Institution: University of South Wales		
Unit of Assessment: B10 Mathematical Sciences		
Title of case study: Enhancing computational models for weather and climate forecasting		
Period when the underpinning research was undertaken: 2015-2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Dr James Kent	**Role(s) (e.g. job title):** Lecturer	**Period(s) employed by submitting HEI:** 2015-2020
Period when the claimed impact occurred: 2016-31st December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

Accurate weather and climate forecasts have an important effect on the economy, agriculture, and public safety, which means improved forecasting methods benefit society through numerous and diverse channels. Central to these forecasts are the use of computer models. Researchers at the University of South Wales have made significant contributions to weather and climate prediction models used by various agencies around the world with impact on practitioners and enhanced performance. These include **1)** numerical schemes constructed for and used by National Aeronautics and Space Administration (NASA) and **2)** new test cases to evaluate computer models for weather and climate predictions have been developed and used by numerous organisations around the world, including European Centre for Medium-Range Weather Forecasts (ECMWF) and Deutscher Wetterdienst (DWD), with concomitant impact on their stakeholders.

2. Underpinning research (indicative maximum 500 words)

To formulate accurate and reliable weather forecasts, computers are used to numerically solve the underlying model equations and thus the predictions obtained rely on the quality of the computation methods applied. Global climate modelling systems are employed for both weather and climate predictions and consist of many different components. One such component is the atmospheric model, which itself comprises two different parts: the dynamical core and the physical parameterizations. The dynamical core is crucial – it is responsible for capturing the dynamical behaviour of the Earth's atmosphere via numerical integration of the governing fluid dynamics equations. No two dynamical cores are alike, and their individual successes suggest that no perfect model exists. It is important to assess the dynamical core in isolation, to understand whether the numerical methods used are capturing the required phenomena (such as positivity and correlations in tracer transport, correct wave propagation, or precipitation when dynamics and physics are coupled). To this end, a standard set of idealized test cases need to be created, having analytical initial conditions and known solutions or features of solutions. These test cases can then be used by operational centres to evaluate the performance of their model whilst in development, and hence influence key design aspects of their dynamical cores. This testing leads to model improvements, and so, builds confidence in an organisation’s model, making them more prepared to share it. This allows broad benefits to the wider operational modelling community and thus, through improved weather and climate forecasting, to society as a whole.

Kent, at the University of South Wales, has been at the forefront of idealised dynamical core testing. He has designed, developed, and implemented new idealised test cases that evaluate the performance of atmospheric dynamical cores. Alongside researchers from University of California Davis, University of Michigan, Stony Brook University and National Centre of Atmospheric Research (all USA), he is also a co-organiser of the Dynamical Core Model Intercomparison Project (DCMIP) and the associated workshops of 2012 and 2016. The goal of DCMIP, which commenced in 2008, is to establish a worldwide community that intercompares cutting-edge dynamical core models and provides a forum to exchange ideas and advance education on dynamical core development **[3.1]**. For example, DCMIP 2016 had attendees from north and south America, Europe, Africa and Asia at various stages of their careers ranging from established researchers through to research students. In particular, **Kent**'s test cases developed for the 2016 workshop (including non-divergent three-dimensional prescribed velocities for tracer transport, the propagation of gravity waves in non-hydrostatic regimes, and simplified cyclone and supercell storm test) have been used or assessed by at least nine international weather and climate modelling groups that attended the DCMIP workshops **[3.1,3.2]** (see also Section 4: Details of impact).

Related to the dynamical core of an atmospheric model is the linear model, which is used to describe the forward evolution of perturbations and the backwards evolutions of sensitivities which are required to measure the discrepancies in the model with respect to observations and the background state. The linear model is computationally efficient and as such is a key tool in data assimilation and the estimation of sensitivity to initial conditions. Although the linear model is based upon the dynamical core, often these are developed independently, and it is important to understand how they interact. Indeed, the optimum numerical methods for the full dynamical core are not always the optimum methods for the linear model.

Since 2015, **Kent** has worked with staff at NASA to help develop their new linear model. **Kent**'s research resulted in the construction of a novel numerical scheme that improves linear tracer transport through improved accuracy and stability and has been implemented by NASA as part of their GEOS-5 weather and climate prediction model **[3.3]**. Further, **Kent** has built on his work with DCMIP to develop a number of test cases for linear models, enabling NASA to have confidence in the performance of the linear model of GEOS-5 **[3.4]**. NASA are currently using the scheme devised by **Kent** for tracer transport within the linear model, with plans to expand its use to the dynamic variables in their model.

