Institute of Geosciences – Satellite- and Aerogeophysics

Christian-Albrechts-Universität zu Kiel

New Heat Flux Model for Antarctica with a Machine Learning Approach

Mareen Lösing & Jörg Ebbing (Kiel University)

Mareen.loesing@ifg.uni-kiel.de

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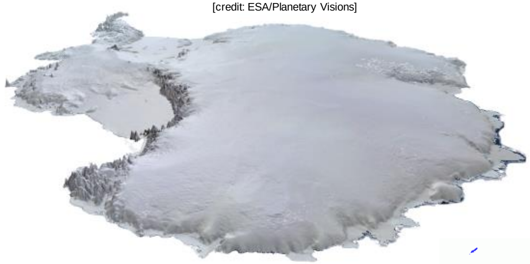
Motivation

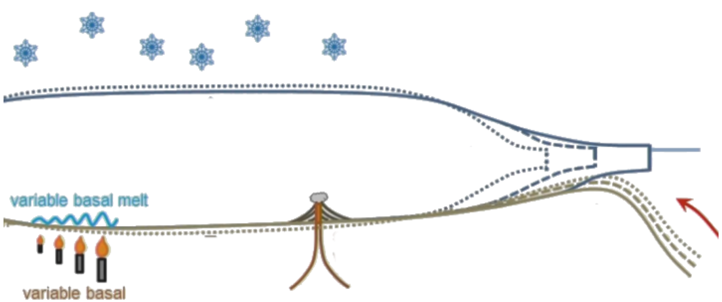
[credit: ESA/Planetary Visions]



- > 99% of Antarctica is covered by Ice
  – Largest potential source for **sea level rise**

[Anarctic Digital Database, 2000, US Digital Outline: ESRI]

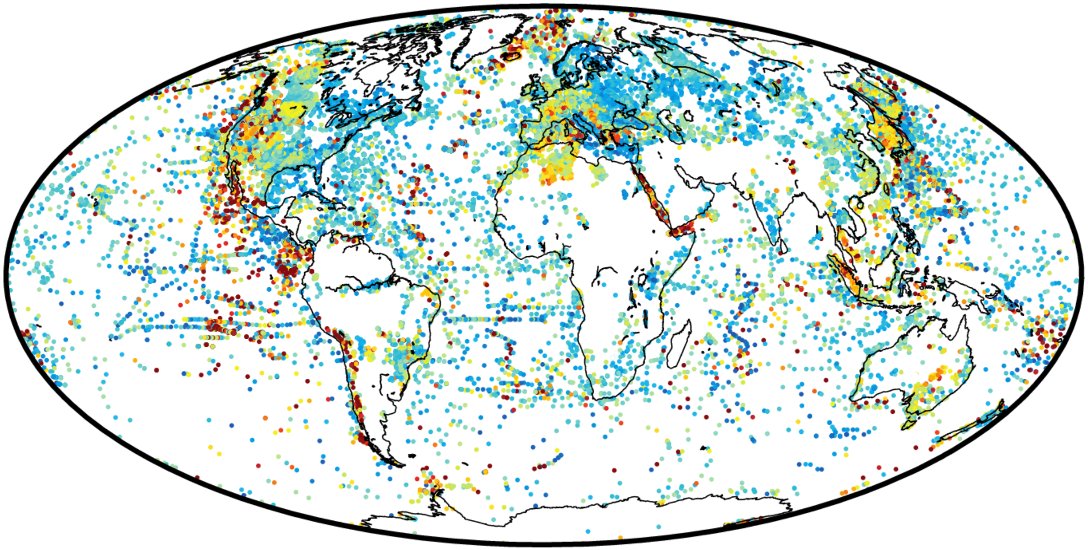
- Geothermal Heat Flux (GHF) is an important boundary condition for **ice-sheet modelling**
  - Affects Ice temperature and rheology
  - Can lead to basal melting and decoupling of ice-bed interface



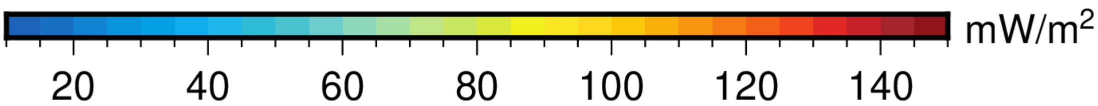
[from Whitehouse et al., 2019]

