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Discussions

Interactive comment on "Using open sidewalls for modelling self-consistent lithosphere subduction dynamics" *by* M. Chertova et al.

M. Chertova et al.

masha@geo.uu.nl

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We thank the two referees T. Gerya and M.I. Billen for their thoughtful comments and suggestions. Our response and changes to our paper are as follows:

Response to T. Gerya:

1) The referee argues that intra-plate stress acting on the lithosphere at the sidewalls are required to model natural plates. We agree and in fact discuss these model settings in more detail in section 3.5. The fully open boundaries with which we start our experiments (sect. 3.1-3.3) are intended as end-member models (as stated in the beginning of section 3) where we focus on using boundary conditions that are as undisturbing as possible to the subduction driven dynamics. However, we favor using open bound-

aries in combination with additional constraints at the sidewalls on the lithosphere, e.g. normal stress conditions, basically allowing for modeling a range of dynamic subduction settings from pure rollback, stationary subduction, to advancing subduction. We discuss this point in the introduction paragraph of section 3 ("Results of numerical modeling") and at the start of section 3.5 ("Constraining the motion of lithosphere plates") and in section 4 ("Discussion and conclusions"; p724 24-28): "Open boundaries can be combined with plate "push" or "pull" conditions, or kinematic conditions on the plates at the sidewalls, to simulate the far-field control of global plate tectonics."

The reviewer also points out that lower aspect ratio models will result in a higher magnitude of the velocity inside the model and higher trench retreat rates. Indeed we noticed this effect that is not strictly limited to models with open boundaries as is explained in section 3.4. In Appendix A we have presented a scaling method that aims to account for the tractions of the part of the plate that is not part of the model domain but is considered part of the same subducting lithospheric plate. In specific applications this part could be estimated from plate tectonic models. This scaling method allows for arbitrary aspect ratio domains for subduction modelling.

We added text to section 3.4 (p. 721, line 5): The scaling procedure compensates the overall velocity field for the effect of bottom-side traction of that part of the plate located outside the model domain, which allows to account for bottom-side traction of the whole plate from the spreading ridge to the trench. In combination with intra-plate stress imposed at the sidewalls it facilitates modelling of a natural subduction process with correct plate length and ridge push within a smaller model domain.

The referee suggests constructing an OROR model for better comparison with model CRCR. Creating an OROR model is not obvious. A ridge at the corner of our model domain (as in CRCR) conflicts with the local assumption of lateral boundary flow. For a dynamically self-consistent ridge evolution we would prefer to initially place the ridge away from the boundary and e.g. apply a normal stress at the boundary to suppress inflow of lithosphere. In this way the ridge can operate (or not). For a good comparison with closed boundary models this would require a similar model set up using free slip sidewalls. Although we do see the merits of such much more detailed experiments, we do not think this will change our main conclusion: We advocate using open boundaries in combination with intra-plate stress conditions on the sidewalls (e.g. avoid artificial return flows forced by closed boundaries) in subduction modelling when using a regional model-box in 2-D or 3-D.

Additional references suggested by the referee: Our work is focused on the investigation of the subduction evolution, particularly, slab rollback, stationary subduction and advancing subduction in regional model boxes. From the suggested references, which invoke the implementation of the free slip boundaries and open bottom boundary, we selected the most pertinent (Duretz et al.2011. Duretz et al. 2012 and Ueda et al. 2012) and refer to them where we discuss previous work on the subduction modelling process (section 1, introduction).

Response to M.I. Billen:

1) We ran models with a fixed depth of 1000 km and focused on sidewall conditions and aspect ratio. We do not expect that running deeper models would basically change our conclusions on the use of open versus closed boundaries. In models with intra-plate stress conditions, simulating more stationary subduction evolution, a slab could penetrate deeper in the lower mantle and a larger model depth would be needed to simulate a longer subduction history. In that case we still expect that the open boundaries would allow for a smaller lateral extent of the domain (e.g. $\sim$2000-3000 km) compared to closed boundaries even when the model depth extends to the CMB.

To discuss these points we added (Discussion part, p.724, line 15): While the width of the model domain was varied we kept the depth of the model constant. In our rollback models, the slab is draping on the “660”-boundary as a result of increasing viscosity in combination with a decrease in negative buoyancy resulting from the 660 km phase transition. In this model scenario, the effect of the bottom boundary will not be very

strong. For the investigation of slab behavior in the lower mantle a model with much larger depth is required. But, for such models we still expect that the open boundaries would allow using a smaller lateral extent of the domain (2000-3000km) in comparison to free-slip models to reduce the effect of the sidewall boundary conditions.

