Report on implementation and evaluation of MORUSES in the UKV (PS37)

June 21, 2016

Sylvia I. Bohnenstengel & Maggie A. Hendry

Contents

Executive Summary

More than 50% of the world's population now live in urban areas and an accurate representation of urban atmospheric processes becomes increasingly important for a wide range of applications such as weather forecasts, air pollution, health, climate impact studies, energy use forecasts and for the building and insurance industry. The development of high-resolution O(1 km) atmospheric numerical models allows us to resolve the urban land-use in much greater detail. Up to now the Met Office has used a simple one-tile urban scheme (urban-1t) in the Unified Model in line with the land surface tiling scheme to account for the larger thermal inertia of urban areas. This approach improved the representation of the urban surface energy balance. However, urban-1t assumes the same urban parameters such as heat capacity over the whole city without taking into account how the building use and layout change throughout an urban area. For instance, commercial districts with high tower blocks have a much larger thermal inertia than small Victorian terraced houses in the suburbs. However, the urban-1t scheme does not account for these differences, since it proves difficult to obtain bulk parameters such as heat capacity or emissivity for an urban area at different scales. Hence, the current one-tile scheme leads to errors in the phasing and amplitude of the urban surface sensible heat flux in some urban areas, which in turn affects the simulation of near surface temperatures and the urban boundary layer structure. This report gives details about the newly implemented Met Office Reading Urban Surface Exchange Scheme (MORUSES) in the UKV which aims to address the aforementioned issues. An important part was the evaluation of MORUSES against urban observations in central London and the performance of MORUSES in the PS37 trials.

A key problem with the development of urban parametrisations is to obtain input data for the different types of urban areas such as commercial districts or terraced houses. MORUSES was designed with this in mind. MORUSES assumes that urban areas consist of two-dimensional infinitely long street canyons consisting of a street canyon with a road and two walls and a separate roof. It then uses a two-tile approach in line with the sub-grid scale land surface tiling scheme to calculate bulk values, for example thermal roughness length, emissivity etc., for the surface energy balance based on the geometry of the street canyon and properties of the building materials, which are easier to obtain. Importantly, MORUSES provides a more physically based approach to calculate the individual terms of the urban surface energy balance than the urban-1t scheme. The geometry based approach allows us to vary the bulk parameters for the surface energy balance at the grid

scale and take into account different building types throughout an urban area to calculate the urban surface energy balance.

MORUSES was tested for a case study in summer 2012, the whole of April 2015 and the PS37 Summer 2014, Winter 2013 and Winter 2015 (as part of the Stretch final package) trial periods. Model performance was determined against standard rural observations for the PS37 trials and observations taken in central London by research groups from University of Reading (Prof. Sue Grimmond, Dr. Simone Kotthaus, Prof. Janet Barlow and Dr. Christos Halios). We found that MORUSES improves the timing and the amplitude of the sensible heat flux in central London and compares well with observed surface heat fluxes and screen level temperatures. MORUSES leads to consistently slightly higher wind speeds than urban-1t, but wind speed and direction compare well against measurements in central London. The representation of the surface sensible heat flux and screen level temperatures has improved compared to urban-1t.

MORUSES has been successfully implemented, configured and tested for O(1 km) resolutions. The next stage of the project will be to configure and test the scheme at O(1 km) resolutions for urban areas outside the UK in central Europe and South-east Asia. In a further step the scheme will be configured and tested for higher resolution simulation of O(100 m) over the UK.

Introduction

The boundary layer and the surface energy balance of urban areas differ from rural areas. Urban areas are associated with warmer temperatures than the rural surrounding areas (urban heat island). The urban heat island is usually most pronounced at night when the boundary layer is relatively shallow and the surface energy balance has a significant impact on near surface air temperatures and the boundary layer structure. The urban heat island intensity is driven by the differences in the surface energy balance between urban and rural areas. During clear skies and calm conditions the differences are most pronounced in the UK. Rural areas have a much lower thermal inertia than urban areas. Consequently, urban areas slow down the cooling of the surface due to outgoing long wave radiation compared to say areas covered by grass, which cool down very quickly due to their low thermal inertia. This difference leads to a phase shift in the sensible heat flux between urban and rural areas with urban areas maintaining a positive sensible heat flux warming the atmosphere later into the night than rural areas. This phase shift causes a temperature difference in the surface and air between urban and rural areas and often a deeper and more well mixed boundary layer over urban areas. Earlier studies by Bohnenstengel *et al.* (2011) have shown that the London urban heat island can be as large as 6 K. With such a noticeable temperature difference it is therefore important to represent urban areas faithfully in high and probably also lower resolution numerical weather forecast models. In addition, air quality forecasts rely on a faithful representation of the boundary layer turbulent structure and will therefore benefit from a better representation of urban processes in the driving meteorology model.

The Met Office now runs their weather forecast model the UKV at a grid length of 1.5 km over the UK. This model represents the land surface in much greater detail than previous models using the ITE land surface dataset for the centre of the domain and the coarser IGBP dataset for France and Ireland. Despite the improved resolution of the land surface the UKV previous to PS37 represents urban areas with a simple one-tile urban surface energy balance scheme (urban-1t). Further urban-1t does not allow to account for the heterogeneity in urban morphology across a city and therefore assumes the same bulk values for emissivity, albedo, heat capacity and conductivity as well as roughness length for momentum and heat everywhere. As a consequence the UKV does not simulate the timing and amplitude of the surface sensible heat flux over urban areas correctly.

A new parametrisation for the surface atmosphere exchange for urban areas has been included into the UKV at PS37. The Met Office Reading Urban Surface Exchange Scheme (MORUSES) has been developed over the last 10 years as a collaboration between the University of Reading and the Met Office. MORUSES provides a more physically based representation of the urban surface energy balance than the current operational one-tile or the existing two-tile urban surface energy balance parametrisation, which has a separate canyon and a roof tile like MORUSES, but has prescribed parameters values like urban-1t. It is anticipated that the MORUSES parametrisation captures the phasing and the amplitude of the diurnal cycle of the urban surface energy balance and especially the sensible heat flux more faithfully when compared to observations in central London. It is further expected that MORUSES improves the diurnal cycle of screen level temperatures in urban areas and has an impact on the boundary layer structure, its evolution and depth.

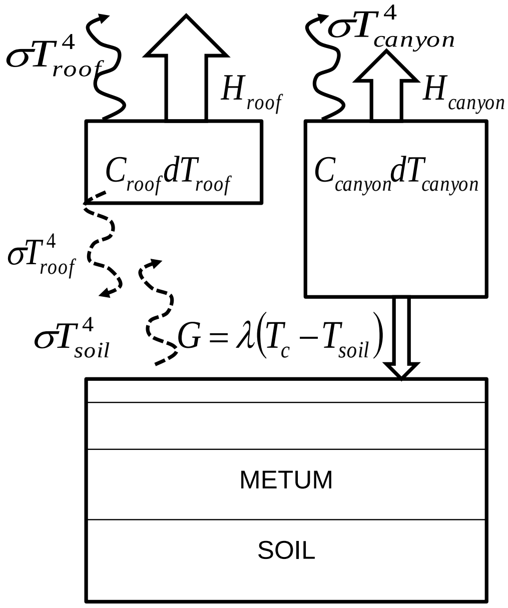
This report summarises MORUSES and presents an evaluation of MORUSES against urban-1t within the UKV and observations taken within central London by the urban working groups at Reading University, namely Prof. Sue Grimmond's and Prof. Janet Barlow's group.

MORUSES - Met Office Reading Urban Exchange Scheme

MORUSES is a two-tile urban surface energy balance parametrisation that was designed to work with easy to measure input parameters such as building geometry and material properties. MORUSES has been extensively documented in Porson *et al.* (2009, 2010a,b) and Bohnenstengel *et al.* (2011, 2014). MORUSES (Figure 2.1) treats the urban surface as a 2D infinitely long street canyon consisting of a street canyon tile, made up of walls and a street, and a separate roof tile. MORUSES calculates separate surface energy balances for the street canyon tile and for the separate roof tile in line with the land surface tiling approach of the UM. Hence, MORUSES captures the large difference in the thermal inertia between the street canyon and the roof. The geometry of the street canyon/roof unit represented by building height H, street canyon width W and repeating ratio R varies at the grid scale and allows MORUSES to account for the impact of the street canyon geometry on every single term of the surface energy balance across an urban area. This enables MORUSES to capture the timing and the amplitude of the surface sensible heat flux, which forces the atmosphere, more faithfully than the current one-tile approach used up to PS36 in the UKV.

