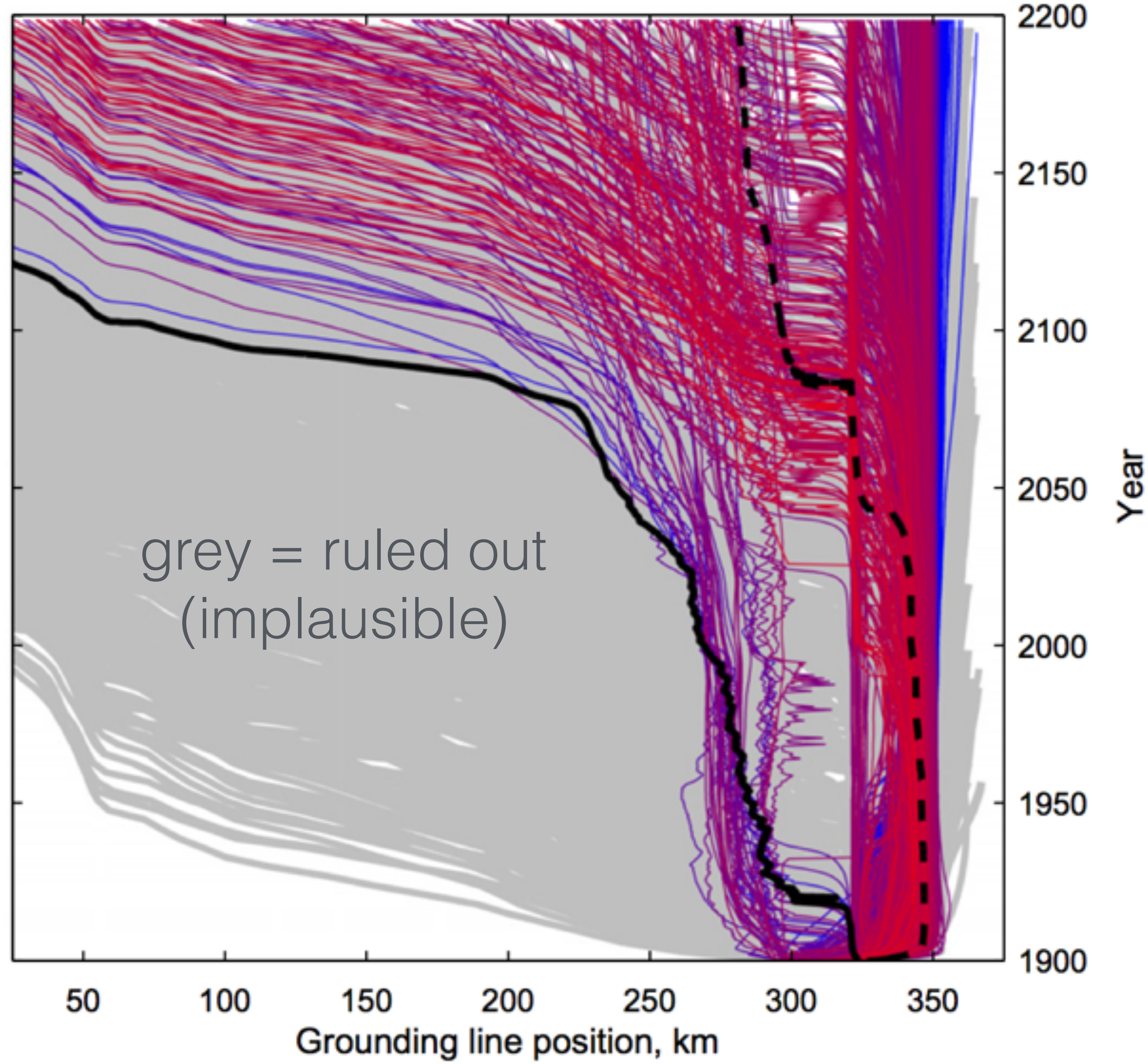
3. choose metric

$$\gamma_t(\phi) = \frac{Z_t - m_t(\phi)}{\sqrt{\mathrm{Var}(\delta_t) + \mathrm{Var}(e_t)}}$$

4. define threshold

$$|\gamma_t(\phi)| \leq 3$$

95% confidence set



Gladstone et al. (2012)

