Challenges Facing Adaptive Mesh Modelling of the Atmosphere and Ocean

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Data Box

TITLE: Newton Institute Scoping Meeting on
Multi-scale Modelling of the Atmosphere and Ocean
WHAT: Leading scientists in adaptive mesh modeling met to identify outstanding issues in multi-scale modeling of the ocean and atmosphere and indicate those that should be addressed during a proposed six month Newton Institute program.
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NOTE: Presentations from the meeting can be downloaded from
http://www.met.rdg.ac.uk/~sws02hs/Newton

We are increasingly feeling the impacts of global warming, which is hastening our need to learn as much as we can about the changes facing the inhabitants of Earth. But climate models cannot yet resolve many small scale processes which control local impacts. For example tropical cyclones, convective clouds, and precipitation in the atmosphere or the continental shelves, marginal sea overflows, and boundary currents in the oceans occur at small scales and interact with the global dynamics. These processes could only be resolved interacting with the global dynamics by using adaptive mesh methods. However, the challenges associated with their efficient application are high. The initial target applications above will enable theoretical development, validation, and parallel performance benchmarking. Adaptive meshes are already beneficial for tsunami prediction and static nested refinement is already beneficial for regional weather forecasts and tropical cyclone prediction. Other processes that will likely benefit from adaptive mesh modelling include storm surges, coastal erosion, pollution dispersion and topographic flows. The simulation of ice sheet dynamics could also benefit from local refinement of relatively narrow ice streams, leading to improved reliability in the prediction of sea level rise. Earth mantle convection, which uses a similar set of equations as ice sheet dynamics, has also already benefited from adaptive mesh methods.

Adaptive meshes have been proposed for use in geophysical models for a few decades but so far have not gained widespread popularity. A number of outstanding issues were identified during this meeting, which are summarized here. Operational use of adaptive meshes is still considered to be some time away but solutions to these issues may bring it closer.

Mesh Refinement Criteria

The atmosphere and ocean possess features which occur on a massive range of spatial scales, only the coarsest of which are typically explicitly resolved. For example, deep convection, clouds and ocean eddies are often at, or below, the spatial scale of the computational mesh and hence their effects on the resolved scales must be parameterised. As the mesh is refined more and more of these features will begin to be resolved but today's computers are orders of magnitude too small to allow convergence of this process. This means that mesh refinement criteria for adaptive meshes based on empirical or mathematically rigorous error indicators will recursively lead to more and more refinement. Additionally, the nonlinear nature of Earth's climate system often leads to an extreme sensitivity of the simulation at one location to processes occurring elsewhere, which may be thousands of kilometers apart. An example is the sensitivity of precipitation in the Southwest United States to the phase and amplitude of ENSO. Adjoint-based error indicators may prove beneficial for identifying regions to refine based on non-local goals and various research groups are already researching this field.

It is unclear how different mesh adaptation strategies (changing the number of mesh points, moving mesh points, and changing the order of the approximation) should best be combined for geophysical applications. Mesh movement has advantages for tracking stratified layers and is similar to the coordinate transforms that have traditionally been used. Further engagement between meteorologists and mathematicians should prove fruitful in combining mesh adaptation strategies as mathematicians have already combined them for applications such as stress analysis in solids by using higher order accuracy where the solution is smooth and more mesh points where the solution is poorly resolved.

Wave Propagation and Filters

With models which use spatially varying resolution, schemes must be developed that allow small-scale features to propagate cleanly out of regions in which they are resolved into regions in which they are partially resolved without spurious wave reflection, refraction, or scattering. This may be possible through the development of appropriate scale selective, anisotropic filters that operate over a transition zone adjacent to a coarser region of mesh. Many ideas from the mathematical community, such as implicit filters, non-dissipative closures, and limiters via Godunov or Riemann methods are currently being considered to solve this problem.

Sub-grid scale parameterizations

Many features of the Earth system, such as cloud microphysics, will never be resolved within global models. Parameterizations for these processes will probably not need to change for use with adaptive meshes. However, buoyant convection in the atmosphere occurs over a range of length scales that are often close to the mesh scale. Current parameterizations for atmospheric convection assume that the mesh is much coarser than the buoyant plumes − an assumption that is good only for mesh sizes above about 50 km. However, resolution used in weather and climate models is already at or well below 50 km, and with ever more powerful computers we know that the model resolutions will continue to get finer. Most atmospheric models can be run stably without a convection scheme at resolutions below 1 or 2 km. But the simulated updrafts and downdrafts are not realistic until resolution reaches about 100 or 200 m. This resolution isn't feasible within a global model, even with adaptive resolution. A resolution dependent convection parameterization scheme is therefore needed such as those developed for mesoscale models.