MORUSES uses a slab approach to account for the storage of heat into the urban surface. It couples the canyon conductively to the underlying soil and we introduced radiative coupling of the roof to the underlying soil in PS37 (see equations in Figure 2.1). It further calculates the sensible heat flux using a resistance network approach to transport heat out of the canyon and accounts for three different flow regimes within the canyon. MORUSES calculates bulk values for the albedo and emissivity by accounting for shadowing and multiple reflections. The latent heat flux is dealt with by the land surface tiling scheme. A detailed description of MORUSES is available in Porson *et al.* (2010a).

Thermal inertia and conductively coupled ground heat flux



Adopted from Harman et al., 2004
and Porson et al., 2009, 2010

Canyon

Conductive coupling i
PS37

$$C_{canyon} = 2\frac{H}{W} c_{wall} \Delta z_{wall} + c_{road} \Delta z_{road}$$

$$G_{canyon} = -\lambda \; \frac{2*(T_{soil} - T_{canyon})}{(\Delta z_{soil})}$$

$$C_{canyon} \frac{dT_{canyon}}{dt} = R_{N,canyon} - Q_{H,canyon} - G_{canyon}$$

Roof

Radiative coupling in
PS37

$$C_{roof} = c_{roof} \Delta z_{roof}$$

$$G_{roof} = \sigma T^4_{roof} - \sigma T^4_{soil}$$

$$C_{roof} \frac{DT_{roof}}{dt} = R_{N,roof} - Q_{H,roof} - G_{roof}$$

Figure 2.1: Schematic of MORUSES adopted from Harman *et al.* (2004) and Porson *et al.* (2009, 2010a). Dashed lines indicate radiative coupling. Note that capital C's are referring to areal heat capacity, while small c's are referring to volumetric heat capacity.

Setup and ancillaries for MORUSES

MORUSES uses morphological input data such as average building height H, height to street canyon width ratio H/W and repeating ratio W/R (Bohnenstengel *et al.*, 2011) to describe the geometry of an urban area at each grid point. These fields are made available to the Unified Model via an ancillary file (qrparm.urb.morph, see ancil:#125 and ancil:#270) containing these three fields. For the UKV set-up these ancillary fields were derived from the sub-grid scale urban land-use fraction (f_u) in the qrparm.veg.frac ancillary file for each grid box using the empirical formulations according to Bohnenstengel *et al.* (2011) and Eq. 3.1.

$$H = 167.41 f_u^5 - 337.85 f_u^4 + 247.81 f_u^3 - 76.37 f_u^2 + 11.48 f_u + 4.48 \qquad (3.1)$$

The qrparm.veg.frac file itself is then modified to include two urban land-use fractions - one for the street canyon ($\frac{W}{R} f_u$) and one for the roof fraction ($[1 - \frac{W}{R}] f_u$) - in line with the land surface tiling scheme. The empirical relationships for H/W and W/R were derived from a configuration of the UM with 1 km grid length based on the ITE land-use dataset and a metre-scale morphological data set for London (Bohnenstengel *et al.*, 2011) and similarly for H. The advantage of the empirical formulations is that they provide a simple way to generate morphological input data based on existing urban land-use data. The disadvantage is that this relationship has so far only been derived and tested for O(1 km) grid lengths for London and it remains open how the relationship between urban morphology and urban land-use fraction varies with grid resolution and type of land-use dataset. If we assume a standard city layout with a dense commercial district with high urban land-use fractions and a decreasing urban land-use fraction towards the suburbs then the relationships will generate smaller buildings towards the less densely populated suburbs and taller and denser building layout towards the city centre. By using the empirical relationship rather than the original morphological parameters some of the variability within the morphology for the same urban land-use fraction is lost; however the morphological ancillary fields are still varying with the underlying urban land-use fraction. As a consequence areas with high urban land-use fractions are always associated with taller buildings and areas with lower urban land-use fractions are always associated with low-rise buildings. However, at the moment high-resolution morphological input data are not available for every city and so the empirical relation provides a simple way to derive a varying geometry ancillary file based on the most basic information such as urban land-use. It needs to be tested how the relationship varies for different cities within the UK, Europe and outside of Europe. The World Urban Database and Access Portal Tools (WUDAPT)[1] is an initiative that will provide urban land-use and categories of different building types worldwide in the future and can hopefully be used to derive morphological data independently from the underlying urban land-use fraction.

Figure 3.1 shows the urban land-use fractions for canyons and roofs for the UKV domain. Due to the use of coarser IGBP land-use data in the outer domain the urban land-use over cities like Paris looks coarser. Since the UKV domain consists of land-use data from both the ITE land cover data for the inner domain and IGBP land cover data for the outer domain, the impact of the coarser IGBP data on the surface energy balance and screen level temperatures was tested for a case study on 25th July 2012 for London. For IGBP data the urban fraction in each grid box is often larger than for ITE data for the bigger cities such as London and Birmingham. For instance, Figure 3.2 shows IGBP land-use over the UK and the suburbs of the larger cities are depicted with a larger urban fraction for canyon and roofs in case of the IGBP dataset compared to the ITE dataset. The ITE dataset (Figure 3.1) shows more variability in the suburbs than the IGBP dataset (Figure 3.2). At the same time, very small urban fractions are less well represented in the IGBP dataset and a lot of detail is lost compared to the ITE dataset in more rural areas. Figure 3.3 (left) shows in more detail a comparison between the urban fraction from the IGBP and PS36 ancillary where the agreement between the IGBP areas from both ancillaries can reassuringly be seen in the 1:1 line. In mainland UK, where the ITE is compared to the IGBP dataset, there is no correlation between the two datasets and so a tuning of the empirical relationship for IGBP areas would not be appropriate. The IGBP also seems to have a minimum urban fraction threshold of 1% compared to the more continuous ITE dataset, where 25% of the urban points have a fraction less than or equal to 0.5%. In this respect, some investigation would be required into the more representative dataset. Figure 3.3 (right) shows the probability distribution of both the PS36 (black) and IGBP (blue) urban fraction where the IGBP clearly favours larger urban fractions. Figures 3.4 and 3.5 show the morphology data derived from the ITE and IGBP datasets respectively.

The live PS37 morphology ancillary differs slightly from that shown in Figure 3.4, but in a bit comparable way for the UKV. It became necessary to enable the `all_tiles` option during the parallel suite to ensure that MOGREPS-UK had sensible values for tiled fields. The `all_tiles` option calculates the surface energy balance on each tile irrespective of the tile fraction. The zero fraction tiles however, are not then passed to the atmosphere. In previous parallel suites MOGREPS-UK was initialised from the global, which currently has an aggregate tile. This is the first parallel suite where MOGREPS-UK has been initialised from the UKV analysis. During reconfiguration from the global, MOGREPS-UK tiled fields are initialised from global equivalent fields and thus have sensible values. However, when the UKV is used to initialise MOGREPS-UK, the reconfiguration from 1.5 to 2.2 km inadvertently leads to values from gridboxes that have zero fraction being interpolated. Without `all_tiles`, the UKV surface temperature on tiles prognostic in particular develops unphys-

