Institution: University of Exeter		
Unit of Assessment: UoA 10 Mathematical Sciences		
Title of case study: Improving the Met Office Weather and Climate Prediction Model: Impacting the Economy and Public Safety		
Period when the underpinning research was undertaken: 2000-2014		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor John Thuburn	Professor	2005 - present
Period when the claimed impact occurred: July 2014 - ongoing		
Is this case study continued from a case study submitted in 2014? Y		

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

Research at the University of Exeter has been integral to the development of the ENDGame `dynamical core', a critical component of the Met Office's weather and climate prediction models used operationally since July 2014. ENDGame enabled the Met Office to refine the resolution of global weather forecasts from 25km to 10km, and resulted in better forecast accuracy and model robustness. Its performance underpins the Met Office's position as a world-leading National Met Service, enabling

- improved weather forecasts that now deliver around £1.5bn pa benefit to the UK economy;
- provision of information vital to public safety in all types of severe weather;
- climate change projections crucial in informing mitigation and adaptation policy.

2. Underpinning research (indicative maximum 500 words)

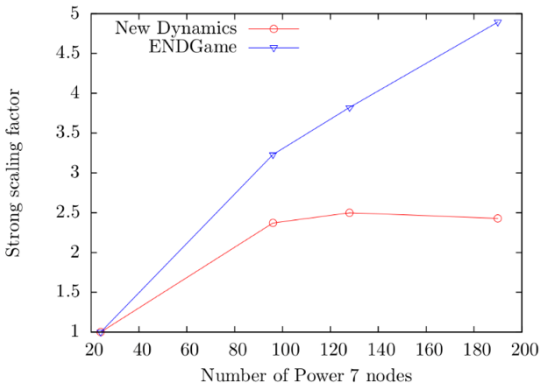
Operational weather and climate prediction are only possible using enormously complex systems built around detailed computer models. The model component that solves the Euler equations, which govern the atmospheric fluid dynamics on the scales resolved by the model grid, is called the 'dynamical core'. Research by Prof John Thuburn and his group at the University of Exeter has been integral to the development of ENDGame, the dynamical core used by the Met Office since 2014 in all of its weather forecasting activities. During 2010/2011, when the viability of the prototype was in doubt, and afterwards, Prof Thuburn contributed to critical advances that improved its scalability, robustness, stability, and accuracy [**5.11**] (described below). These were crucial factors in the decision to implement ENDGame operationally.

Scalability and efficiency. Scalability is the ability of a computer code to execute faster, given more computing processors. In 2013 ENDGame's predecessor was approaching its scalability limit (figure 1), preventing the Met Office from refining its global model resolution beyond about 25 km. The work of Prof Thuburn's group led to a significant improvement in the efficiency of ENDGame's iterative solver through understanding the effect of different back-substitution strategies on error growth/decay. This increased efficiency enabled ENDGame to run in approximately the same time as its predecessor, despite the greater complexity of its algorithm, and enabled refinements of forecast model resolution.

Robustness and stability. Model failures cause major disruption to operational forecasters and lead to delays in delivering products to customers. Prof Thuburn's research made key contributions to the development of a numerically stable formulation for ENDGame so that it would run reliably and require less artificial damping than its predecessor. This was achieved through (a) improving the calculation of semi-Lagrangian departure points [**3.1**] and (b) through analysis showing the need for a space-and-time-dependent reference state for the iterative solver [**3.2**]. The introduction of ENDGame contributed to significant

improvements in stability (an example is shown in figure 2), resulting in a dramatic reduction in the rate of operational model failures [**5.11**].

Figure 1. Comparison of the strong scaling behaviour at 17km resolution of the Met Office model using the ENDGame dynamical core and its predecessor (`New Dynamics') on an IBM Power 7 supercomputer (from [**5.11**]). For ENDGame the computational throughput increases with number of compute nodes (each Power 7 node contains 32 compute cores) while for New Dynamics it saturates at around 100 nodes. At this resolution New Dynamics could not complete the forecast within the required operational window.



