Institution: University of Reading		
Unit of Assessment: UoA7		
Title of case study: Novel model improves Met Office urban weather forecasting and informs strategic planning for urban heatwaves and climate projections		
Period when the underpinning research was undertaken: 2000-2013		
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:**
Peter Clark	(Manager of Met Office Mesoscale Modelling Group, Joint Centre for Mesoscale Meteorology, University of Reading) Professor	(2008-2010 de facto Category C) Between 2012 and Present
Janet Barlow	Professor	Between 2000 and Present
Stephen Belcher	Professor	Between 2000 and 2012 (Full-Time); Between 2012 and 2016 (Part-Time)
Period when the claimed impact occurred: Between August 2013 and 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Forecasting temperatures in urban areas is extremely challenging owing to the complexity of urban surfaces, and yet it benefits a range of users, including the road, rail and aviation sectors. In collaboration with the UK Met Office (MO), researchers at Reading produced a model of how buildings exchange heat with the atmosphere in a representative "street canyon," validated using a novel wind tunnel technique. Further development and testing against unique unit field data produced the MO-Reading Urban Surface Exchange Scheme or MORUSES. MORUSES was implemented in the UK operational forecast model (UKV) in 2016 which led directly to improved temperature forecasts, critical for public health through early warning forecasts of heatwaves in urban areas. Its inclusion in the world-leading UKCP18 Local (2.2 km) climate projections is improving the capability of city authorities such as Bristol and London to plan for future climate adaptation. One of the MO's strategic goals is to provide urban forecasts approaching 100 m resolution by 2030: MORUSES is at the heart of its aim to provide high quality predictions of urban weather and climate.

2. Underpinning research

In 2018, the United Nations reported that 83% of the UK population lived in urban areas, where 10,000 people or more are living. Urban areas have their own micro-climate, with major impact on wind, temperature and even humidity. When heated by the sun, urban surfaces cool down more slowly than surrounding areas, producing "urban heat islands" (UHI). Within cities, neighbourhoods consist of buildings of different materials and streets of different widths which affect how heat is exchanged between the surface and the atmosphere. The challenge is to capture the diversity of neighbourhoods yet represent the physics simply enough to include in a weather forecast model. Work to devise an urban surface scheme by scientists in the unit was led by Professor Stephen Belcher who worked in the unit until 2016.

A simple starting point is to assume that all streets are 'street canyons' – parallel rows of buildings of the same height. Heat is transferred from four different facets - street, two walls and roof - to the atmosphere, like electric current flowing through a network of resistors, at a rate controlled by wind patterns. In 2004, a novel wind tunnel modelling technique was used by Janet Barlow to investigate the impact of street width on heat transfer from each facet [R1]. This innovative data proved critical in validating a new street canyon resistance 'network model' devised by Reading PhD student Ian Harman [R2], supervised by Stephen Belcher and Met Office (MO) CASE Award co-supervisor Martin Best, who had devised the 'urban-1tile' scheme implemented in the MO Unified Model (UM) at the time.

Building materials store up heat in the daytime that is released slowly at night due to thermal inertia. Heat is also 'trapped' because walls and street radiate to each other. It is crucial to capture these physical characteristics to simulate urban heat islands. Further research by PDRA Aurore Porson [R3], under Belcher's supervision, compared simplified versions of the network model with only one, two or three facets represented. When Porson evaluated against observations at an urban site, she obtained the best results, when compared to the four-facet version, using two facets: roof, and merged street and walls. This was because the street-wall facet has large thermal inertia, whilst the roof has a low value, and street and walls exchange heat through radiation. For streets of different widths, heights and building materials, the weighted combination of the two facets provides flexible parameter control for diurnal temperature range and rate of cooling, which the earlier urban-1tile scheme was unable to achieve (as it only has one facet).

This was a critical finding that enabled the development of the MO Reading Urban Surface Exchange Scheme or MORUSES, which was a collaboration between University of Reading scientists and MO staff (Peter Clark, Martin Best) and is described fully in [R4]. The new scheme represents the urban area as a composition of two 'tiles' – roof, and merged street and walls – where a tile is the fraction of a weather forecast model grid-box (typically 1.5km square) taken up by a single type of surface. When implemented in the UM and set up to mimic the urban-1tile scheme, MORUSES produced results that were consistent with it physically which was an important sense-check [R4]. However, MORUSES offers more flexibility than the urban-1tile scheme in the representation of buildings. Heat stored in the MORUSES roof tile could be modelled in two different ways – using a thin roof or changing the material properties [R5]. When compared against observations of heat fluxes (i.e., flows of heat between building surfaces and the air), the MORUSES thin roof configuration gave a 33% reduction in error compared to the urban-1tile scheme [R5]. Accurate simulation of heats fluxes leads to better temperature forecasts.