[1] See `http://www.wudapt.org`

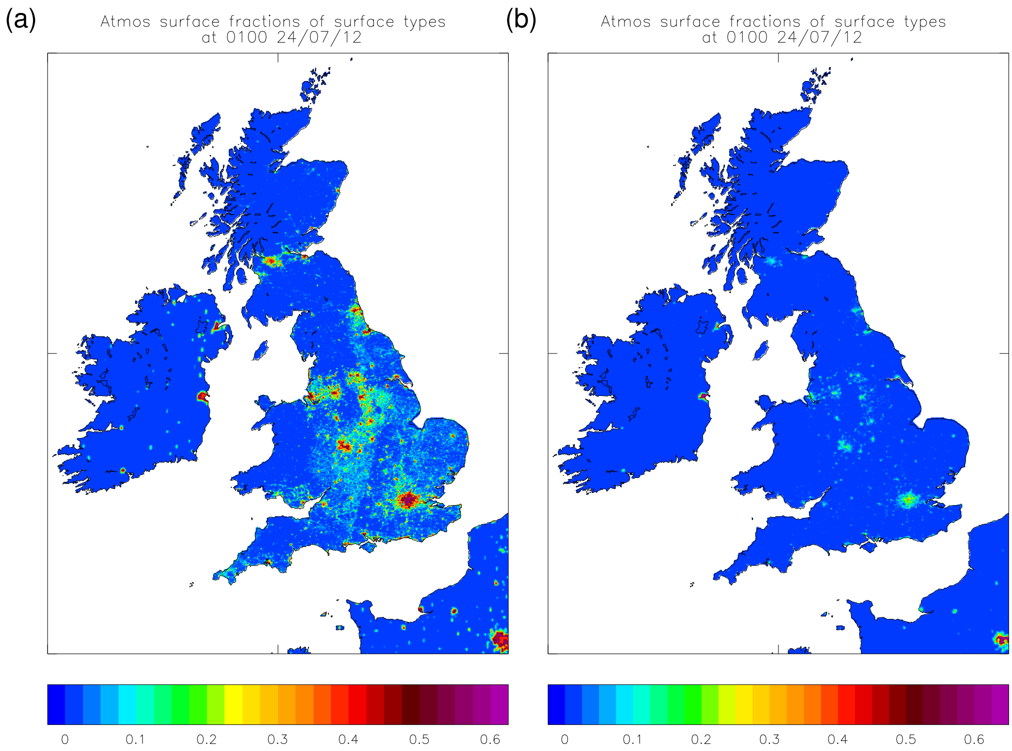


Figure 3.1: Urban land-use fractions for canyon (a) and roof (b) derived from ITE land-use dataset for varying morphology for inner domain and IGBP land-use fractions for outer domain.

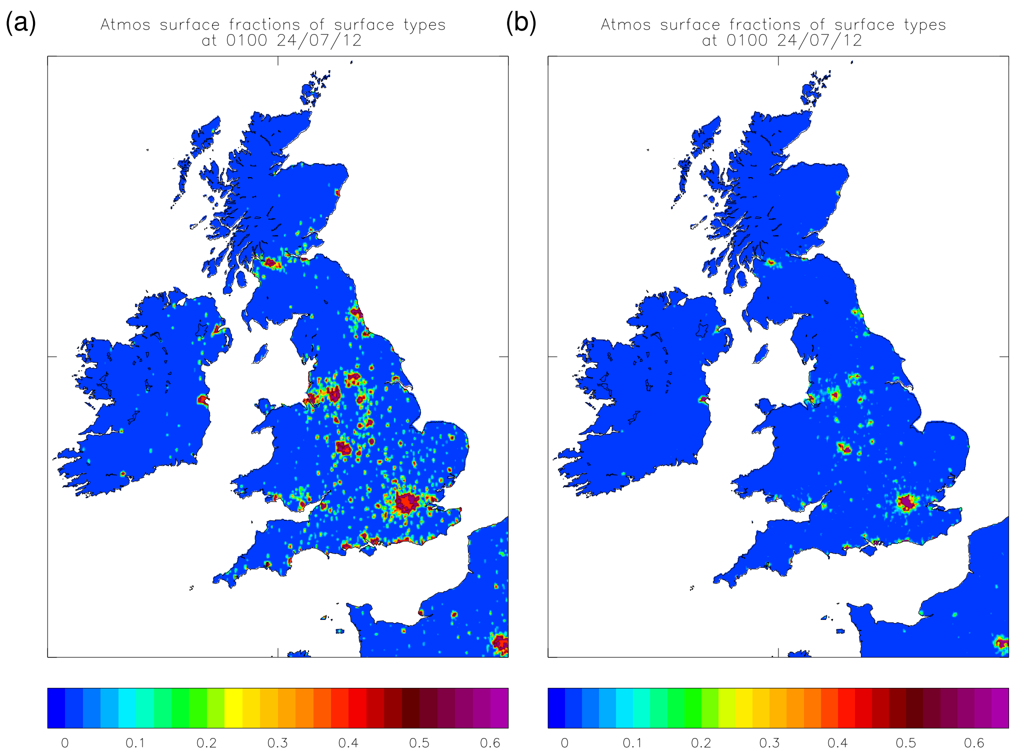


Figure 3.2: Like Figure 3.1, but for IGBP land-use data.

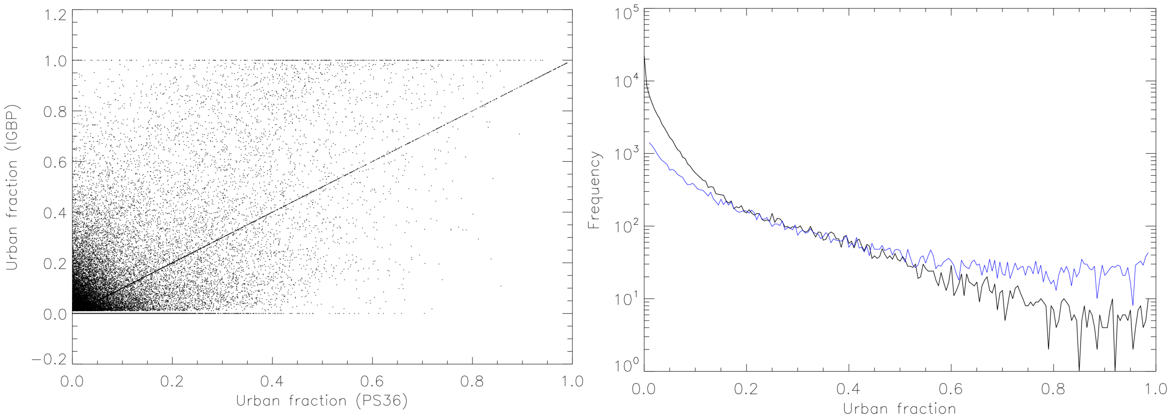


Figure 3.3: Comparison of urban fraction from IGBP and operational PS36 UKV ancillary (left) and the probability distribution of the same (right); black = PS36 and blue = IGBP.

ical values in the zero fraction fields. This is probably a result of data assimilation which applies an increment to all tiles irrespective of surface type fraction, the increment is then not dissipated as calculations are not performed on these tiles. The PS37 MOGREPS-UK trials had a fix for this where the tiles with zero fraction were set to the gridbox mean before interpolation, however, no other tiled field had similar treatment. Without `all_tiles`, the tiled fields contain values from the global model left over from the last cold start, which could be from an entirely inappropriate time of year. In order to enable `all_tiles` with MORUSES a change to the ancillaries was necessary as the morphology where the urban fraction was zero (i.e. H = 0 m, H/W = 0.0 & W/R = 1.0), caused a fatal error. The gridboxes with zero fraction were populated using the empirical relationships with an urban fraction of 0.5% as a representative low urban fraction as previously discussed. This is equivalent to around 47 dwellings in each zero fraction gridbox given the average housing density in England of 42 dwellings per hectare[2]. The new ancillaries have not been shown here as the change only affects gridboxes with zero fraction; they have no impact on the UKV or the results in this report.

To determine the impact of morphology and land-use datasets on the surface energy balance and temperatures as independently as possible from each other two sensitivity studies were performed. In a first step an UKV configuration with ITE land-use was compared against an UKV configuration with IGBP land-use cover and the same constant morphology parameters for every grid box in order to determine the impact of the resolution of the sub-grid scale land-use on London without the impact of the morphology. In a second step the morphology was allowed to vary according to the empirical formulation based on the respective land-use information. When comparing the morphology fields derived from IGBP data (Figure 3.5) against the fields from ITE data (Figure 3.4) it becomes evident that the coarser IGBP data lead to a more urbanised land cover in the cities with less greening in the suburbs and urban morphology in the suburbs that is more representative of a densely built city centre. In case of the IGBP data the average building height in the larger cities is

[2]According to `http://www.insidehousing.co.uk/journals/insidehousing/legacydata/uploads/pdfs/IH.060623.035-037.pdf`.

