Decoupling the crustal and mantle gravity signature at subduction zones with satellite gravity gradients: case study Sumatra

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Project website: 3D Earth

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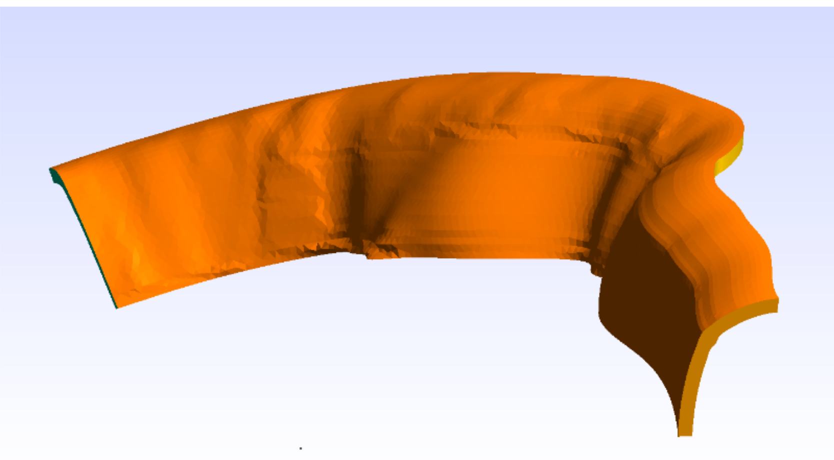
The GOCE satellite mission of the European Space Agency has delivered an unprecedented view of the gravity field of the Earth. In this data set, the strongest gravity gradient signals are observed at subduction zones in the form of a dipole. Despite numerous studies on subduction zones, it is still unclear what is causing this strong signal. Is the source of the observed dipole situated in the crust, mantle, or a combination of these?

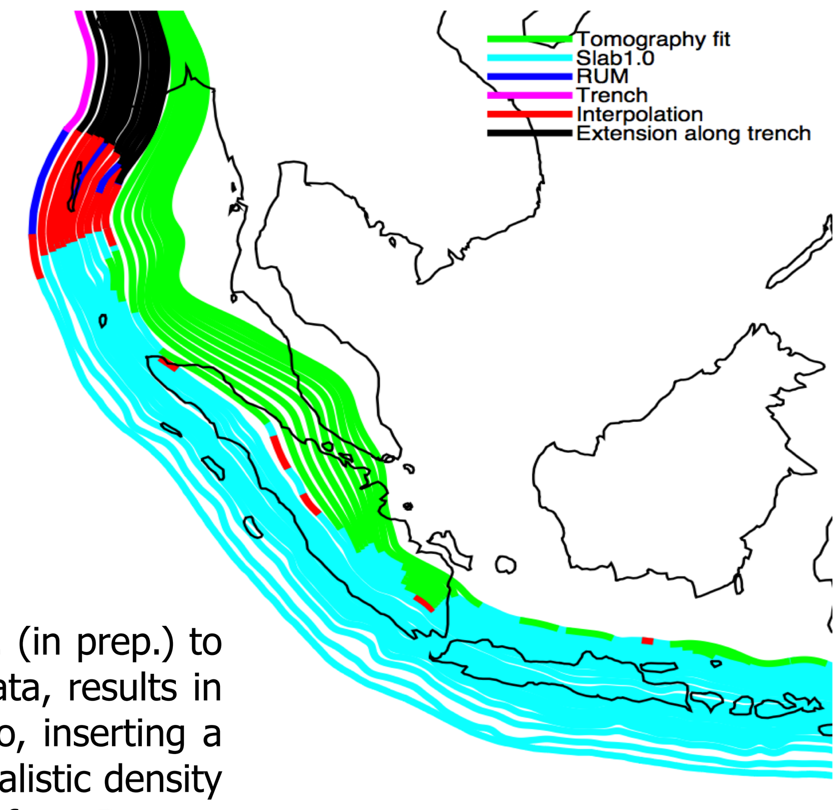
We have constructed a 3D geometry of the Sumatra slab using the global SLAB1.0 model. This geometry is substituted in a global upper mantle model WINTERC5.2, a product of the ESA Support to Science Element: 3DEarth. The density in the subducting crust, mantle, or a combination of both is fitted to the gravity gradients at satellite height. Lateral varying Green's functions are used to compute the gravity gradients from the densities. In the case of a combined crust/mantle model, spectral information of the sensitivity of satellite gradients is used to construct a weighted inversion.