Bayesian calibration: Antarctica

1. model ensemble

3000 simulations
varying 16 inputs

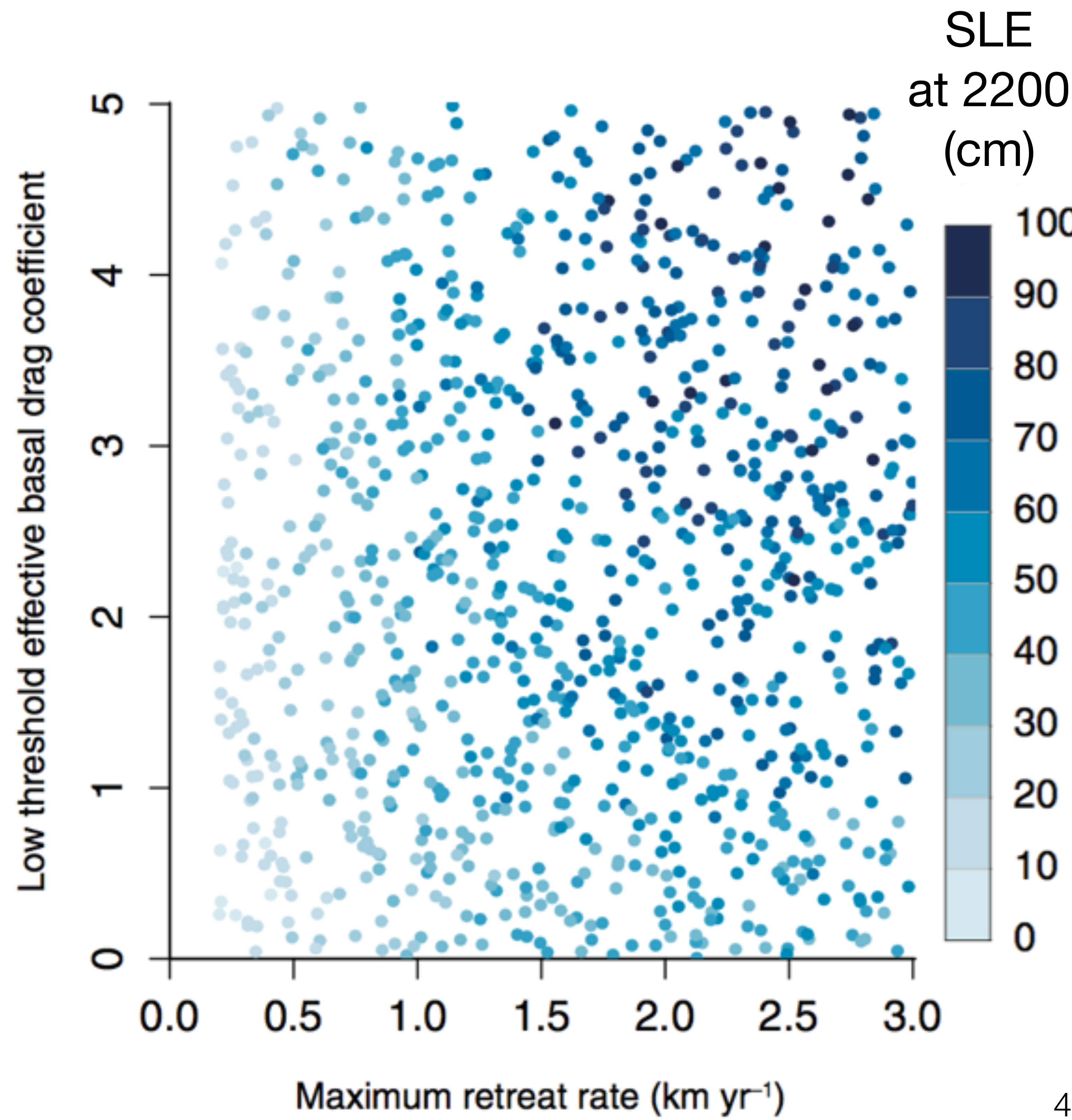
2. observations

Amundsen Sea Embayment
mass trend (IMBIE)

3. choose likelihood

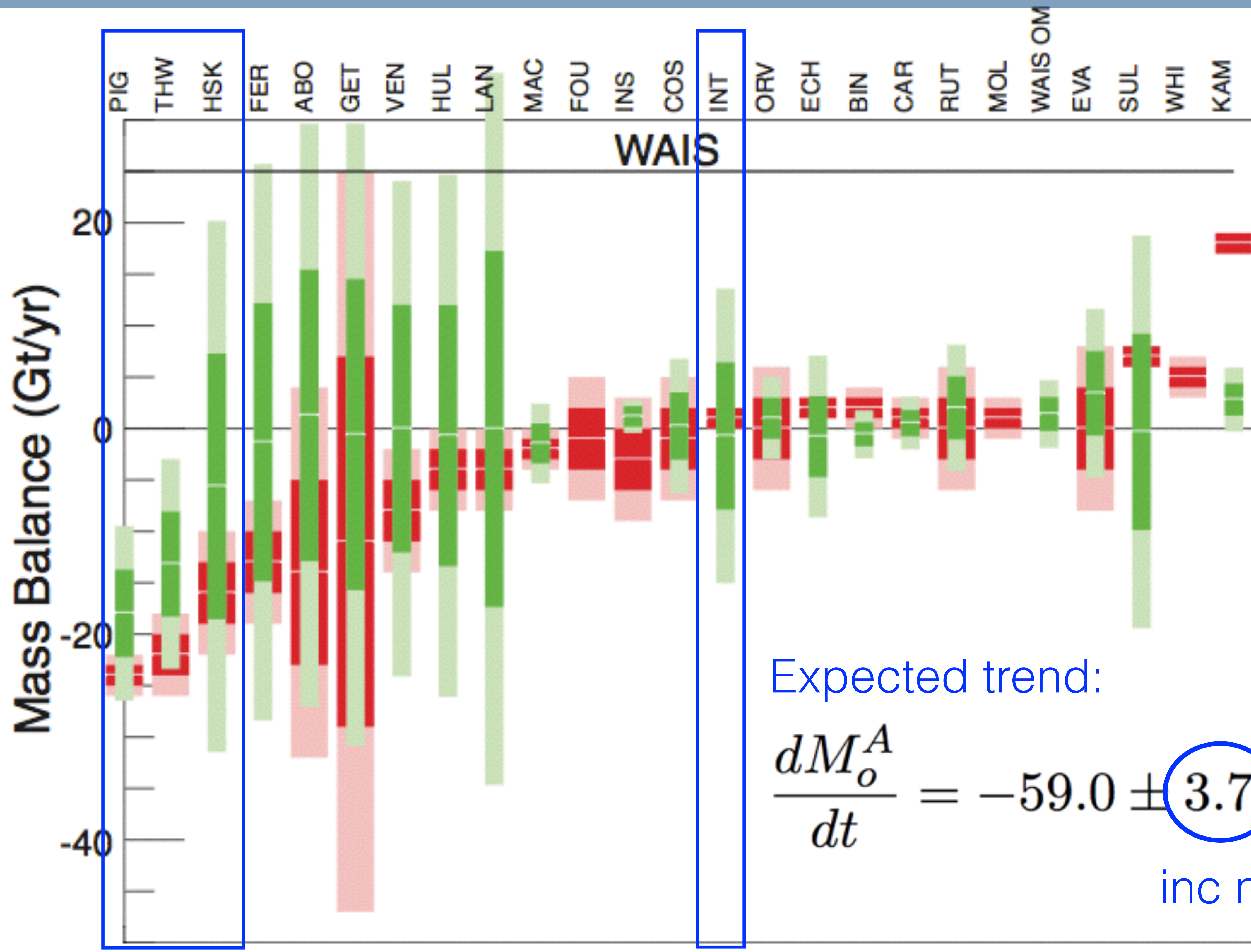
$$w(\phi) \propto \exp\left\{\frac{-(\mathrm{Z}-\mathrm{m}(\phi))^2}{2(\mathrm{Var}(\delta)+\mathrm{Var}(\mathrm{e}))}\right\}$$

4. normalise and reweight



Ritz et al. (2015)

Amundsen Sea Embayment mass trend (1992-2011)



