

A Machine Learning Heat Flow Model of Antarctica

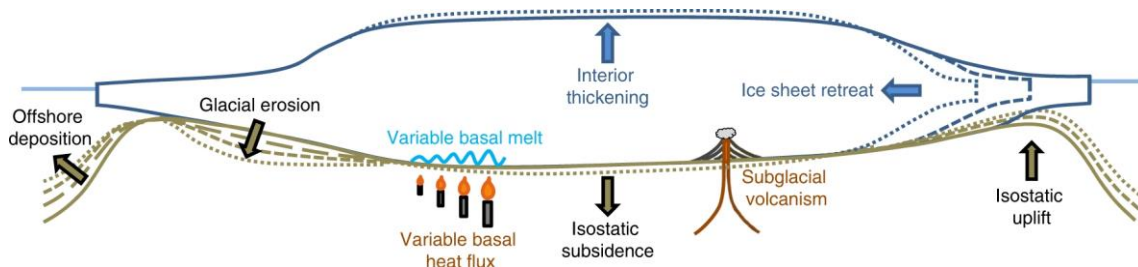
 **General
Assembly 2021**

Mareen Lösing¹, Jorge Bernales², Jörg Ebbing¹

[1] Kiel University, Institute of Geosciences; [2] Marum Center of Marine Environmental Sciences, University of Bremen

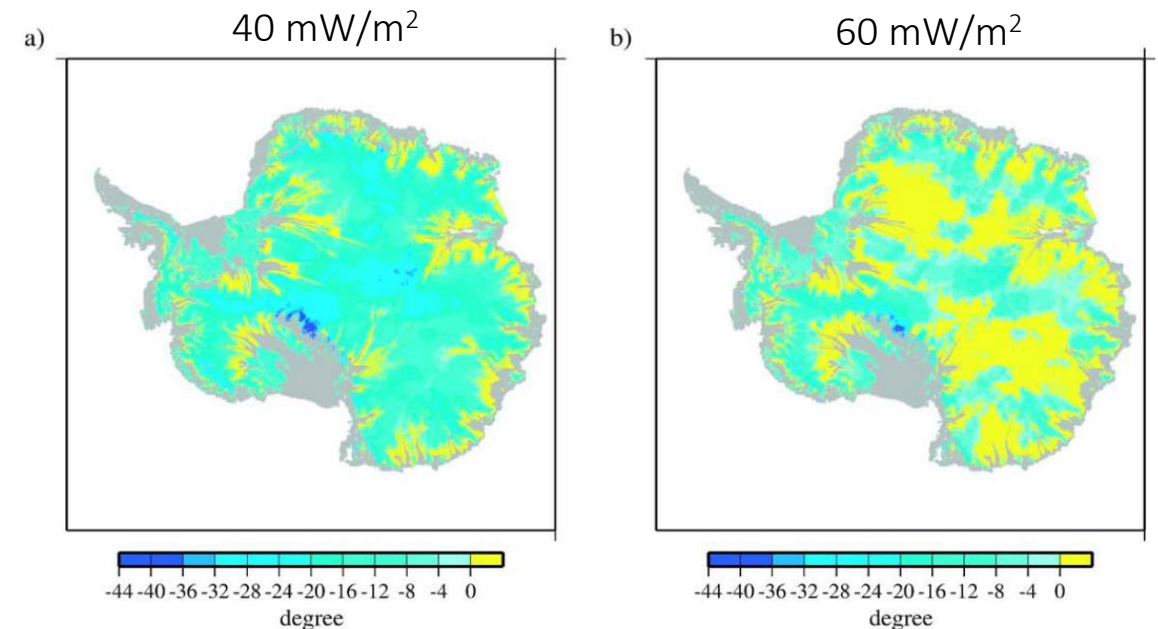
Motivation

- Important boundary condition for **ice sheet modeling**
- Important for modeling **isostatic response**
- Provide evidence for mantle dynamics



[Whitehouse et al., 2019]

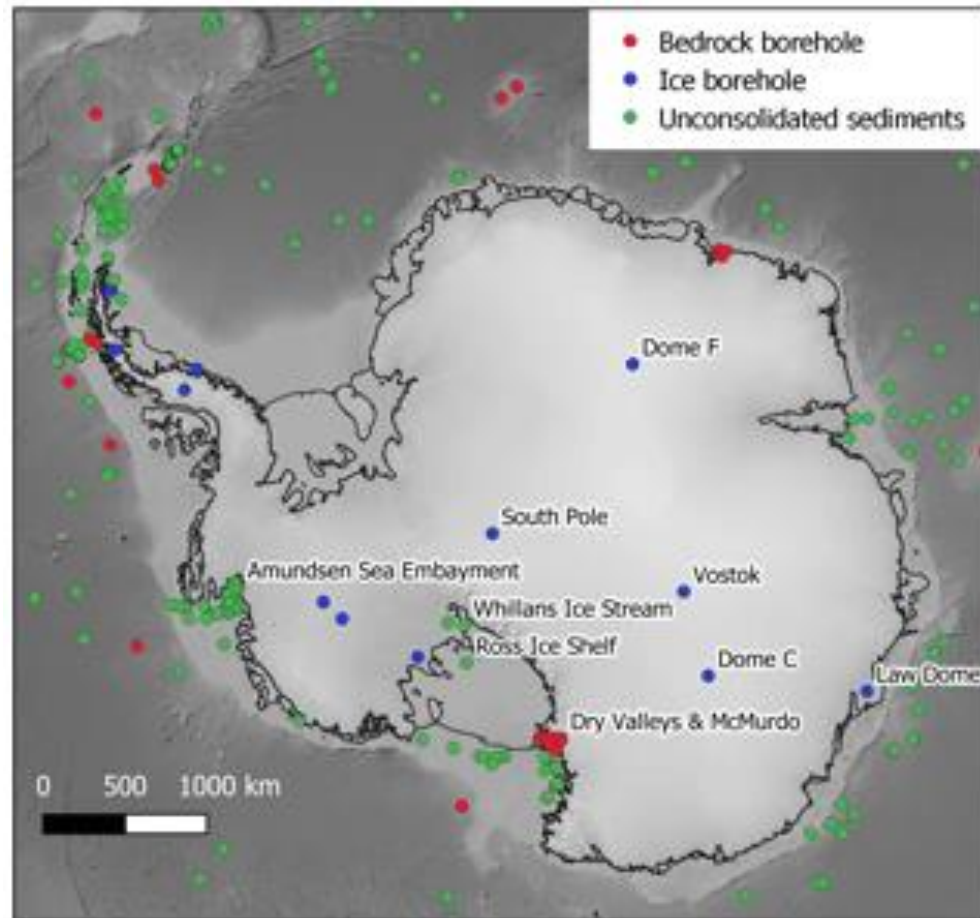
- Llubes et al. (2006) increased a homogeneous heat flow (from 40 to 60 mW/m²) for whole continent in their ice sheet model
- Basal temperature increases by 6°C, melt rate increases by 11 km³/yr