Preliminary results show that crustal mass transport (mostly from the overriding plate) in the direction of the subducting plate is mostly responsible for the negative anomaly observed in between the trench and the volcanic arc. This signal is, however, not visible along the complete subduction zone. Most crustal transport is seen where normal subduction takes place. Oblique subduction shows less crustal transport and more intra-crustal faulting. The satellite gravity gradients show high sensitivity to this particular crustal signature and therefore can be used to analyse subduction zones globally.

1. Introduction

The Sumatra subduction zone is well-known for its mega-earthquake in 2004. To better study the behaviour of the slab, we use satellite gravity and gravity gradients data to improve the density and geometrical structure of the slab.



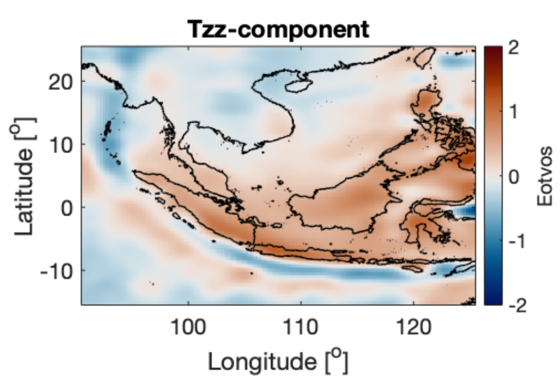


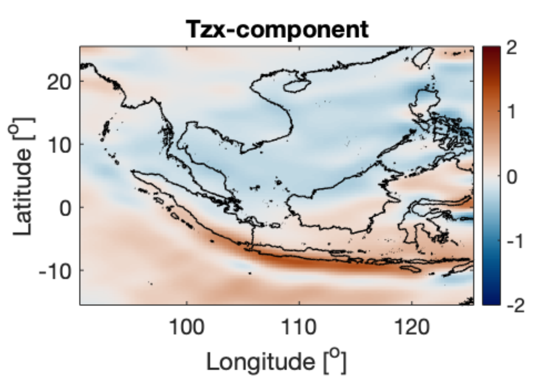
Broerse (2016, pers. comm.)

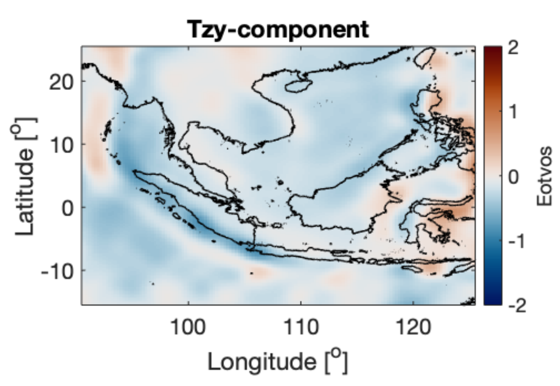
The approach in Root et al. (2017) and Fullea et al. (in prep.) to invert the density in the lithosphere from gravity data, results in unrealistic density structures close to the trench. So, inserting a **geometrical slab** can help in estimating a more realistic density structure. The **top** of the **slab** is obtain by a model from Broerse (pers. comm.), who combined SLAB1.0 with tomographic observations to determine the geometry. The goal of the study is to see if satellite gravity gradient data can help in study the density structure of the downing slab. By using the full gradient components som sort of depth sensitivity is expected.