Motivation

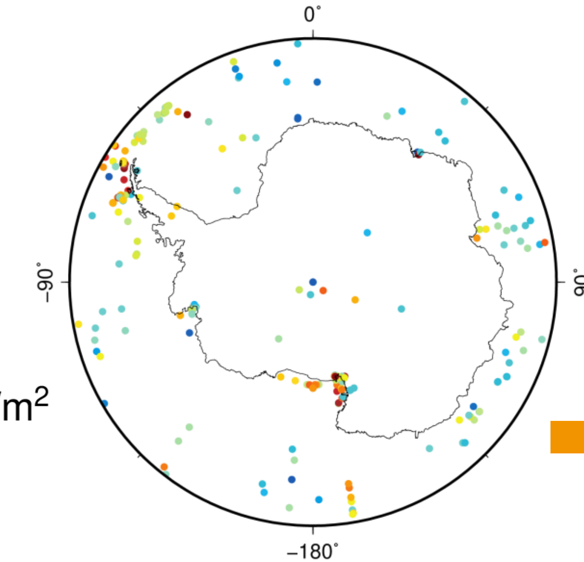
Global existing GHF measurements



[From http://www.heatflow.org, Lucazeau, 2019 (https://doi.org/10.1029/2019GC008389) and Martos et al., 2017 (https://doi.org/10.1002/2017GL075609)]



- Very sparse data in Antarctica
- Different approaches for estimation of continent wide GHF distribution

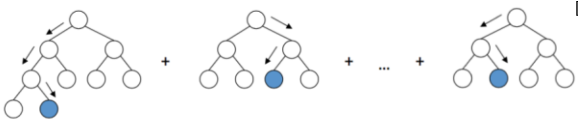


Method

- **Idea**: GHF is related to its geodynamic environment

⟶ Machine learning for prediction

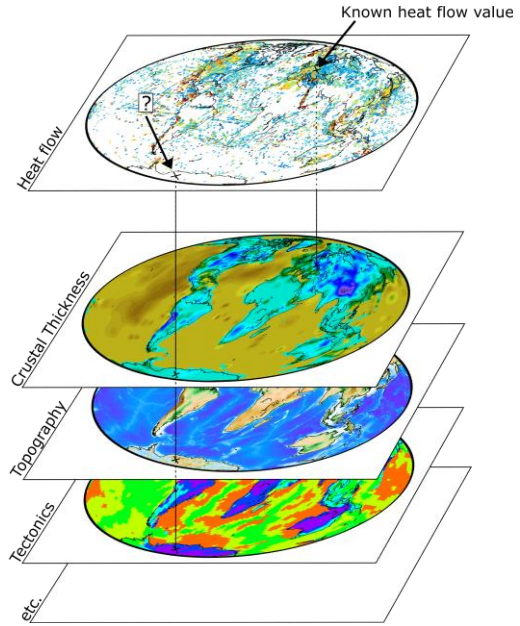
Gradient Boosting Regression Tree Algorithm [1]



1)Loss function needs to be optimized (e.g. squared error)

2)Weak learners make predictions (e.g. decision trees)

3)Additive model adds weak learners to minimize the loss function



[1] More information here: https://www.jstor.org/stable/2699986 (Friedman, 2001) or
[2] github.com/arogozhnikov

Method - Data

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Feature	Source
Moho	Szwillus et al., 2019
LAB	Afonso et al., 2019
Topography	Hirt & Rexer, 2015 (Earth 2014) & Morlinghem et al., 2019 (BedMachine)
Susceptibility	Inferred from Hemant & Maus, 2005
Tectonic units	Schaeffer & Lebedev, 2015
Mean curvature from grav. gradients	Ebbing et al., 2018
Vertical magnetic component	Yixiati et al. (In prep.)
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 volcanos	Global Volcanism Program & Van Wyk de Vries et al., 2018

- Available heat flow higher than 200 mW/m^2 is filtered out and subsequently binned with a resolution of 0.5°
- Only continental data is used (> -1 km)
- Data is split randomly into training (80 %) and test data (20 %)