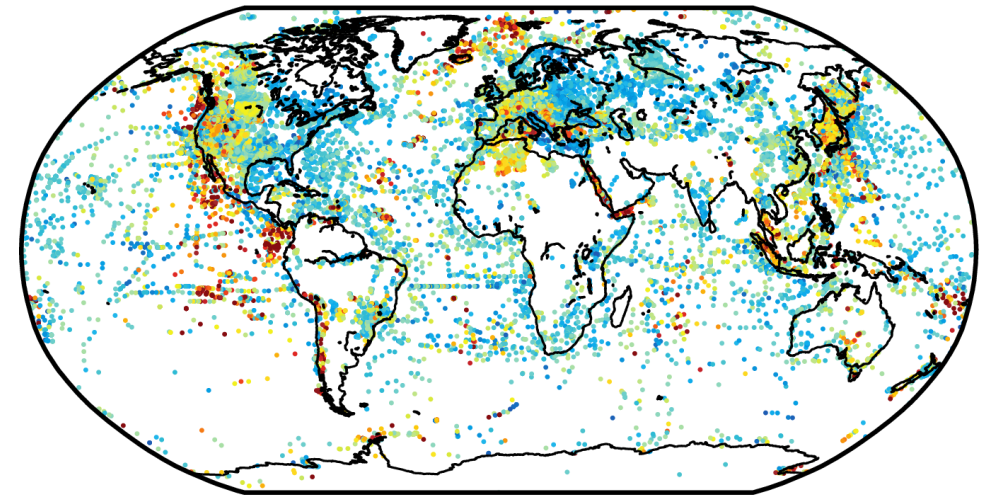
Basal temperature with respect to fusion temperature [Llubes et al. (2006)]

Geothermal Heat Flow (GHF)

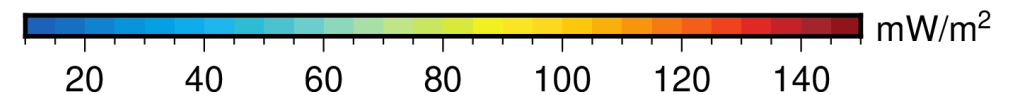
Available heat flow measurements



[Burton-Johnson et al. (2020)]



[Lucazeau et al., 2019, Hasterok, 2019 heatflow.org]



- Measurements are often influenced by surface temperature variations, hydrothermal circulation and/or frictional heating
- Antarctica is sparsely covered → indirect methods are needed

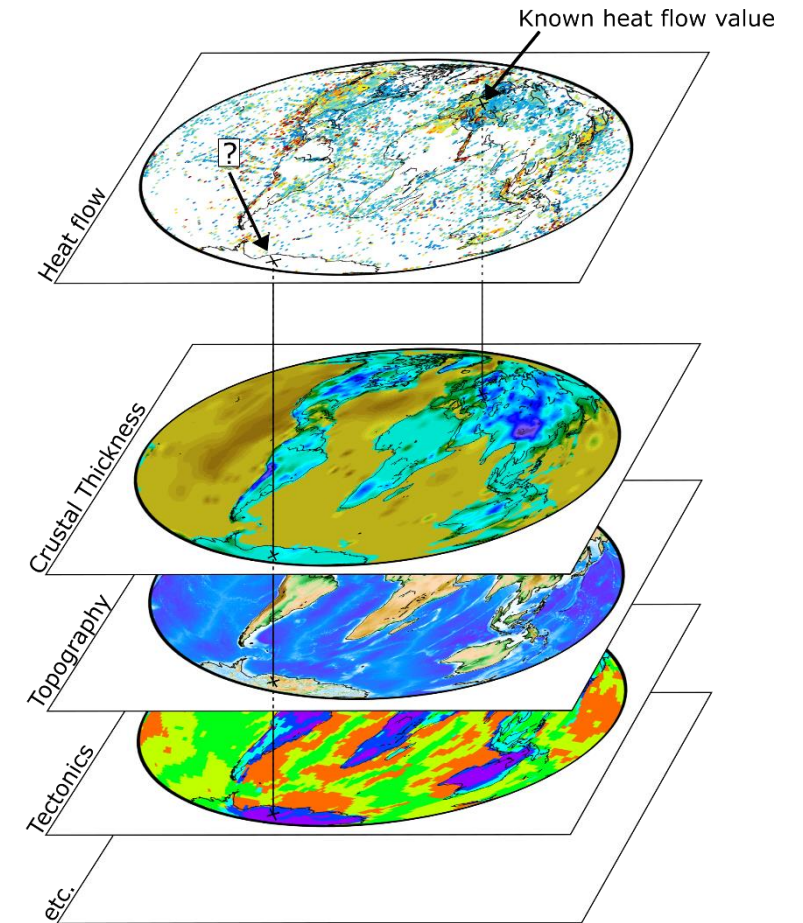
Machine Learning

- A machine learning approach could use several observables at a time and decide which is most important
- Incorporate existing heat flow measurements

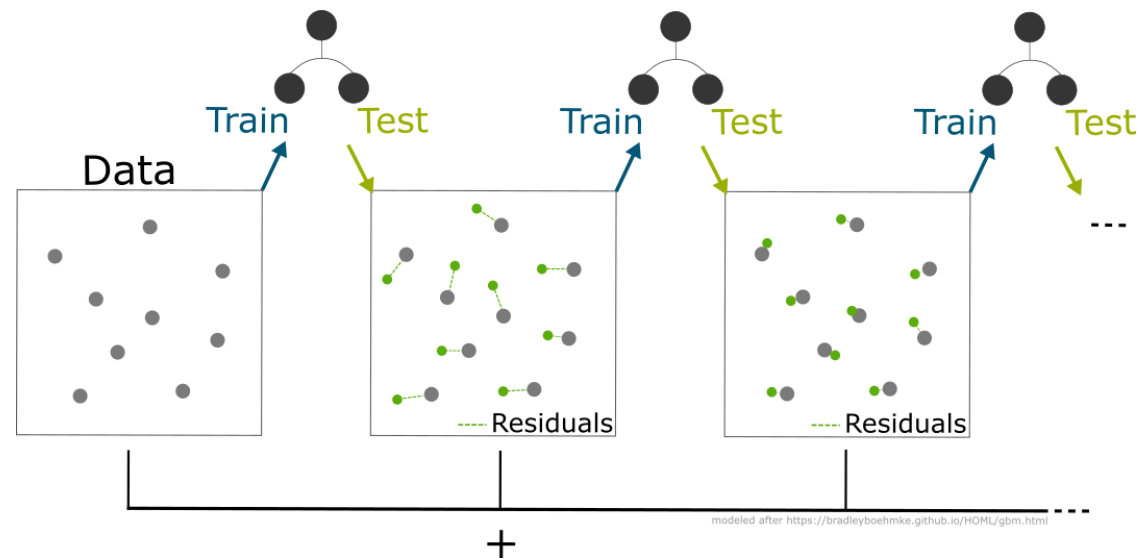
- Goal: create a model (f), which fits the input variables (X) to the output variables (y)

$$y = f(X)$$

- Final model can make predictions for new set of variables (X)