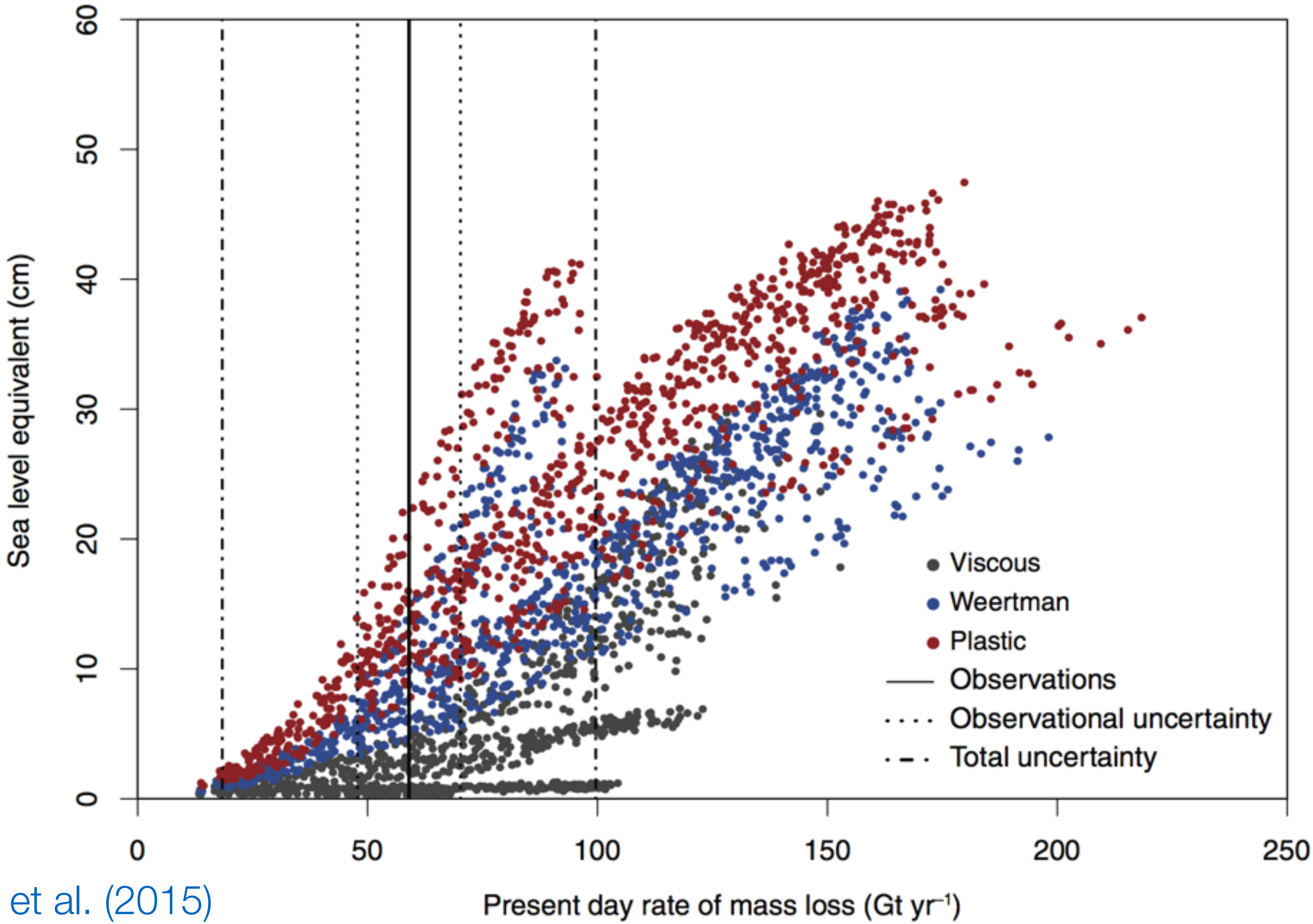
Expected trend:

$$\frac{dM_o^A}{dt} = -59.0 \pm 3.7 \text{ Gt a}^{-1}$$

inc model error

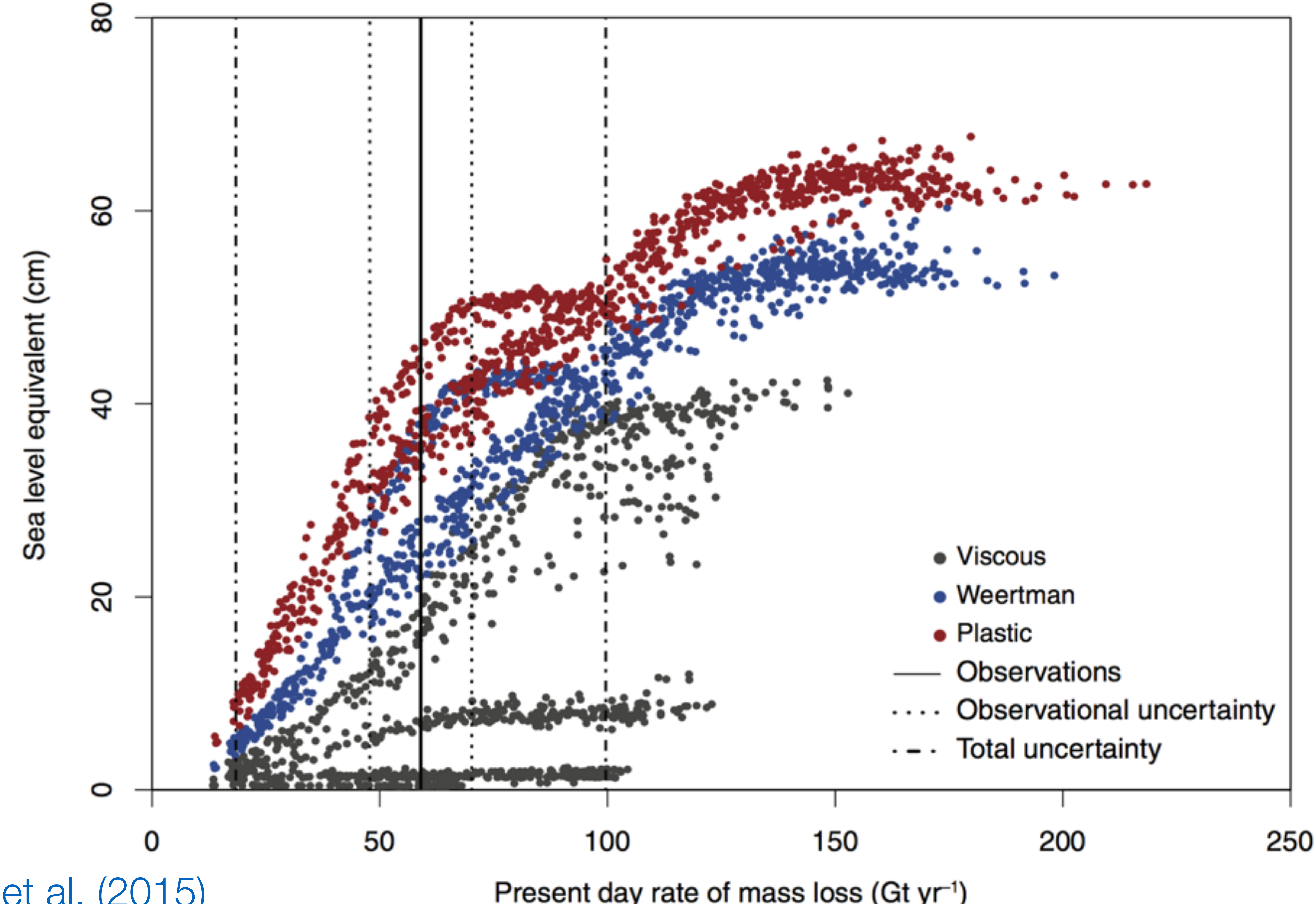
Shepherd et al. (2012)