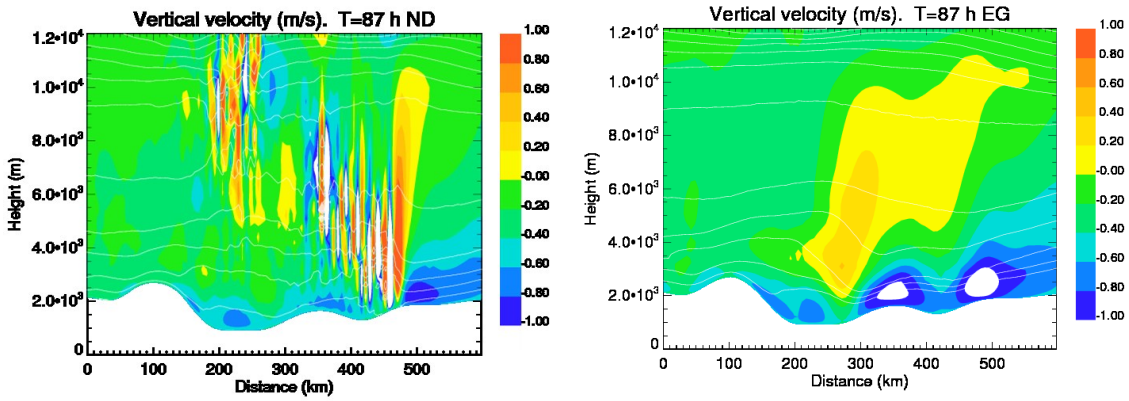


Figure 2: Improved stability for ENDGame (right panel) over Antarctica for a September forecast case in which the previous operational dynamical core became unstable (left panel).

Accuracy. Key features of the atmospheric circulation that are important for weather and climate prediction are captured more accurately by ENDGame than by its predecessor. These include improvements to extratropical storm strength, extreme weather events, and tropical cyclones, maintenance of atmospheric eddy kinetic energy, and large-scale tropical waves that play an important role in forecasting tropical weather such as convective rainfall. [**5.11**]. Work done at the University of Exeter has contributed to this improved accuracy in several ways.

- Through ENDGame's ability to run robustly with reduced artificial damping, discussed above.
- Through a better understanding of how to represent wave propagation and large-scale dynamical balance as accurately as possible in the model. Building on his previous work, Thuburn 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 [**3.3**]. In a separate study, Thuburn showed how to formulate the Coriolis terms, associated with the Earth's rotation, so as to improve the accuracy of Rossby wave propagation and ensure that balanced flows can be represented accurately while respecting energy conservation [**3.4**]. A three-dimensional extension of this idea is employed in ENDGame [**3.2**].

- Through a firmer theoretical basis for the model's conservation properties. 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 [**3.5**] was prompted by discussion with the Met Office Dynamics Research team. The handling of marginally-resolved scales and the exchange of quantities like energy and potential enstrophy between resolved and unresolved scales is crucial for good model behaviour. A PhD project co-funded by the Met Office under the Great Western Research scheme [**3.6**] has improved our understanding of this issue and put the ENDGame formulation on a firmer theoretical basis.

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

3.1: 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**.** doi.org/10.1002/qj.1962

3.2: Wood, N., A. Staniforth, A. White, T. Allen, M. Diamantakis, M. Gross, T. Melvin, C. Smith, S. Vosper, M. Zerroukat, **J. Thuburn.** An inherently mass-conserving semi-implicit semi-Lagrangian discretisation of the deep-atmosphere global nonhydrostatic equations. *Quarterly Journal of the Royal Meteorological Society*, 2014, **140**, 1505-1520. doi.org/10.1002/qj.2235

3.3: 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. doi.org/10.1256/qj.06.10

