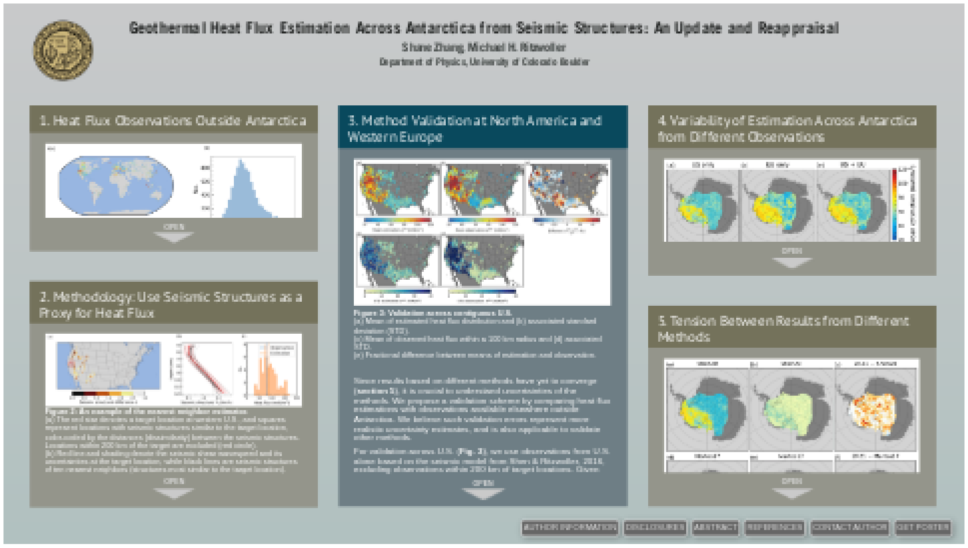
Geothermal Heat Flux Estimation Across Antarctica from Seismic Structures: An Update and Reappraisal



Shane Zhang, Michael H. Ritzwoller

Department of Physics, University of Colorado Boulder

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1. HEAT FLUX OBSERVATIONS OUTSIDE ANTARCTICA

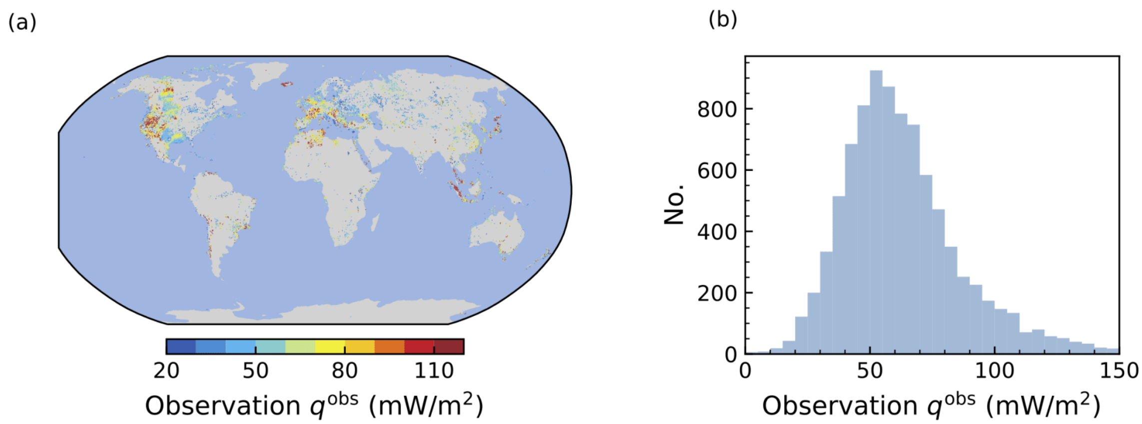

Figure 1: Global continental heat flux observations.
(a) Geographical distribution of heat flux observations at single locations (Lucazeau, 2019). North America and Western Europe have the most observations.
(b) Histogram of heat flux observations, showing a heavy tail towards higher values.

Geothermal heat flux across Antarctica can serve as an important boundary condition for glacial modeling to understand the mechanical stability and thermal state of the ice sheet, and thus may affect the prediction of global sea level rise and climate change.

However, observations of heat flux remain rare in Antarctica (Lucazeau, 2019; **Fig. 1a**). Our earlier estimation of Antarctica heat flux assimilated heat flux observations from regions with seismic structures (global scale) similar to Antarctica (Shapiro and Ritzwoller, 2004).

