3D instantaneous dynamics numerical modelling of the surface motion associated with East European subduction zones

- MSc Thesis Preliminary Results -

Utrecht University

A.J. (Bert) van Amerongen, W. Spakman, L. Verbrugh, E. van der Wiel, and C. Thieulot

Department of Earth Sciences, Utrecht University

Background & Observed surface flow field

Modelling geodynamics is a key method to understand the physical drivers generating the stresses in the lithosphere that drive earthquakes. Drivers confined to the lithosphere are known to have a contribution to this stress-buildup, but the role of the Earth's mantle is less substantiated.

Here we present a 3D model of the lithosphere and mantle on the East Mediterranean and Carpathians. This region features the old and large Aegean slab - slowly sinking into the mantle, demonstrating roll-back at the surface - and the much smaller Vrancea slab below the Carpathians.

A 3D initial density-temperature field is constructed and used to predict the flow of Earth's surface using the numerical solver ASPECT (Bangerth et al. 2022). This is then compared to the observed GNSS surface motion field.

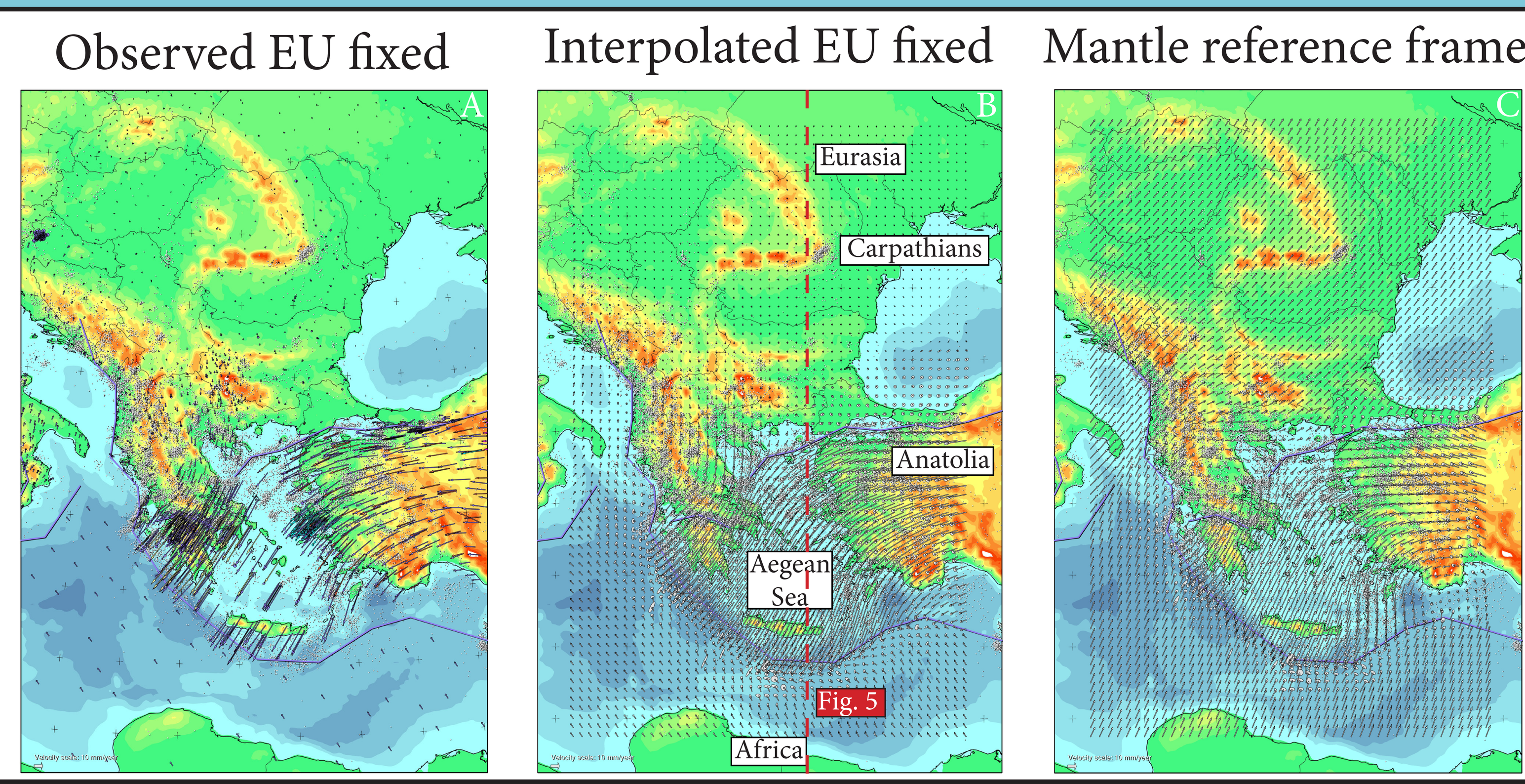


Figure 1
A. The observed Global Navigation Satellite System (GNSS) surface flow field, as observed for a fixed Eurasia.
B. The interpolated of this surface flow field.
C. The surface flow field in the Global Mantle Hotspot Reference Frame, where the plates move on top of a 'fixed' Earth mantle.

The most prominent features are:

- The west to south-westward extrusion of Anatolia.
- The roll-back of the Hellenic Trench, south of Crete.

1. Model setup

3D model structure

The complex 3D initial density-temperature field of the model is created using the novel Geodynamic World Builder (Fraters et al. 2019).

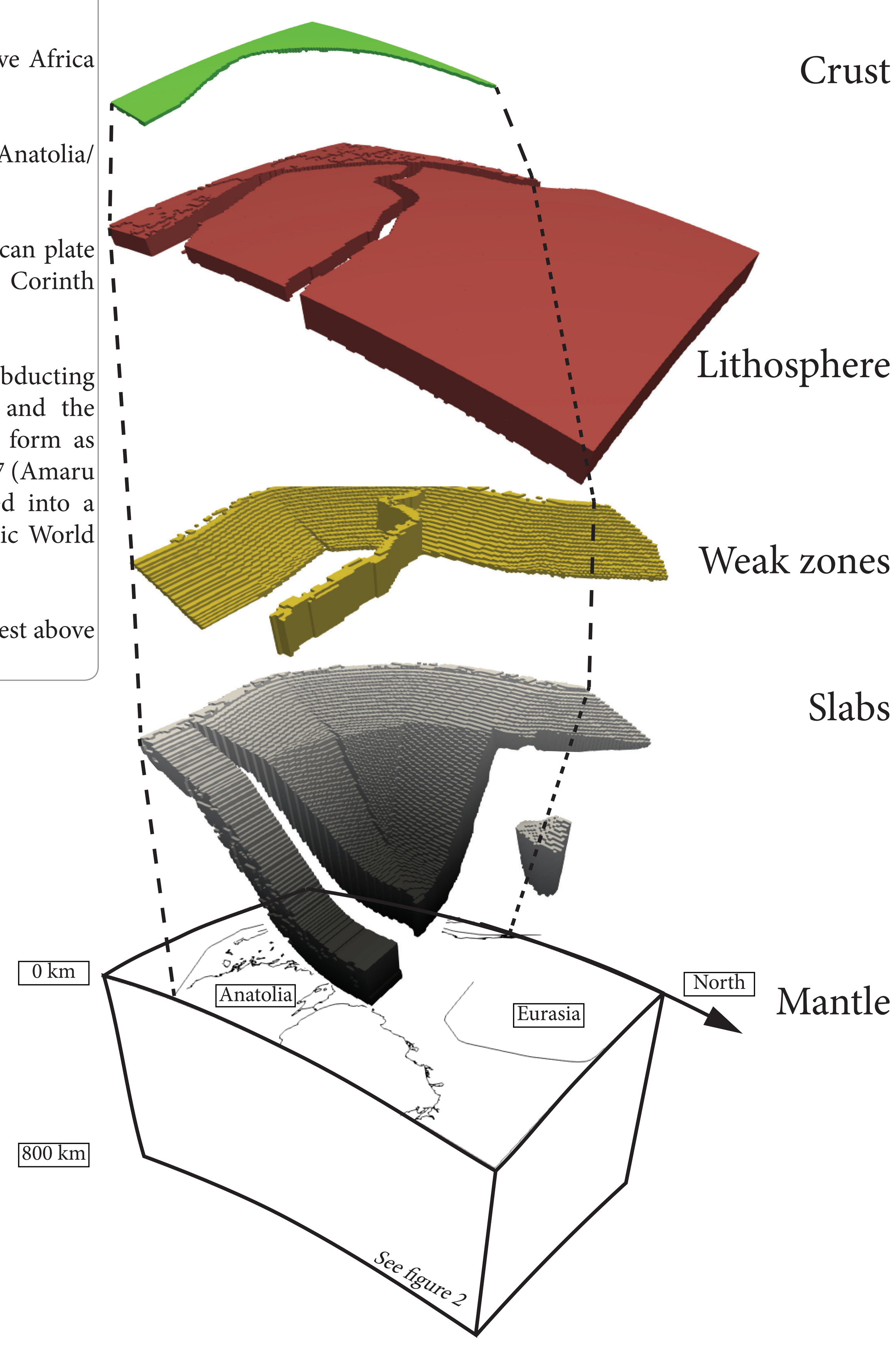
The model consists of a 22.5 km thick crust above Africa (orange).

