Isaac Newton Institute Programme: Multiscale Numerics for the Atmosphere and Ocean

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FIGURE - I really like the Voronoi mesh and precipitaion figure

Background. For more accurate and efficient simulation of the earth's atmosphere and ocean, for weather and climate prediction, the long-held view that adaptive meshing would be beneficial has not yet fulfilled its promise and recent developments in computer architecture have meant that there is now an urgent need for new algorithms, that are highly efficient for fixed meshes, running on modern, massively parallel computers with low memory bandwidth,

Ever increasing model complexity to answer more and more complex scientific questions demands higher resolution and wider process coverage. This complexity creates a seemingly insatiable appetite for computational resources amongst the weather and climate modelling community and this already significant challenge is elevated to a new level when combined with requirements from operational centres of reliability of compute platforms, models, and the scientific quality of the results. This appetite can probably be sated by the next generation of supercomputers with their overwhelming increase in core counts and use of accelerators. However efficient use of these new machines demands reduced memory access, improved parallel scalability of the code and, in parts, major rewrites of existing codes and formulations.

The overarching aim of this programme was to create the necessary mathematics to enable this rapid development. Research undertaken during this programme, included the detailed numerical analysis of discretisation methods, implicit solution techniques and sparse matrix solvers, design of the next generation Met Office weather and climate forecasting model, mesh adaptivity, new, speculative time-stepping methods and much more. Some of the outcomes are now being adopted by meteorological forecasting centres.

Outcomes and Achievements. *Gung Ho* is a UK-based project to design numerical methods suitable for efficient and accurate weather and climate prediction on the anticipated architectures of exascale supercomputers. It will be at the core of the next Met Office model. During this programme, decisions were taken on the mathematical methods to be used in that next model and an entirely new software framework began to take form that should deliver to the public the full benefits of these new scientific developments.

A recurring theme throughout the INI programme was the need to distinguish between real wave propagation and wave propagation in numerical models. New analysis of continuous and discontinuous finite elements, mixed finite elements and finite volumes, revealed that all discretisations of relevant models admitted spurious computational modes (usually arising as spurious, stationary grid-scale oscillations) which can be controlled by upwinding or filtering. Discontinuous Galerkin (DG) methods suffer least from spurious artefacts and progress was made in creating implicit solution techniques for DG.

Advances made with local time-stepping will be used by a number of modelling centres and highly innovative new time-stepping approaches for massively parallel architectures and GPUs were developed.

The programme gave a much needed opportunity for making comparisons between different numerical methods, by creating new test cases and revisiting old ones. For example,

- shallow water test cases were undertaken by different groups to compare local mesh refinement strategies.

- Mesoscale eddies are important because they produce the majority of poleward ocean heat transport and the nonlinear interactions with between ocean and atmosphere. Recent improvements in numerical methods now allow multiscale simulation of the global ocean that resolve these mesoscale eddies locally. During the programme new test cases were developed to test a model's ability to simulate such mesoscale ocean activity.

Dynamic Adaptivity. Non-conforming Adaptive Mesh Refinement (AMR), r-adaptivity for unstructured meshes on the sphere, and variable resolution for spectral models were improved. For example, *Kopera* and *Giraldo* worked on a unified AMR strategy for a discretization of the shallow-water equations and Euler equations. Their work showed very good accuracy when the mesh is non-conforming and may soon be used in US Navy weather forecasts.

Some of their results are shown in figure .

FIGURE

captionDiscontinuous Galerkin results (from *Kopera* and *Giraldo*) dynamically adapting to a bouyancy current.

Representation of sub-grid-scale processes. Ideas were developed, on the use of variational multiscale methods to represent the effects of sub-grid scale processes and filter high frequency variability, that will be implemented in the Community Earth System Model (CESM). New derivations of ocean parameterisations were also made to work well across a large range of spatial scales. These will be implemented in MPAS ocean which will form part of the Community Earth System Model.

The workshop *Adaptive Multiscale Methods for the Atmosphere and Ocean* attracted presentations from Europe, North America and Asia. Dynamically adaptive simulation techniques based on mesh refinement, mesh movement and polynomial order increase were presented for ocean and atmosphere applications, as were recent developments in numerics suitable for unstructured and adaptive meshes. Some presentations demonstrated performance and/or qualitative advantages using adaptive techniques for some problems, however whether adaptive techniques provide an advantage in more general classes of ocean and atmosphere simulation remains open.

The workshop series on *Solution of Partial Differential Equations on the Sphere* serves as a beacon for progress in global atmosphere and ocean numerical methods. The meeting at the Isaac Newton Institute saw notable improvements in finite-volume collocated methods, discontinuous Galerkin methods, unstructured finite-volume methods and high-order transport schemes.

The workshop *Weather and Climate Prediction on Next Generation Supercomputers: Numerical and Computational Aspects* was a satellite meeting at the UK Met Office in Exeter. The main topics covered were: State of the art in weather and climate modelling, outlook in a historic context; Discretisations, equation-sets, grids and solvers for the resulting systems; Operational aspects of weather and climate modelling; Computational trends, limiters and opportunities.

Lectures were delivered by representatives from the leading NWP and climate forecasting centers, DWD (Germany), NCAR (USA), ECMWF, Met Office (UK) and the US Navy and there was significant representation from the HPC industry, such as CRAY and IBM and several academic institutions. There were also delegates from Australia, Brazil, Canada, China, France, Italy, New Zealand, Russia and elsewhere.