Adaptive mantle convection simulations at the global scale

Personnel: Stephan Kramer (6 months)

Background and numerical challenges

Mantle convection is the process of heat convection through the very slow, creeping motion of material in Earth's mantle which lies between the core and crust. It is thought to play a key role in plate tectonics. Therefore, the study of mantle convection processes is vital for a better understanding of various near-surface geological phenomena, such as mountain formation, volcanism and earthquakes. Numerical models play a fundamental role, both in idealised studies into the fundamental physical processes, and for realistic large-scale models of the mantle over geological time-scales.

Some of the challenges in the numerical modelling of the mantle are: 1) The complex, non-linear rheology of the mantle, with viscosities that have orders of magnitude jumps, leads to tightly coupled and ill-conditioned systems of equations. 2) A large range of length scales with localised features in e.g. boundary layers near the surface, subduction zones and mantle plumes that affect global scale flow patterns. The latter has led to the use of Adaptive Mesh Refinement (AMR) techniques in several geodynamical models [3, 1, 10] that allow the focusing of mesh resolution in regions of dynamical importance, thus reducing the overall computational expense.

The open-source finite element modelling framework Fluidity [13], developed in the Applied Modelling and Computation Group, Imperial College London, and under the PRISM project, has the unique capability of anisotropic mesh refinement. In contrast with standard hierarchical AMR techniques, this allows it to vary mesh resolution independently in different directions, which may lead to a further reduction in required mesh resolution in the presence of anisotropic flow features. This makes the technique very suitable for mantle dynamics [2]. In boundary layers and mantle plumes, it allows for a higher resolution in the direction of strong gradients perpendicular to the flow, without having to simultaneously increase the resolution in the flow direction. This not only leads to a large saving in required degrees of freedom, but also leads to less severe time-step restrictions due to a reduced Courant criterion.

Fluidity is a flexible and highly configurable model and because it has been applied to a range of very different application areas, offers some functionality that is not typically found in other geodynamical models. As an example, the free surface approach developed for the ocean modelling capability of Fluidity, was the inspiration for the novel implicit time-integration technique developed for geodynamical models in Kramer, Wilson, and Davies [9].

In Davies, Wilson, and Kramer [2] the model was introduced to the geodynamical modelling community, and a validation of the code as a geodynamical model was presented through a number of benchmarks. Further validation is provided through the community benchmark in Tosi et al. [14]. The model has already been used in a number of scientific publications, studying the physics of subduction zones [11, 5, 4, 12, 6] and mantle plumes [7, 8]. It is used by a growing number of geodynamicists at a.o. Imperial College London, the Australian National University (ANU), Cardiff University, and Universite de Montpellier.

This work is done as a collaborative effort between Rhodri Davies at ANU, Stephan Kramer at Imperial College, and Cian Wilson at the Carnegie Institution of Science.

Project objectives and work plan

Further work is required to validate the model to be suitable for global simulations on the sphere, and analyse and optimise the scaling behaviour of the model on the high performance computational platforms required for such simulations. Additionally, the dynamic mesh adaptivity process needs adjusting to correctly handle the spherical geometry of the Earth. These activities will be performed during this project, with the motivation and target of global scale mantle convection simulations, but performed within Fluidity in a generic manner which will be applicable to other science and engineering areas.

Retention and development of key staff

This funding will allow Stephan Kramer to further develop an important, independent, international collaboration, leading to high profile science and publications, as well as an increased user base for the key PRISM code base Fluidity.

Alignment with PRISM and supporting long-term research

Firstly, as per one of the supported activities for researchers under PRISM, three months of this period will be spent on secondment to the Australian National University (ANU). This will allow Stephan to immerse himself in a different research environment, developing his profile and collaborations. Secondly, the ability to handle more complex rheologies in Fluidity will be applicable to other problems in both the Earth Sciences (e.g. granular material) as well as industrial (e.g. non-Newtonian) flows. Thirdly, the knowledge gained and methods developed in the use of mesh adaptivity to capture features such as boundary layers and convective plumes while operating within spherical-like geometries in Cartesian space, will be of significant value in the application of similar techniques to large-scale ocean and atmospheric flows. This will include ongoing and planned applications of Fluidity, as well as the further development and application of the new Thetis model developed under PRISM in collaboration between ESE, Maths and Computing.

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