Amundsen Sea Embayment at 2100 vs recent mass trend



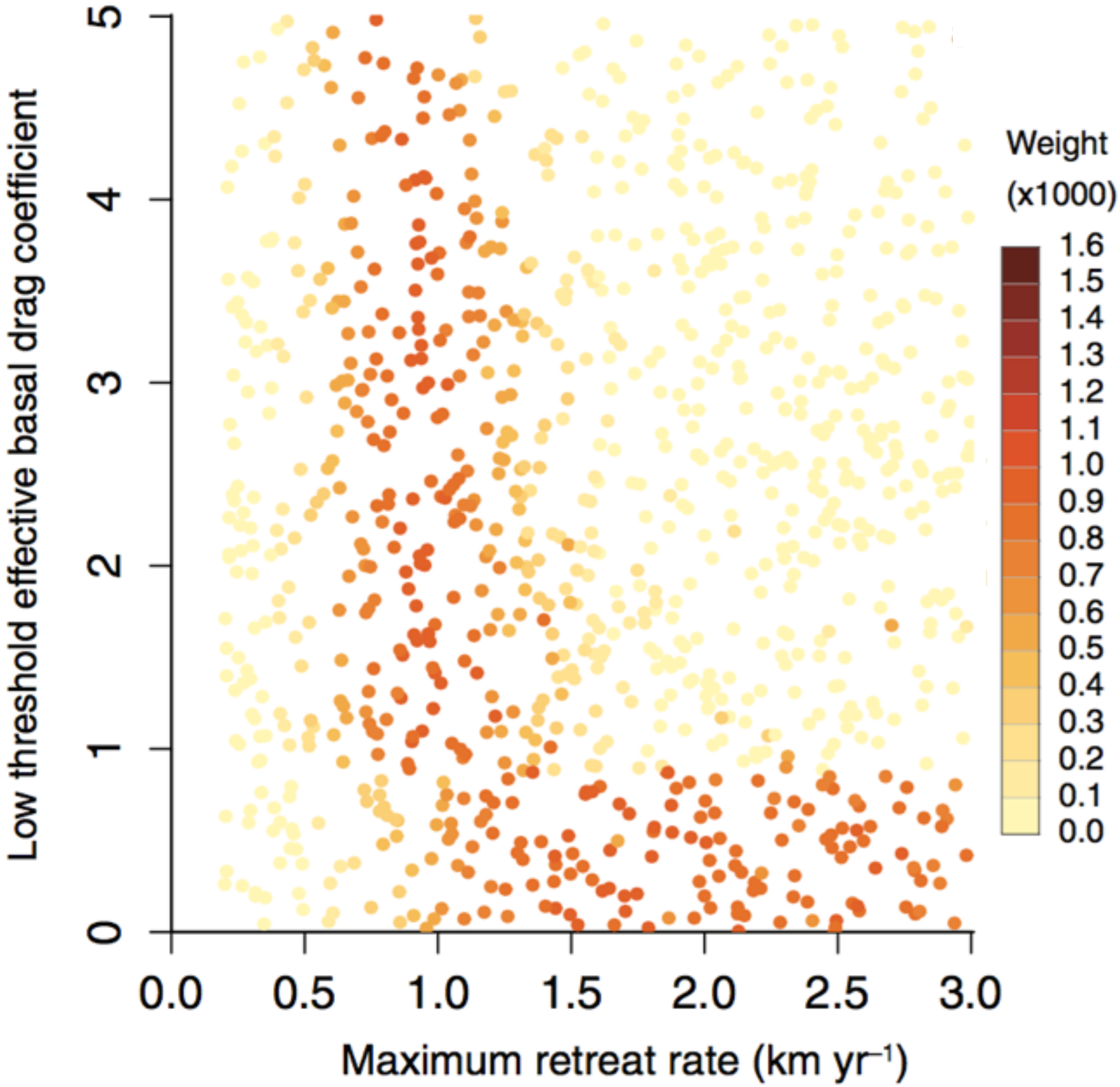
Ritz et al. (2015)

Amundsen Sea Embayment at **2200** vs recent mass trend



Ritz et al. (2015)

