Institution: University of Exeter

Unit of Assessment: 10 Mathematical Sciences

Title of case study: Improving the Met Office Weather and Climate Prediction Model

1. Summary of the impact (indicative maximum 100 words)

Research by Professor John Thuburn and his group at the University of Exeter has made several key contributions to the formulation and development of ENDGame, the new dynamical core of the Met Office weather and climate prediction model. ENDGame has been shown to deliver improved accuracy and better computational performance at high processor counts compared to the current operational dynamical core, directly impacting the technological tools available to the Met Office. These improvements will benefit users when ENDGame becomes operational in early 2014: the economic value to the UK of the weather forecasts produced by the Met Office has been estimated to be in excess of £600M pa, while climate change projections inform policy decisions on mitigation and adaptation with huge economic implications.

2. Underpinning research (indicative maximum 500 words)

Operational weather and climate prediction are carried out using enormously complex systems, at the heart of which is a numerical model. The model component that solves the equations of atmospheric dynamics and thermodynamics, on the scales resolved by the model grid, is called the `dynamical core'. Of the order of 50 person years of effort are required to research and develop a state-of-the-art dynamical core. Over the last decade the Met Office has developed a new dynamical core, known as ENDGame. Through close collaboration with the Met Office Dynamics Research group, Prof John Thuburn (appointed 2005) and his group at the University of Exeter have made several key contributions to the formulation and development of ENDGame.

One major contribution has been to understand how to represent wave propagation as accurately as possible in the model. Accurate wave propagation is essential for an accurate representation of large-scale dynamical balance in the atmosphere. Building on his previous work, Thuburn (2006) [1] showed that by an appropriate choice of predicted variables and vertical grid staggering, combined with an appropriate formulation of the pressure gradient term, an optimal representation of wave propagation could be achieved for all families of atmospheric waves while predicting density, allowing a mass conserving formulation. This work has recently been extended under an EPSRC Mathematical Sciences CASE PhD studentship (D. R. E. Holdaway), showing that the optimal configuration remains optimal when the dynamical core is coupled to an eddy diffusivity model of the atmospheric boundary layer of the sort used operationally.

An important factor affecting the accuracy of wave propagation on the kind of staggered grid used by ENDGame is the formulation of the Coriolis terms (associated with the Earth's rotation). Thuburn (2007) [2] showed how to formulate the Coriolis terms so as to improve the accuracy of Rossby wave propagation and ensure that balanced flows can be represented accurately, while respecting energy conservation.

The coupling of a conservative semi-Lagrangian advection scheme for the mass variable with a semi-implicit treatment of fast waves is a novel feature of the ENDGame formulation. Thuburn et al. (2010) [3] demonstrated how to improve the accuracy of this coupling through an accurate representation of the trajectory-averaged flow divergence in a prototype shallow-water model.

Conservation properties of weather and climate model dynamical cores are a controversial subject, with no consensus on which is most important or desirable. The review by Thuburn [4] was prompted by discussion with the Met Office Dynamics Research group. The handling of marginally-resolved scales and the exchange of quantities like energy and potential enstrophy between resolved and unresolved scales is of particular interest. A PhD project co-funded by the Met Office under the Great Western Research scheme [5] has improved our understanding and provided some theoretical justification for the ENDGame formulation in this respect.

Finally, the ENDGame formulation requires the iterative solution of a stiff and nonlinear coupled system of equations at every time step. Efficiency and stability of the model depend on ensuring that the iterative solver converges quickly. During 2010/2011 significant progress was made in improving the convergence, stability, and efficiency of ENDGame, one aspect of which is documented in [6].

3. References to the research (indicative maximum of six references)

Evidence of the quality of the research that underpins this case study is provided through the following peer-reviewed publications and grants secured through competitive funding sources.

[1]** Thuburn, J. Vertical discretizations giving optimal representation of normal modes: Sensitivity to the form of the pressure gradient term. *Quarterly Journal of the Royal Meteorological Society*, 2006, **132**, 2809-2825.

[2] Thuburn, J. Rossby wave propagation on the C-grid. *Atmos. Science Letters*, 2007, **8**, 37-42.

[3]** Thuburn, J., M. Zerroukat, N. Wood, A. Staniforth. Coupling a mass conserving semi-Lagrangian scheme (SLICE) to a semi-implicit discretization of the shallow-water equations: minimizing the dependence on a reference atmosphere. *Quarterly Journal of the Royal Meteorological Society*, 2010, **136**, 146-154.

[4] Thuburn, J. Some conservation issues for the dynamical cores of NWP and climate models. *Journal of Computational Physics*, 2008, **227**, 3715-3730.

[5] Kent, J., J. Thuburn, N. Wood. Assessing implicit large eddy simulation for two-dimensional flow. *Quarterly Journal of the Royal Meteorological Society*, 2012, **138**, 365-376.

[6]** Thuburn, J., A. A. White. A geometrical view of the shallow-atmosphere approximation, with application to the semi-Lagrangian departure point calculation. *Quarterly Journal of the Royal Meteorological Society* 2013, **139**, 261-268**.**

** Papers that best indicate the quality of the underpinning research.

Key Supporting Grants

- Met Office Joint Chair in Geophysical Fluid Dynamics, 1 Jan 2005 – ongoing.
- Numerical Methods for Weather and Climate Models I: Coupling resolved scales to subgrid models. Great Western Research / Met office studentship, Oct 2006 – Sept 2009, £55,000.
- Physics-Dynamics Coupling for Weather and Climate Prediction Models. EPSRC Mathematical Sciences CASE studentship (with the Met Office), Oct 2006 – March 2010, £60,864 + £16,950.