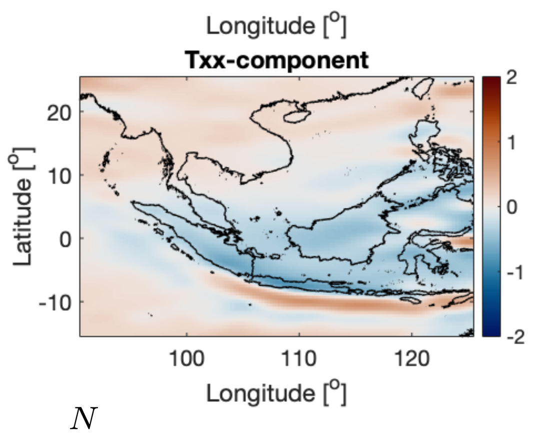
2. Gravity data and inversion

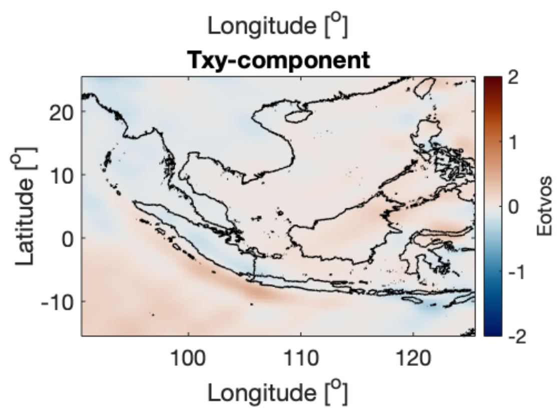
The gravity field model XGM2016 are used in this study. We calculate the full gradient tensor components from the spherical harmonic coefficients (SHC: 2-359 at 225km with C_{20} removed).

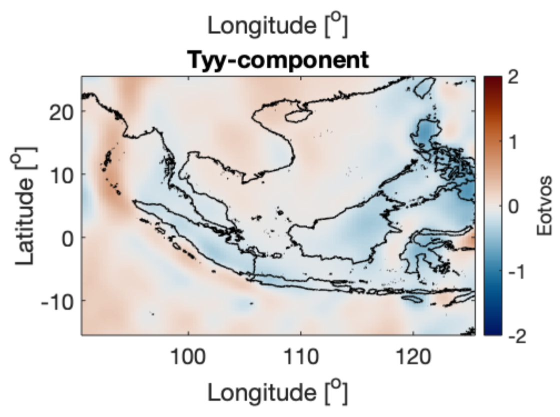












The inversion starts with assuming that the gravitational potential can be modelled as point masses.

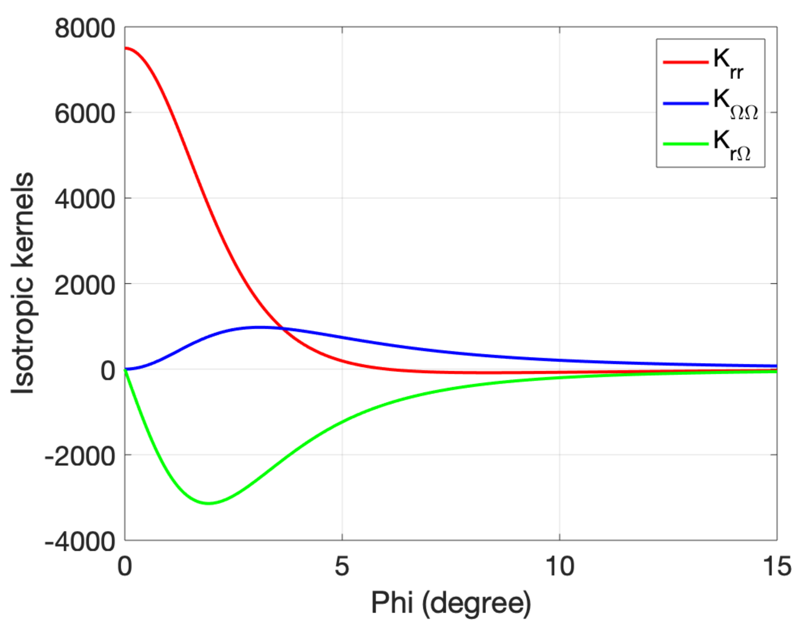
$$\Gamma(\bar{r}) = \kappa \int_V \rho(\bar{r}')\mathbf{G}(\bar{r},\bar{r}')dV \approx \sum_{i=0}^{N} \kappa\rho_i \mathbf{G}(t,x)V_i$$

Here, κ is the gravitational constant, density and volume of each point mass is depicted by ρ_i and V_i, and the these are multiplied by the Green's functions of different gradient component assemblies constructed by Martinec (2015). The Green's functions can be found by the following relationship.

$$\mathbf{G} = gradgrad\frac{1}{L} = \frac{1}{r^3}\Big[K_{rr}(t,x)\mathbf{e}_r r + 2K_{r\Omega}(t,x)(\cos\alpha\mathbf{e}_{r\theta} - \sin\alpha\mathbf{e}_{r\phi})$$

$$K_{\Omega\Omega}(t,x)(\cos 2\alpha(\mathbf{e}_{\theta\theta} - \mathbf{e}_{\phi\phi}) - 2\sin 2\alpha\mathbf{e}_{\theta\phi})$$

$$-\frac{1}{2}K_{rr}(t,x)(\mathbf{e}_{\theta\theta} + \mathbf{e}_{\phi\phi})\Big]$$