Improvement in the resolution of regional seismic models (empowered by seismic ambient noise tomography) and expansion of heat flux observations prompt an update to our earlier results. Furthermore, we reappraise the inference methodology by comparing predictions with observations outside Antarctica including North America and Western Europe.

2. METHODOLOGY: USE SEISMIC STRUCTURES AS A PROXY FOR HEAT FLUX

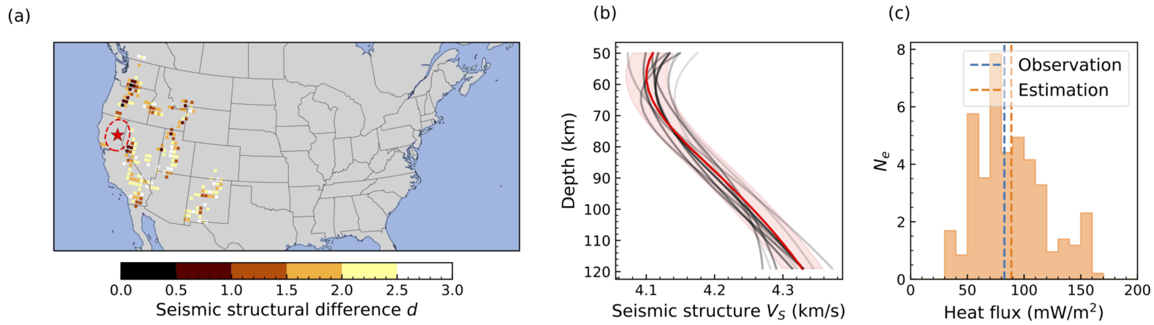

Figure 2: An example of the nearest neighbor estimator.
(a) The red star denotes a target location at western U.S., and squares represent locations with seismic structures similar to the target location, color-coded by the distances (dissimilarity) between the seismic structures. Locations within 200 km of the target are excluded (red circle).
(b) Red line and shading denote the seismic shear wavespeed and its uncertainties at the target location, while black lines are seismic structures of ten nearest neighbors (structures most similar to the target location).
(c) Histogram of heat flux distribution estimated from the nearest neighbors. The means of estimation and observation (within 100 km) are shown as orange and blue dashed lines, respectively.

Our method is motivated by the strong (anti-)correlation between uppermost mantle seismic shear wave structures and heat flux in both global (e.g., Pollack et al., 1993; Röhm et al., 2000) and regional (e.g., Shen et al., 2020) scales, presumably due to the strong temperature dependence of seismic structures there.

The success of the method depends on several assumptions: (1) Uppermost mantle seismic structures are a robust estimator of heat flux. (2) Seismic structures at Antarctica and elsewhere are consistent. (3) Heat flux observations are available at regions with seismic structures similar to Antarctica.

We test assumption (1) in **section 3** and assumptions (2) and (3) in **section 4**.

