Institution: University of Leeds

Unit of Assessment: 7 - Earth Systems and Environmental Sciences

Title of case study: Aerosol model adopted nationally and internationally to deliver climate projections and services

Period when the underpinning research was undertaken: 2003 - 2018

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:
Ken Carslaw	Professor	01/01/1999 to present
Graham Mann	Lecturer	01/01/2007 to present
Dominick Spracklen	Professor	01/11/2009 to present
Kirsty Pringle	Research Scientist	01/01/2010 to present
Leighton Regayre	Research Fellow	03/05/2016 to present
Carly Reddington	Research Fellow	01/05/2012 to present
Jill Johnson	Research Fellow	03/12/2012 to present
Masaru Yoshioka	Research Scientist	01/10/2012 to present
Jo Browse	Research Fellow	01/11/2012 to 30/09/2016
Hamish Gordon	Research Fellow	11/07/2016 to 17/08/2019
Paul Field	Professor	01/02/2013 to present

Period when the claimed impact occurred: 2013 - 2020

Is this case study continued from a case study submitted in 2014? N

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

Leeds researchers developed the Global Model of Aerosol Processes (GLOMAP), which has been adopted as a core component of the UK Met Office's national climate and weather model development strategy. As an integrated component of the Met Office models, the underpinning science from GLOMAP has contributed to international climate modelling efforts via the Hadley Centre Climate Programme and supported the UK Climate Projections 2018. GLOMAP is used internationally through the Unified Model partnership. The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, has adopted the model for use in air quality assessments, where it has contributed evidence to support improved air quality monitoring and management in New South Wales.

2. Underpinning research (indicative maximum 500 words)

Atmospheric aerosol particles from air pollution and natural sources have a substantial effect on climate by altering Earth's energy balance. Accurate simulations of aerosol properties are an important aspect of climate model development in order to provide reliable data to governments to support informed climate mitigation pathways and adaptation options. Furthermore, anthropogenic aerosol pollution (particulate matter) has a substantial effect on human health. Therefore, regulatory agencies need accurate models to quantify these effects and determine mitigation options.

In 2003, Carslaw and Spracklen (PGR at Leeds) began development of the Global Model of Aerosol Processes, or GLOMAP [1]. GLOMAP was a major advance beyond models available at that time because it simulated the full aerosol particle size distribution and chemical composition, which are critical for accurate quantification of how aerosols affect the climate. Leeds researchers developed a computationally faster version of GLOMAP [2] specifically for inclusion in the UK climate model, and other operational models that are required to perform long climate

change scenario simulations. Leeds researchers began testing the use of GLOMAP in the Met Office climate model from 2008 onwards.

In over 100 publications by Leeds researchers, the GLOMAP models have been used to study almost all aspects of the global aerosol-climate problem, including the first global study of how particles form in the atmosphere, the critical role of natural aerosols in climate change [3], as well as studies of dust, air pollution and health, forest fires, volcanic aerosols, geoengineering, ice formation and Arctic climate. Consequently, the model has undergone considerable further development to improve its realism and to maintain the model at the leading edge.

To contribute to improving climate projections, Leeds researchers have undertaken extensive research using GLOMAP to reduce the uncertainty in how aerosols affect climate [4]. Leeds pioneered the use in this research field of very large sets of model simulations (perturbed parameter ensembles) combined with advanced statistical techniques to identify the most important model processes. Leeds also led the Global Aerosol Synthesis and Science Project, which compiled the largest ever synthesis of aerosol measurements for model evaluation [5]. These datasets formed an important aspect of the Met Office's model evaluation prior to acceptance of GLOMAP for operational purposes.

Leeds further developed GLOMAP for high-resolution regional simulations of aerosol interactions with clouds in order to tackle the largest cause of uncertainty in aerosol effects on climate [6]. This research has directly influenced the Met Office's strategy to implement the coupling of aerosol and cloud microphysics in the operational models.

The University of Leeds is a member of the Met Office Academic Partnership (MOAP). Atmospheric composition is one of the three research themes of the partnership and has enabled co-creation via joint projects, studentships and exchanges between scientists in both institutions to further the development and application of GLOMAP.