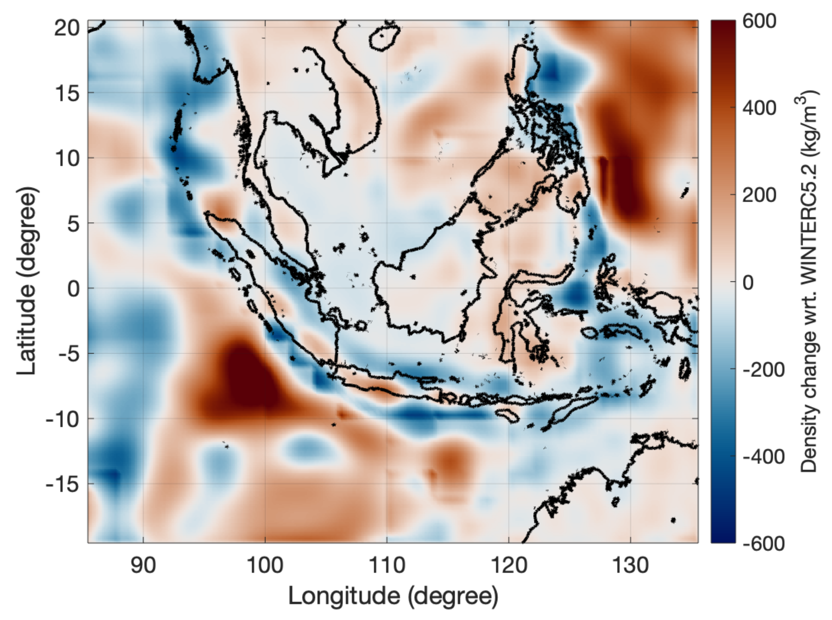
The kernel functions are show in red (K_{rr}), blue ($K_{\Omega\Omega}$), and green ($K_{r\Omega}$). These kernel functions are plotted for observations done at 225 km height and for mass elements at 200 km depth, where we expect the average mass of the subducting slab is situated. Similar kernels were computed for crustal structures and lithospheric mantle structures.

The kernels are computed for average distances, but because the volumes are 3D, some iteration is needed to reduce the residual

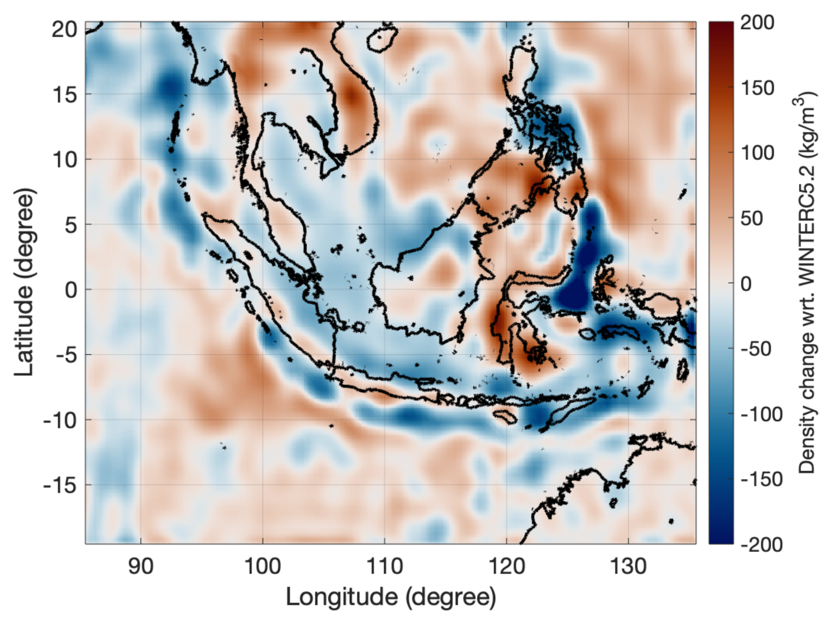
3. Results

We have inverted the gravity gradient tensor for averaged density changes with respect to the WINTERC5.2 model for three different case: (1) crustal structure, (2) mantle structure, and (3) a 2-layer model (crust + mantle).