Weights ensemble members

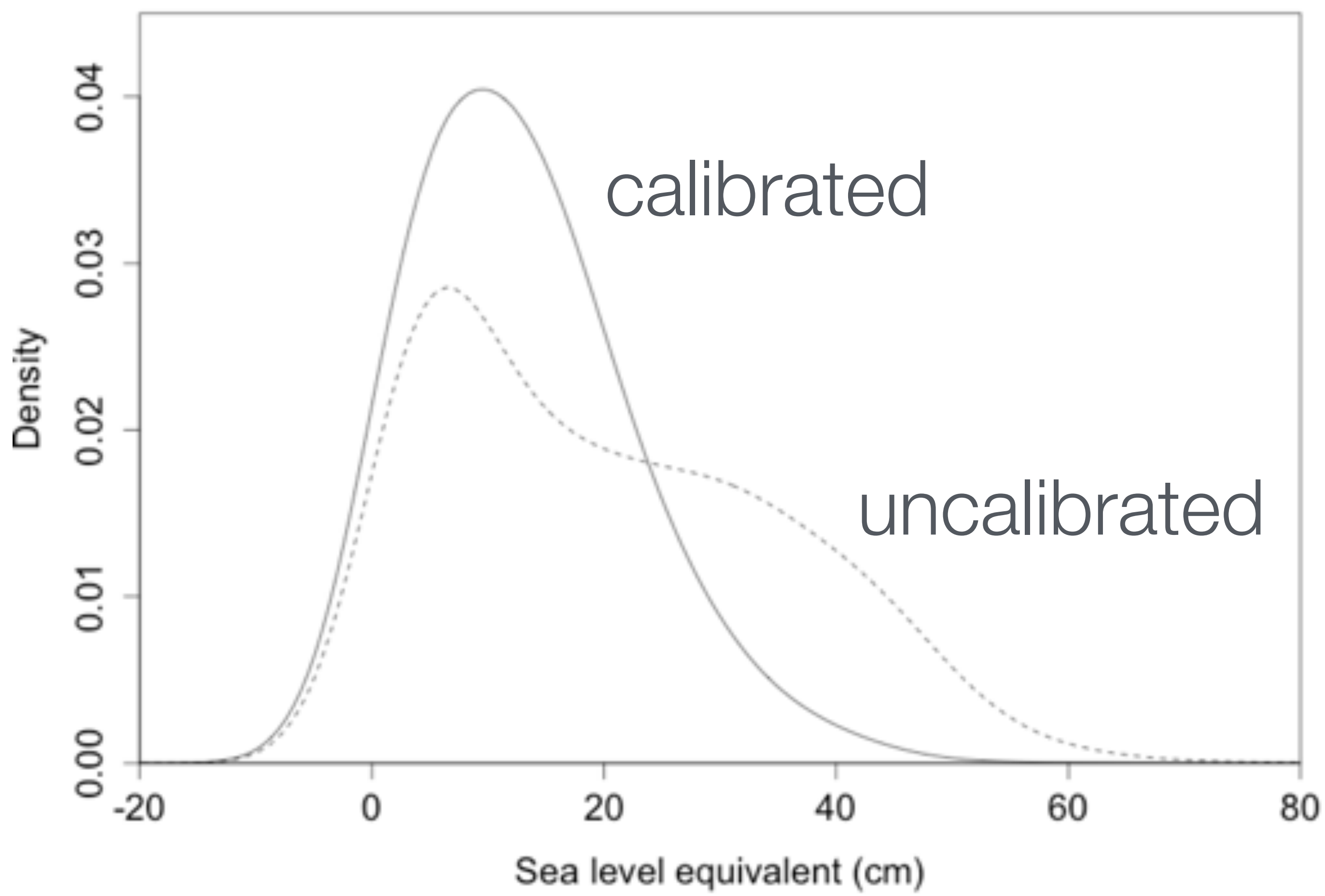


darkest =
highest weight
(highest likelihood)

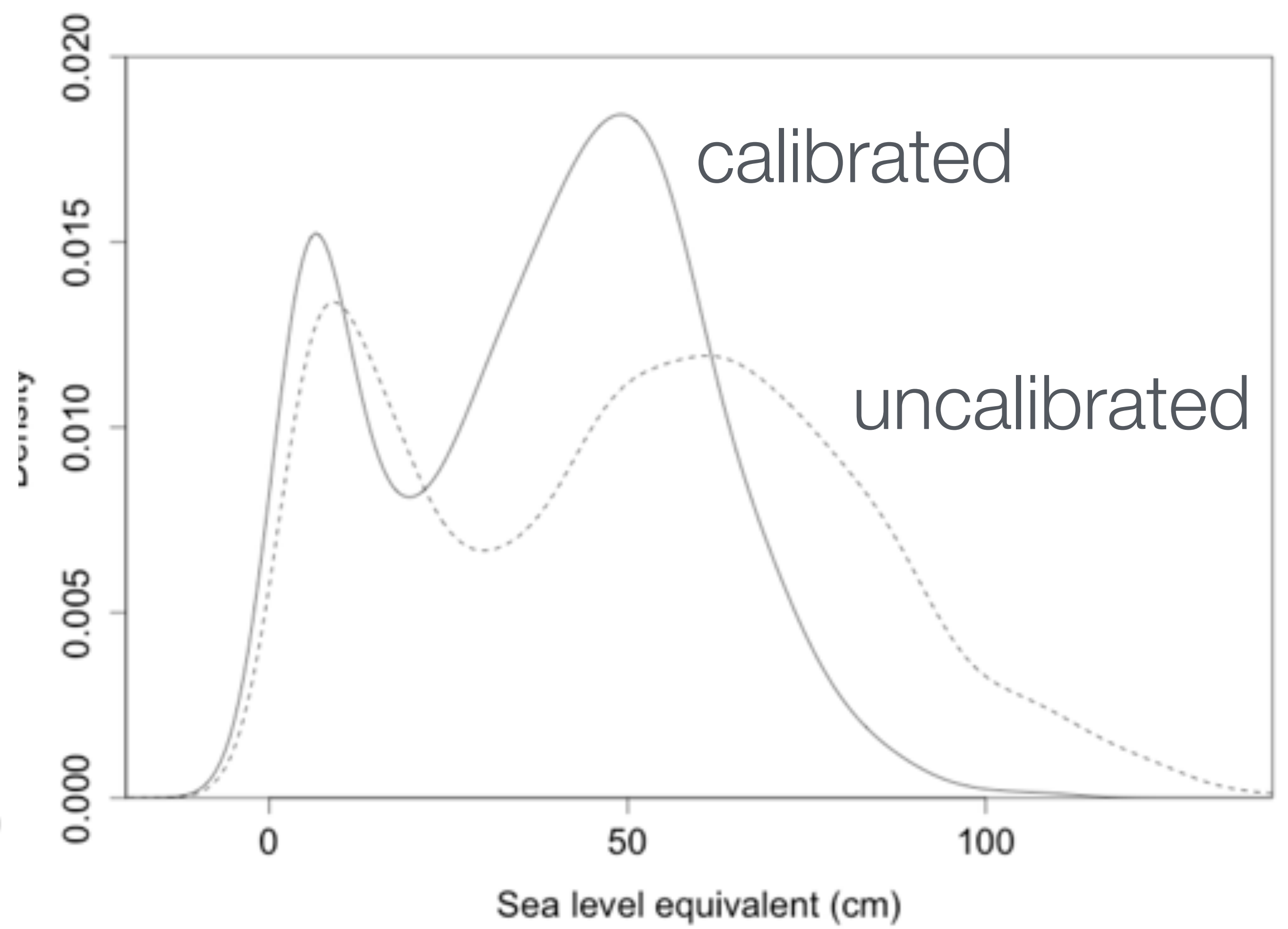
Ritz et al. (2015)

