Heat Flow Partitioning Between Continents and Oceans - from 2D to 3D

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Abstract

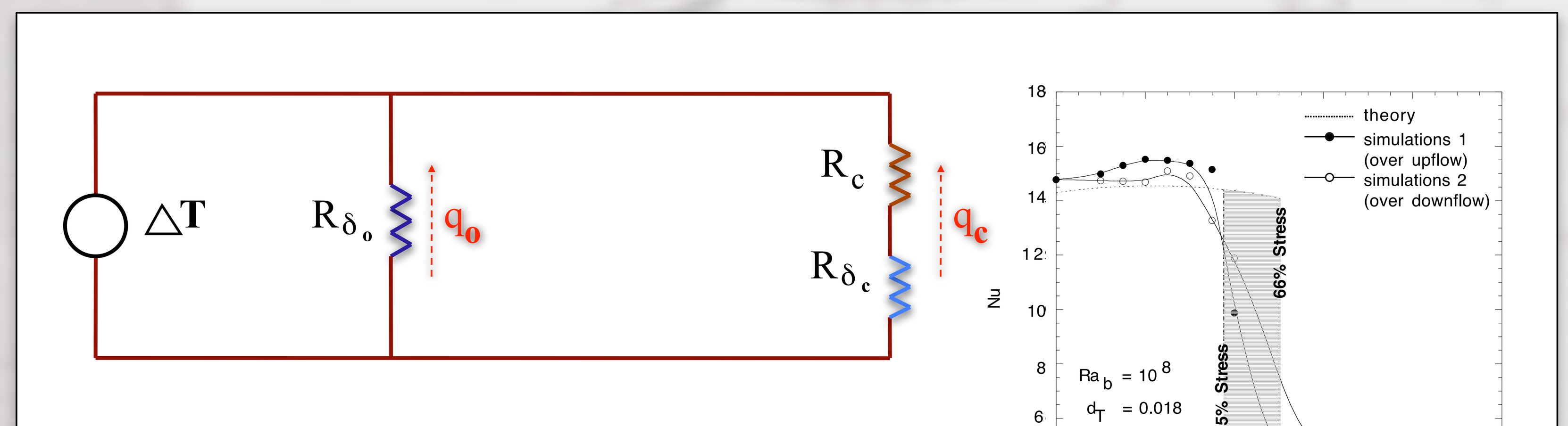
Scalings derived from thermal network theory explain how the presence of continents can influence the Earth's overall heat loss. Intuitively, it may seem that increasing the proportion of a planet's surface area covered by continents would decrease the efficiency of heat transfer given that continents do not participate in convective overturn. However, this ignores the potential feedback between the insulating effect of continents and the temperature-dependent viscosity of the mantle (Lenardic et al, 2005, Cooper et al, 2007). When this feedback is considered, a clear regime exists in which the partial stagnation and insulation of the surface by buoyant continental crust can lead to an increase in heat flow compared to the uninsulated case.

The numerical results used to verify the scalings have mostly been conducted in two dimensions in order to cover a very wide range of Rayleigh number, fraction of continental coverage, and continental thickness. However as more recent results show that the configuration of the crust also plays a role in determining the heat flow partitioning and global heat flow (We hope you saw Lenardic et al, "Continents, Super-Continents, Mantle Thermal Mixing, and Mantle Thermal Isolation" — U43B-04), we have begun to repeat this exhaustive and exhausting 2D study in 3D.

Cooper, C.M., A. Lenardic, and L.-N. Moresi "Effects of continental insulation and the partioning of heat producing elements on the Earth's heat loss." Geophys. Res. Lett., 33 ,10.1029, 2006.