3. METHOD VALIDATION AT NORTH AMERICA AND WESTERN EUROPE

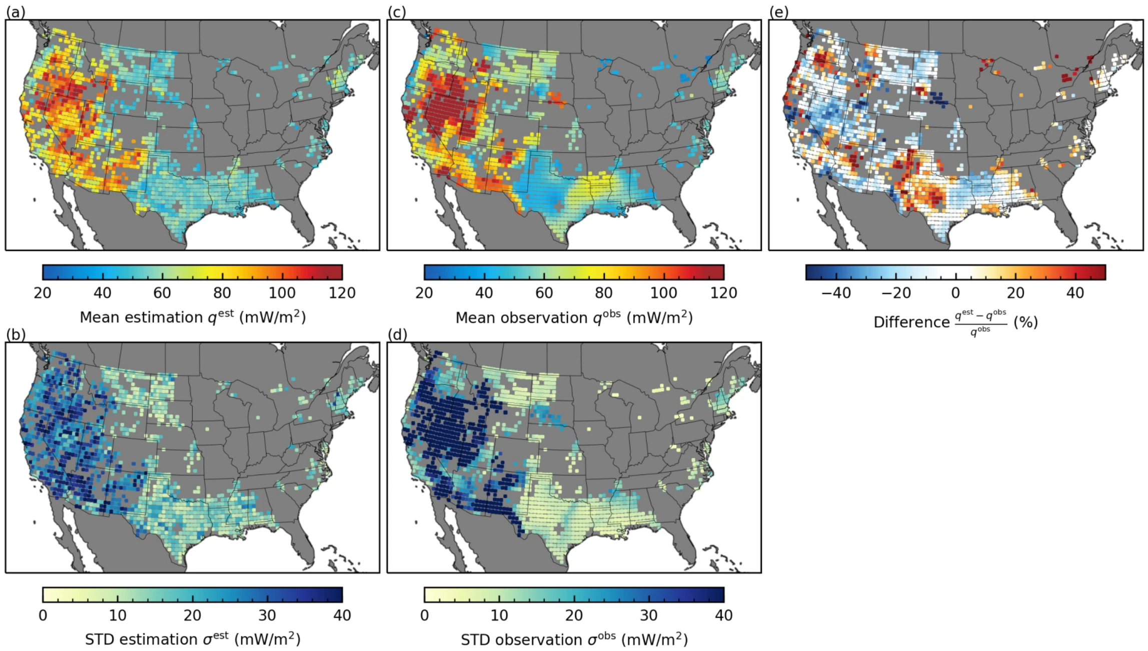

Figure 3: Validation across contiguous U.S.
(a) Mean of estimated heat flux distribution and (b) associated standard deviation (STD).
(c) Mean of observed heat flux within a 100 km radius and (d) associated STD.
(e) Fractional difference between means of estimation and observation.

Since results based on different methods have yet to converge (**section 5**), it is crucial to understand uncertainties of the methods. We propose a validation scheme by comparing heat flux estimations with observations available elsewhere outside Antarctica. We believe such validation errors represent more realistic uncertainty estimates, and is also applicable to validate other methods.

For validation across U.S. (**Fig. 3**), we use observations from U.S. alone based on the seismic model from Shen & Ritzwoller, 2016, excluding observations within 200 km of target locations. Given the sparsity of heat flux observations across Antarctica, a more realistic approach will be to use observations from other continents, which will probably make the estimation more challenging (Goutorbe et al., 2011, Rezvanbehbahani et al., 2017).

We note the STD is correlated with the mean for both estimation and observations (for σ^{obs}: Median ± MAD = 13 ± 9 mW/m² or 24 ± 15 %), i.e., higher heat flux values are more variable (**Figs 3b and d**). Thus fractional differences between estimation and observations are perhaps more illuminating (**Fig. 3e**). The differences are summarized as follows: Median ± MAD = -2 ± 15 mW/m² or -3 ± 23 % or -0.1 ± 0.9 σ^{obs}.