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

1. Spracklen, D.V., Pringle, K.J., Carslaw, K.S., Chipperfield, M.P., Mann, G.W., 2005. A global off-line model of size-resolved aerosol microphysics: I. Model development and prediction of aerosol properties. *Atmos. Chem. Phys*., 5, pp. 2227-2252. https://doi.org/10.5194/acp-5-2227-2005
2. Mann, G.W., Carslaw, K.S., Spracklen, D.V., Ridley, D.A., Manktelow, P.T., Chipperfield, M.P., Pickering, S.J., Johnson, C.E., 2010. Description and evaluation of GLOMAP-mode: a modal global aerosol microphysics model for the UKCA composition-climate model. *Geosci. Model Dev.,* 3, pp. 519-551. https://doi.org/10.5194/gmd-3-519-2010
3. Carslaw, K.S., Lee, L.A., Reddington, C.L., Pringle, K.J., Rap, A., Forster, P.M., Mann, G.W., Spracklen, D.V., Woodhouse, M.T., Regayre, L.A., Pierce, J.R., 2013. Large contribution of natural aerosols to uncertainty in indirect forcing. *Nature,* 503, pp. 67-71. https://doi.org/10.1038/nature12674
4. Regayre, L.A., Johnson, J.S., Yoshioka, M., Pringle, K.J., Sexton, D.M.H., Booth, B.B.B., Lee, L.A., Bellouin, N., Carslaw, K.S., 2018. Aerosol and physical atmosphere model parameters are both important sources of uncertainty in aerosol ERF. *Atmos. Chem. Phys.,* 18, pp. 9975-10006. https://doi.org/10.5194/acp-18-9975-2018
5. Reddington, C., Carslaw, K.S., Stier, P., Schutgens, N., Coe, H., Liu, D., Allan, J., Browse, J., Pringle, K., Lee, L.A., Yoshioka, M., Johnson, J.S., Regayre, L.A., Spracklen, D.V., Mann, G.W., Clarke, A., Hermann, M., Henning, S., Wex, H., Kristensen, T.B., Leaitch, W.R., Poeschl, U., Rose, D., Andreae, M.O., Schmale, J., Kondo, Y., Oshima, N., Schwarz, J.P., Nenes, A., Anderson, B., Roberts, G.C., Snider, J.R., Leck, C., Quinn, P.K., Chi, X., Ding, A., Jimenez, J.L., Zhang, Q., 2017. The global aerosol synthesis and science project (GASSP): Measurements and modelling to reduce uncertainty. *Bulletin of the American Meteorological Society,* 98, pp. 1857-1877. https://doi.org/10.1175/BAMS-D-15-00317.1
6. Gordon, H., Field, P.R., Abel, S.J., Dalvi, M., Grosvenor, D.P., Hill, A.A., Johnson, B.T., Miltenberger, A.K., Yoshioka, M., Carslaw, K.S., 2018. Large simulated radiative effects of

smoke in the south-east Atlantic. *Atmos. Chem. Phys.,* 18, pp. 15261-15289. https://doi.org/10.5194/acp-18-15261-2018.

Research Funding
- NERC Global aerosol synthesis and science project to reduce the uncertainty in aerosol radiative forcing (GASSP, 2012-2016), GBP830K (GBP436K to Leeds)
- NERC Appraising the direct impacts of aerosol on climate (ADIENT, 2007-2011), GBP1.2million (GBP187K to Leeds)
- NERC Aerosol-cloud interactions - A directed programme to reduce uncertainty in forcing through a targeted laboratory and modelling programme (ACID-PRUF, 2011-2015), GBP2.9million (GBP684K to Leeds)
- NERC Aerosol model robustness and sensitivity study for improved climate and air quality prediction (AEROS, 2010-2013), GBP626K (GBP338K to Leeds)
- European Union Impact of biogenic versus anthropogenic emissions on clouds and climate: towards a holistic understanding (BACCHUS, 2013-2018), EUR8.7million (EUR316K to Leeds)

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

The development of modelling tools, statistical techniques and collation of observational datasets has enabled the Met Office and international agencies to make GLOMAP part of their strategic programme of model development. This has led to its use in the UK climate projections, the development of a new UK Earth System model (UKESM1), and the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP), which is the global climate-modelling programme that informs climate policy.