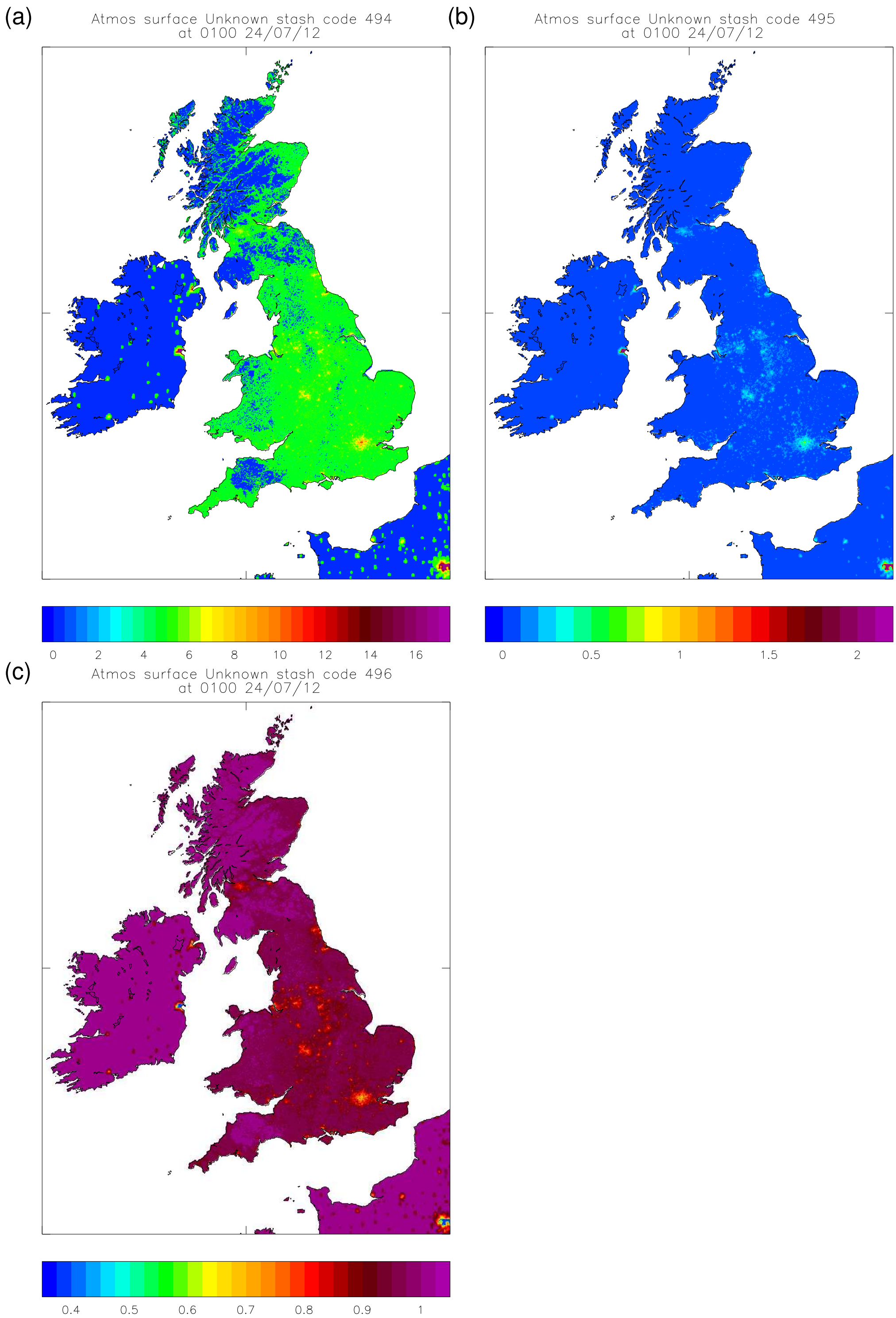


Figure 3.4: Varying morphology for (a) average building height in meters (stash code 494), (b) height-to-width ratio H/W (stash code 495) and (c) repeating ratio W/R (stash code 496) based on empirical relationship and using ITE land-use data for the inner UK and IGBP for the outer domain.

higher and spread out further. Further the height-to-width ratio is higher and the repeating unit is lower in the city centre. For areas with small urban fractions building heights are substantially lower and many areas with small urban fractions are missing.

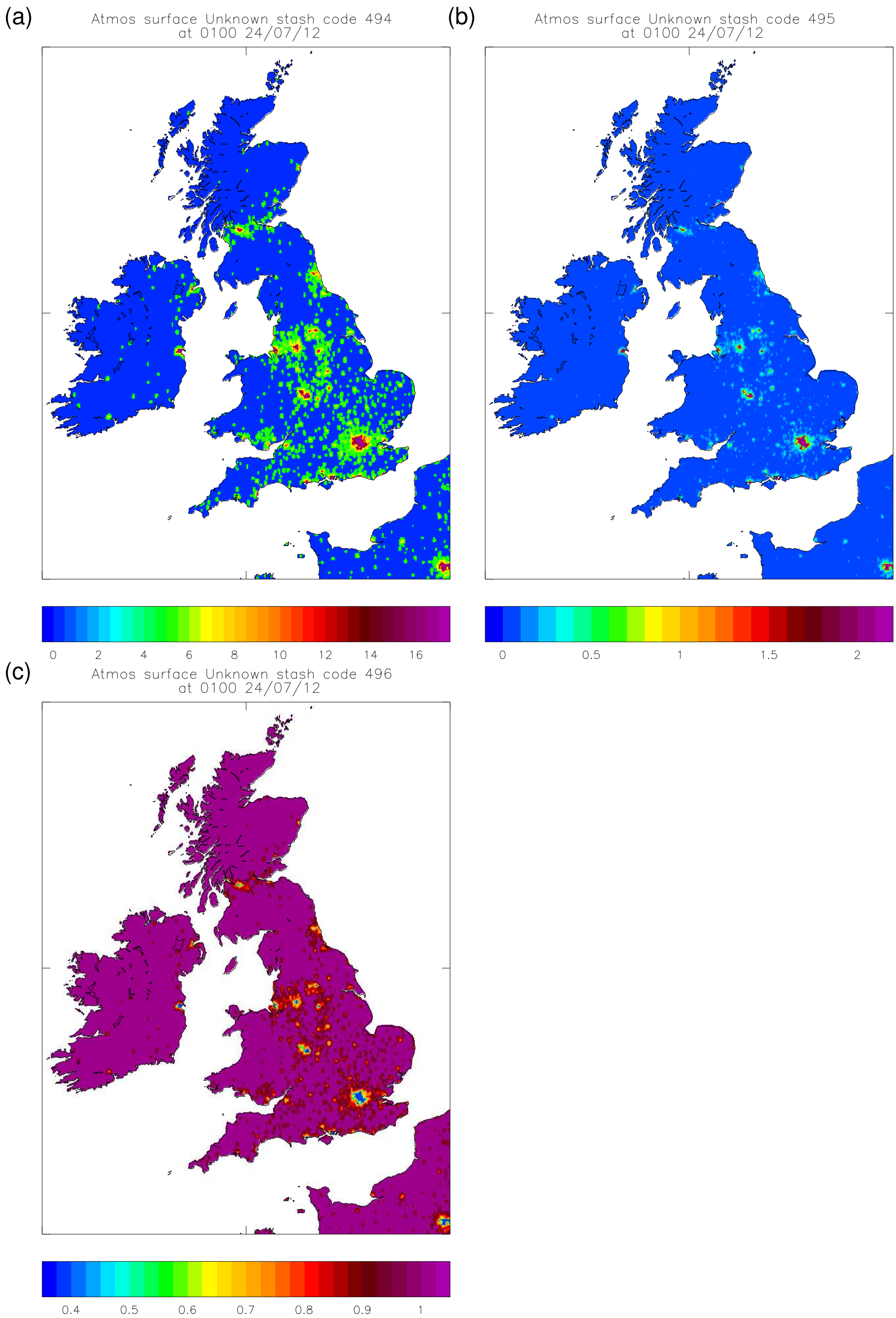
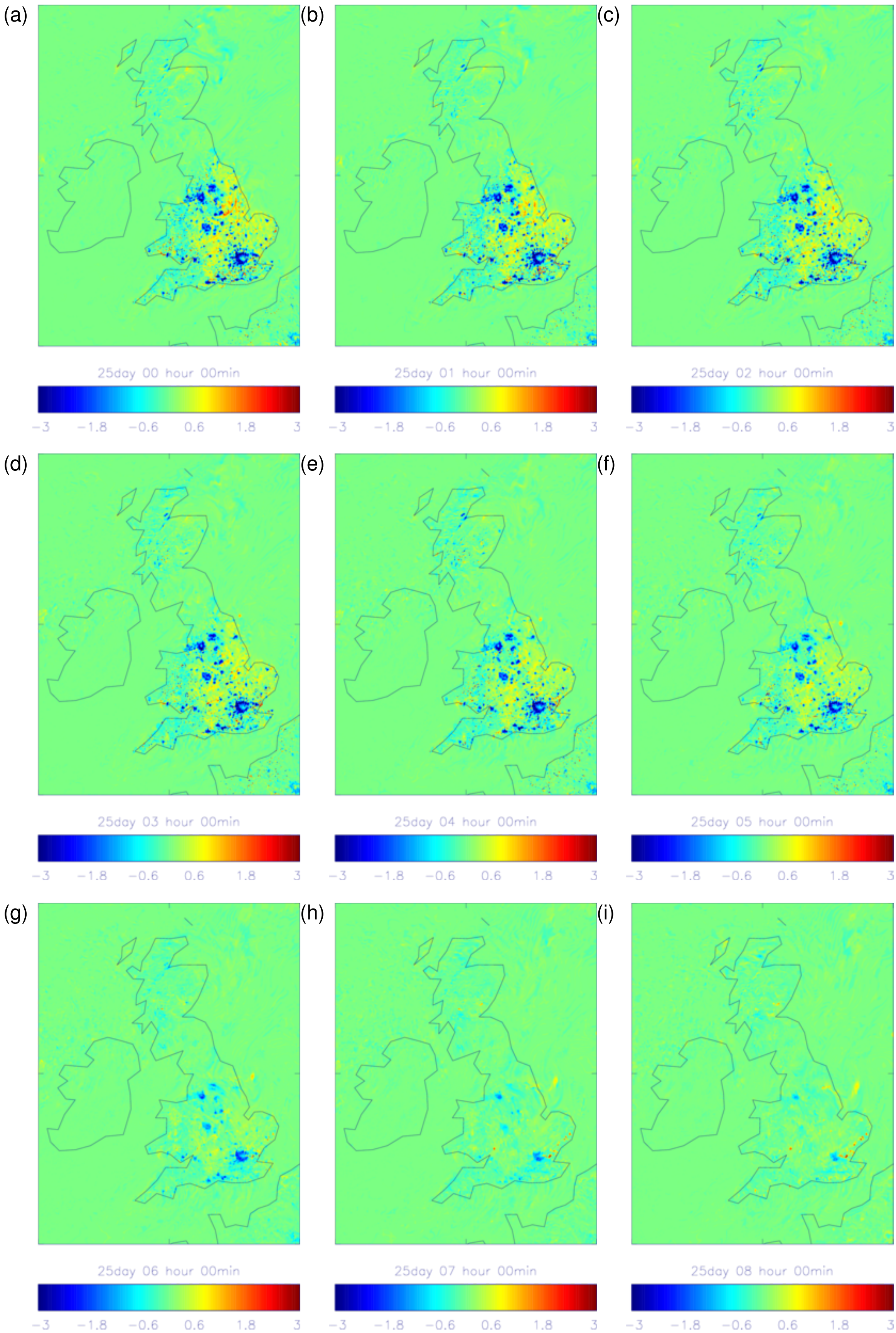