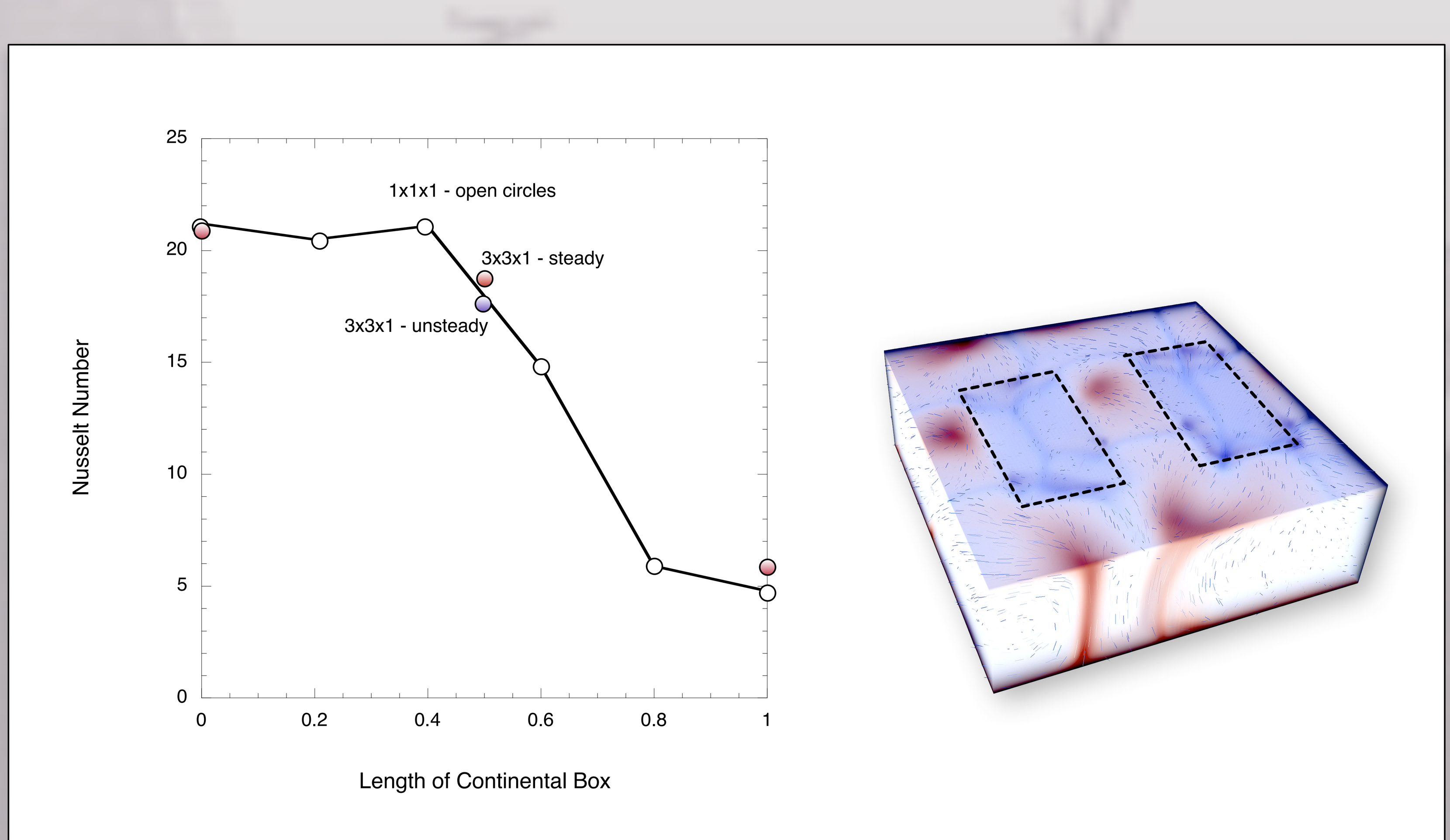
Lenardic, A., L.-N. Moresi, A.M. Jellinek, and M. Manga "Continental insulation, mantle cooling, and the surface area of oceans and continents." Earth Planet. Sci. Lett., 234 ,317-333, 2005.

From 2D to 3D

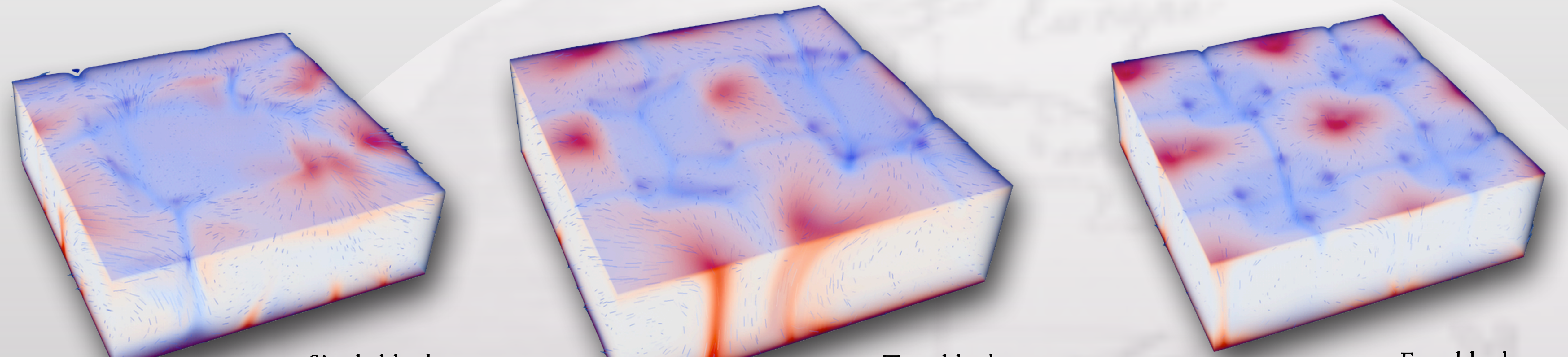


A. Lenardic, L. Moresi, A. M. Jellinek, and M. Manga. Continental insulation, mantle cooling, and the surface area of oceans and continents. *Earth Planet. Sci. Lett.*, 234:317–333, 2005.