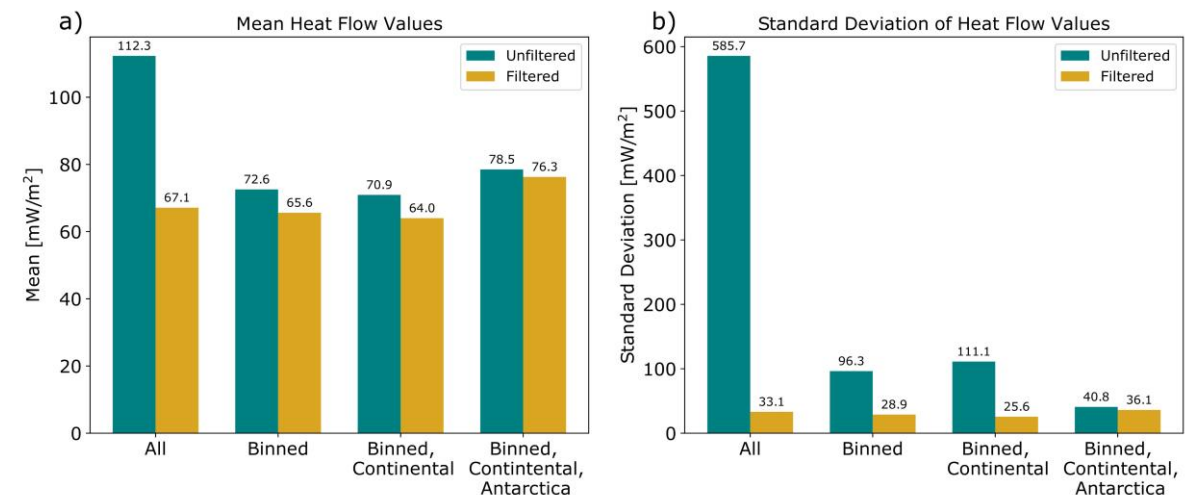
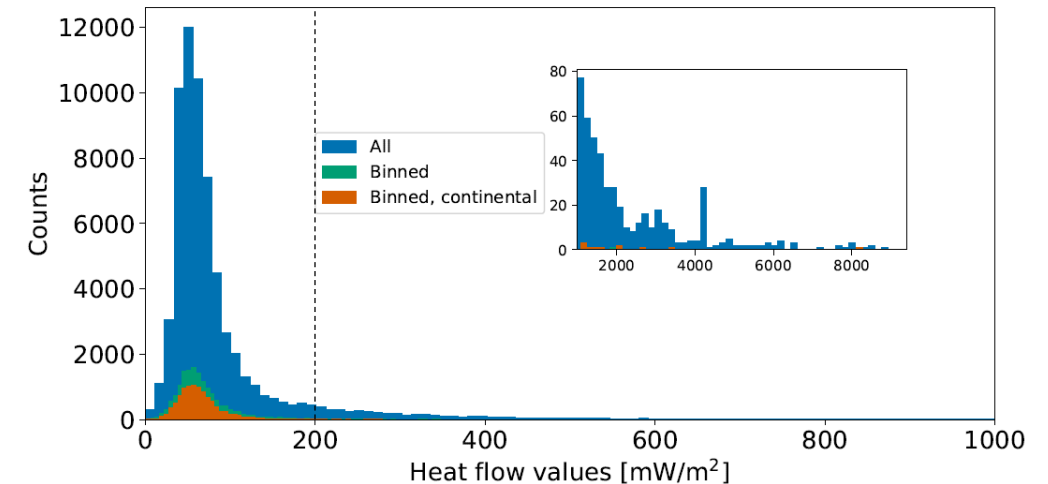
- We use **Gradient Boosting Regression** [Friedman (2001)] which iteratively creates an ensemble of decision trees



- Each tree is additively fit to the residual of the previous prediction
- Here we use the [XGBoost](#) python package

Machine Learning - Data

- Available heat flow higher than 200 mW/m² is filtered out
- binned with a resolution of 0.5°
- Only continental data is used (down to 1 km below sea level)
- Data is split randomly into training (80 %) and test data (20 %)
 - Antarctic Observations within training set



Unfiltered: All records

Filtered: Only records < 200 mW/m²

Machine Learning - Data

Feature	Source
Moho	Szwillus et al., 2019; Pappa et al., 2019; An et al., 2015; Shen et al., 2018; Kennett & Chopping, 2018; Youssof et al., 2013
LAB	Afonso et al., 2019; Pappa et al., 2019; An et al., 2015a
Topography	Hirt & Rexer, 2015 (Earth2014) & Morlighem et al., 2017 (BedMachine)
Susceptibility	Inferred from Hemant & Maus, 2005
Tectonic units	Schaeffer & Lebedev, 2013
Mean curvature from grav. gradients	Ebbing et al., 2018
Vertical magnetic component (Bz)	Ebbing et al. 2021
Distance to ridges	Coffin et al., 1997, UTIG (Plates project)
Distance to trenches	Coffin et al., 1997, UTIG (Plates project)
Distance to transform faults	Coffin et al., 1997, UTIG (Plates project)
Distance to young rifts	Celal & Natalin, 2001
Distance to volcanoes	Global Volcanism Program & Van Wyk de Vries et al., 2018

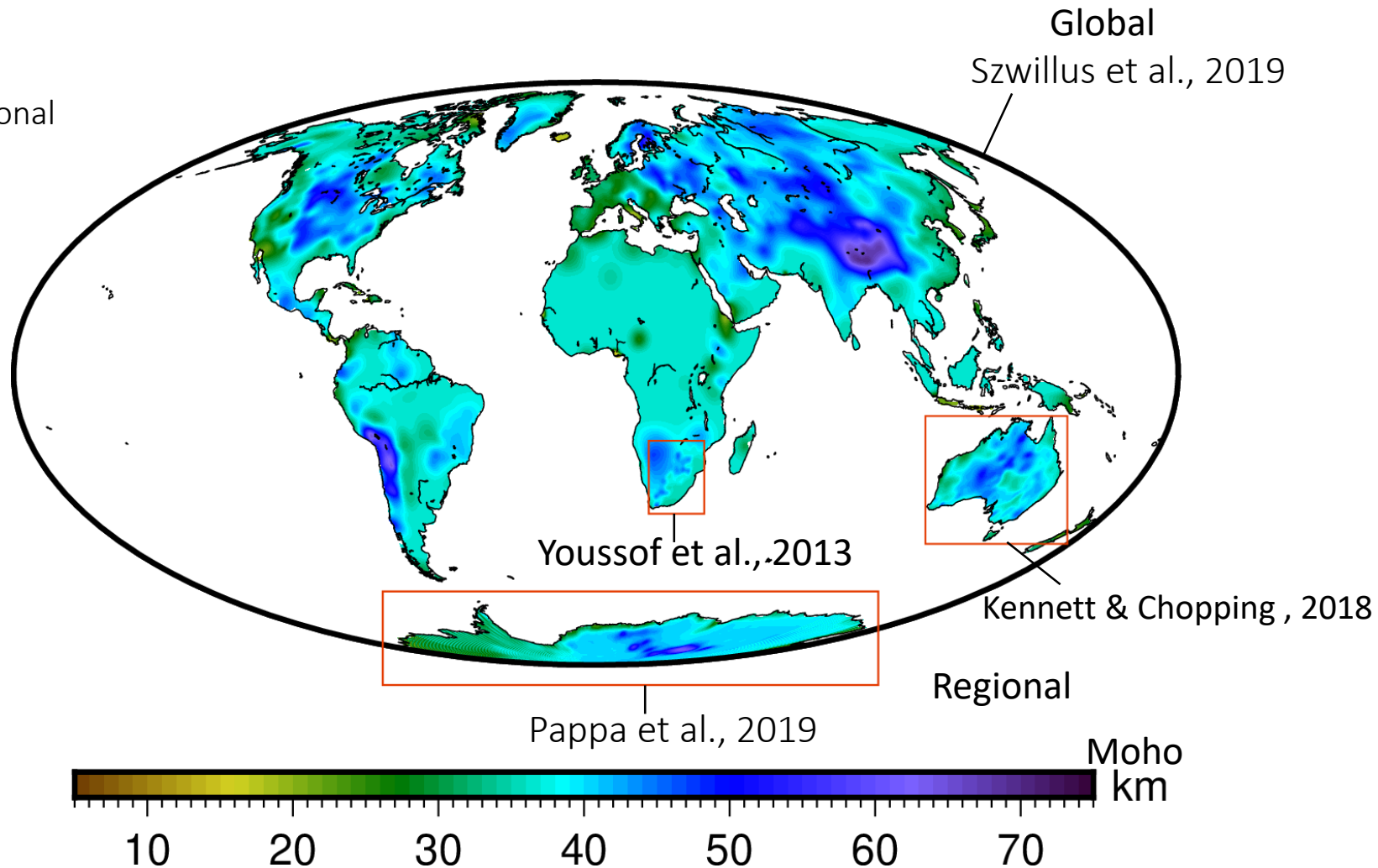
We use global and regional input models for Antarctica but also for Africa and Australia