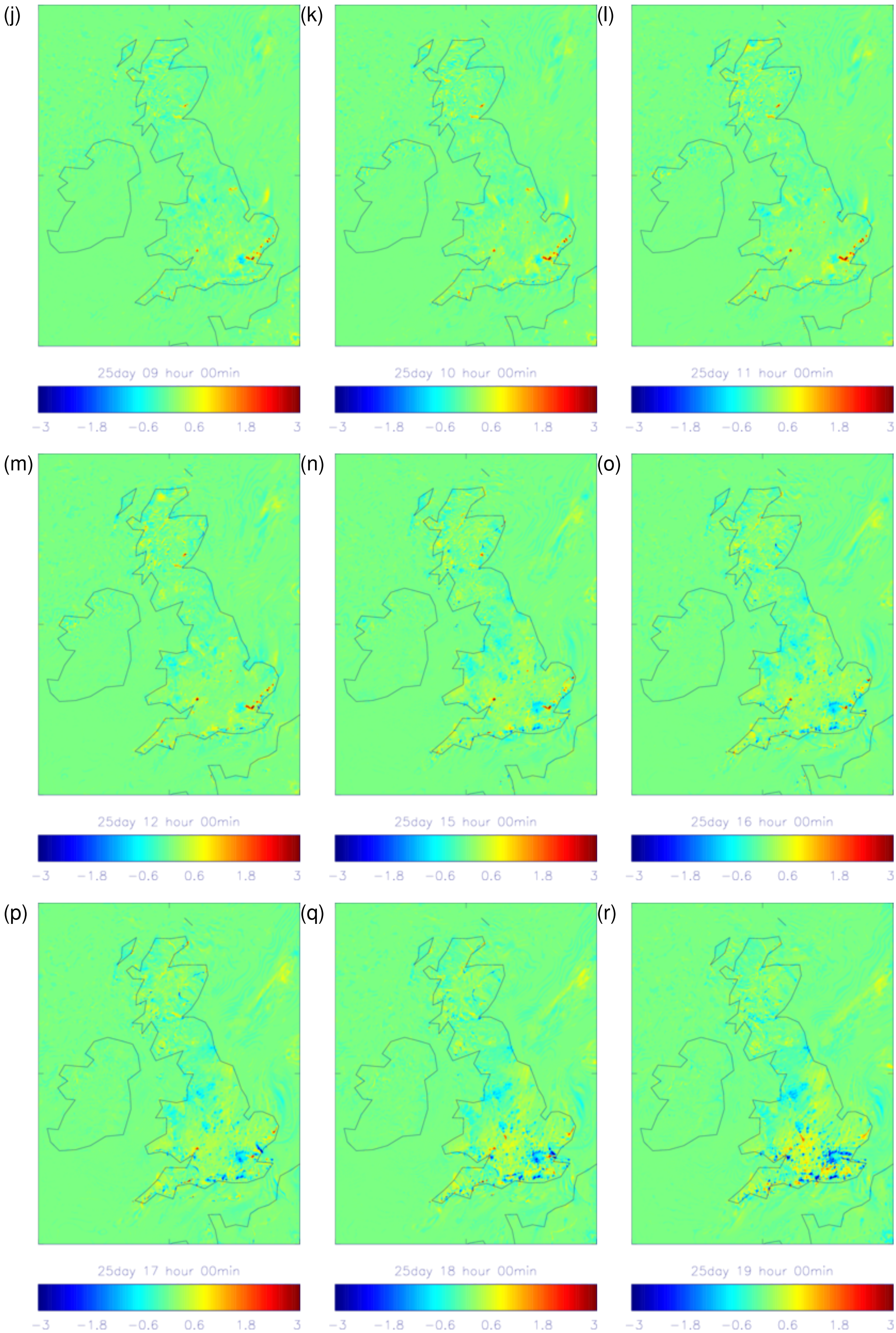
Figure 3.5: Like Figure 3.4 but based on empirical relationship when using IGBP land-use data for the whole domain.

Figure 3.6 shows the spatial plots of screen level temperatures at hourly intervals for constant morphology as ITE minus IGBP. During the night the ITE simulation is cooler in London's suburbs compared to the IGBP simulation. However, ITE shows slightly warmer temperatures in rural areas with low urban land-use fraction. When comparing the land-use datasets it becomes evident that the urban land-use is larger in the suburbs in the IGBP case leading to comparatively cooler temperatures in the ITE simulation. The thermal inertia and hence the ability to store heat during the daytime and maintain higher surface and air temperatures during the night is reduced with ITE. The opposite is happening in the more rural areas. In those areas the ITE simulation shows slightly larger urban fractions than the IGBP configuration and hence the ITE simulation is associated with a larger thermal inertia that in turn leads to warmer screen level temperatures at night. The differences in the city centre of London are smaller, since the ITE and IGBP datasets both show a high urban land-use fraction. The maximum temperature difference in the suburbs is up to 3 K. During the morning transition the differences between the two configurations start to vanish. This is partly caused by the deeper boundary layer that allows for more mixing and any differences in the surface energy balance are feeding into a deeper boundary layer during daytime which in turn leads to smaller differences in near surface air temperatures. Towards the evening transition the larger suburban IGBP land-use leads to warmer temperatures compared to ITE.

In a second step the urban morphology was allowed to vary as a function of the underlying urban land-use fraction. Consequently, the morphology between the ITE and IGBP configuration now differed. When including changes in morphology the temperature differences between the two configurations are smaller in amplitude and spatial extent and up to 2 K in the suburbs (Figure 3.7). The diurnal cycle of sensible heat fluxes for central London shows that the highest daytime values are seen in both IGBP simulations (Figure 3.8). When using varying morphology in combination with IGBP data this reduces the inner city peak sensible heat flux by about 60 Wm^{-2}. Replacing the IGBP data with ITE data then reduces the peak sensible heat flux by a further 40 Wm^{-2}. This translates into a 0.5 K temperature difference during noon (Figure 3.9). It is worth noting that even the IGBP dataset with constant morphology outperforms the timing and amplitude of the one-tile operational scheme during this case study, especially with regards to the timing of the forcing sensible heat flux. The sensible heat flux from urban-1t peaks too late in the day and its amplitude is too small. The IGBP simulations clearly overestimate the night and daytime temperatures in the city centre and the smaller ITE land-use fraction leads to a better comparison especially with regards to night time temperatures.