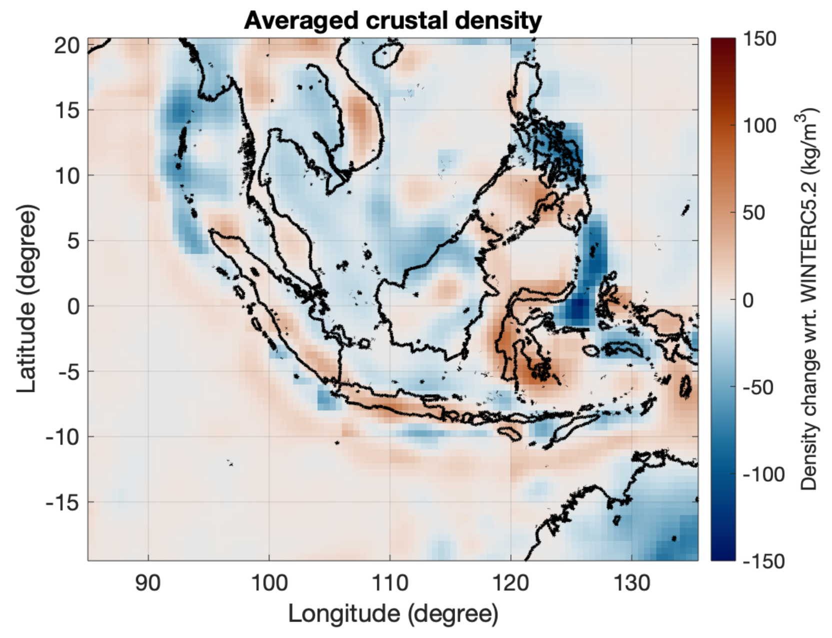
(1) crustal inversion

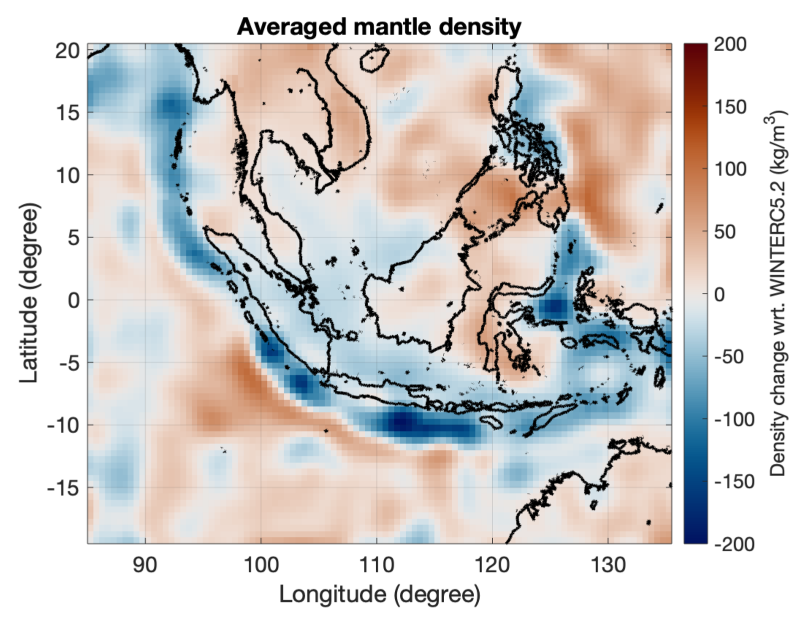


(2) mantle inversion



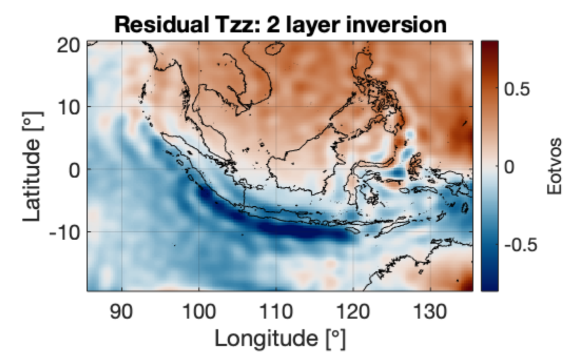
(3) 2 layer inversion

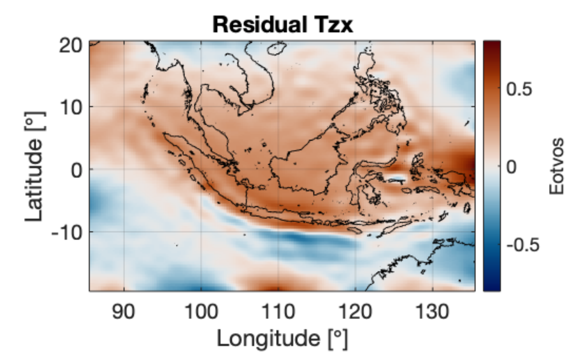


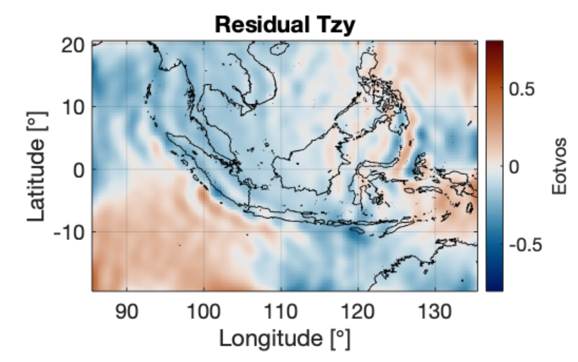


4. Discussion

The inversion setup is constructed, capable to invert for the full gradient tensor for a model with multiple geological structures. However, the gravity gradient residual shows several unresolved issues.

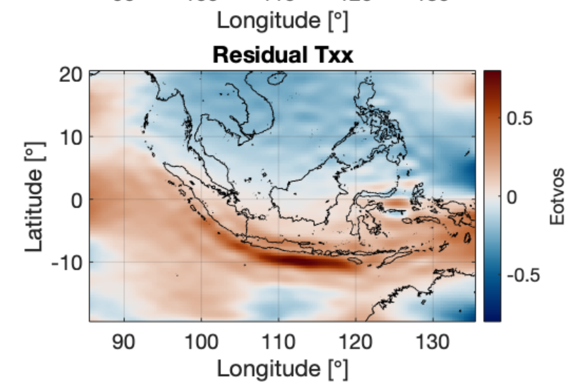


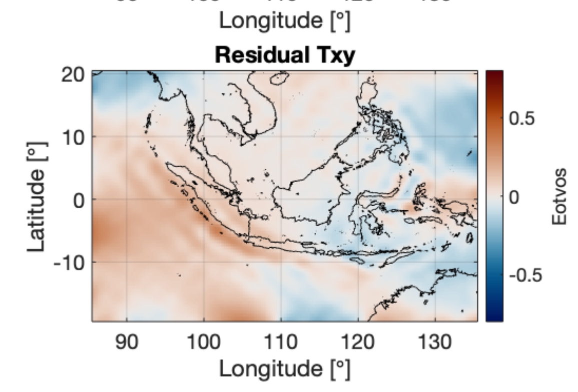


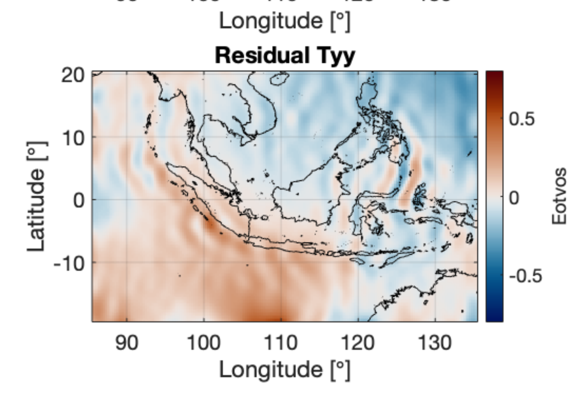


Unresolved (for now) issues:

1. Strong residual in model where slab is at large depths
2. Long-wavelength residual in all gradient components







First, the slab related residual is expected to be resolved when a 3-layer inversion is initiated. The sub-mantle slab structure will be inverted separately with different sensitivity kernels.

Second, the long-wavelength residual can be related to the large sensitivity of gravity gradients at satellite level. A global inversion of the model could mitigate this and resolve for the long-wavelength residual now observed.

5. Future work

- We have constructed a forward model for the Sumatra subduction zone, combining model sand data: SLAB1.0, CRUST1.0, oceanic sediments, tomographic interpretation and satellite gravity gradients.
- Set-up a full gradient inversion for multiple geological layers. Some Tikonov regularisation is needed to increase the stability (Picard stability condition) for certain components. Boundary effect mitigation works partially, long-wavelength residual is still present (possible due to the sensitivity of the gradients at satellite height).
- Future work: 3-layer inversion, where we can separate crustal, mantle, and sub-mantle slab structures.

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