Results – Heat Flow Map

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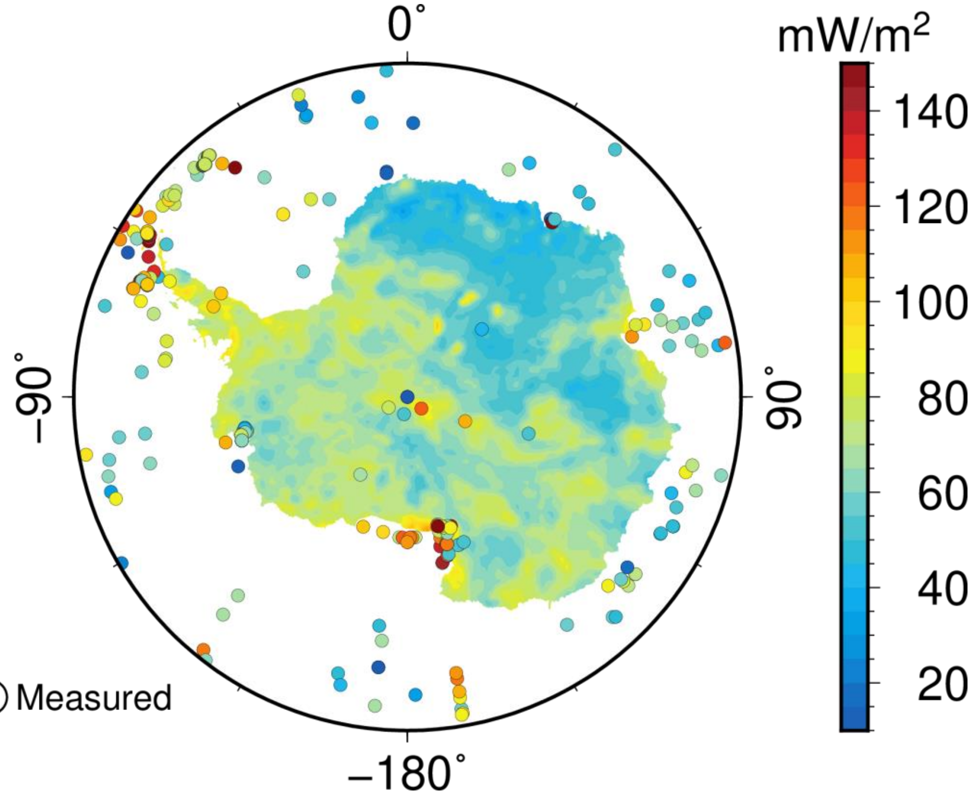
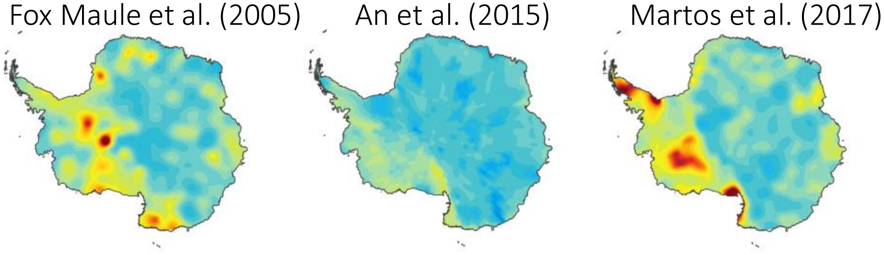
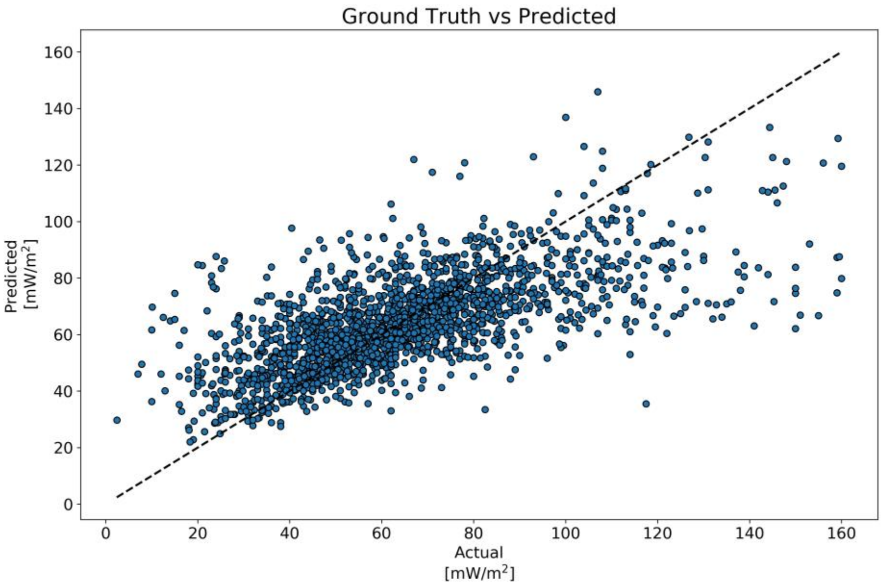