Adoption of GLOMAP as a core component of Met Office strategy across climate and weather

Leeds' development of GLOMAP has changed the Met Office strategic approach to the modelling of aerosols. Following GLOMAP's implementation and successful testing in research versions of the Met Office Unified Model (UM) from 2008, the Met Office Aerosol Strategy Review in 2013 [A] proposed a coordinated approach to aerosol modelling across climate prediction, weather prediction and air quality. *"In 2013 the Met Office was actively trying to support four different aerosol representations used across our modelling systems. The move to adopt the University of Leeds-developed GLOMAP representation was driven primarily by the recognised scientific superiority of GLOMAP to better capture processes that are important for accurate climate projections (principally, GLOMAP simulates aerosol particle size and number, replacing a much simpler in-house model that simulated just the aerosol mass)"* [B].

The strategy was reviewed by the Met Office Scientific Advisory Committee (MOSAC), which exists to evaluate the ability of the Met Office's research plans to meet its customer's requirements. The strategy concluded: *"The objective of the Met Office and University partners should be to implement GLOMAP in full and simplified versions across all UM [Unified Model] configurations."* [A].

In 2015, the national Joint Weather and Climate Research Programme (JWCRP) between NERC and the Met Office initiated the UK Earth System Modelling project UKESM1 choosing the aerosol component provided by GLOMAP. GLOMAP was subsequently implemented in the atmospheric configuration of the UK Met Office climate model (GC3.1) in 2017 and released as part of the Earth system model (UKESM1) in 2019. "*The GLOMAP code is one of the largest components of the climate model to have been provided by external partners"* [B].

GLOMAP replaced a much simpler aerosol model (CLASSIC) developed by the Met Office that had been part of the climate model since 2006. The Met Office's documentation paper of the atmosphere configuration of the climate model (Walters et al., 2019) concludes that the Global Atmosphere model (version 7) includes *"significant structural improvements that increase the*

complexity and improve the fidelity of climate simulations, namely the UKCA GLOMAP-mode aerosol scheme…" [C]

Leeds' research on cloud microphysics and aerosols [6] allowed the Met Office to state in their 2016-2021 Science Strategy that a *"…fully coupled aerosol and cloud microphysics scheme will be developed" …*which *"builds on important developments in simulating and predicting aerosol concentrations" … "This will cement a common approach across weather and climate modelling and will enable a more robust assessment of the indirect effects of aerosol emissions on climate change through their influence on cloud radiative properties."* [D].

To achieve its strategy, the Met Office undertook an organisational restructuring in order to create a dedicated team for aerosol modelling, with a new Head of Aerosol Modelling and a new scientist post within the cross-Office Foundation Science rather than being within the Hadley Centre climate team: *"We appointed a new manager to oversee the continued implementation of GLOMAP, and expanded the remit of the cloud modelling group to work on aerosol (an increase from 4 to 6 dedicated personnel working on clouds and aerosols), creating an aerosol and cloud microphysics team."* [B]

Assuring the reliability of climate model projections in national and international assessments

The UK Government is obliged to contribute to international climate modelling efforts. This effort is undertaken through the Hadley Centre Climate Programme reporting to the Department for Business Energy and Industrial Strategy (BEIS). As an integrated component of the Unified Model this includes the underpinning science from GLOMAP: *"The current CMIP6 programme uses GLOMAP aerosol representation. This represents a large change to the previous CMIP5 contribution, enabling the UK's climate model to tackle aerosol effects on clouds, recognised as a large uncertainty in climate prediction, more accurately than before."* [B]. In addition, Leeds' underpinning research directly supported the Met Office's task of assuring the performance of the climate and Earth system models prior to their release. Leeds researchers provided a bespoke and extensive synthesis of aerosol measurement data to the Met Office [5] for model evaluation [C]. Furthermore, vital model adjustments implemented by the Met Office [E] that improved the simulation of historical climate, were based on Leeds' underpinning research on natural aerosols [3] and model uncertainty analysis [4] [B].