3.4: Thuburn, J. Rossby wave propagation on the C-grid. *Atmospheric Science Letters*, 2007, **8**, 37-42. doi.org/10.1002/asl.148

3.5: Thuburn, J. Some conservation issues for the dynamical cores of NWP and climate models. *Journal of Computational Physics*, 2008, **227**, 3715-3730. doi.org/10.1016/j.jcp.2006.08.016

3.6: 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. doi.org/10.1002/qj.925

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

During the period 2005 – 2014 Prof John Thuburn and his group worked with the Met Office Dynamics Research team to develop the ENDGame dynamical core, which is the basis for all Met Office weather and climate predictions. The importance of the University of Exeter contribution was summarised by the Met Office Director of Meteorological Science: *"The work carried out by Professor Thuburn and his group at the University of Exeter delivered considerable improvements to the performance and reliability of the ENDGame dynamical core. This resulted in much greater accuracy… more robust model performance and also a real saving in terms of supercomputer time (and hence power consumption and cost). These contributions formed a critical component in the decision to make ENDGame operational in July 2014. As a result of this, the resolution of the global model used for operational weather forecasts has been refined from 25km to 10km and in doing so, resulted in significantly improved forecast skill."* [**5.1**] Since becoming operational in the Global Forecast Model in July 2014 and Regional Models in February 2015, ENDGame has been a fundamental part of the Met Office's weather and climate-prediction activities, underpinning the delivery of major economic, public safety, and policy benefits to the UK and internationally.

Economic impact

Independent economic analysis has estimated that the provision of integrated weather and climate services by the Met Office will deliver a net economic value of £29.5bn over the ten years from 2015 to 2025 [**5.2**]**.** This is consistent with the findings of a Value for Money

Review of the 'Public Weather Service' (PWS), a subset of the services delivered by the Met Office, which concluded that the benefits to the UK were likely to be close to £1.5bn per annum. Key groups and sectors benefitting include the public (estimated benefit of £480m per annum), aviation (£400m per annum), land transport (£100m per annum), and storm and flood damage avoidance (£144m per annum) [**5.3,5.4**]. Most of the business areas at the Met Office rely on its world-class numerical model (the Unified Model), of which the dynamical core is a fundamental part; thus, ENDGame currently underpins virtually all of the economic benefit delivered by the Met Office. Some of the key impacts that are particularly dependent on the improvements delivered through ENDGame are outlined below.

Civil aviation - improved safety and efficiency. Accurate weather forecasting is essential for efficient and safe operation of aviation. The accuracy of the Met Office weather forecasts relies fundamentally upon the formulation of the dynamical core; the improvements arising from Prof Thuburn's work have delivered much greater accuracy than was possible before, enabling the Met Office to maintain its reputation for high quality World Area Forecast Centre Aviation services. Specific examples include levels of accuracy in predicting 'jet stream' winds, and improvements to the representation of gravity waves, including mountain-waves that cause clear air turbulence, and trapped lee waves, which cause downdraughts and gusts that are a hazard to light aircraft [**5.11**]. Overall, the Met Office's weather forecasting services to the Aviation sector are estimated to contribute £8.4bn net economic value over the ten year period 2015-2025 [**5.2**].

Value from International partnerships. The significant improvements in model performance and efficiency delivered by ENDGame have contributed significantly to maintaining the Met Office's position amongst its international equivalents as a leading National Met Service (NMS). ENDGame has been implemented in the models of several Met Office international partners including the Australian Bureau of Meteorology, the National Institute of Water and Atmospheric Research in New Zealand, the Korean Met Service, Met Service Singapore, and the NMS of the Philippines [**5.1,5.5,5.6**]. If the Met Office had lost its position as a leading NMS, it was estimated that its ten year net economic value to the UK would have reduced by £6.8bn [**5.2**].

