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One-sided subduction in self-consistent models of global mantle convection: the importance of a free surface and a weak crustal layer

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Abstract

Previous dynamical models of global mantle convection indicated that a visco-plastic rheology is successful in generating plate tectonics-like behaviour self-consistently [1][2][3][4]. Yet, these models fail to create Earth-like plate tectonics: so far in all published models subduction is two-sided and more or less symmetric, whereas terrestrial subduction is one-sided and characterized by a distinctive asymmetry.

One simplification used in previous models is that of a free-slip upper boundary, in which the shear stress is zero but the vertical position of the boundary is fixed. In contrast, subduction zones display some of the largest variations in surface topography on Earth. For the case of a slab that is initially placed at the surface and allowed to freely subduct, [5] showed that it is necessary to include a proper free surface in numerical models in order to reproduce laboratory results. According to their benchmark study, mimicking a free surface by a low viscosity, zero density layer on top of the crust is an adequate approach. For this reason, we have implemented such a "sticky air layer" in our global numerical model.

We here study the effect of a free surface on the mode of subduction in 2D and 3D global, fully dynamic mantle convection models with self-consistent plate tectonics. For this we use the finite volume multigrid code StagYY [6], with strongly temperature-dependent viscosity, ductile and/or brittle plastic yielding, and non-diffusive tracers tracking compositional variations (the 'air' layer in this case).

We observe that indeed, a free surface leads to single-sided subduction, whereas identical models with a free slip upper boundary develop double-sided subduction (Figure 1). A free surface is thus an essential ingredient to obtain realistic subduction behaviour in numerical models, probably because it allows the slab to bend in a natural manner.

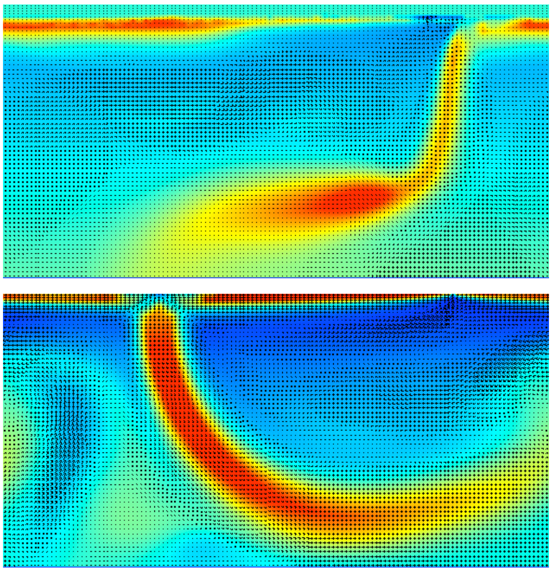

Figure 1. Viscosity fields for convection with a strongly temperature-dependent visco-plastic rheology and (top) a free surface or (bottom) a free-slip surface.

Although the above models appear one-sided from the temperature or viscosity fields, there is strong mechanical coupling between the slab and the mantle wedge that makes them mechanically double-sided. Regional models of subduction [7] indicate that one requirement for stable one-sided subduction is a low strength interface between the plates achieved by the presence of metamorphic fluids in the subduction channel. Such a lubrication layer consisting of weak hydrated sediments accommodates stable one-sided subduction by strain localization, while the absence of a weak shear zone leads to

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mechanically two-sided subduction since in this case the plastic strength of the entire plates needs to be sufficiently low to allow for subduction [7]. We test the influence of weak hydrated sediments in global convection by introducing a weak crustal layer. This low-viscosity crust is found to support the formation of subduction zones and stabilize subduction. In cases with a free-slip upper boundary, subduction is still typically double sided, although in some cases the weak crust increases the tendency for asymmetric subduction.

In conclusion, a free surface is the key ingredient to obtain thermally one-sided subduction, while additionally including a weak crust is essential to obtain subduction that is both mechanically and thermally one-sided.

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