● Global

● Regional

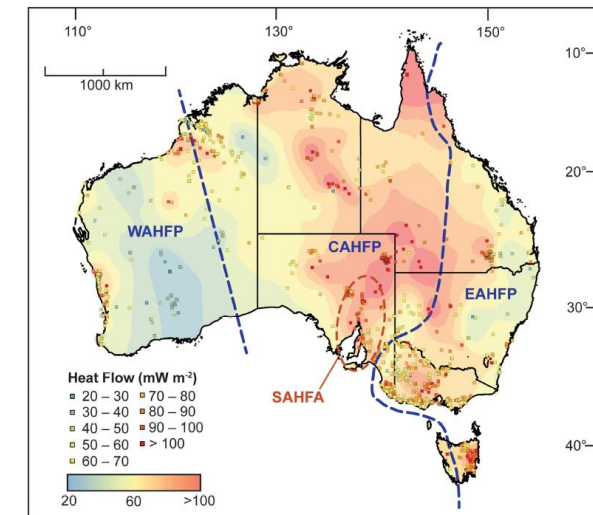
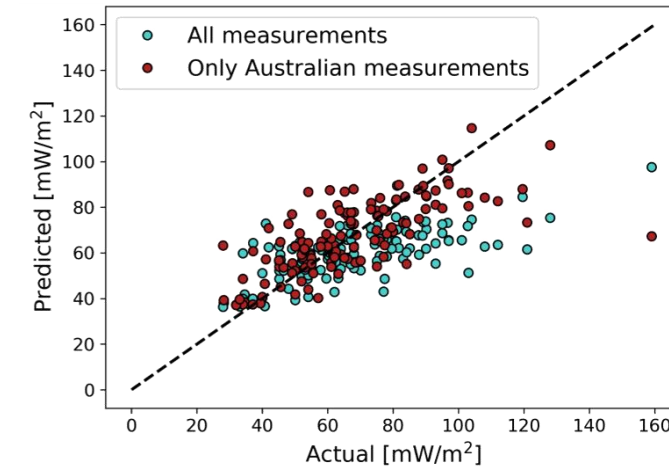
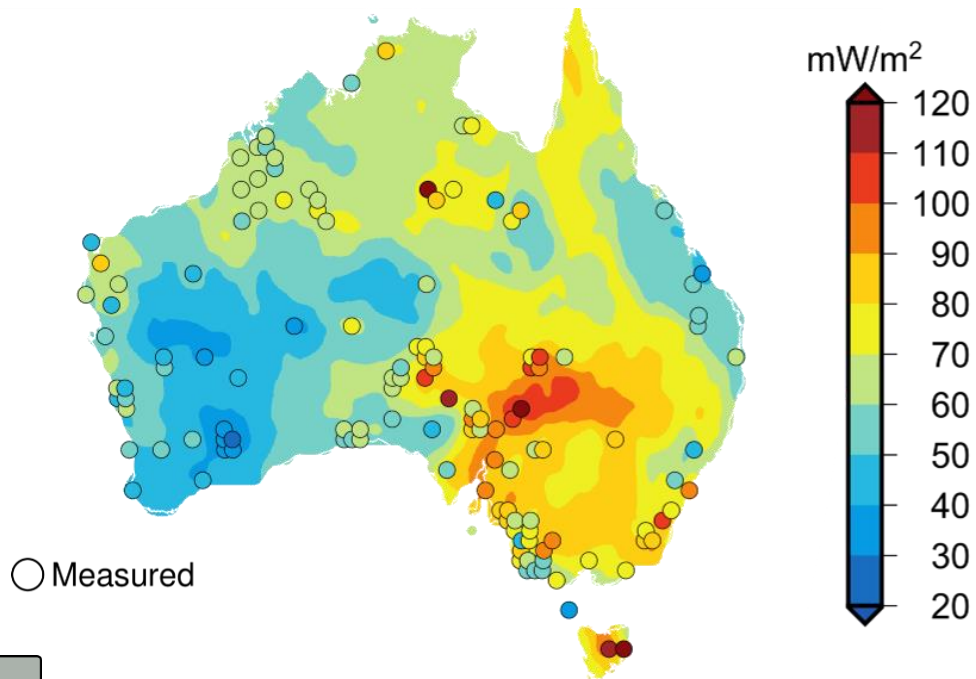
Machine Learning - Data

Here we replaced the
global Moho with regional
models for Antarctica,
Australia, and Africa