As part of the UK Climate Projections 2018 (UKCP18), the Department for the Environment, Food and Rural Affairs (Defra) tasked the Met Office with producing a set of probabilistic climate projections that show how the 21st Century climate may evolve. The projections were created over several years at the Met Office based on a process involving the assessment of many uncertain model parameters. Leeds researchers directly influenced UKCP18 [F] by selecting the aerosol-related parameters based on an extensive body of work on uncertainty quantification in the Global Aerosol Synthesis and Science Project [5] and through development of GLOMAP: *"To create this dataset, climate prediction simulations at greater than normal spatial resolution using GLOMAP, were carried out to drive the high resolution UK simulations used in UKCP-18. These high resolution simulations employed a simplified aerosol scheme using parameters derived from the aerosol representation in the GLOMAP climate projections."* [B]. UKCP18 climate projection data [G] is available for user groups to download and use and underpins strategic climate change planning by the UK government, local authorities and businesses [B].

International adoption of GLOMAP

International adoption of GLOMAP has been via the Unified Model Partnership: *"The Met Office has world-wide partners that use the latest configurations of this model for weather and climate prediction. Partners using the Unified Model, including GLOMAP configurations, to provide deliverables to their respective governments include National Meteorological Services in Australia (BoM) and the Republic of Korea (KMA), as well as national weather and climate research institutes in New Zealand (NIWA), India (NCMRWF) and Australia (CSIRO)"* [B]

The Director of the Climate Science Centre at CSIRO stated that *"GLOMAP is the premier atmosphere aerosol science model of the CSIRO Climate Science Centre (CSC)"… "CSIRO and the Climate Science Centre are now routinely using GLOMAP for air quality research, strategic air quality management projects, and short-term forecasting for the Australian state and federal governments."* [H]. CSIRO made the decision to couple the GLOMAP model to their in-house Chemical Transport Model (C-CTM) due to *"the quality of the science built into GLOMAP, together with the computational efficiency of the software"* [H]

As a specific example, C-CTM-GLOMAP formed an important component in assessment of the impact of shipping emissions on population health in Sydney, New South Wales [H]. The study [I] was one of three lines of evidence considered by a government-industry stakeholder workshop in 2015 that focussed on the public health impacts of shipping emissions. The New South Wales (NSW) Environmental Protection Authority (EPA) subsequently implemented legislation to reduce emissions by requiring the use of low sulphur fuel and an air quality monitoring system was introduced [H]. Subsequent inspections have found very good compliance with the NSW requirements [J].

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

A. Strategy Review Paper. Met Office Science Advisory Committee. *Aerosol strategy review.* 2013. Explains the Met Office rationale for the adoption of the GLOMAP aerosol model.
B. Letter from the Director of the Met Office Hadley Centre.
C. Met Office Publication. Walters, D., et al., 2019. The Met Office Unified Model Global Atmosphere 7.0/7.1 and JULES Global Land 7.0 configurations. *Geoscientific Model Development,* 12(5), pp. 1909-1963. A publication that describes the Met Office model version with GLOMAP integrated.
D. Science Strategy 2016-2021 Met Office. States that the planned aerosol and cloud microphysics scheme builds on important developments in simulating and predicting aerosol concentrations across weather and climate models (p. 22).
E. Met Office Publication. Mulcahy, J. P., Jones, C., Sellar, A., Johnson, B., Boutle, I. A., Jones, A., et al., 2018. Improved aerosol processes and effective radiative forcing in HadGEM3 and UKESM1. *Journal of Advances in Modeling Earth Systems*, 10, pp. 2786–2805. Publication detailing further model adjustments implemented by the Met Office for climate modelling.
F. Report. Department for Environment Food and Rural Affairs/Department for Business Energy and Industrial Strategy/Met Office/Environment Agency *UKCP18 Land Projections Science Report*. November 2018.
G. Website. Met Office. UK Climate Projections 2018. https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/
H. Letter from Director of the Climate Science Centre, Commonwealth Scientific and Industrial Research Organisation, Australia.
I. Publication. Broome, R. A., et al., 2016. The mortality effect of ship-related fine particulate matter in the Sydney greater metropolitan region of NSW, Australia. *Environment International,* 87, pp. 85-93. Publication led by the Public Health Observatory, Sydney referencing use of the GLOMAP model.
J. Website. New South Wales Environmental Protection Agency. Identifies the contribution of study [I] and details of air quality monitoring and compliance in Sydney.