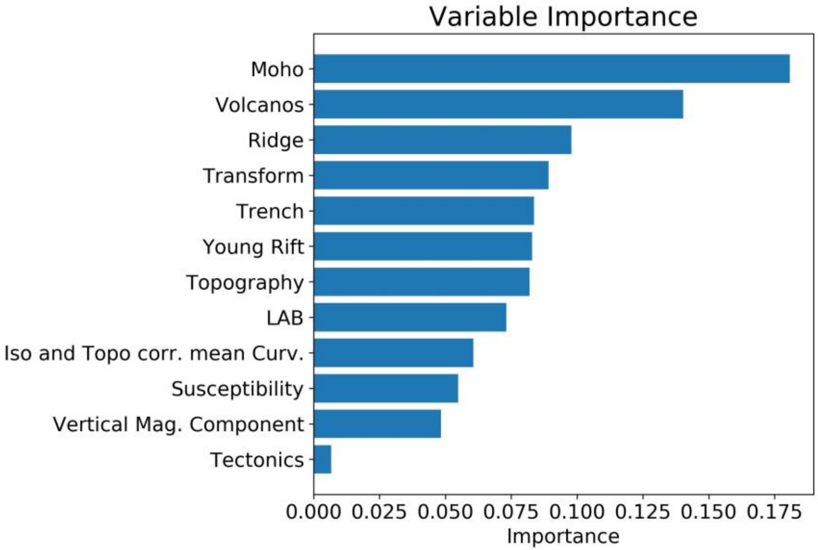
- Preliminary predicted heat flow for Antarctica
- Overall higher in West Antarctica, especially on Peninsula and Viktoria Land
- Some measurements fit quiet well, others (e.g. near the south pole) are underestimated by the prediction
- Not enough measurements for meaningful evaluation

For Comparison:



Results - Statistics





- Plot of the actual and the predicted test data set
- A perfect prediction model would lie exactly on the diagonal line
- Lower GHF is closer to the line than higher values, which are mainly underestimated (due to rather rare occurrences)

- Moho depth, distance to volcanos and ridges are selected as most important features for heat flow prediction by the machine learning algorithm

Results – Well Known Area

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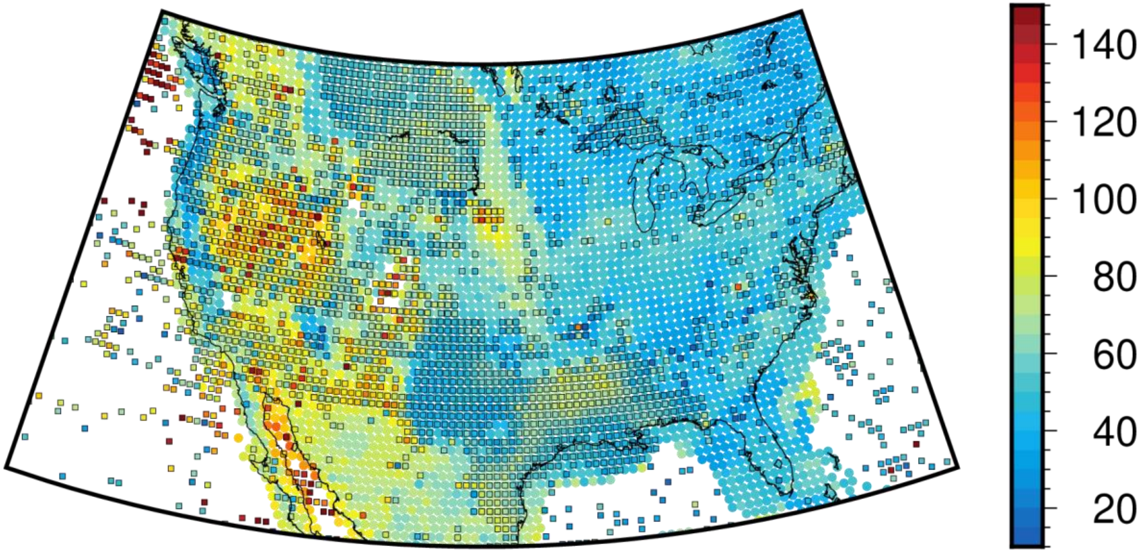
Predictions for USA



☐ Binned Measurements

- Relatively high amount of measurements in USA
- Helpful for interpretation of reliability of prediction model
  - Overall trends are predicted well
  - Isolated high values could not be predicted

Conclusions & Outlook

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- Still room for improvement: parameter testing, filtering of data, using more/other features, etc ...