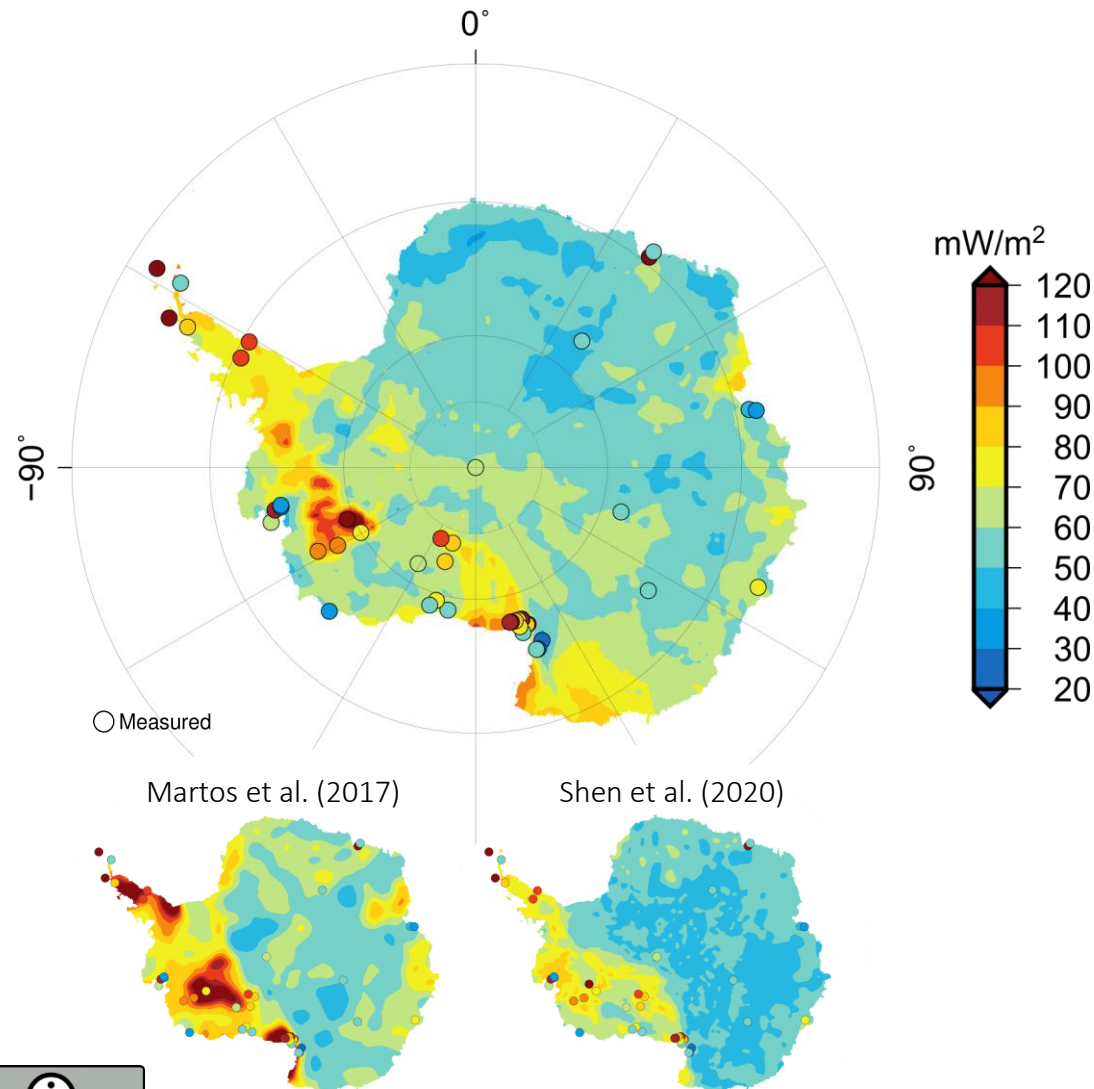
Results - Australia

- Test algorithm for well-known continent: Australia
- Using exclusively Australian measurements to build the model results in a slightly better fit
- Prediction is similar to kriging model by Pollett et al., 2019



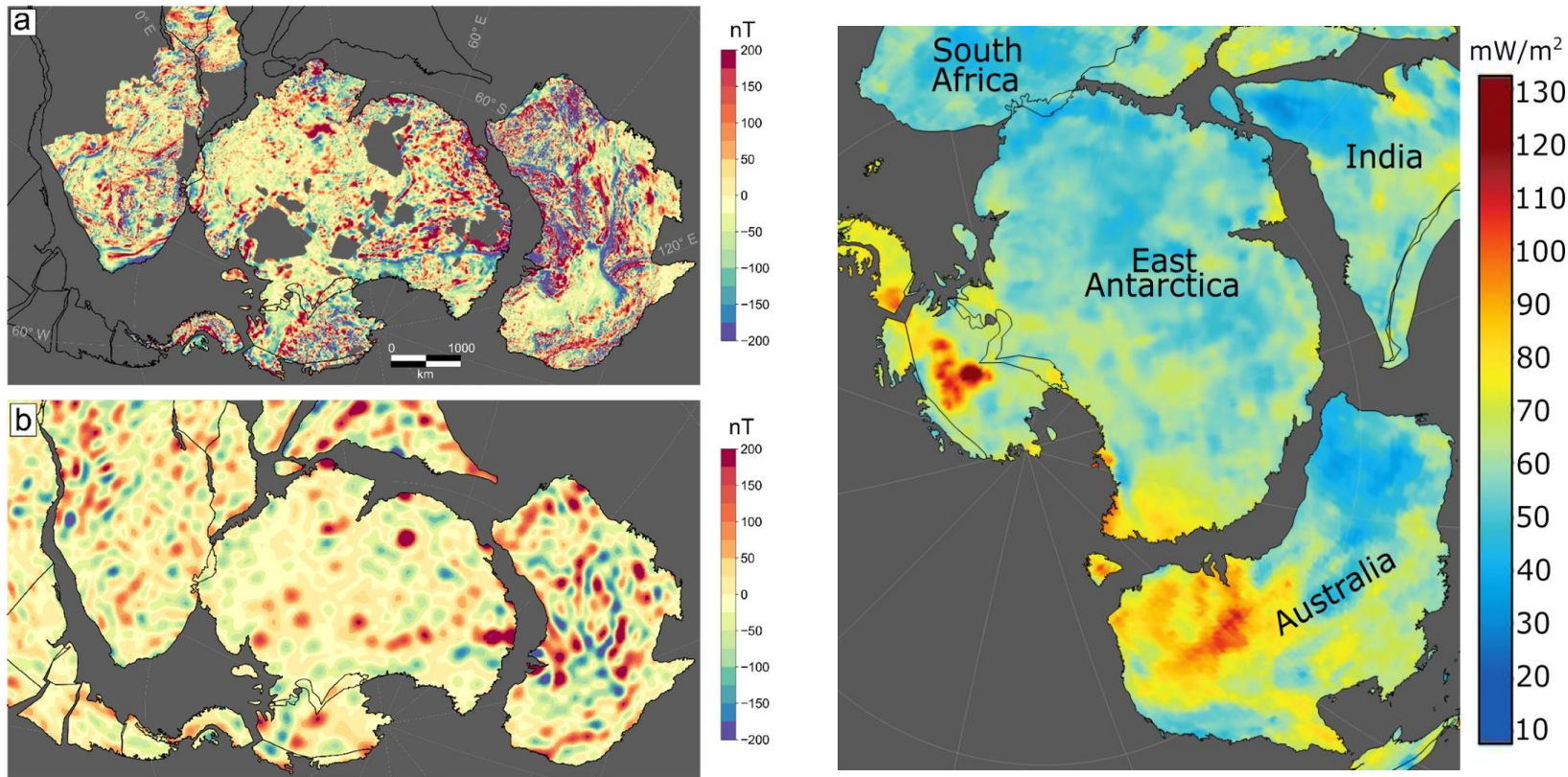
[Pollett et al., 2019]

Results - Antarctica



- Predicted heat flow in Antarctica
- Overall **higher in West Antarctica**, especially Marie Byrd Land, the Peninsula, Ross Ice Shelf and George V Land
- Some measurements fit quite well, but are generally **rather underestimated** by the prediction
- Two high observations of $> 180 \text{ mW/m}^2$ lead to significantly higher predictions in West Antarctica and but not in Enderby Land
- The limited amount of heat flow measurements makes an **evaluation challenging**. Our approach results in values between the model by Martos et al. (2017) and by Shen et al. (2020)