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

[3.1] Ullrich PA, Jablonowski C, **Kent J**, Lauritzen PH, Nair R, Reed KA, Zarzycki CM, Hall DM, Dazlich D, Heikes R, Konor C, Randall D, Dubos T, Meurdesoif Y, Chen X, Harris L, Kühnlein C, Lee V, Qaddouri A, Girard C, Giorgetta M, Reinert D, Klemp J, Park S-H, Skamarock W, Miura H, Ohno T, Yoshida R, Walko R, Reinecke A, and Viner K (2017), DCMIP2016: A Review of Non-hydrostatic Dynamical Core Design and Intercomparison of Participating Models. *Geosci. Model Dev*., 10, 4477-4509. https://doi.org/10.5194/gmd-10-4477-2017

[3.2] Zarzycki CM, Jablonowski C, **Kent J**, Lauritzen PH, Nair R Reed KA, Ullrich PA, Hall DM, Dazlich D, Heikes R, Konor C, Randall D, Chen X, Harris L, Giorgetta M, Reinert D, Kühnlein C, Walko R, Lee V, Qaddouri A, Tanguay M, Miura H, Ohno T, Yoshida R, Park S-H, Klemp J, and Skamarock WC (2019), DCMIP2016: The Splitting Supercell Test Case. *Geosci. Model. Dev.*, 12, 879-892, https://doi.org/10.5194/gmd-12-879-2019

[3.3] Holdaway D, and **Kent J** (2015), Assessing the tangent linear behavior of common tracer transport schemes and their use in a linearized atmospheric general circulation model. *Tellus A*. 67, 1. https://doi.org/10.3402/tellusa.v67.27895

[3.4] Kent J, and Holdaway D (2017), An Idealised Test Case For Assessing The Linearization of Tracer Transport Schemes in NWP Models. *Quarterly Journal of the Royal Meteorological Society*. 143, p. 1746-1755. https://doi.org/10.1002/qj.3027

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

Improved weather forecasts and climate predictions have a significant effect on the economy and on public safety, ranging from better use of energy reserves to advanced warnings of natural disasters **[5.1]**. Accurate global modelling systems rely on accurate numerical methods to solve the corresponding equations. The development of these methods, along with their careful assessment and evaluation, is essential for improving forecasting capabilities and having confidence in the model results. **Kent**'s new approach has significantly improved the accuracy, stability and computational efficiency compared to older schemes and enhanced confidence in the predictive capabilities of the models.

Novel modelling system developed by Kent leads to improvements in NASA's technologies

Kent designed and developed a new tracer transport scheme for NASA's GEOS-5 (their operational model for weather and climate prediction) linear model. This scheme became the default option in NASA's GEOS-5 linear model in 2018 **[5.2, 5.3]** and, as a direct result, showed immediate improved performance over the previous model version as confirmed by the Data Assimilation Lead for the Global Modeling and Assimilation Office at NASA:

"*The improvements in the linearized GEOS model as a result of the implementation of the dynamical core with HK [Holdaway and Kent] scheme were very impressive, and significant compared against gains seen for implementation of other components*." **[5.2]**

[Text removed for publication] the NASA model improves their forecast ability, and thus impacts their model and data users. NASA's work on global weather and climate predictions is used to inform industry, government and the public in the both the United States and world-wide **[5.1,5.5]**, with vast volumes of data being open-access (e.g. https://earth.nullschool.net/). Within the Global Modeling and Assimilation Office of NASA alone, 20 missions currently exploit aspects of the GEOS system which in turn impact on further campaigns **[5.6]**. Since NASA share their climate data and models with other centres, such as the National Oceanic & Atmospheric Administration (NOAA) **[5.7]**, improvements to their model mean improvements to the quality of this data world-wide and allow NASA to achieve its key missions. The GEOS linear model is also being used by the Joint Center for Satellite Data Assimilation (JCSDA) whose member organisations include NASA, NOAA, the U.S Navy and the U.S. Air Force. JCSDA is developing JEDI, a data assimilation system, to become a world-leader in environmental analysis and prediction. The use of **Kent**'s method in GEOS-5 has led to [text removed for publication] the JEDI system as stated by JEDI's Development Team Research Member **[5.3]**:

"*The HK scheme is by far the most efficient transport scheme available in the GEOS linearized model, making it very attractive for use in JEDI…. [The HK scheme] offers excellent matching between the nonlinear transport and the linearized transport and the best performance compared to other forms of linearized advection tested in GEOS*." **[5.3]**

Following the success of **Kent**'s scheme within the GEOS system, NASA is currently implementing another method of **Kent** for other variables within the linear model of GEOS-5, such as vorticity, temperature and pressure **[5.3, 5.4a]**.

Creating a worldwide standard for test cases in atmospheric models

In 2016, **Kent** presented his research at a DCMIP workshop, providing at least 9 atmospheric modelling groups around the world with attendees from 5 different continents with a new set of standard idealised test cases that assess the dynamical core's performance when coupled to simplified physics routines. The groups that took part in the workshop are truly international and drawn from a mixture of higher educational institutions and governmental funded agencies including:

- National Center for Atmospheric Research, Boulder, CO, USA.
- Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace (IPSL), Paris, France.