Below are the three lithospheric domains of Africa, Anatolia/Aegean and Eurasia (red).

These are cross-cut by weak zones along the African plate boundary, North Anatolian Fault and Gulf of Corinth (green).

Piercing through all is the 3D model of the subducting Dinarides-Aegean slab, the Anaximander slab and the Vrancea slab. These slabs follow the shape and form as imaged by the Utrecht tomography model UU-P07 (Amaru et al. 2007). The tomographic model is mapped into a temperature-density model using the Geodynamic World Builder.

These units lie within an upper mantle layer and rest above a lower mantle layer.



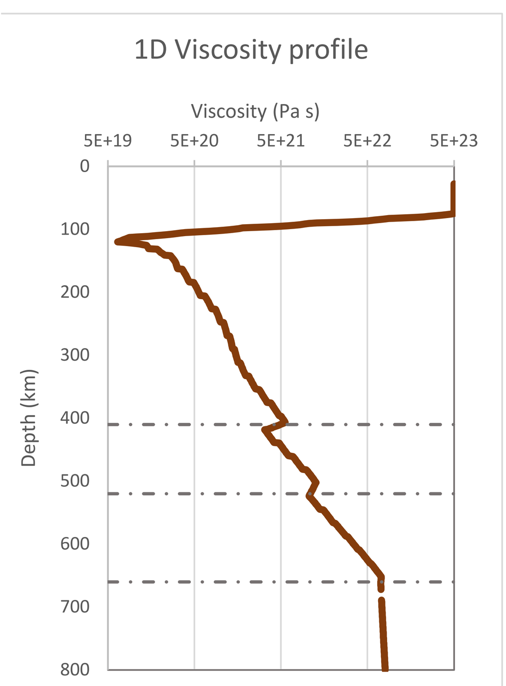


Figure 3. A typical viscosity-depth plot for a region in the model relatively undisturbed by subduction.