Damage avoidance. The UK is prone to windstorms as a result of its position under the North Atlantic storm track and estimates of damage from past storms are significant; the 'Great Storm' of October 1987 is estimated to have caused £2.2bn worth of damage. Improved forecasting enables appropriate mitigation action to be taken in advance, for example, issuing severe weather warnings in the media and closing parts of the rail network. The added value to the UK through the prevention of storm damage from more accurate weather forecasting, such as that enabled by ENDGame, is valued at £80m per annum [**5.4**].

Although it is not meaningful to directly attribute financial value to any one part of the forecasting system, clearly none of these benefits would be possible without the complex models built upon the dynamical core. The current and previous Met Office Science Strategies [**5.7**] highlight the central role of the dynamical core, especially the additional accuracy that comes from being able to run at finer resolution.

Societal Impact – Public Safety

Arguably, the greatest impact of the Met Office forecasts is on public safety. Overall, it is difficult to quantify an average annual figure for the number of lives that are saved as a result of weather forecasts and warnings. However, it has been suggested that improved forecasting accuracy, dissemination of warnings, and resulting mitigating action may be saving many tens of lives each year from direct impacts of the weather. For extreme events, such as North Sea coastal flooding, hundreds of lives are potentially being saved. Also,

excess deaths from heatwaves may be reduced by about 40 per event due to heat health warnings. Although precise figures are unknowable, there is no doubt that the quality of forecasting enabled by ENDGame is making a major contribution to public safety [**5.2**].

Policy impact

Climate change mitigation. Climate change projections produced by the Met Office are crucial for informing mitigation and adaptation policies from local to national level [**5.8**]. A notable example is UKCP18 [**5.9**], a comprehensive dataset of state-of-the-art probabilistic climate projections for the UK under a range of greenhouse gas emission scenarios. The dataset, which is derived using global and regional climate models based on the ENDGame dynamical core, provides projections over land, coast, and sea for means and extremes of variables such as temperature, rainfall, sea level, wave height, and tidal surges.

Supercomputing infrastructure and Met Office strategy. ENDGame enabled the Met Office to fully exploit a £97m government investment in High Performance Computing delivered in 2016 [**5.11**] and to make the case for a further £1.2bn investment announced in February 2020. The University of Exeter work has also supported significant investment in a wider programme of next generation model development. In the words of the Director of Meteorological Science *"Professor Thuburn's work has continued to provide significant impact through his contributions to the next generation GungHo dynamical core, which seeks to exploit next generation supercomputer architectures and further improve computational efficiency while retaining accuracy and stability. Along with the improved scalability of the ENDGame code, it underpins the Met Office's future supercomputing strategy, which will see an investment of up to £1.2bn over the 10-year period 2022 to 2032."* [**5.1, 5.10**].

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

5.1. Letter from Met Office Director of Meteorological Science Simon Vosper to Prof Neil Gow, University of Exeter.
5.2. London Economics (2015) Met Office General Review Economic Summary
5.3. How valuable is the Met Office? https://www.metoffice.gov.uk/about-us/what/pws/value (accessed 10/03/2020)
5.4. Gray (2015) Public Weather Service Value for Money Review, Met Office
5.5. Joint WMO Technical Report on the Global Data Processing and Forecasting System and Numerical Weather Prediction Research Activities for 2016, Korea Met Administration, 2016
5.6. Webster (2015**)** Progress in tropical regional modelling, Report to MOSAC and SRG paper 20.11. Met Office,
5.7. Met Office Science Strategy 2016-2021, page 32
5.8. Michael Gove Speech on UK Climate Change Projections https://www.gov.uk/government/speeches/michael-gove-speech-on-uk-climate-change-projections (accessed 10/03/2020)
5.9. UKCP18 Science Overview Report (2018)
5.10. Met Office Press Office (2020) https://www.metoffice.gov.uk/about-us/press-office/news/corporate/2020/supercomputer-funding-2020 (accessed 10/03/2020)
5.11. Walters et al., (2017) The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations, *Geoscientific Model Development*, 10, 1487-1520 https://gmd.copernicus.org/articles/10/1487/2017/