Effect of calibration on sea level projections

2100

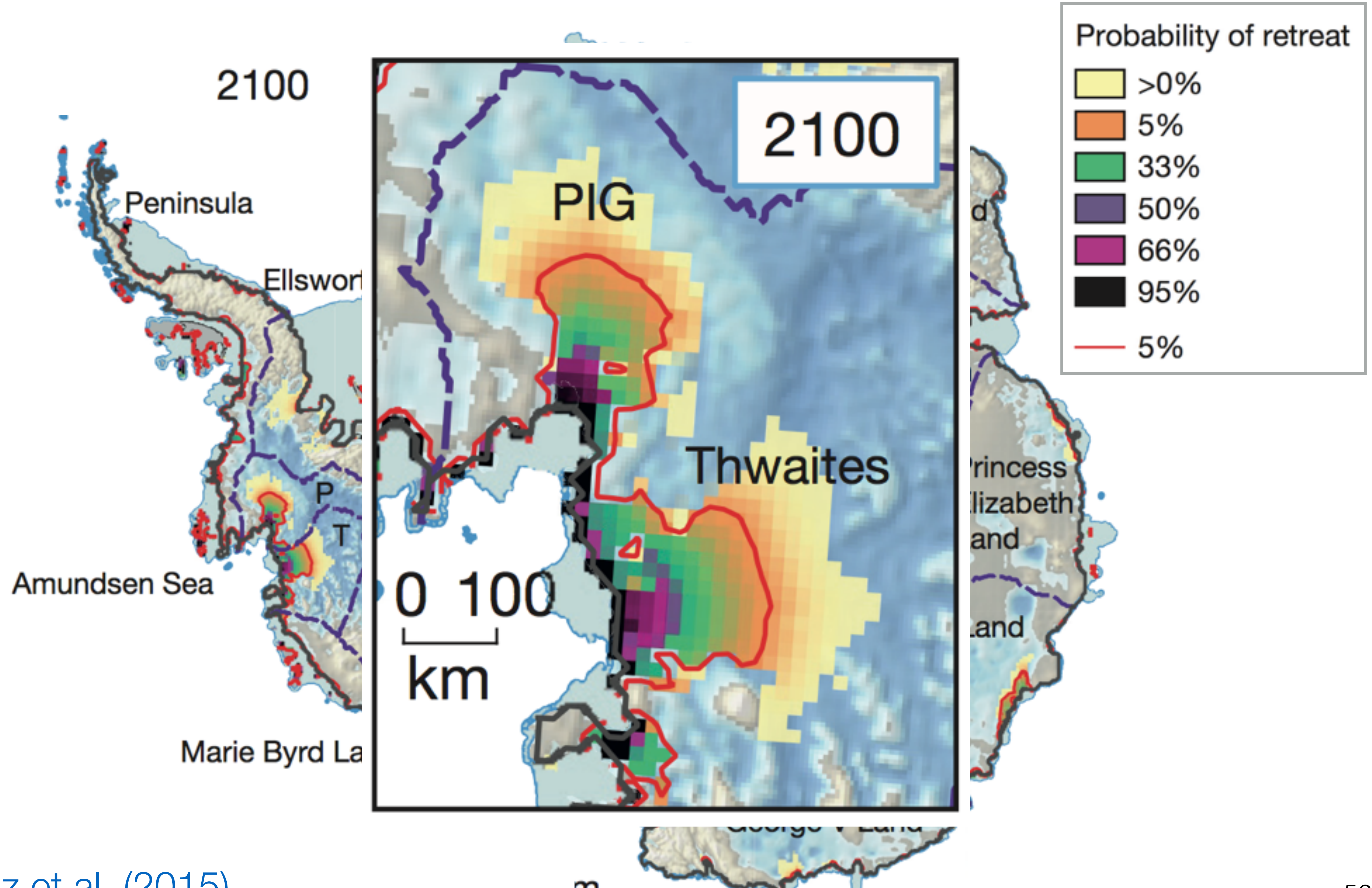


2200



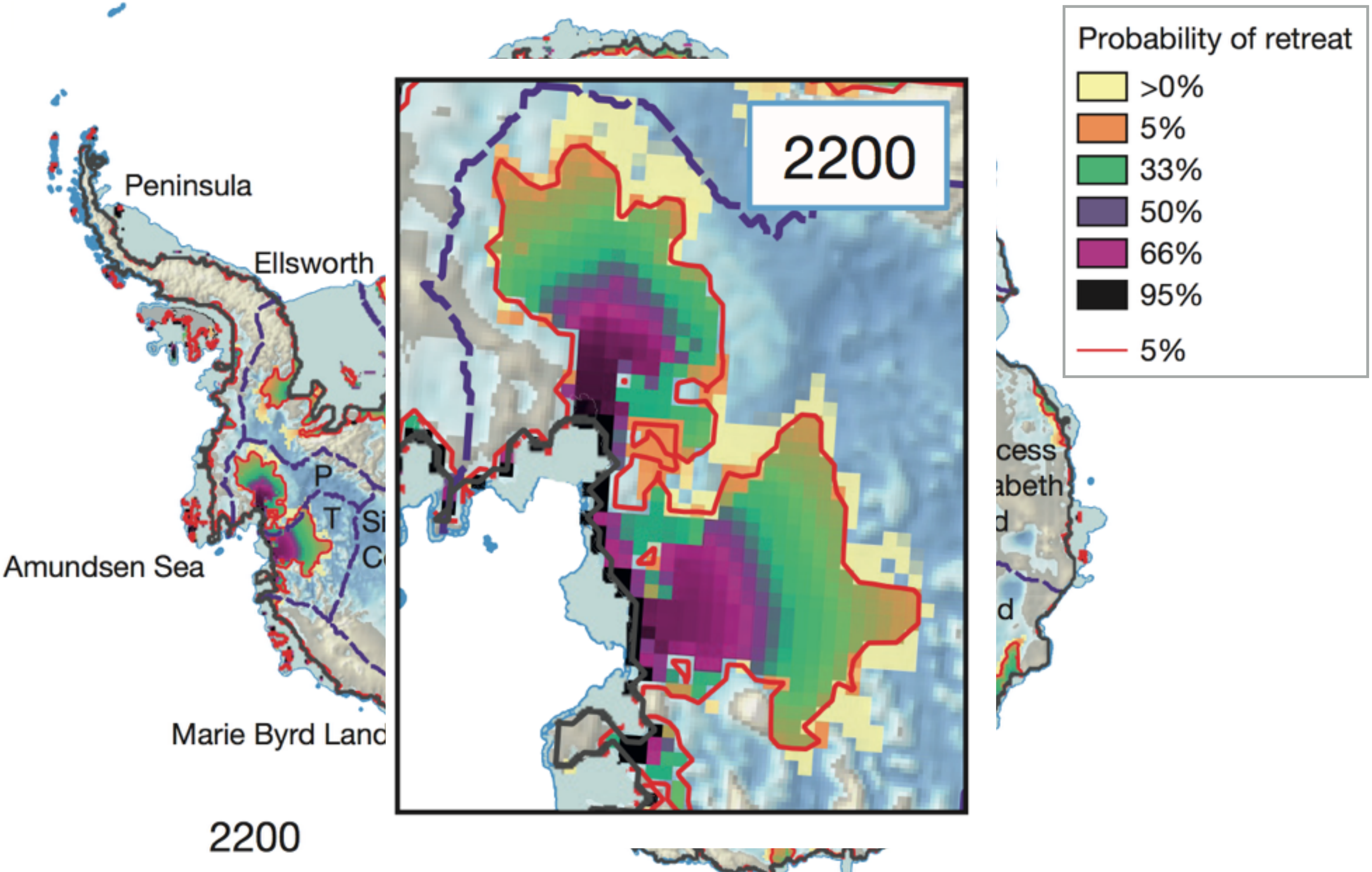
Ritz et al. (2015)