The ultimate test of the model was to simulate the UHI of a whole city. In 2011, PDRA Sylvia Bohnenstengel, under Belcher's supervision, used MORUSES, implemented in the UM, to simulate London's UHI at a model resolution of 1 km^2 as part of the EPSRC-funded LUCID project [R6]. An important step was to derive input parameters for MORUSES – such as street width – from available data. Research was undertaken to relate a sophisticated but limited dataset detailing all of London's buildings to a simpler but more freely available urban land-use fraction dataset, already used in the UM. This parametrization is important as it underpins the application of MORUSES to all urban areas in the UK without needing high-resolution building data. Simulated temperatures agreed well with LUCID observations at a range of sites across London. This would not have been possible with the urban-1tile scheme, which lacks the capability to vary building shape and material properties in different neighbourhoods. This important improvement in physics representation allows much greater benefit to be obtained from running models at higher grid resolutions in urban areas. For instance, the modelled UHI showed subtle variation across the city in unprecedented detail and its relationship to local land use was studied to inform policies for climate adaptation [R6].

In summary, Barlow et al. used novel wind tunnel experiments [R1] to evaluate a new model of heat fluxes and temperatures in street canyons [R2]. Further insight gained by the Reading researchers into the physical processes controlling the fluxes allowed a simpler version of the model to be developed [R3]. This allowed the Reading team to develop the MORUSES scheme [R4] which was able to match results from the existing MO scheme but demonstrated much more flexibility in representing different types of buildings [R5]. Simulations of London's climate using MORUSES agreed well with measured data [R6] which paved the way for its use in MO operational weather forecasting and climate projections.

3. References to the research

Research Quality Statement: All references were published in the peer-reviewed literature and meet or exceed the two-star quality criteria ("provides useful knowledge and influences the field"; "involves incremental advances"). Evidence of influence is indicated by Web of Science Citations in square brackets, as at December 2020.

[R1] Barlow, J.F., Harman, I.N. and Belcher, S.E. (2004). 'Scalar fluxes from urban street canyons. Part I: Laboratory simulation'. *Boundary-Layer Meteorology*. **113**(3), 369-385. DOI: https://doi.org/10.1007/s10546-004-6204-8 [82]
[R2] Harman IN, Barlow JF, Belcher SE. (2004). 'Scalar fluxes from urban street canyons. Part II: Model'. *Boundary-Layer Meteorology*. **113**, 387–410. DOI: https://doi.org/10.1007/s10546-004-6205-7 [69]
[R3] Porson, A., Harman, I.N., Bohnenstengel, S.I., and Belcher, S.E. (2009). 'How many facets are needed to represent the surface energy balance of an urban area?'. *Boundary-Layer Meteorology*. **132**(1),107-128. DOI: https://doi.org/10.1007/s10546-009-9392-4 [23]
[R4] Porson, A., Clark, P. A., Harman, I. N., Best, M. J. and Belcher, S. (2010). 'Implementation of a new urban energy budget scheme in the MetUM. Part I: Description and idealized simulations'. *Quarterly Journal of the Royal Meteorological Society*. **136** (651), 1514-1529. ISSN 1477-870X. DOI: https://doi.org/10.1002/qj.668 [36]
[R5] Porson, A., Clark, P. A., Harman, I. N., Best, M. J. and Belcher, S. (2010). 'Implementation of a new urban energy budget scheme into MetUM. Part II: Validation against observations and model intercomparison'. *Quarterly Journal of the Royal Meteorological Society*. **136** (651), 1530-1542. ISSN 1477-870X. DOI: https://doi.org/10.1002/qj.572 [19]
[R6] Bohnenstengel, S. I., Evans, S., Clark, P. A. and Belcher, S. E. (2011). 'Simulations of the London urban heat island'. *Quarterly Journal of the Royal Meteorological Society*, **137** (659), 1625-1640. ISSN 1477-870X. DOI: https://doi.org/10.1002/qj.855 [115]

4. Details of the impact

Met Office (MO) Operational Forecast Model

In March 2016, MORUSES was implemented in the MO's regional UK operational weather forecast model, the UKV, run at 1.5 km resolution. This was as the result of evidence from two reports, the first of which involved evaluation of the UKV, including MORUSES, by a MO CASE student and MO Category C staff at Reading. They compared MORUSES with the University of Reading heat flux data in London that the MO does not routinely measure [S1a], and demonstrated that it produced a sensible heat flux (i.e. the turbulent flow of heat from surface to atmosphere) that was the right size and with a much more accurate daily pattern than its predecessor, the urban-1tile scheme. This reduced errors in predicted urban temperatures and boundary layer depth, as detailed in a second Reading-authored MO Report that extended the analysis for London [S1b]. MORUSES further proved its validity when it was trialled in the operational forecast and results were compared with standard MO observation sites across the UK. Even in rural areas, MORUSES improved the temperature forecast because of downwind transport of heat from larger conurbations, whereas the urban-1tile scheme had made little impact [S2].