Domain

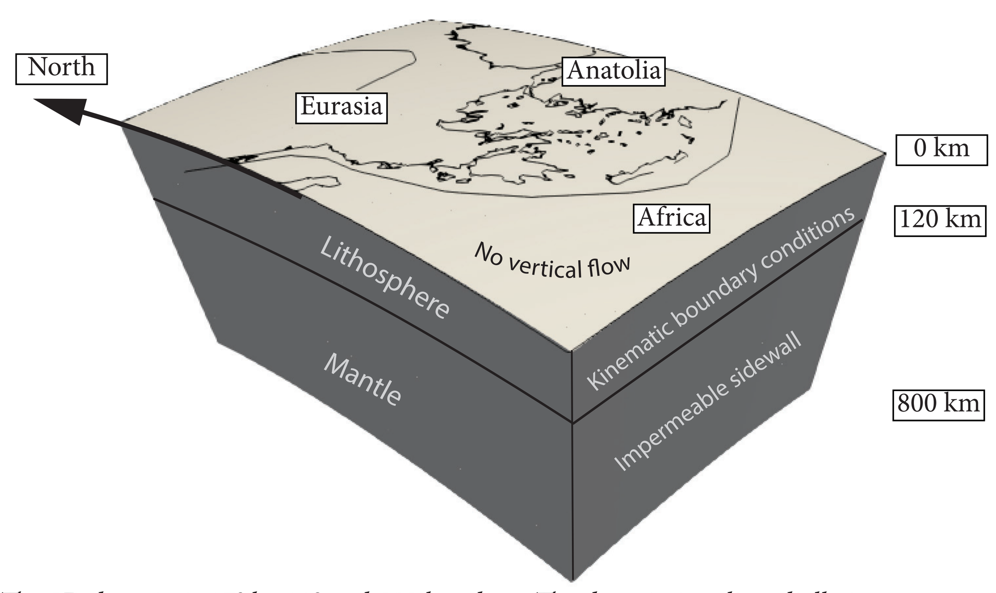
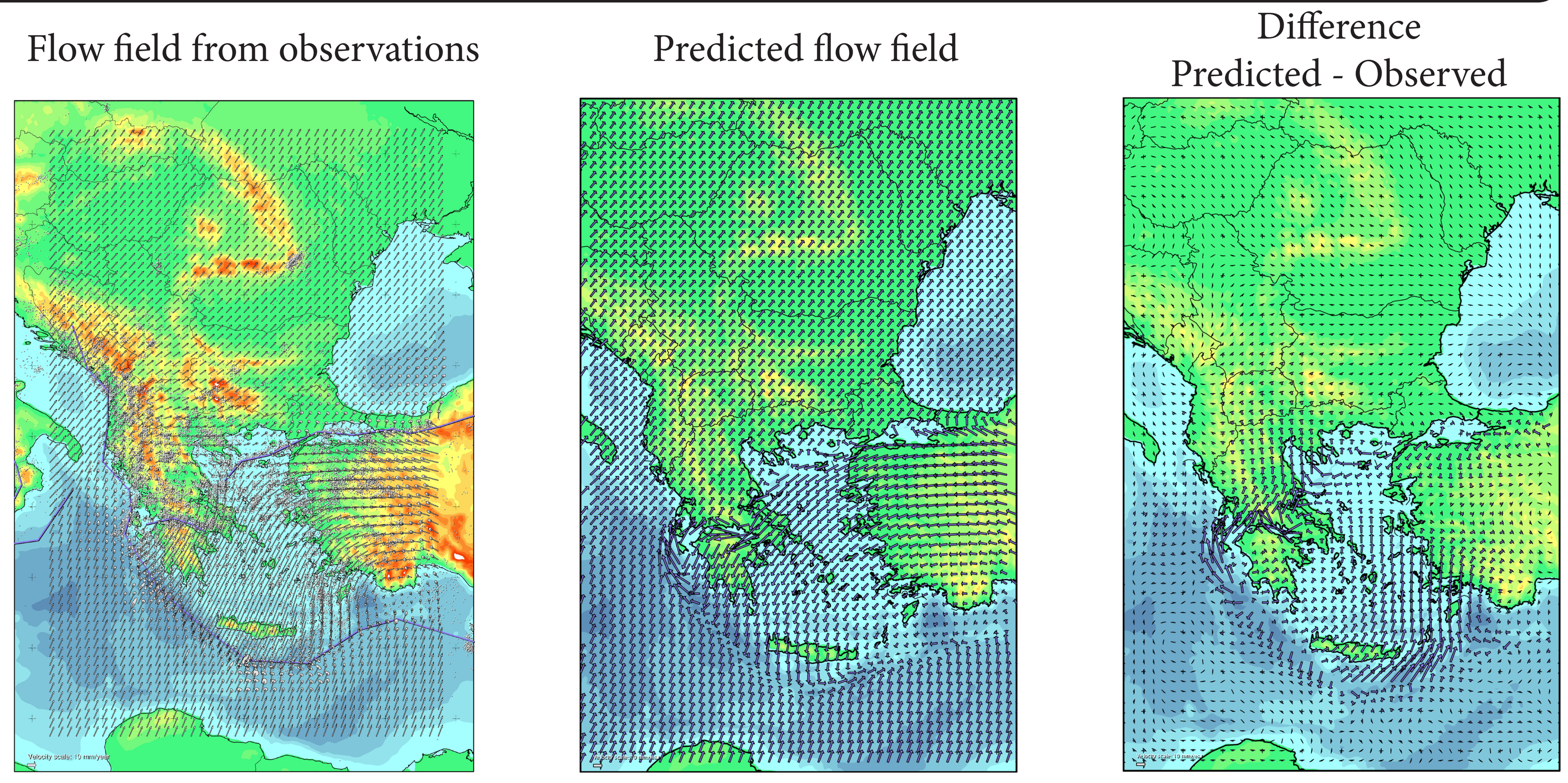