2) Indeed so far we modelled open boundaries with lateral flow only, as opposed to the more usual free slip boundaries, which do not allow for any exchange of material with the surrounding mantle. We agree with the statement of the reviewer that any, open or closed, boundary condition poses constraints on the flow. The advantage we experience from using open boundaries is that we can deal with lateral in- and outflow of the lithosphere in a more general way (in 2-D and current 3-D models), e.g. by prescribing intraplate stress, or even just by imposing kinematic constraints on the side walls, while lateral flow below the lithosphere can fully develop, in the sense that it is not influenced by (possibly remote) impermeable vertical boundaries. The independence of model aspect ratio allows us to focus our computational resources on smaller model domains.

We appreciate the referee’s words of caution. In the discussion section we added: Open boundary flow, if any, is restricted to be perpendicular to the sidewall. This condition, as any type of boundary condition, poses constraints on the internal flow. but the advantage we experience from using open boundaries is that we can deal with lateral in- and outflow of the lithosphere in a more general way (in 2-D and current 3-D models), e.g. by prescribing intra-plate stress, or even just by imposing kinematic constraints on the side walls, while lateral flow below the lithosphere can fully develop, in the sense that it is not influenced by (possibly remote) impermeable vertical boundaries.

We added the following to our shortened abstract (see below) to highlight our findings: Open boundaries allow for subduction to evolve freely and avoid the adverse effects (e.g. forced return flows) of free-slip boundaries. We conclude that open boundaries in combination with intra-plate stress conditions are to be preferred for modelling subduction evolution (rollback, stationary or advancing) using regional model domains.

3) The referee notices similarity between slab shapes in different experiments and asks if its local buoyancy/strength balance does not mainly control the deformation of the slab. Particularly, the question was whether the slab shape for models CO3 and CCR3 would be similar if they were allowed to run to similar stage. These two models were run for 30 Ma and the shape of the slab proved different. Indeed, the local balance between slab buoyancy and strength determines to a large extent the local subduction behavior. However in all experiments we observe different slab evolution. Flow patterns in the vicinity of the slab are different and affect the local viscosity (sometimes by a an order of magnitude). Free lateral flow of the asthenosphere versus return flows induced by closed boundaries has an important effect on the details of slab evolution affecting slab dip, stress, contact stress with the overriding plate, and details in slab morphology. This is discussed in more detail in section 3.1.

Technical comments:

1) P should indeed be Pin and we will add the description of j to the text.

2) If we will apply different velocity scaling to the different models in one figure this may be difficult to perceive for many readers. Not everybody may pay attention to different scaling in the same figure at the risk of missing the huge velocity differences. We prefer to submit a high-resolution figure enabling visualization of small velocity vectors.

3) We corrected this and long paragraphs were split up.

4) The abstract was shortened to:

Subduction modelling in regional model domains, in 2-D or 3-D, is commonly performed using closed (impermeable) vertical boundaries. Here we investigate the merits of using open boundaries for 2-D modelling of lithosphere subduction. Our experiments are focused on using open and closed (free-slip) sidewalls while comparing results for two model aspect ratios of 3:1 and 6:1. Slab buoyancy driven subduction with open bound-

aries and free plates immediately develops into strong rollback with high trench retreat velocities and predominantly laminar asthenospheric flow. In contrast, free-slip sidewalls prove highly restrictive on subduction rollback evolution, unless the lithosphere plates are allowed to move away from the sidewalls. This initiates return flows pushing both plates toward the subduction zone speeding up subduction. Increasing the aspect ratio to 6:1 does not change the overall flow pattern when using open sidewalls but only the flow magnitude. In contrast, for free-slip boundaries, the slab evolution does change with respect to the 3:1 aspect ratio model and slab evolution not resemble the evolution obtained with open boundaries using 6:1 aspect ratio. For models with open side boundaries we could develop a flow-speed scaling based on energy-dissipation arguments to convert between flow fields of different model aspect ratios. We have also investigated incorporating the effect of far-field generated lithosphere stress in our open boundary models. By applying realistic normal stress conditions to the strong part of the overriding plate at the sidewalls, we can transfer “intra-plate” stress to influence subduction dynamics varying from slab roll-back, stationary subduction, to advancing subduction. The relative independence of the flow field on model aspect ratio allows for a smaller modelling domain. Open boundaries allow for subduction to evolve freely and avoid the adverse effects (e.g. forced return flows) of free-slip boundaries. We conclude that open boundaries in combination with intra-plate stress conditions are to be preferred for modelling subduction evolution (rollback, stationary or advancing) using regional model domains.

Interactive comment on Solid Earth Discuss., 4, 707, 2012.