Altogether for this case study the sensible heat flux starts to increase more quickly than the observations and slightly underestimates the nocturnal heat flux. However, all UKV configurations tested here only contain a small anthropogenic heat flux of the order of 18 Wm^{-2}, which is lower than what is suggested in Bohnenstengel *et al.* (2014) for a city centre locations. The inclusion of a larger anthropogenic heat flux would likely increase the nocturnal heat flux in the inner city centre slightly.


(a)
(b)
(c)
25day 00 hour 00min
25day 01 hour 00min
25day 02 hour 00min
(d)
(e)
(f)
25day 03 hour 00min
25day 04 hour 00min
25day 05 hour 00min
(g)
(h)
(i)
25day 06 hour 00min
25day 07 hour 00min
25day 08 hour 00min
−3 −1.8 −0.6 0.6 1.8 3


(j)
25day 09 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(k)
25day 10 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(l)
25day 11 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(m)
25day 12 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(n)
25day 15 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(o)
25day 16 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(p)
25day 17 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(q)
25day 18 hour 00min
−3 −1.8 −0.6 0.6 1.8 3
(r)
25day 19 hour 00min
−3 −1.8 −0.6 0.6 1.8 3

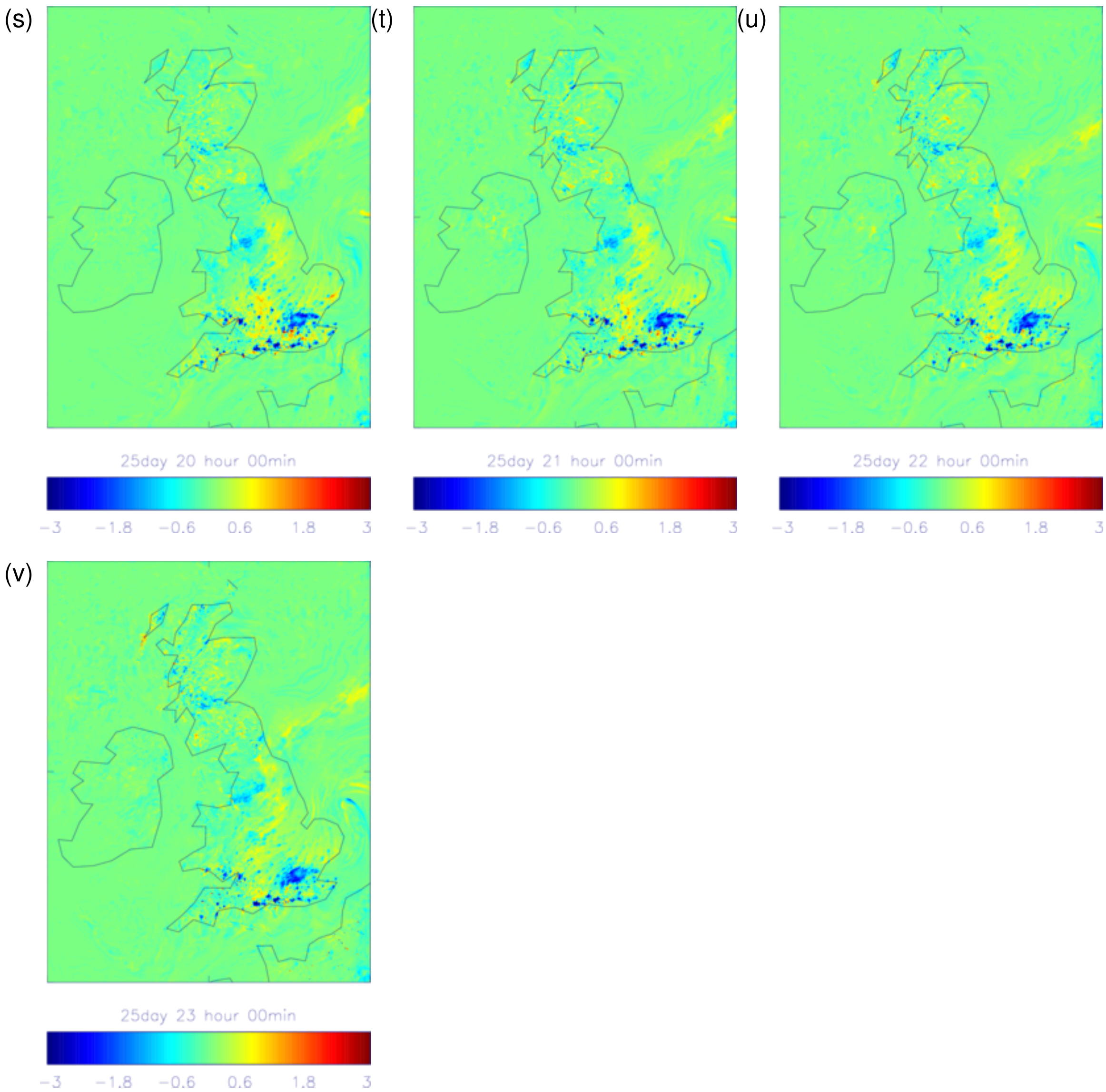
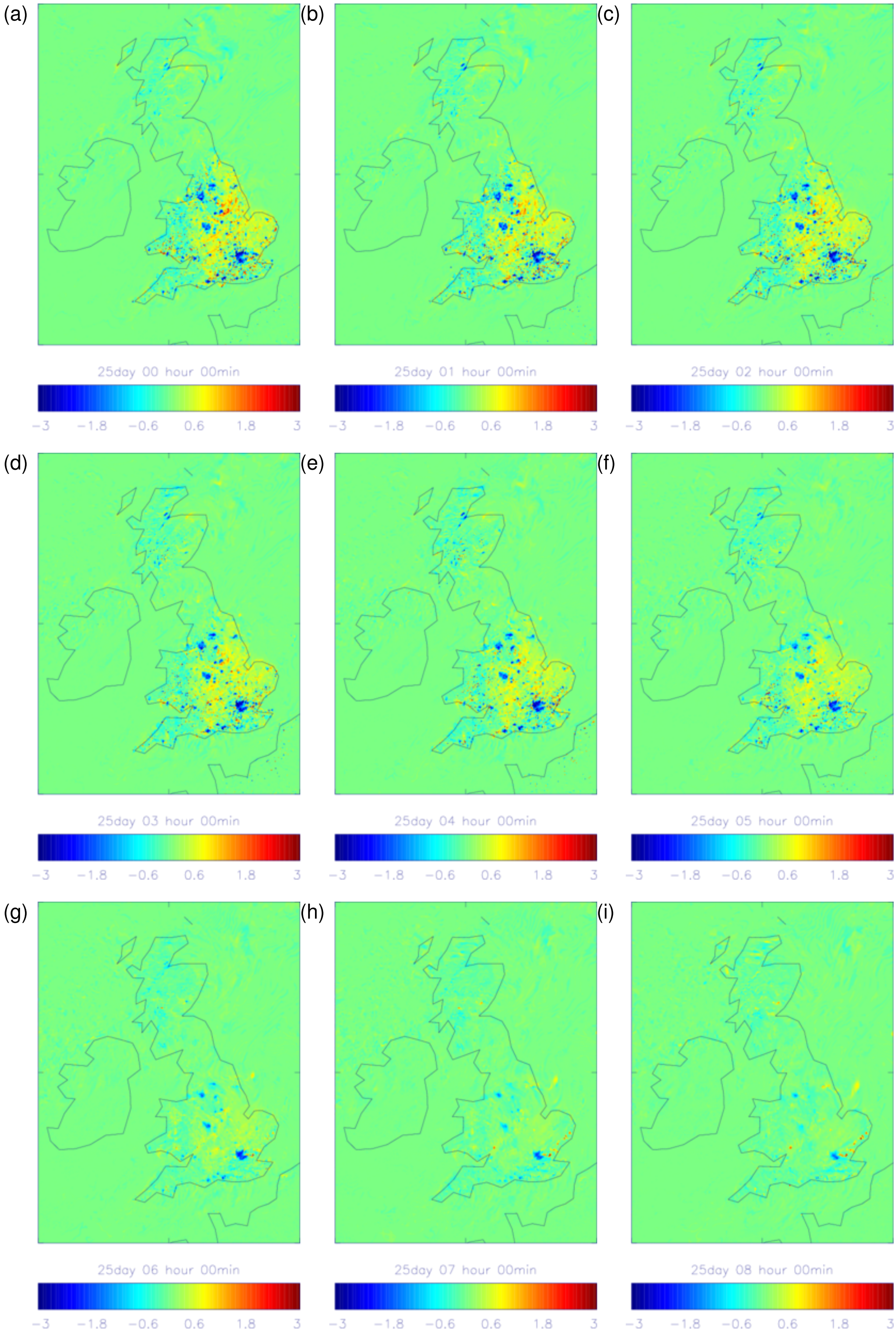
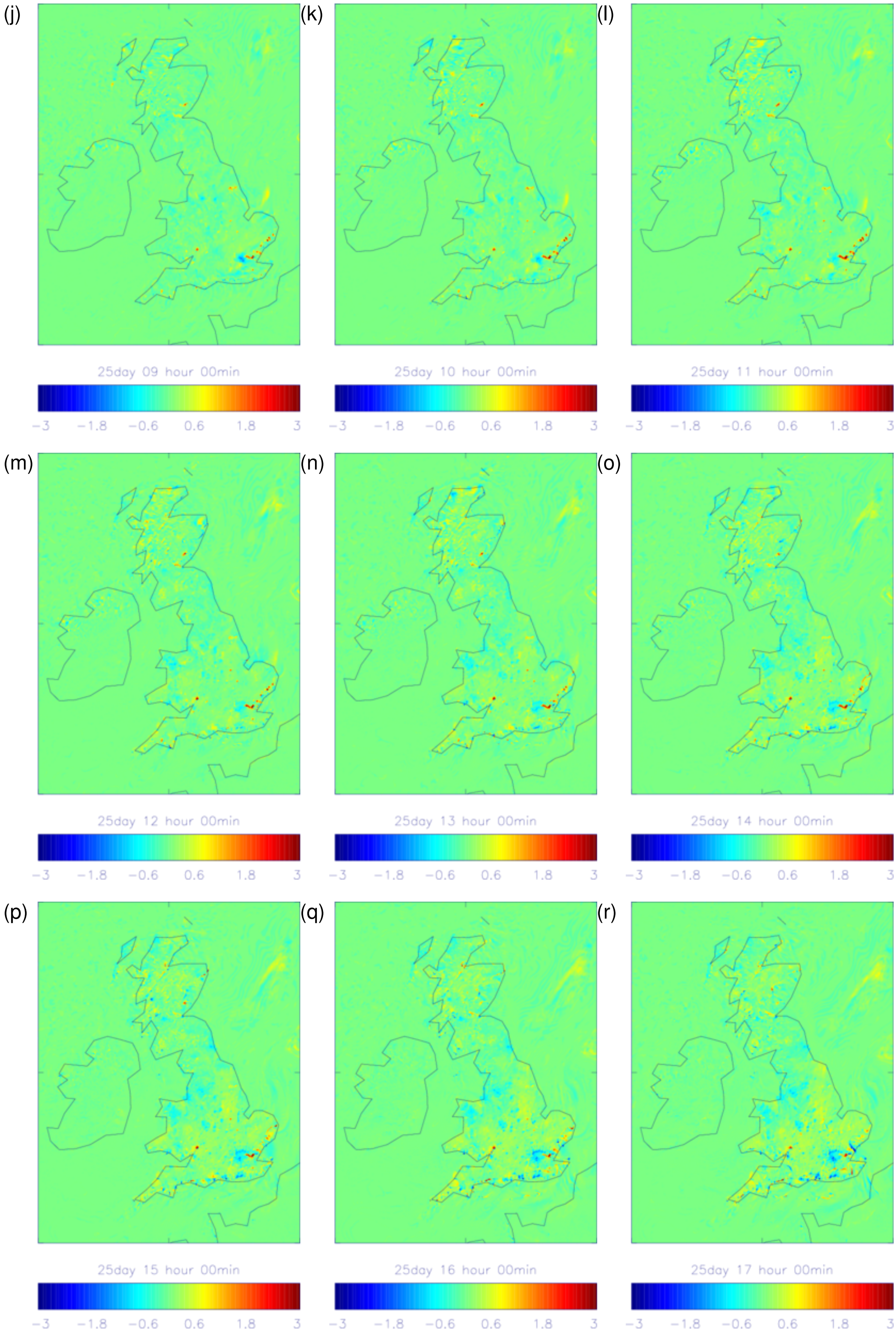