4. Details of the impact (indicative maximum 750 words)

The public and a wide range of UK services and industries benefit from weather forecasts provided by the Met Office, including agriculture, aviation, construction, energy, retail, and transport [see evidence **item a**]. The economic value of the forecasts has been estimated to be in excess of £600M pa, and perhaps much more [evidence **item b**]. Forecasts of severe weather have a huge value in terms of public safety. Although it would not be meaningful to put a financial value on any one component of the forecasting system, the accuracy and value of the forecasts clearly depend crucially on the accuracy, as well as efficiency, of the forecast model dynamical core.

Climate change, forced by anthropogenic greenhouse gas emissions, will have major impacts on society in the UK and worldwide. Both mitigation and adaptation measures will have huge costs, from the level of individual businesses and organizations up to national government level [evidence **item c**]. Policies on mitigation and adaptation therefore require the best possible predictions of the future evolution of the climate, and our best available tools for making those predictions are sophisticated numerical models such as the Met Office / Hadley Centre climate model (a variant of the Met Office weather prediction model). Again, the accuracy and value of the predictions depend crucially on the accuracy of the model and its dynamical core.

The newest generation of the Met Office dynamical core, known as ENDGame, is designed to retain the advantages of the current operational dynamical core, while making several improvements. Prof Thuburn's group at the University of Exeter has made several key contributions to the formulation and development of ENDGame, some of which are documented in section 2, and which have impacted on its robustness, accuracy, and efficiency.

Robustness, stability and convergence. For operational use, the dynamical core must be robust and free from numerical instability within its planned operating regime. Prof Thuburn made key contributions to obtaining a stable formulation (a) through improving the calculation of semi-Lagrangian departure points (reference [6] above) and (b) through analysis showing the need for a space-and-time-dependent reference state for the iterative solver [evidence **item d**]. Tests have shown ENDGame to be more stable and robust than the current operational dynamical core [see evidence **item f**]:

> *``…work by Prof Thuburn helped to improve our understanding of the ENDGame iterative solver and other aspects of the formulation, which eventually led to a breakthrough in achieving numerically robust solutions. This specific aspect is of crucial importance to our operational forecasters for whom model failure causes major disruption, leading to delays in delivery of products to our customers.''* [evidence **item f**]

Accuracy. ENDGame combines accurate wave propagation with an optional conservative semi-Lagrangian transport of mass and trace species, considered essential for some climate simulations (references [1], [2] and [3] above). In addition, the improved stability and robustness imply reduced dependence on ad hoc scale-selective dissipation. These improvements have led to several measurable gains in model accuracy and realism in trials, including better maintaining the atmospheric eddy kinetic energy, which helps to increase the spread in ensemble forecasts (a desirable property) and to maintain the natural variability in climate simulations, more realistic stratospheric gravity wave activity, and improved climate precipitation fields [see evidence **item e** and evidence **item f**].

> *``The performance of ENDGame in pre-operational trials suggests that it delivers significant improvements in accuracy over the current operational dynamical core. An important element of this improvement is that the new model has much better variability. This leads, for example, to improved tropical cyclone tracks and intensity, improved summer Asian monsoon rainfall and improved wind speed forecasts.''* [evidence **item f**]

Efficiency. Prof Thuburn's group made a key contribution to the efficiency of the iterative solver through understanding the effect of different back-substitution strategies on error growth/decay. The improvement helped enable ENDGame to run in approximately the same time as its predecessor, despite the greater complexity of its algorithm. Indeed, ENDGame is slightly more efficient on large numbers of processors. This efficiency was a crucial factor in the decision to take ENDGame forward to operational use [see evidence **item e** and evidence **item f**].

> ``*The improved understanding of the iterative solver also allowed a reformulation that significantly reduced the number of iterations needed, and hence the cost of ENDGame. This has been critical in enabling ENDGame to run within the same time window as the current operational dynamical core. Indeed, the formulation of ENDGame achieves better scaling on large numbers of processors and, when ENDGame goes operational, this will allow us to increase the resolution of the forecasts (from 25km to 17km) beyond what we would be able to do with the current model.''* [evidence **item f**]

(Further improvements in efficiency may be possible using an `incremental' version of the solver proposed and tested by Prof Thuburn, and by using the longer timesteps permitted by the improved stability of ENDGame.)

ENDGame will be used operationally from early 2014. At that point the impact of this research will begin to reach the public, policy makers, and businesses and services that use Met Office weather and climate forecasts.Prof Thuburn engaged with the ENDGame project at an early stage (2005) by providing an independent review of a draft ENDGame formulation. The pull through of the research into pre-operational development has been facilitated by frequent close contact between Professor Thuburn and the Dynamics Research group at the Met Office; since 2005 he has typically spent one day per week visiting the Met Office. He has co-authored several papers with the Met Office Dynamics Research Group (Section 2).

5. Sources to corroborate the impact (indicative maximum of 10 references)

a. Met Office 2010: http://www.metoffice.gov.uk/services

b. (A summary of some of the UK services and industries benefiting from Met Office weather forecasts and climate services.)

c. PA Consulting Group 2007: The Public Weather Service's Contribution to the UK Economy

d. http://www.metoffice.gov.uk/about-us/what/pws/value

e. Stern, N. (2010): Stern Review on the Economics of Climate Change

f. http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/sternreview_index.htm

g. These statements may be corroborated by Head of Dynamics Research group, Met Office.

h. Met Office Scientific Advisory Committee 2012 (MOSAC-17), paper 17.3: Foundation Science (A Brown). http://www.metoffice.gov.uk/media/pdf/b/p/MOSAC_17.3_Brown.pdf

i. Letter from Met Office Director of Science to Prof Nick Talbot (Deputy Vice Chancellor, University of Exeter).