Probability of grounding line retreat at 2100

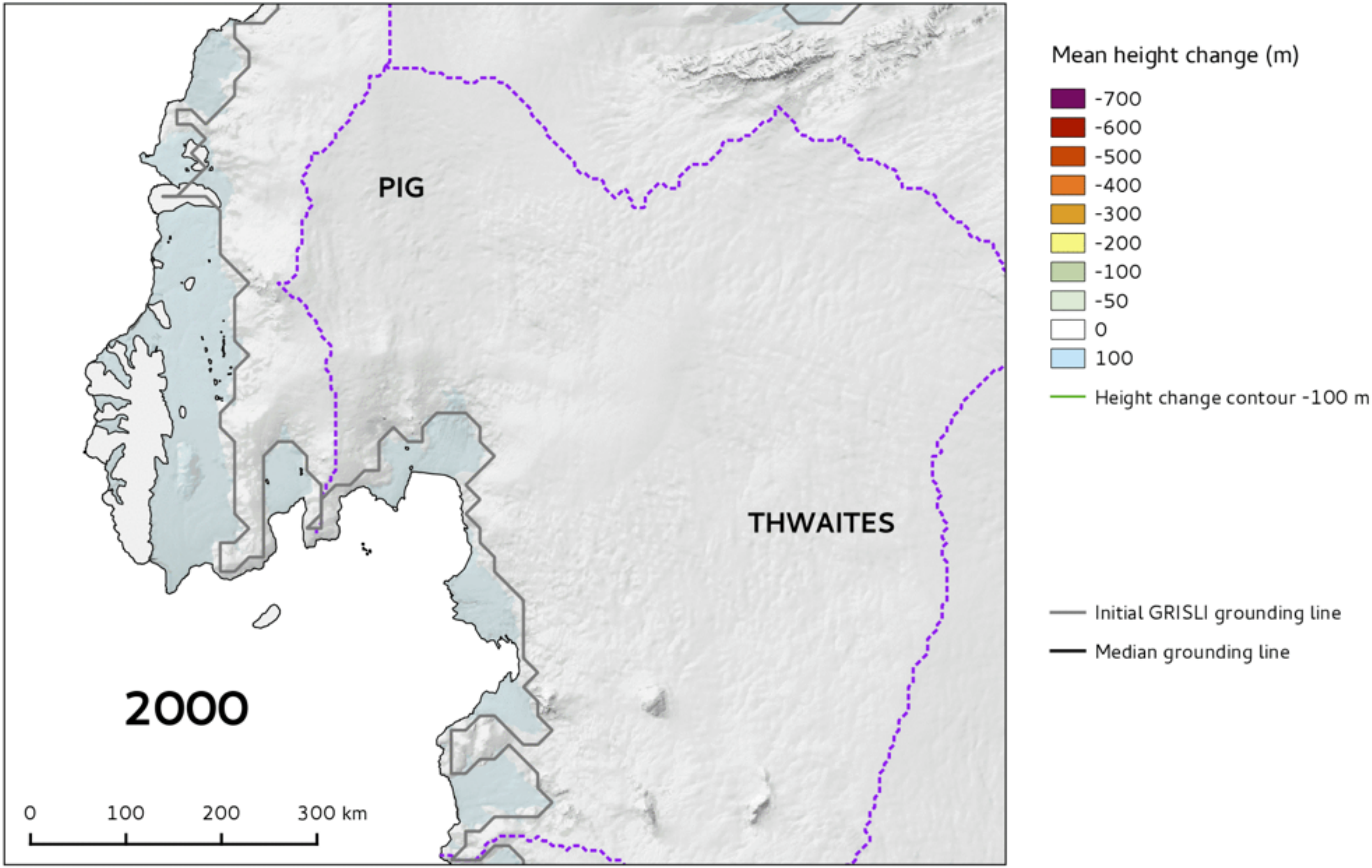


Ritz et al. (2015)

Probability of grounding line retreat at 2200



Ritz et al. (2015)