Accurate forecasting of urban weather in different climate zones is important for international operational and research centres that partner with the MO to use and develop the UM (the 'UM Partnership'). Together with the Meteorological Service of Singapore, the MO developed the SINGV numerical weather prediction model which became operational in 2019 [S3a]. The National Environment Agency of Singapore sponsored a 300m resolution study using SINGV incorporating MORUSES and using bespoke urban land use data which found a temperature *"bias … smaller than predicted by other Urban Canopy Parametrisations reported in the literature"* and *"that MORUSES is clearly able to represent the impacts of different neighbourhoods on the thermal environment"* [S3b]. MORUSES was proving valuable in improving temperature forecasts both in the UK and for an international city. Its good performance in a high-resolution model (300 m) was especially promising.

MO London model and research and innovation strategy

The MO set up a one third of a km resolution regional 'London model' (LM) in September 2013 to pioneer high-resolution urban forecasts, initially aimed at improving forecasts of fog around Heathrow airport [S4a]. Run once daily, LM output is provided to complement the UKV forecast which does not have the resolution to capture small-scale fog, which is very disruptive to flights and operations at Heathrow [S4b]. Early feedback from meteorologists based at Heathrow suggested that the LM tended to over-forecast fog in urban areas. When MORUSES was tested in the LM and compared to the urban-1tile scheme, it led to earlier warming in the morning and slightly later cooling in the evening. As fog evaporates when temperatures rise, this resulted in higher visibilities in urban regions and reduced the over-prediction of fog as detailed in the MO Clean Air Report [S4c]. Since March 2019, MORUSES has been implemented in the LM, which is still run daily.

Improving urban forecasting is of increasing importance to the MO as it needs to provide weather and climate services down to the scale of neighbourhoods, requiring model resolutions approaching 100 m. This is reflected in the 'Ready to resolve' theme of the current MO Research and Innovation Strategy (2019-2024), in which urban forecasting at high resolution is a key goal by 2030. To date, the MO has invested in the scientific development of MORUSES through time of seven members of University staff, as well as sponsorship of University of Reading higher-degree students through four CASE Awards [S5]. MORUSES became operational in 2016 and proved its effectiveness at higher resolution in the LM. In 2019, the MO stated in their internally distributed MOSAC (Meeting of the MO Scientific Advisory Committee) paper that *"We wish to standardise this [MORUSES] to be the only urban-S(urface)E(nergy)B(alance) scheme used within the Unified Model"* [S6]. Professor Simon Vosper, Director of Science at the MO affirms that *"MORUSES remains at the heart of our strategy to deliver high quality predictions of urban weather and climate"* [S5].

High-resolution UKCP18 and UKCP local climate projections

Future heatwaves are projected to increase in intensity due to climate change. Urgent action is required to address overheating in buildings (with its impact on people) and to reduce the impact of urban heat islands – according to the 2017 UK Climate Change Risk Assessment. The previous climate projections produced by the MO Hadley Centre in 2009 were limited in model resolution (25 km) and provided only coarse information about urban temperature rise. The UK Climate Projections 2018 (UKCP18) give the most comprehensive picture yet of how the climate could change in the UK at 12 km resolution in the coming decades. UKCP18 gives *"governments, local authorities, land managers, national infrastructure bodies and other businesses an invaluable set of tools with which to assess the nature and scale of challenges and take decisions accordingly,"* says Michael Gove, then UK Secretary of State for Environment, Food and Rural Affairs in a Speech on UK Climate Change Projections in 2018 [S7a]. In September 2019, for the first time internationally, projections were provided at a resolution of 2.2 km ('UKCP Local') which allows these important stakeholders to assess risk of future extreme weather events, not just climate trends. Because of its proven benefits in higher resolution models, MORUSES was included in UKCP Local, allowing meteorologists to discriminate between neighbourhoods with different building types [S7b]. This is critically important for local authorities who are using the local projections to plan for climate adaptation.