Results - Gondwana



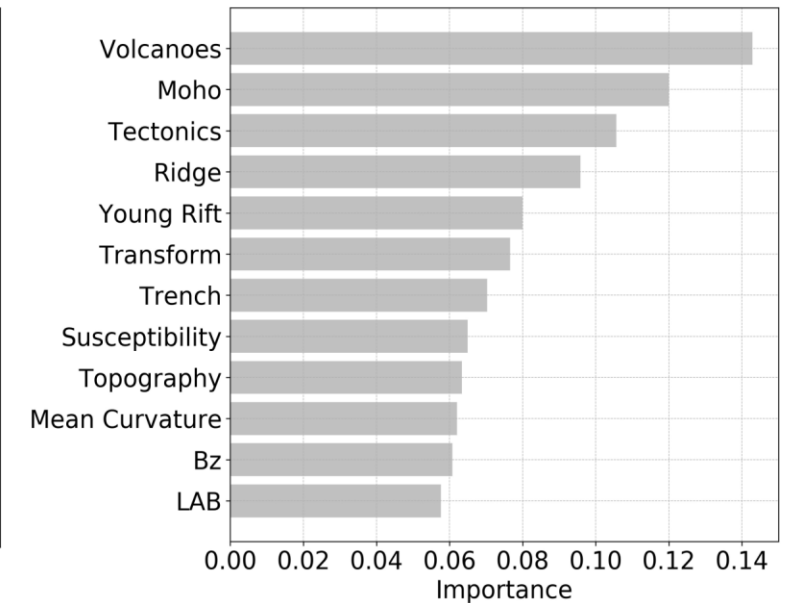
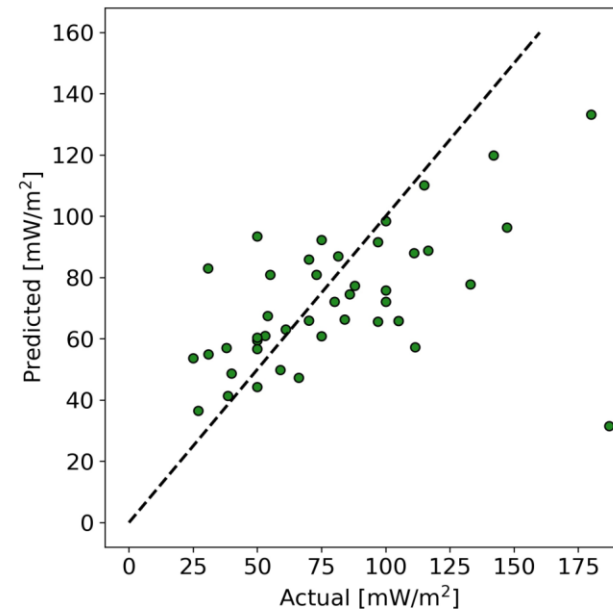
[Ebbing et al., 2021]

Conformed aeromagnetic and satellite data show tectonic linkages between adjacent continents within a reconstructed* Gondwana framework

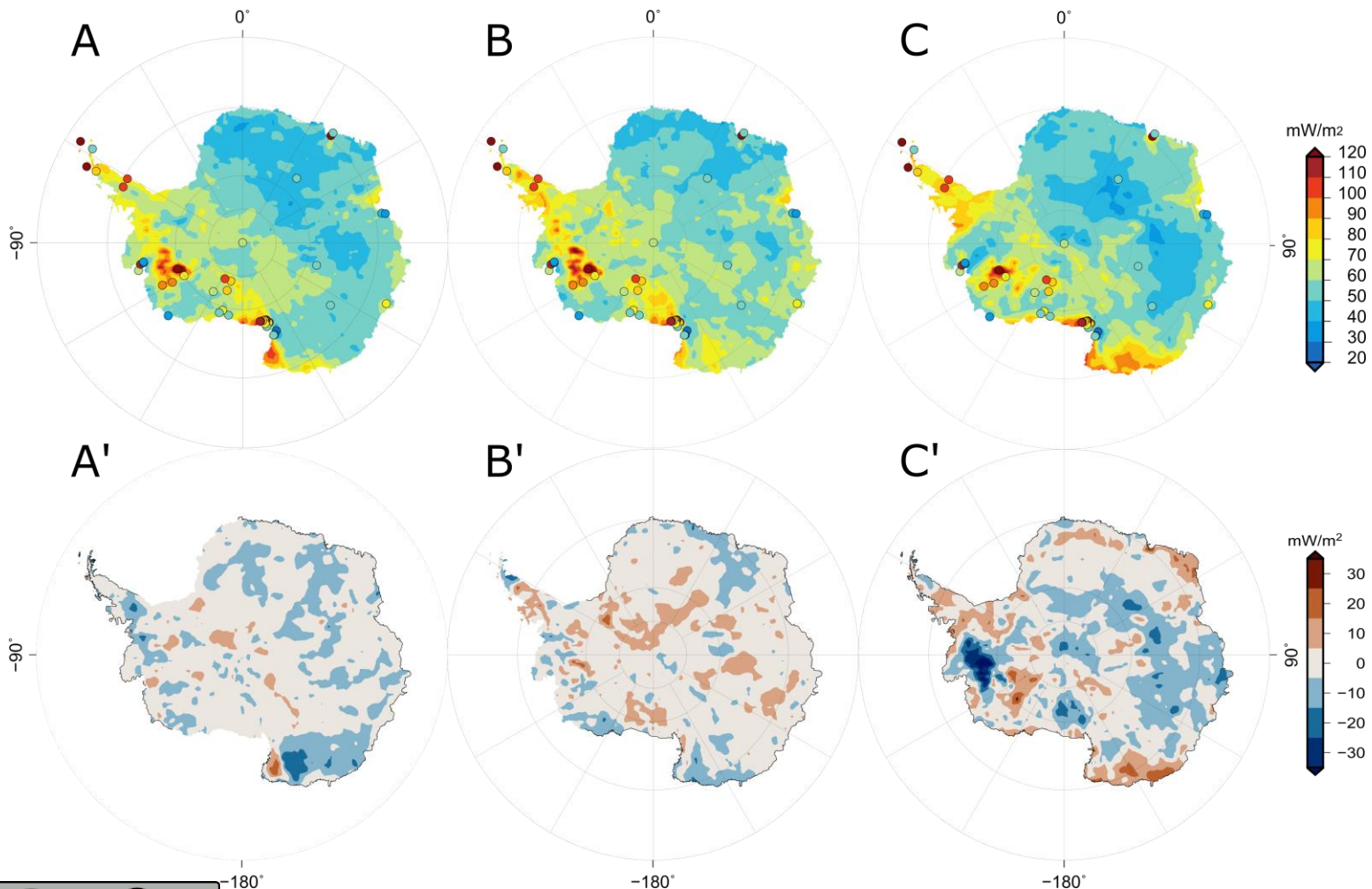
Predicted heat flow also shows **visible connections** at conjugate margins, especially at the Australo-Antarctic margin

Results - Antarctica

- Plot of the **actual against the predicted** test data set
- Lower GHFs are closer to the line than higher values ($> 90 \text{ mW/m}^2$), which are **mainly underestimated** (due to rather rare occurrences)
- **Importances** of different features for the model selected by the algorithm
- **Distance to volcanoes and Moho depth** seem to have the strongest effect on prediction



Results - Uncertainties



Three additional heat flow maps with different feature set-ups are predicted to assess the direct uncertainties