Data assimilation

A number of groups have started working on how to perform data assimilation to initialize a model on a multi-resolution mesh. It is frequently the case that building the data assimilation system is more difficult than building the forward model. In addition, if an adjoint problem is being solved then this system has its own numerical requirements which could mean using a mesh for the adjoint calculation which is distinct from the forward mesh. This could yield advantages in terms of the efficiency of the overall data assimilation process, but at the expense of an inconsistent and harder to produce adjoint code. This is clearly an emerging field of research which was considered beyond the scope of this meeting.

Preservation of balance, local conservation, and monotonicity under adaptation

While fixed meshes can maintain discrete analogues of balance, conservation, and monotonicity, mapping solutions to a newly adapted mesh may alter these analogs. The consequence of not preserving balance is that spurious waves are generated upon adaptation, which can contaminate the solution and may lead to runaway adaptation. The consequence of not conserving mass is that, after many adaptations, sparse species can almost disappear. And the consequence of not preserving monotonicity is that new unphysical peaks and troughs in solution variables could be created; especially problematic are unphysical negative concentrations.

To preserve balance it was suggested that balanced variables such as various functions of potential vorticity should be mapped instead of primitive variables. This would be more expensive as primitive variables (velocity, pressure, density, etc.) must be recovered by inverting elliptic equations. However this may well be inevitable since balance is a non-local phenomenon; for example velocity is geostrophically balanced with pressure gradients defined based on pressure differences over long distances. Conservation is relatively straightforward when mapping fields between block structured meshes as the smaller cells fit exactly into the larger cells. But, when mapping between unstructured meshes, all overlapping volumes between old and new meshes must be calculated to ensure that quantities are transferred without loss. Works is underway on each of these three constraints under adaptation separately and further work will be needed to combine them.

Equation Sets

At coarse resolution, some terms in the full Navier-Stokes equations are insignificant and can be ignored such as, for strongly stratified flow, the non-hydrostatic effects. As resolution increases, all terms must be included at additional cost. Non-hydrostatic models are now frequently used for high resolution weather forecasts but have not yet been used routinely for large scale ocean modelling. It may be beneficial in a multi-resolution mesh to exploit the efficiency gains of ignoring terms of the equations where the mesh is coarse. The validity of this approach should be assessed with appropriate transitions between flow regimes found, for example ignoring non-hydrostatic terms below a specified Froude number.

Computational efficiency, parallelization and time stepping

Weather and climate forecasts have very tight efficiency constraints; for example the supercomputing time slot for a one day global weather forecast at the UK Met Office is six minutes. Adaptive meshing inevitably comes at some computational cost and it is essential to demonstrate that adaptive methods can be more computationally efficient than current operational models for the same prediction skill.

Since increases in computing power require the efficient use of more and more processors, it is essential that new algorithms are highly scalable. Techniques that optimize parallelization of adaptive meshes have been developed using structured refinement (maintaining the “children” of coarse cells and the “parents” of fine cells) and ordering cells using space filling curves. In contrast, unstructured mesh methods make small local changes to the domain decomposition to ensure a balanced load while minimizing data migration.

Explicit time stepping can be used in conjunction with algorithms that are scalable to hundreds of thousands of processors, but explicit time stepping comes at the expense of very small time steps dictated by the speed of the fastest explicitly resolved waves (usually acoustic). Algebraic multigrid implicit solvers can scale to tens of thousands of processors for mantle convection applications, but it remains unclear whether semi-implicit time stepping for atmosphere and ocean simulations can be scaled to this extent. Semi-implicit time stepping requires global communication, which intrinsically slows parallel performance. But the longer stable time steps that may be taken can make semi-implicit time stepping beneficial. Further comparisons are necessary to prove superior accuracy, efficiency and parallelisability of either explicit or semi-implicit time stepping.

More demanding test cases

Many novel numerical methods perform outstandingly well on simple test cases. However, when diabatic processes are included, results can deteriorate dramatically. More demanding test cases for the atmosphere should directly include the small-scale diabatic affects of moisture, while test cases for the ocean should be three-dimensional and at basin scale.

Conclusion

There is much research needed before adaptive meshes can be used for operation weather and climate forecasts but no issues were identified as show stoppers and the potential advantages are huge. Some of this work could be addressed during a proposed Newton Institute program and all of the work described is ripe for new inovative ideas and research proposals.

Sidebar: Issues for a Newton Institute Program

- Mesh refinement criteria
- Filters between regions with different mesh spacing
- Preservation of balance, local conservation and monotonicity under adaptation
- Identification of appropriate equation sets
- Computational efficiency and parallelisability
- Time stepping
- New test cases