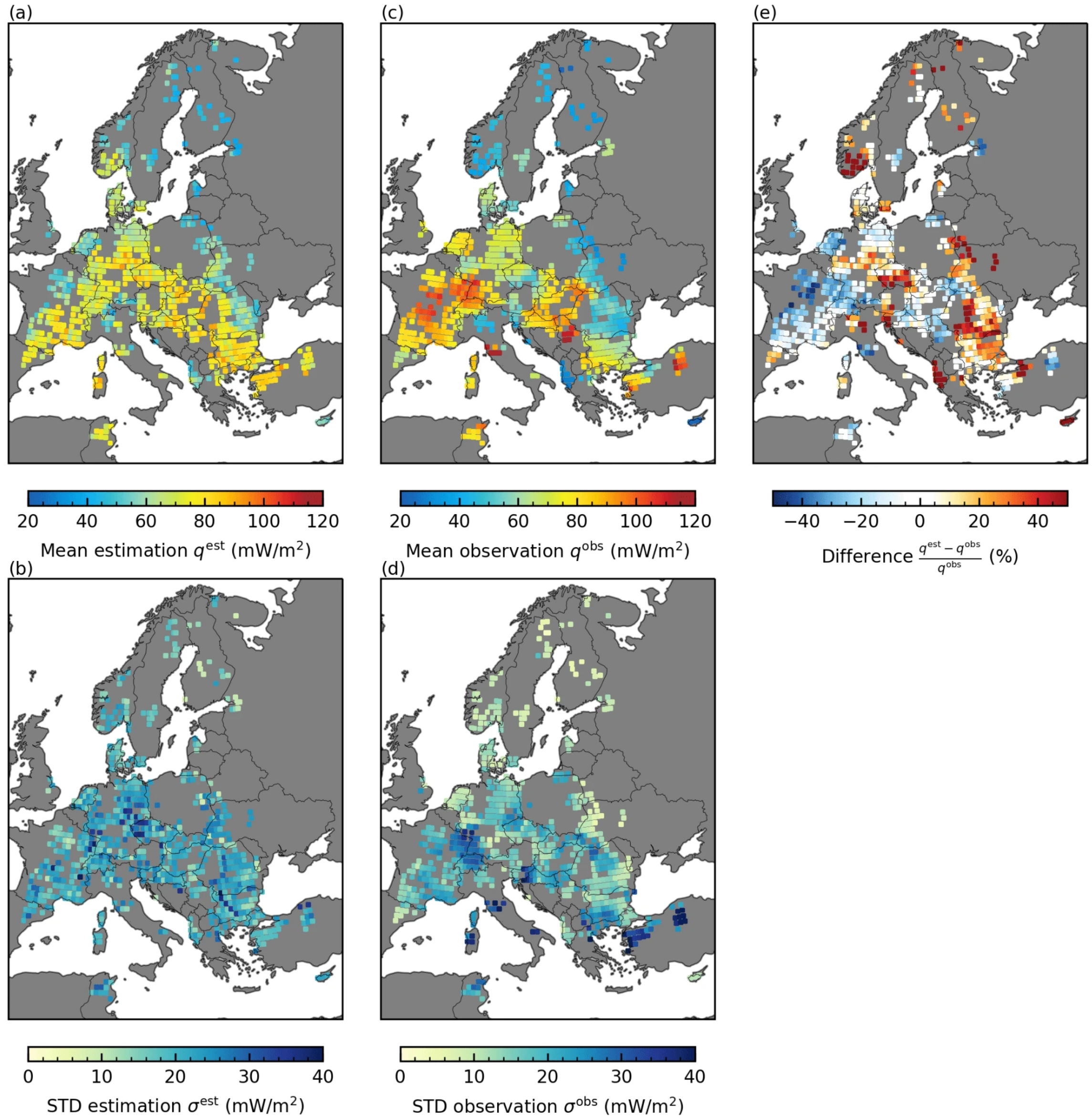

Figure 4: Validation across western Europe.
Similar to Fig. 3 except for western Europe.

The validation across western Europe is based on the seismic model from Lu et al., 2018 and observations are from Europe alone (**Fig. 4**). Our method performs slightly worse than across the U.S. (Median ± MAD = 1 ± 17 mW/m² or 2 ± 28 % or 0.1 ± 1.1 σ^{obs}; **Fig. 4e**). The STD for observation σ^{obs} is summarized as: Median ± MAD = 15 ± 7 mW/m² or 24 ± 9 %.

To sum up, we found the typical difference between estimation and observation to be 23% to 28%, which are comparable to the STD of observation σ^{obs} about 24% in both U.S. and Europe.