Figure 2. The 3D domain is 17° by 11° and 800 km deep. The domain is split radially in an upper 120 km where kinematic boundary conditions are prescribed on the sides, and no vertical flow is allowed on the surface. The lower 680 km allows for parallel-flow along the sides. A net outflow is prescribed on the bottom to satisfy mass conservation as a result of the plate convergence at the top.

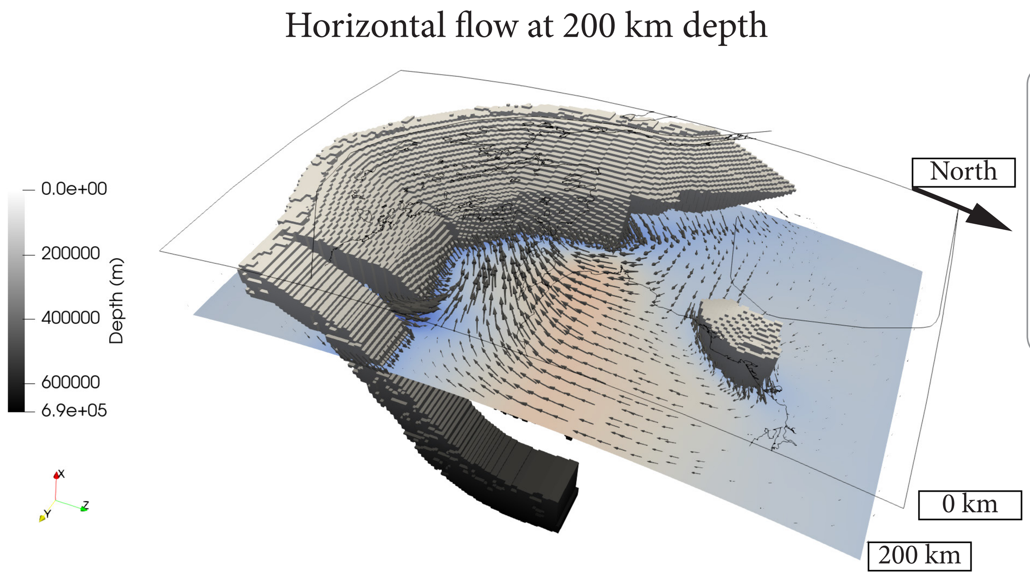
2. Reference model surface flow field



Our model obtains a good first order fit. The westward motion of Anatolia is reproduced in the model and the south-west flow of the Aegean is also approximately antipolar to the north-east flow of Africa. Noticable misfits occur in west Anatolia and the larger Aegean region. Preliminary research results suggest this is a complex interplay between the Anatolia/Aegean plate viscosity, the subducting slab viscosity and the plate boundary weak zone viscosity.