3D results are in agreement with the scalings and numerical results obtained from 2D computations (shown above). The same transition from an un-insulated mode to a mode dominated by the stabilisation of the boundary layer occurs when the surface area covered by continents exceeds 20-40%. The nature of this transition is influenced by the planform of convection and whether the system achieves a natural steady state or remains time-dependent. This, in turn, is a function of the distribution of the continents upon the surface, and whether they form a coherent block.



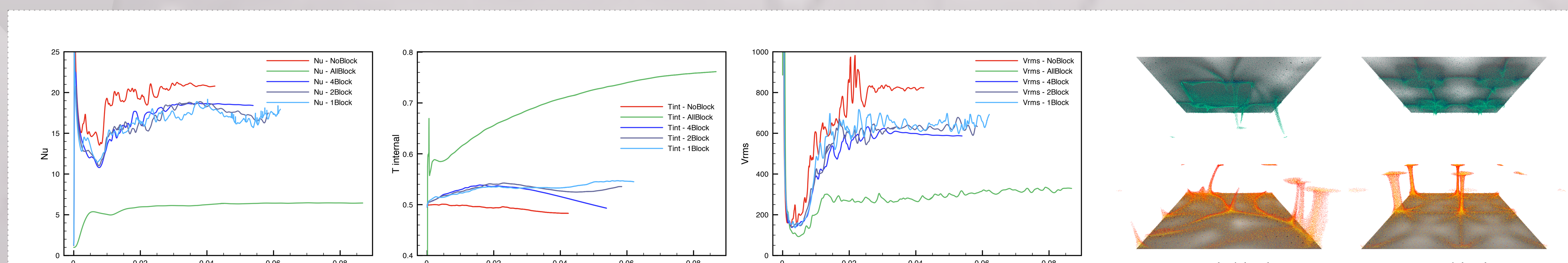
Never Mind the Blocks Here's the Planforms



Single block Two blocks Four blocks

In these models, all isoviscous with Ra=10^6 the total volume/area of the blocks is the same, covering 25% of the surface of the domain, but the configuration varies. There is a competition between the lateral size of the blocks and the natural horizontal scale of the convection patter which influences the stability of the models over time., and the efficiency of heat transport. In the case with 4 smaller blocks, a stable planform exists with upwellings permanently avoiding the blocks; in the 1 and 2 block cases, the imposed scale is larger than the preferred scale of the convection pattern and upwellings are unable to avoid the blocks altogether. The effects are most obvious in plots below which show the time series for Nusselt number, internal temperature and rms velocity.

The images of the boundary layers at a dimensionless time t'=0.04 also show very clearly how the preferred behaviour of downwellings to localise at the edge of regions with a mechanically stabilised boundary layer is permanently stable in the case with 4 smaller blocks, but time-varying in the large, single block case.



Single block Four blocks

Numerical Model

The models are setup using the Underworld code [Moresi et al, 2007] to solve a linear-viscous Stokes flow convection system in an $N\,x\,N\,x\,M$ Cartesian domain. The method uses a Lagrangian particle swarm to carry material data. The domain has periodic side boundaries, and no-slip velocity boundary conditions are applied to the interior points in the continental blocks so that the mantle drifts relative to the coordinate system while the continents remain fixed (simplifying analysis).

In this case the swarm carries only a compositional variable used to follow the blocks and to give them a stabilising viscosity contrast of 10000 times that of the interior fluid.

A robust PETSc-based geometrical multigrid solver used as a preconditioner for a Schur-complement formulation of the incompressible Stokes flow problem. Over the years this has proven to be one of the most robust approaches to this particular set of equations when dealing with Finite Elements. It is effective for strong material property variations which arise from strongly non-linear rheology and material interfaces.

An augmented Lagrangian (cf penalty method) formulation is used to speed the convergence of the Schur-complement system; this significantly reduces the number of iterations but each becomes more expensive to perform. Fine tuning of the MG is imperative !

L. Moresi, S. Quenette, V. Lemiale, C. Mériaux, W. Appelbe, and Mühlhaus. Computational approaches to studying non-linear dynamics of the crust and mantle. *Phys. Earth Planet. Inter.*, 163:69–82, 2007.