4. VARIABILITY OF ESTIMATION ACROSS ANTARCTICA FROM DIFFERENT OBSERVATIONS

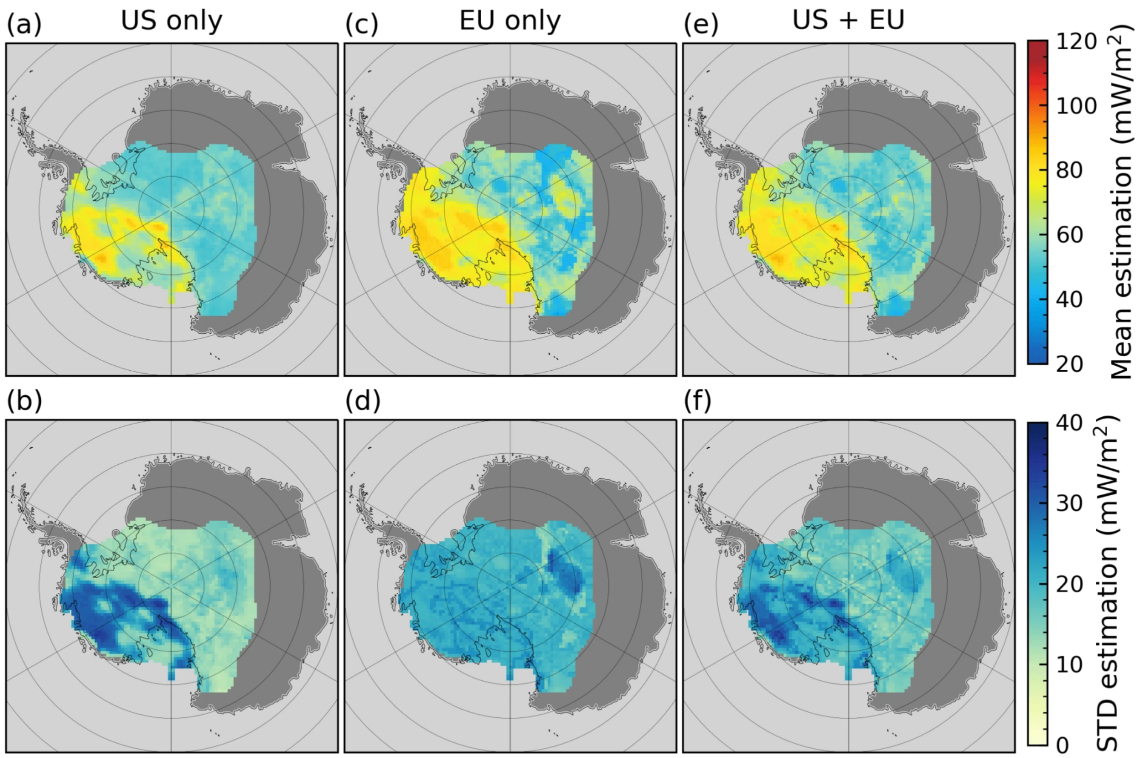

Figure 5: Estimation across Antarctica using U.S. data alone.
(a) Heat flux estimation and (b) associated standard deviation (STD). Only heat flux observations from the contiguous U.S. are used.
(c) & (d) Similar to (a) & (b) except only heat flux observations from western Europe are used.
(e) & (f) Similar to (a) & (b) except heat flux observations from both U.S. and western Europe are used.

To test the consistency between seismic models and quantify the variability of heat flux estimation from different observations, we present estimation using U.S. and Europe observations (**Fig. 5**) based on the Antarctica seismic model by Shen et al., 2018. The Europe-only estimation is systematically higher than the US-only estimation (Median ± MAD = 6 ± 6 mW/m² or 9 ± 11 %), suggesting the importance of including observations from different regions to reduce sampling bias.