Figure 3.6: Difference in screen level temperature at hourly intervals between ITE and IGBP set-up with constant urban morphology with repeating ratio W/R = 0.5, height-to-width ratio H/W = 0.5, average building height H = 10 m.



(a)
(b)
(c)
25day 00 hour 00min
25day 01 hour 00min
25day 02 hour 00min
(d)
(e)
(f)
25day 03 hour 00min
25day 04 hour 00min
25day 05 hour 00min
(g)
(h)
(i)
25day 06 hour 00min
25day 07 hour 00min
25day 08 hour 00min
−3 −1.8 −0.6 0.6 1.8 3


(j)
25day 09 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(k)
25day 10 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(l)
25day 11 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(m)
25day 12 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(n)
25day 13 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(o)
25day 14 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(p)
25day 15 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(q)
25day 16 hour 00min
-3 -1.8 -0.6 0.6 1.8 3
(r)
25day 17 hour 00min
-3 -1.8 -0.6 0.6 1.8 3

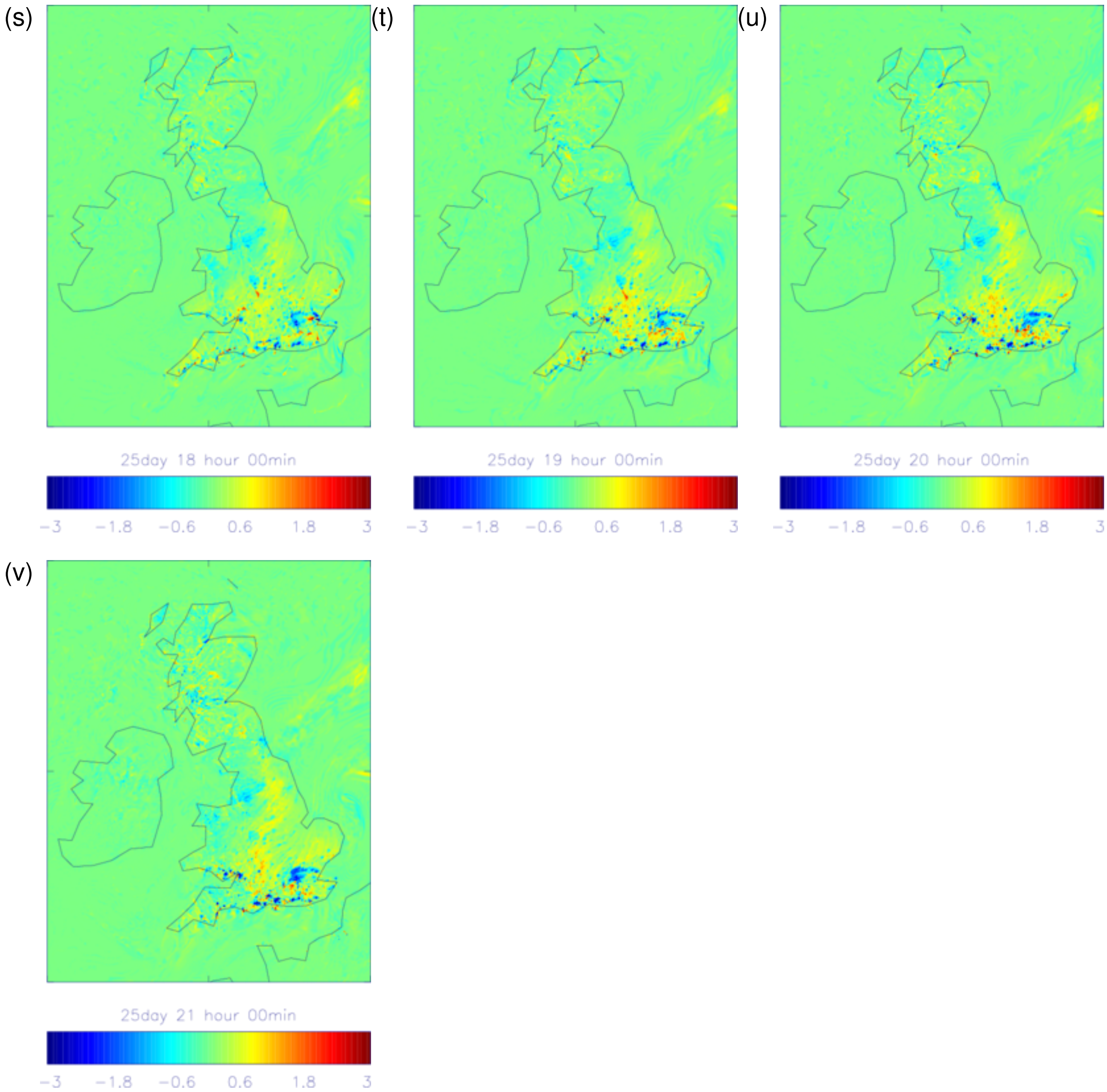


Figure 3.7: Difference in screen level temperature at hourly intervals between ITE and IGBP set-up with varying urban morphology.