3. Reference model mantle flow field

Horizontal flow at 200 km depth

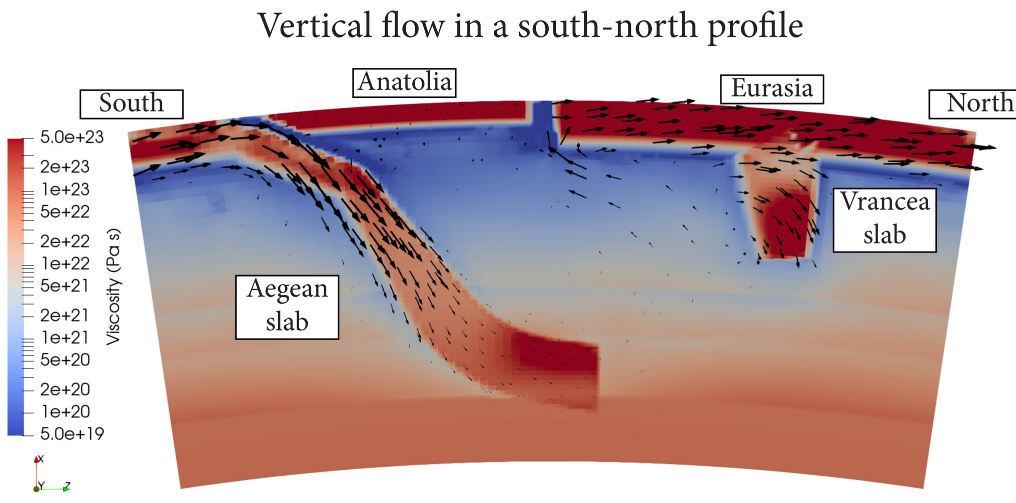


The main features seen are:

- Strong flow around the edges of the slab.
- Dominant flow towards the center of the sinking Aegean slab.
- Flow from the Aegean slab edge affects the Vrancea slab.
- The Vrancea slab moves northeast-ward, following the overlying Eurasian lithosphere as a ship's keel.

Figure 4. 3D model of the subducting slabs coloured in white to black. A crosscut is given at 200 km. The velocity vectors are shown for the flow of the slabs and of the surrounding mantle. The magnitude of N-S flow is shown in blue (north) to red (south).