5. TENSION BETWEEN RESULTS FROM DIFFERENT METHODS

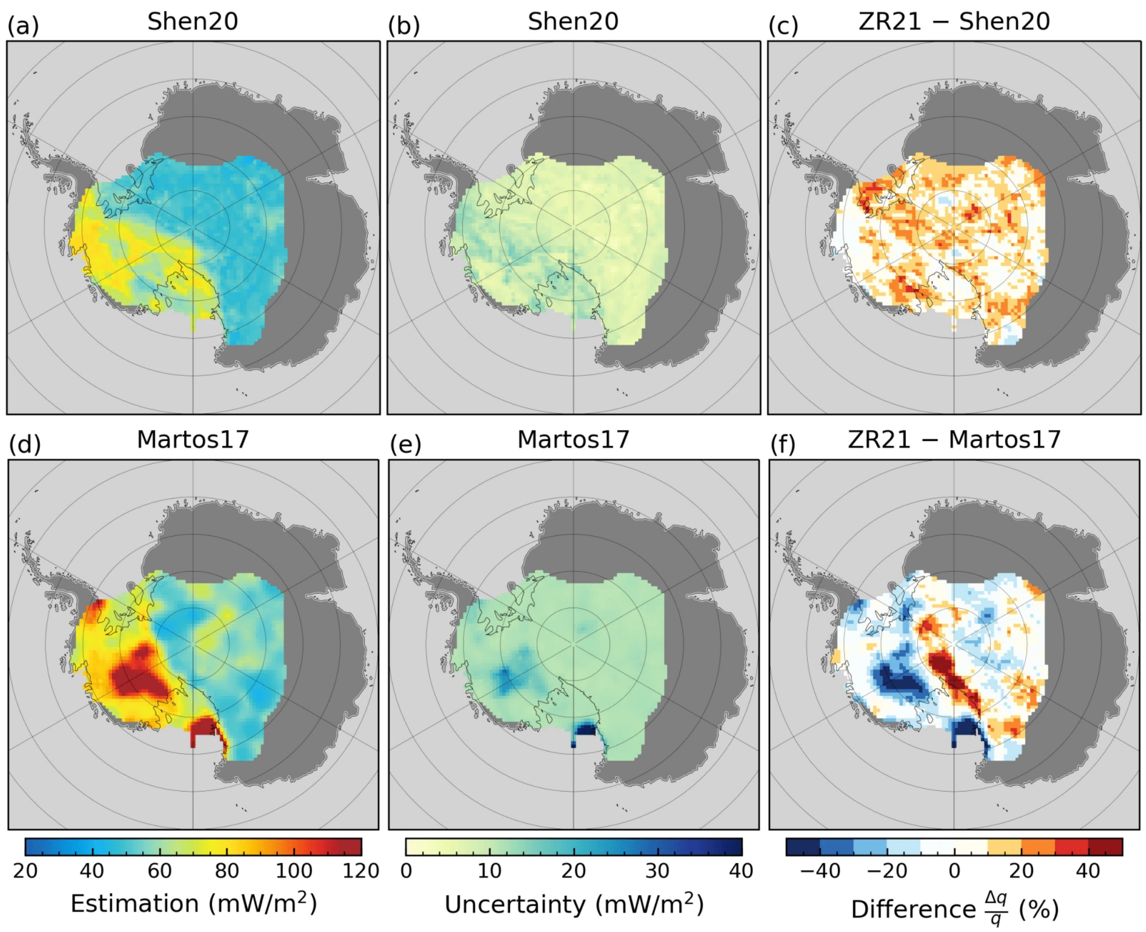

Figure 6: Comparison with previous studies.
(a) Mean and (b) uncertainties of estimation from Shen et al., 2020 (henceforth "Shen20"), which also use seismic structures as a proxy except they only use observations from the contiguous U.S.
(c) Fractional difference between the mean of our estimation (ZR21) and theirs (Shen20).
(d)–(f) Similar to (a)–(c) except results from Martos et al., 2017 (henceforth "Martos17") are compared. They first estimate Curie depths from geomagnetic anomalies, and then use a 1-D conductive model to predict heat flux, assuming the Curie depths correspond to an isotherm.

We compare our preliminary estimation with another study based on a seismic proxy by Shen et al., 2020 (Shen20; **Figs 6a–c**). The key difference is that we also assimilate observations from Europe, which makes our estimation systematically higher than Shen20 (Median ± MAD = 6 ± 5 mW/m² or 10 ± 9 %; **Fig. 6c**).

We also compare our results with a study based on geomagnetic anomalies by Martos et al., 2017 (Martos17; **Figs 6d–f**). For reasons we do not understand yet, our estimation is significantly lower in western Antarctica and higher in central Antarctica, where the differences can be larger than 3σ of their uncertainties (**Fig. 6f**). Our result is generally lower than Martos17 (Median ± MAD = -3 ± 9 mW/m² or -5 ± 14 %; **Fig. 6f**).

Although all estimations show a west-east dichotomy, the typical values across east and west Antarctica differ significantly, especially at west Antarctica. The median heat flux is 55 mW/m², 56 mW/m² and 49 mW/m² across east Antarctica (60°W to 150°E), and 73 mW/m², 78 mW/m² and 66 mW/m² across west Antarctica, for ZR21, Marto17 and Shen20, respectively. Thus the dichotomy is about 18 mW/m², 22 mW/m² and 17 mW/m² for ZR21, Marto17 and Shen20, respectively. In contrast, the lower-resolution result of Shapiro & Ritzwoller, 2004 shows a larger dichotomy of 35 mW/m² (median about 48 mW/m² and 82 mW/m² across east and west Antarctica respectively).

DISCLOSURES

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AUTHOR INFORMATION

Shane Zhang

shane.zhang@colorado.edu

https://shane-d-zhang.github.io (https://shane-d-zhang.github.io)

Mike Ritzwoller

michael.ritzwoller@colorado.edu

http://ciei.colorado.edu/ritzwoller_m (http://ciei.colorado.edu/ritzwoller_m)

ABSTRACT

Geothermal heat flux across Antarctica can serve as an important boundary condition for glacial modeling to understand the mechanical stability and thermal state of the ice sheet, and thus may affect the prediction of global sea level rise and climate change. However, in situ measurements of heat flux remain rare in Antarctica. Our earlier estimation of Antarctica heat flux (Shapiro and Ritzwoller, 2004) assimilated heat flux measurements from regions with seismic structures (global scale) similar to Antarctica. Our method is motivated by the strong correlation between global uppermost mantle seismic shear wave structures and heat flux (presumably due to the strong temperature dependence of seismic structures there). Improvement in the resolution of regional seismic models (empowered by ambient noise tomography) and expansion of heat flux measurements prompt an update to our earlier results. Furthermore, we reappraise the inference methodology by comparing predictions with measurements outside Antarctica (e.g., North America., Western Europe). We believe such generalization errors represent more realistic uncertainty estimates than the dispersion of inference caused by spatial variability. Realistic uncertainty estimation is key to comparing different predictions, especially since results based on different observables or methods have yet to converge.

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