Bristol City Council, the first UK local authority to declare a climate emergency in November 2018, commissioned engineering consultants Arup to make a preliminary climate resilience assessment based on regional UKCP18 data at 12 km resolution, acknowledging that higher resolution data was not yet available at that time [S8a]. Ongoing at the time of writing, the MO is working directly with Bristol City Council *"on development of a tiered urban heat service. This uses the 2.2 km data, with future work to "link heat to a particular city vulnerability that Bristol are interested in"* [S8b]. Mayor of London Sadiq Khan has *"asked the Met Office to issue a London version of the UKCP18 data…there are a few significant differences between 2018 and the 2009 projections that the London Environmental Strategy is based on. We … will … update our analysis if necessary"* [S9]. The Greater London Authority (GLA) has already made use of MORUSES data. Temperature data for London generated during the LUCID project for an extremely hot summer, 2006, are available through the GLA website [S10a] and were used by Arup in a project together with the GLA to identify urban heat risk [S10b]. Heat-Health Watch alerts, example from August 2020 here, based on regional temperature forecasts by the MO in association with Public Health England, are issued by the GLA to health professionals and emergency planners to manage heatwave periods. It now provides early warnings by region and London is given its own, recognising its unique urban heat island. In addition to the emerging impact of the UKCP Local dataset in tackling urban heat risk in the future, accurate, high-resolution, urban heatwave forecasting is clearly needed now by a wide range of stakeholders.

Summary

The complexity of urban surfaces makes forecasting temperatures in cities extremely challenging. Weather forecast models require representation of the microclimatic processes controlling temperature that are simple enough to implement and yet sophisticated enough to represent different urban neighbourhoods. Researchers at Reading produced and validated a model of how radiation and turbulence transfer heat from buildings in a simple 'street canyon.' Further collaborations led by the Reading team produced MORUSES; research measurements demonstrated its accuracy and, as a result, it has been used in the MO Unified Model since 2016 and in the London Model since 2019. MORUSES produced improvements in temperature forecasts across the UK and has improved performance in Singapore. The model is at the heart of MO strategy and capability in high resolution urban forecasting and climate projections. It allows the MO to develop much needed urban climate services for stakeholders such as local authorities who need climate projection data in unprecedented detail to protect neighbourhoods against future urban heat risk.

5. Sources to corroborate the impact

[S1] (a) King (2015): Comparison of UKV with MORUSES and JULES in Urban Areas, MO report on parallel suite trials for MORUSES implementation in UKV. R. King on MO internal secondment, supervised by S. Bohnenstengel (MO staff at the time).
(b) Bohnenstengel and Hendry (2016): MO Report on implementation and evaluation of MORUSES in the UKV (PS37).

[S2] Bornemann (2016), MO WGOS PS37 Impacts Summary Report.

[S3] (a) Huang et al. (2019) SINGV – the Convective-Scale Numerical Weather Prediction System for Singapore, ASEAN J. Sci. Tech. Development, 36(3), 81-90. DOI: https://doi.org/10.29037/ajstd.581
(b) Simón-Moral et al. (2019) Application of MORUSES single-layer urban canopy model in a tropical city: Results from Singapore, Q. J. R. Meteorol. Soc., 146(727), 576-597. DOI: https://doi.org/10.1002/qj.3694

[S4] (a) Boutle et al. (2016) The London model: forecasting fog at 333 m resolution, Q. J. R. Meteorol. Soc., 142, 360-371. DOI: https://doi.org/10.1002/qj.2656
(b) Heathrow forecaster email quote, October 2019. "The London model is extremely useful … It is especially used … as the resolution enables capture of fog banks and small scale fog which is the common fog type at Heathrow…it is really important for the team to use."
(c) Finnekotter et al. (2019) MO Clean Air WP 4.4 Deliverable Report: Sub-km Atmospheric Models.

[S5] Testimonial from Director of Science, Met Office, September 2020

[S6] MOSAC paper 23.15. Towards 100 m urban-scale modelling. Meeting of the MO Scientific Advisory Committee, January 2019. pages 122-125

[S7] (a) UK Secretary of State for Environment, Food and Rural Affairs, Speech on UK Climate Change Projections, November 2018.
(b) Kendon et al. (2019) MO Report on "UKCP Convection-permitting model projections: Science report".

[S8] (a) Arup report "Bristol One City Climate Strategy – Preliminary climate resilience assessment". P7, February 2020.
(b) Email from the Manager for Urban Climate Services, MO to Janet Barlow, University of Reading, September 2020.

[S9] Letter from London Mayor Sadiq Khan to MP Caroline Russell concerning the "Climate Change Risks for London" report based on UKCP18, June 2019.

[S10] (a) Greater London Authority dataset "London's urban heat island – during a warm summer" – created 2017, accessed July 2020.
(b) Arup report "Reducing urban heat risk", July 2014 – Reference to Reading data on page 17 under "Air Temperature Data."