- Geophysical Fluid Dynamics Laboratory (GFDL), Princeton, NJ, USA (the developers of the dynamical core used in NASA's GEOS-5 model).
- European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK.
- Environment and Climate Change Canada (ECCC), Dorval, Québec, Canada.
- Max Planck Institute for Meteorology, Hamburg, Germany.
- Deutscher Wetterdienst (DWD), Offenbach am Main, Germany.
- Naval Research Laboratory, Monterey, CA, USA.
- Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa, Japan.

The Scientist attending on behalf of the European Centre for Medium-Range Weather Forecasts, an independent intergovernmental organisation supported by 34 member states, noted that:

"*The test cases developed by Dr. James Kent of the University of South Wales and used at the DCMIP 2016 workshop are becoming a worldwide standard in evaluating dynamical cores in the atmospheric modelling community*." **[5.8]**

These groups used the test cases to assess and give confidence in their different models and used the results to guide their model design decisions **[5.8, 5.9]**:

"*… by using these tests, we have great confidence in the performance of IFS-FVM and hence are continuing to develop this technology*." **[5.8]**

This increased model confidence and improved design decisions impacts both the model data itself and external users. For example, DWD provide services to numerous organisations including the German Government, private weather forecast agencies, TV stations, as well as more than 20 national weather services worldwide **[5.10a]**. Following DCMIP-2016, DWD used **Kent**'s test cases to assess and verify their ICON model dynamical core giving them, and hence their stakeholders, confidence that the ICON model is performing well and producing accurate forecasts. Indeed, DWD acknowledged that **Kent**'s test cases have made valuable contributions to their ICON model **[5.10b]**:

"*… we discovered that the ICON dynamical core erroneously conserves total mass instead of just dry air mass…. we have designed a new approach to remedy the conservation problem….*" **[5.10b]**

In addition, using his knowledge of test cases from DCMIP along with the requirements of the tracer transport linear model from NASA, since 2017 **Kent** has also created a new set of idealised test cases specifically for linear models. These tests have subsequently been used on NASA's GEOS-5 linear model, which again highlight the improvements made by **Kent [5.4]**.

Kent's research has therefore directly impacted multiple national and international weather and climate modelling groups, which make use of his modelling systems. By enhancing their performance and services, his research has also indirectly impacted these groups' extensive partner organisations and customers worldwide.

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

[5.1] NASA Socio-Economic Impacts: https://www.nasa.gov/sites/default/files/files/SEINSI.pdf (pages 14-16)

[5.2] Letter from the Data Assimilation Lead for the Global Modeling and Assimilation Office at NASA, confirming Kent's key contributions to the project and the resultant impact. **CONFIDENTIAL**

[5.3] Letter from Research Member of the Joint Effort for Data assimilation Integration (JEDI) development team, NASA and UCAR, confirming Kent's contributions to the GEOS-5 linear model and impact on JEDI. **CONFIDENTIAL**

[5.4] NASA technical reports:

[5.4a] Development and Applications of the FV3 GEOS-5 Adjoint Modeling System, https://ntrs.nasa.gov/search.jsp?R=20170005229

[5.4b] Comparison of the Tangent Linear Properties of Tracer Transport Schemes Applied to Geophysical Problems, https://ntrs.nasa.gov/search.jsp?R=20150010242&qs=Nm%3D4293208573%7CAuthor%7CKent%2C%2520James%26N%3D0

[5.5] NASA provides capabilities to predict climate, weather, and natural hazards; manage resources; and inform environmental policy https://www.nasa.gov/sites/default/files/atoms/files/fy_2020_congressional_justification.pdf (SCMD-8, page 271 of PDF file)

[5.6] Users of GEOS data within NASA: https://gmao.gsfc.nasa.gov/NASA_missions/

[5.7] Use of FV3 by NASA, National Centres for Environmental Prediction (NCEP) and National Oceanic and Atmospheric Administration (NOAA) https://cpaess.ucar.edu/sites/default/files/meetings/2019/documents/Holdaway.pdf (page 3)

[5.8] Letter from Scientist at ECMWF, confirming DCMIP impact on IFS-FVM model verification. **CONFIDENTIAL**

[5.9] Dynamical Core Model Intercomparison Project: https://www2.cisl.ucar.edu/events/summer-school/dcmip/2016/dcmip-2016

[5.10] Deutscher Wetterdienst's use of Kent's test cases:

[5.10a] DWD's ICON model and users. https://www.dwd.de/EN/research/weatherforecasting/num_modelling/01_num_weather_prediction_modells/icon_description.html

[5.10b] Letter from Scientist at DWD, confirming DCMIP impact on ICON model verification. **CONFIDENTIAL**