A different lithosphere models

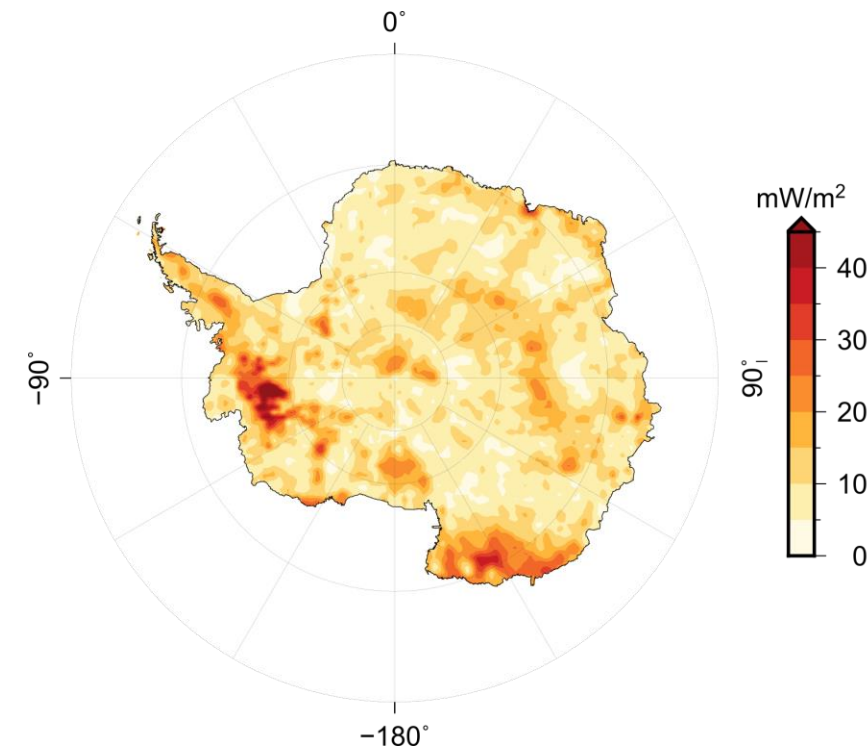
B only global models

C only six features

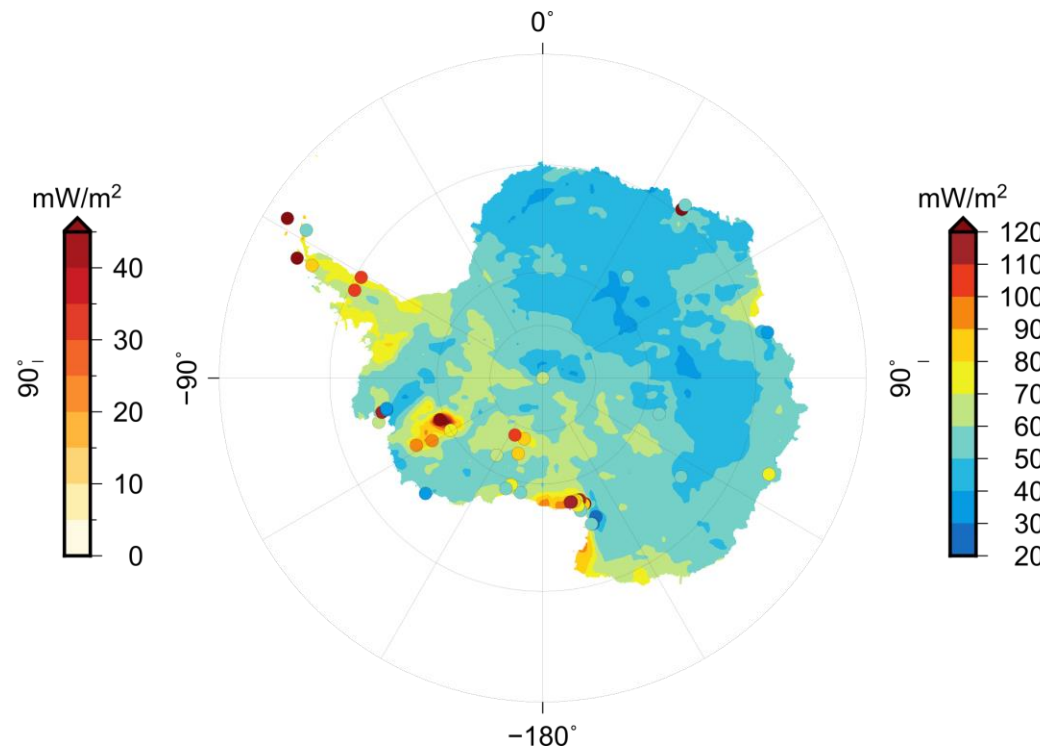
A', B', C' differences to the final model (slide 10)