Vertical flow in a south-north profile

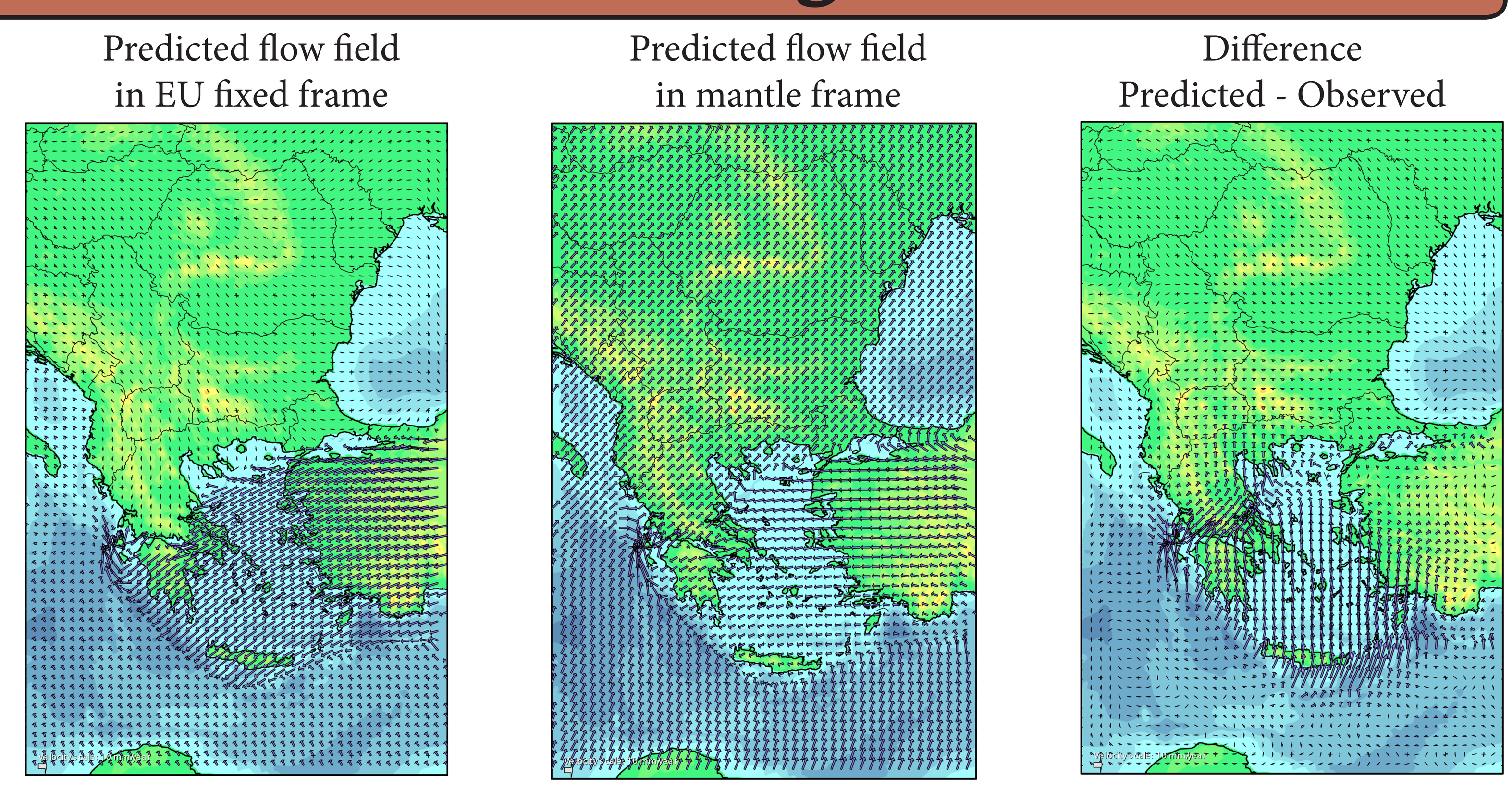


The main features seen are:

- Subduction and sinking of the Aegean slab is fastest in the top 300 km. Sinking is slowed in the lower section where the slab rests on top of the more viscous lower mantle.
- The Vrancea slab is coupled to the Eurasian plate, pulling the slab northward through the upper mantle. At depth, the slab demonstrates a vertical sinking component which is not translated to shallower depths.

Figure 5. A 2D south-north cross-cut of the Aegean slab subducting beneath Anatolia and Eurasia. Velocity vectors are shown in black (vectors at the trench and within Eurasia are ~ 14 mm/yr and 9 mm/yr respectively). The background shows the viscosity profile in blue-red.

4. Removed Aegean slab



The Aegean slab is removed to test the effect that it has on the surface flow field. The Anatolian/Aegean plate moves west as this is prescribed on its boundary (Figure 1C). Striking is that the predicted flow of the Aegean appears to rotate SW-ward in the EU fixed reference frame, apparently disproving that a slab is necessary for this flow field. This interpretation falls apart, however, when observed in a mantle hotspot reference frame (center). The Aegean in fact displays southward velocities that are much too low (right). This demonstrates the contribution of the southward pull of the Aegean slab that is missing.

To conclude,
This dynamic model demonstrates that slab roll-back is the physical driver of surface motion in the Aegean, a fact which was previously only derived from kinematic observations.

References:
Fraters, Menno, Cedric Thieulot, Arie Van Den Berg, and Wim Spakman. 2019. "The Geodynamic World Builder: A Solution for Complex Initial Conditions in Numerical Modeling." Solid Earth 10 (5): 1785–1807.
Amaru, Maisha. 2007. "Global Travel Time Tomography with 3-D Reference Models" Utrecht: Faculteit Geowetenschappen Univ. Utrecht.
Bangerth, Wolfgang, Juliane Dannberg, Menno Fraters, Rene Gassmoeller, Anne Glerum, Timo Heister, Robert Myhill, and John Naliboff. 2022. ASPECT v2.4.0 (version v2.4.0). Zenodo. https://doi.org/10.5281/zenodo.6903424.