- Overall reasonable results and solid predictions for highly sampled areas

Next:

- Review reliability of the few existing heat flow measurement estimates on the continent

- Train and test model only with Australian data

- Global data often not reliable in polar regions
    - Use regional data for Antarctica and neighbors during Gondwana

References and Further Reading

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❶ Friedman, J. H. (2001). Greedy function approximation: a gradient boosting machine. *Annals of statistics*, 1189-1232

Nice explanation of Gradient Boosting:
❷ https://arogozhnikov.github.io/2016/06/24/gradient_boosting_explained.html

Heat Flux Models of Antarctica:
❸ Maule, C. F., Purucker, M. E., Olsen, N., & Mosegaard, K. (2005). Heat flux anomalies in Antarctica revealed by satellite magnetic data. *Science*, *309*(5733), 464-467

❹ An, M., Wiens, D. A., Zhao, Y., Feng, M., Nyblade, A., Kanao, M., ... & Lévêque, J. J. (2015). Temperature, lithosphere-asthenosphere boundary, and heat flux beneath the Antarctic Plate inferred from seismic velocities. *Journal of Geophysical Research: Solid Earth*, *120*(12), 8720-8742

❺ Martos, Y. M., Catalán, M., Jordan, T. A., Golynsky, A., Golynsky, D., Eagles, G., & Vaughan, D. G. (2017). Heat flux distribution of Antarctica unveiled. *Geophysical Research Letters*, *44*(22), 11-417

Nice Study with machine learning for heat flux prediction:
❻ Rezvanbehbahani, S., Stearns, L. A., Kadivar, A., Walker, J. D., & van der Veen, C. J. (2017). Predicting the geothermal heat flux in Greenland: A machine learning approach. *Geophysical Research Letters*, *44*(24), 12-271

Graphic from 2nd Slide:
❼ Whitehouse, P. L., Gomez, N., King, M. A., & Wiens, D. A. (2019). Solid Earth change and the evolution of the Antarctic Ice Sheet. *Nature communications*, *10*(1), 1-14

References of Used Features

- Szwillus, W., Afonso, J. C., Ebbing, J., & Mooney, W. D. (2019). Global crustal thickness and velocity structure from geostatistical analysis of seismic data. *Journal of Geophysical Research: Solid Earth*, *124*(2), 1626-1652.

- Afonso, J. C., Salajegheh, F., Szwillus, W., Ebbing, J., & Gaina, C. (2019). A global reference model of the lithosphere and upper mantle from joint inversion and analysis of multiple data sets. *Geophysical Journal International*, *217*(3), 1602-1628

- Hirt, C., & Rexer, M. (2016). The 1 arc-min resolution Earth2014 global topography model. In *International Symposium on Gravity, Geoid and Height System 2016-1st Joint Commission 2 and IGFS Meeting*

- Morlighem, M., Williams, C. N., Rignot, E., An, L., Arndt, J. E., Bamber, J. L., ... & Fenty, I. (2017). BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation. *Geophysical research letters*, *44*(21), 11-051.

- Hemant, K., & Maus, S. (2005). Geological modeling of the new CHAMP magnetic anomaly maps using a geographical information system technique. *Journal of Geophysical Research: Solid Earth*, *110*(B12).

- Schaeffer, A. J. and S. Lebedev, Global shear-speed structure of the upper mantle and transition zone. Geophys. J. Int., 194 (1), 417-449, 2013. doi:10.1093/gji/ggt095

- Ebbing, J., Haas, P., Ferraccioli, F., Pappa, F., Szwillus, W., Bouman, J. – Earth tectonics as seen by GOCE – Enhanced satellite gravity gradient imaging, *Nature Scientific Reports*, Vol. 8, 1-9, 2018.

- Coffin, M. F., Gahagan, L. M., & Lawver, L. A. (1997). *Present-day plate boundary digital data compilation*. Institute for Geophysics.

- Celal, S. A., & Natalin, B. A. (2001). Rifts of the world. The educational-information aids. *Geological Society of America Special Paper.*, (352), 389.

- Global Volcanism Program, 2013. Volcanoes of the World, v. 4.8.8 (17 Apr 2020). Venzke, E (ed.). Smithsonian Institution. Downloaded 10 March 2020. https://doi.org/10.5479/si.GVP.VOTW4-2013.

- de Vries, M. V. W., Bingham, R. G., & Hein, A. S. (2018). A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. *Geological Society, London, Special Publications*, *461*(1), 231-248.