Results - Uncertainties

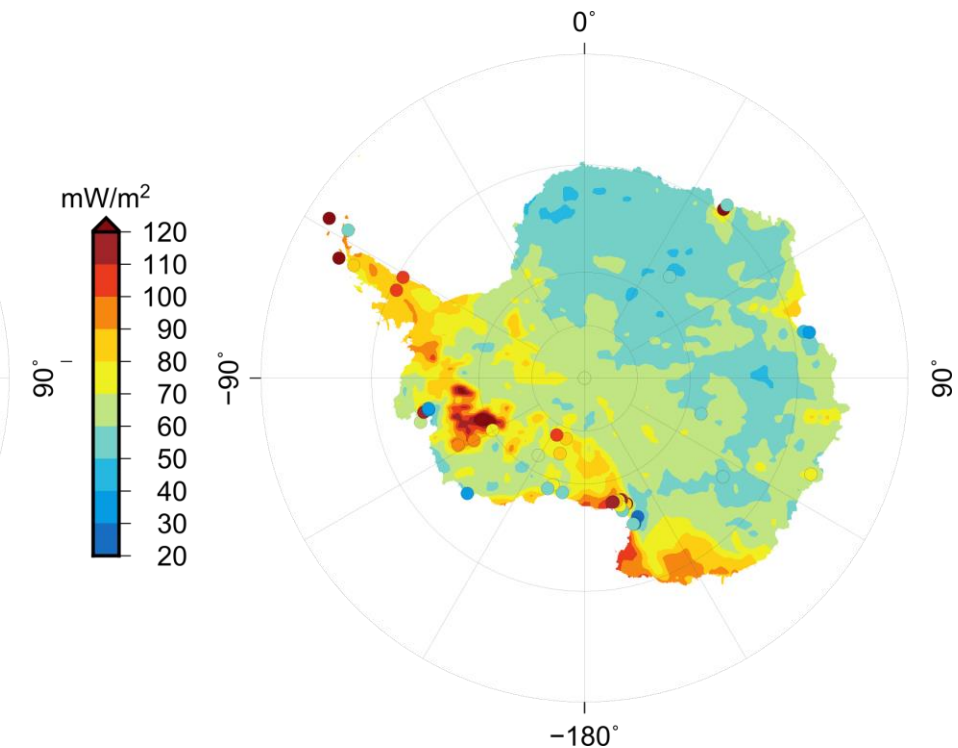
Absolute Difference



Minimum Heat Flow



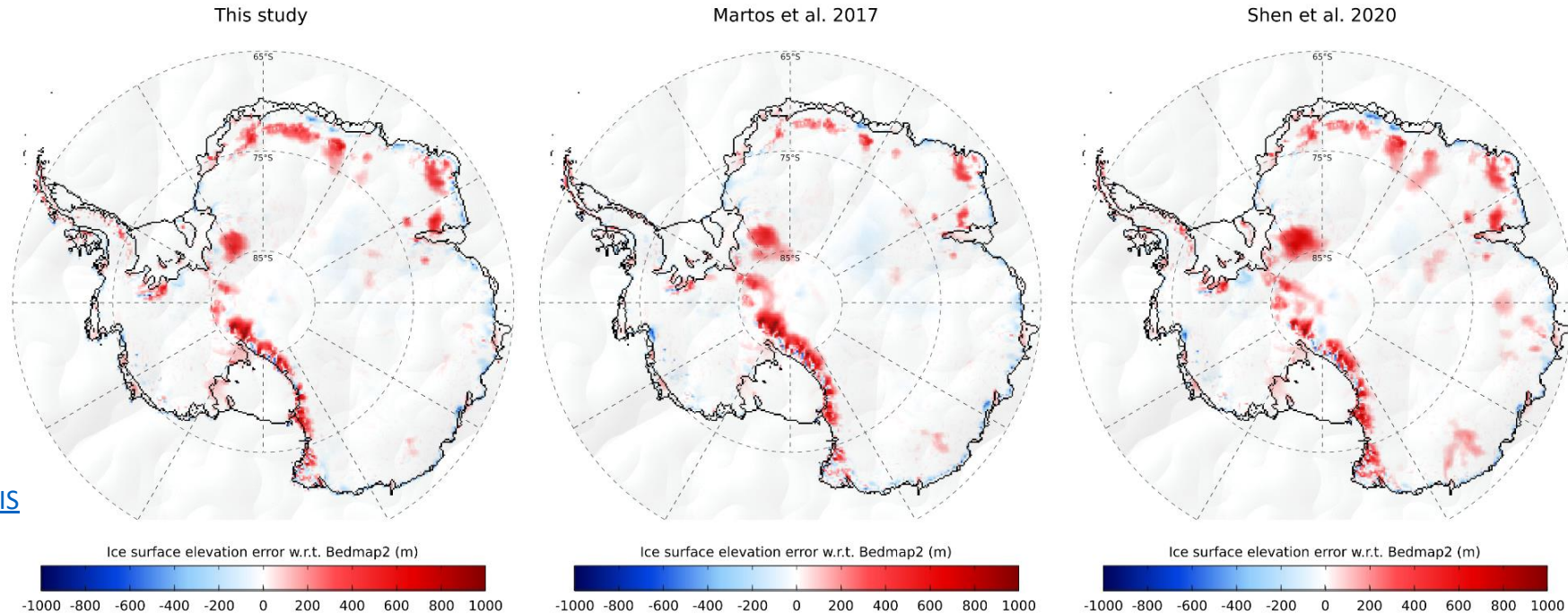
Maximum Heat Flow



Calculated from models A, B, C and the final model (slide 10)

Results – Ice Sheet Modeling

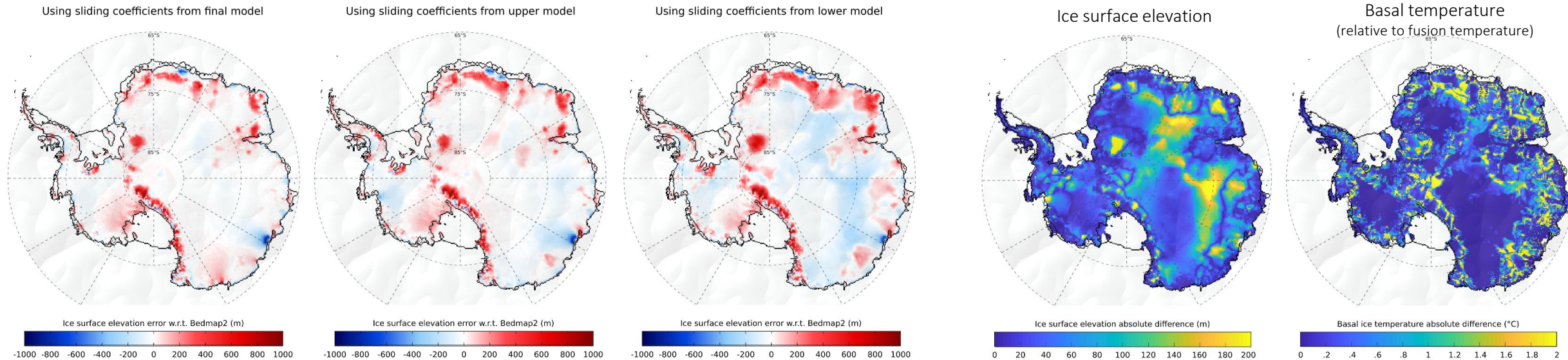
- Our model (slide 10) is applied as boundary condition in a 3D thermomechanical Antarctic ice sheet model* and compared to the Martos et al. (2017) and Shen et al. (2020) models
- Simulations run under transient Holocene climate conditions with tailored model calibrations for each GHF map
- All simulations yield reasonable present-day ice distributions, relative to Bedmap2 [Fretwell et al., 2013]
- Ice volume difference between smallest (Martos) and biggest (Shen) simulated ice sheets is ~ 0.5 m of sea level equivalent



*Ice sheet model [SICOPOLIS](#)

Results – Ice Sheet Modeling

- Basal conditions are recalibrated against observations using the final (slide 10), maximum, and minimum (slide 14) HF maps resulting in three different model set-ups (final, upper, lower)
- Holocene transient simulations are run for each set-up, using only the final GHF map
 - i. e. fixed GHF, varying model calibration
- Resulting present-day ice sheets differ up to ~1 m of sea level equivalent between set-ups
- Basal temperatures change significantly with up to 2°C absolute differences



- Knowledge about antarctic heat flow is crucial for **ice sheet modelers** and **Glacial isostatic adjustment** calculations
- We predicted a **heat flow model for Antarctica** with different geological features and the help of globally available observations
- Global data sets are needed but are **notoriously unreliable in polar regions** as these are not covered as well with geophysical data as other continents
- Including **regional lithospheric models** changes slightly the prediction pattern but might be more accurate than global models
- We see connections to former adjacent continents in the **Gondwana** framework, which are supported by magnetic anomalies
- Possible ranges of heat flow have significant influence on **ice sheet sliding conditions** leading to varied basal temperatures and different ice surface elevations

INStabilities and Thresholds in ANTarctica – INSTANT

There will be a new SCAR Group: [INSTANT](#) with a
Geothermal Heat Flow Subcommittee

Leader: Tobias Stål (University of Tasmania) - tobias.staal@utas.edu.au
Co-Leader: Mareen Lösing (Kiel University) - mareen.loesing@ifg.uni-kiel.de
Co-Leader: Alex Burton-Johnson (British Antarctic Survey)

Supported by:
Jacqueline Halpin (University of Tasmania)
Anya Reading (University of Tasmania)
Jörg Ebbing (Kiel University)
Brice Van Liefferinge (Norwegian Polar Institute)

Goals:

- International and interdisciplinary communication
- Data access
- Highlighting and communicating developments, challenges and questions

Feel free to contact me or Tobias Staal if you want to join or have more
questions about the programme



Questions?



Mareen.loesing@ifg.uni-kiel.de

G3.5

EDI 

Glacial Isostatic Adjustment and Parameters Controlling Ice Sheet-Solid Earth Interaction ▶

Co-organized by CR3/GD8

Convener: Holger Steffen  | Co-conveners: Valentina R. Barletta , Tanghua Li^{ECS} , Anya Reading , Bart Root^{ECS} 

▶ vPICO presentations  | Mon, 26 Apr, 13:30–15:00 (CEST) 

<https://meetingorganizer.copernicus.org/EGU21/session/39903>

Acknowledgements

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