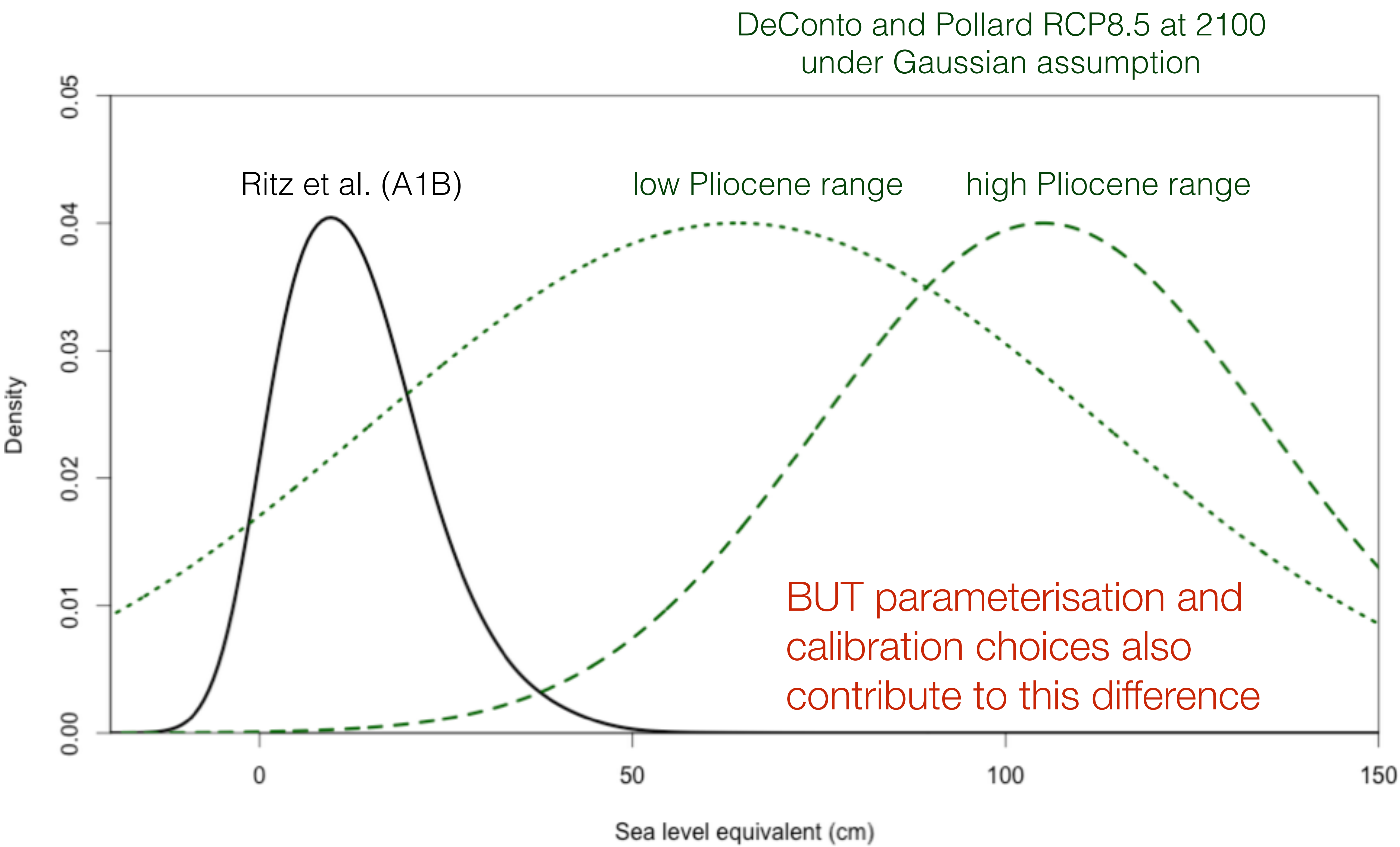


Ritz et al. (2015)

Outlook

- Previous examples: independent model-data comparisons
  - sub-sampled locations (Gladstone et al., 2012)
  - average of region (Ritz et al., 2015)
- Future: use full spatio-temporal information from EO
  - e.g. Won Chang et al.
- Potentially more powerful model calibration
  - But more pitfalls in statistical inference
  - In particular: correlated uncertainties in models and observations
- Key question (in my view)
  - maximum rate of Antarctic ice loss
  - does calibration with satellite data bias predictions?

Satellite vs palaeodata bias?



Ritz et al. (2015); DeConto & Pollard (2016)

Summary

- Initialisation of ice sheet models a major uncertainty
  - EO: e.g. geometry, velocity
  - initMIP first semi-systematic step to assessing impact on predictions
  - More to be done here
- Evaluation of ice sheet models is developing
  - EO: e.g. elevation changes, grounding line, mass changes
  - Formal statistical framework gives meaningful inference
  - Moving towards use of EO spatio-temporal patterns
    - Essential to understand correlated uncertainties
  - Antarctica: max rate of ice loss is key uncertainty
- EO will continue to help in reducing & quantifying ice sheet model prediction uncertainties

References

Bamber, J.L. et al., 2013. A new bed elevation dataset for Greenland. The Cryosphere, 7(2), pp.499–510.
Cornford, S.L. et al., 2015. Century-scale simulations of the response of the West Antarctic Ice Sheet to a warming climate. The Cryosphere, 9(1), pp.1–22.
Deconto, R.M. & Pollard, D., 2016. Contribution of Antarctica to past and future sea-level rise. Nature, 531(7596), pp.591–597.
Edwards, T.L. et al., 2014. Effect of uncertainty in surface mass balance–elevation feedback on projections of the future sea level contribution of the Greenland ice sheet. The Cryosphere, 8(1), pp.195–208.
Favier, L. et al., 2014. Retreat of Pine Island Glacier controlled by marine ice-sheet instability. Nature Climate Change, 5(2), pp.1–5.
Fretwell, P. et al., 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. The Cryosphere, 7, 375–393.
Gillet-Chaulet, F. et al., 2012. Greenland Ice Sheet contribution to sea-level rise from a new-generation ice-sheet model. The Cryosphere, 6(6), pp.1561–1576.
Gladstone, R.M. et al., 2012. Calibrated prediction of Pine Island Glacier retreat during the 21st and 22nd centuries with a coupled flowline model. Earth And Planetary Science Letters, 333-334(C), pp.191–199.
Goelzer, H. et al., 2013. Sensitivity of Greenland ice sheet projections to model formulations. Journal of Glaciology, 59(216), pp. 733–749.
Howat, I.M., Negrete, A. & Smith, B.E., 2014. The Greenland Ice Mapping Project (GIMP) land classification and surface elevation data sets. The Cryosphere, 8(4), pp.1509–1518.
Joughin, I. et al., 2010. Greenland flow variability from ice-sheet-wide velocity mapping. Journal of Glaciology, 56(197), 415–430.
Lee, V., Cornford, S.L. & Payne, A.J., 2015. Initialization of an ice-sheet model for present-day Greenland. Annals of Glaciology, 56(70), pp.129–140.
Morlighem, M. et al., 2014. Deeply incised submarine glacial valleys beneath the Greenland ice sheet. Nature Geo., 7(6), 418–422.
Nowicki, S.M.J. et al., 2016. Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6. Geoscientific Model Development Discussions, pp.1–42.
Rignot, E., Mouginot, J. & Scheuchl, B., 2011. Ice Flow of the Antarctic Ice Sheet. Science, 333(6048), pp.1427–1430.
Ritz, C. et al., 2015. Potential sea-level rise from Antarctic ice-sheet instability constrained by observations. Nature, 528, 115–118.
Rogozhina, I. et al., 2012. Effects of uncertainties in the geothermal heat flux distribution on the Greenland Ice Sheet: An assessment of existing heat flow models. Journal of Geophysical Research, 117(F2), p.F02025.
Saito, F. et al., 2016. SeaRISE experiments revisited: potential sources of spread in multi-model projections of the Greenland ice sheet. The Cryosphere, 10(1), pp.43–63.
Shapiro, N., 2004. Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. Earth And Planetary Science Letters, 223(1-2), pp.213–224.
Timmermann, R. & Hellmer, H.H., 2013. Southern Ocean warming and increased ice shelf basal melting in the twenty-first and twenty-second centuries based on coupled ice-ocean finite-element modelling. Ocean Dynamics, 63(9-10), pp.1011–1026.