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Adaptive mesh refinement and adjoint methods in geophysics simulations

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It is an ongoing challenge to increase the resolution that can be achieved by numerical geophysics simulations. This applies to considering sub-kilometer mesh spacings in global-scale mantle convection simulations as well as to using frequencies up to 1 Hz in seismic wave propagation simulations. One central issue is the numerical cost, since for three-dimensional space discretizations, possibly combined with time stepping schemes, a doubling of resolution can lead to an increase in storage requirements and run time by factors between 8 and 16. A related challenge lies in the fact that an increase in resolution also increases the dimensionality of the model space that is needed to fully parametrize the physical properties of the simulated object (a.k.a. earth).

Systems that exhibit a multiscale structure in space are candidates for employing adaptive mesh refinement, which varies the resolution locally. An example that we found well suited is the mantle, where plate boundaries and fault zones require a resolution on the km scale, while deeper area can be treated with 50 or 100 km mesh spacings. This approach effectively reduces the number of computational variables by several orders of magnitude. While in this case it is possible to derive the local adaptation pattern from known physical parameters, it is often unclear what are the most suitable criteria for adaptation. We will present the goal-oriented error estimation procedure, where such criteria are derived from an objective functional that represents the observables to be computed most accurately. Even though this approach is well studied, it is rarely used in the geophysics community.

A related strategy to make finer resolution manageable is to design methods that automate the inference of model parameters. Tweaking more than a handful of numbers and judging the quality of the simulation by adhoc comparisons to known facts and observations is a tedious task and fundamentally limited by the turnaround times required by human intervention and analysis. Specifying an objective functional that quantifies the misfit between the simulation outcome and known constraints and then minimizing it through numerical optimization can serve as an automated technique for parameter identification. As suggested by the similarity in formulation, the numerical algorithm is closely related to the one used for goal-oriented error estimation. One common point is that the so-called adjoint equation needs to be solved numerically. We will outline the derivation and implementation of these methods and discuss some of their pros and cons, supported by numerical results.