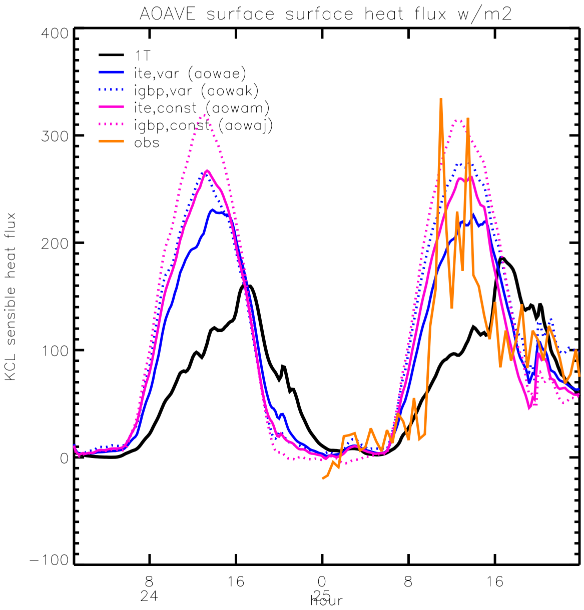


Figure 3.8: Diurnal cycle of sensible heat flux for central London for ITE (blue lines) and IGBP (magenta lines) and varying morphology (solid lines) and constant morphology (dotted lines). Observations from King's College London (KCL), in Central London, are depicted in orange.

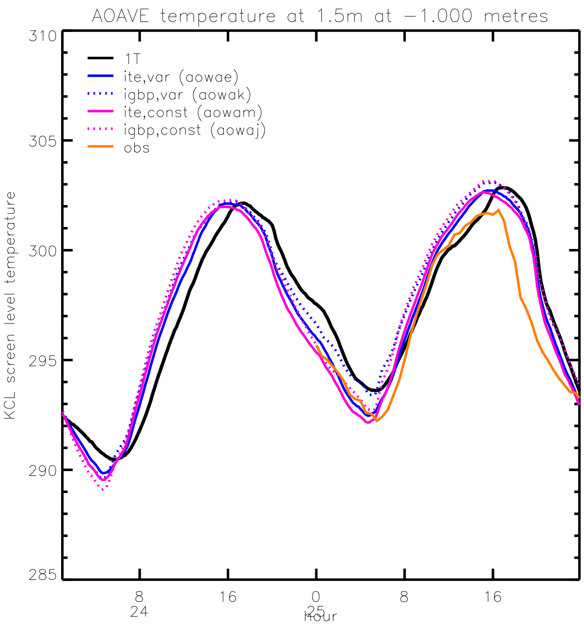


Figure 3.9: Diurnal cycle of screen level temperature for central London for ITE (blue lines) and IGBP (magenta lines) and varying morphology (solid lines) and constant morphology (dotted lines). Observations from KCL are depicted in orange.

Derived surface properties

MORUSES has parametrisations for the roughness length for momentum (MacDonald *et al.*, 1998) & heat, effective albedo & emissivity and heat capacity. These parametrisation are well documented in Porson *et al.* (2010a). In addition to these derived surface properties there are also differences in the coupling to the soil compared to urban-1t, however the derived properties are themselves comparable. Figures 4.1–4.3 show these parameter values for urban-1t (black), the canyon (blue) and the roof (pink). In additional they also have a weighted average of the canyon and the roof properties (orange) to aid comparison with urban-1t. However, this is not to say that you can replace the urban-1t parameter with this aggregate value and achieve the same result, as the energy balances are very different between the canyon and the roof.

Currently the parameters are constant with time with the exception of the effective albedo as it has a zenith angle dependence. As a consequence of this the albedo varies with time as well as location. Figure 4.2 (left) therefore has a spread of values rather than a well defined line like the other plots. The blue line shows the average of the effective albedo over the sunlit hours and the maximum and minimum values are shown in cyan. The latitude dependence can be seen where the individual cities at different latitudes separate out particularly in the larger urban fractions and in the minimum albedo. These data were from the case study on 25th July 2012.

Met Office

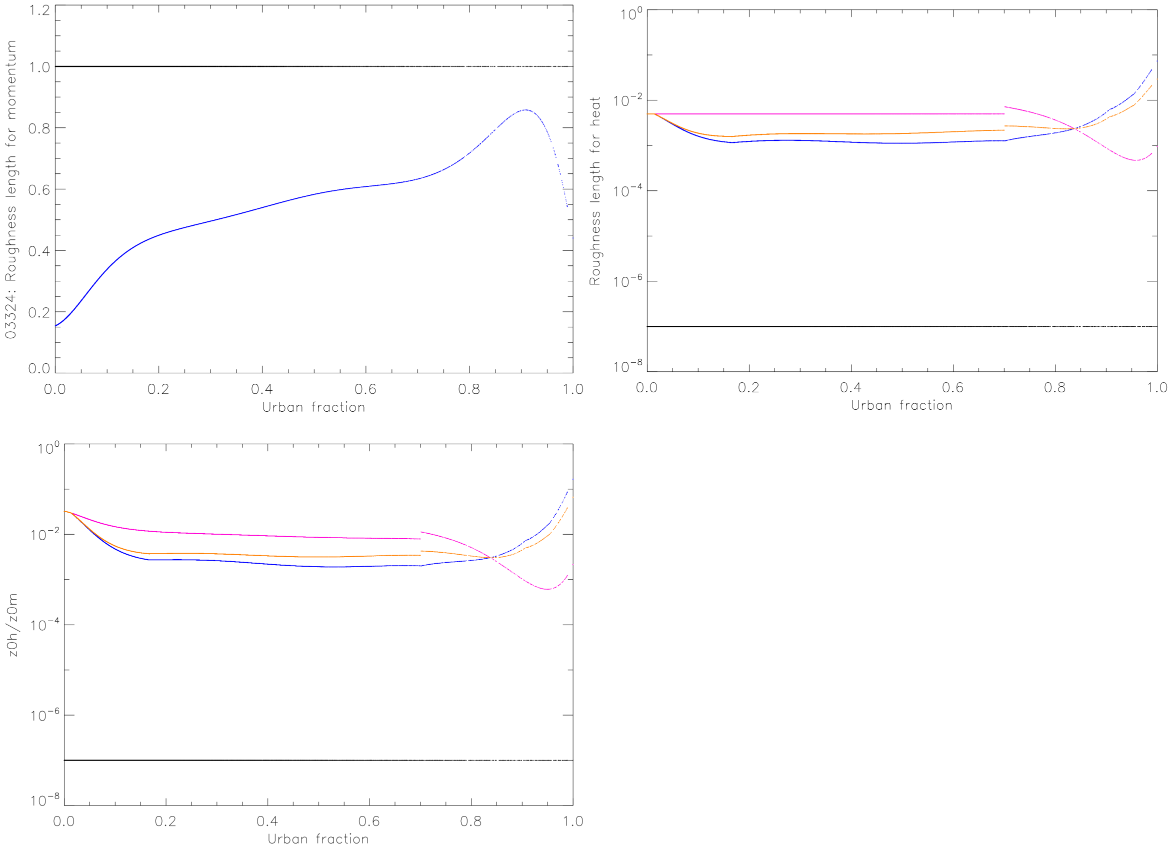


Figure 4.1: Roughness length for momentum (top left, using MacDonald *et al.*, 1998), heat (top right) and their ratio (bottom) against against urban fraction from the operational PS36 UKV ancillary; black = urban-1t, blue = canyon, pink = roof and orange = weighted average. The roughness length for momentum is the same for the canyon and the roof.

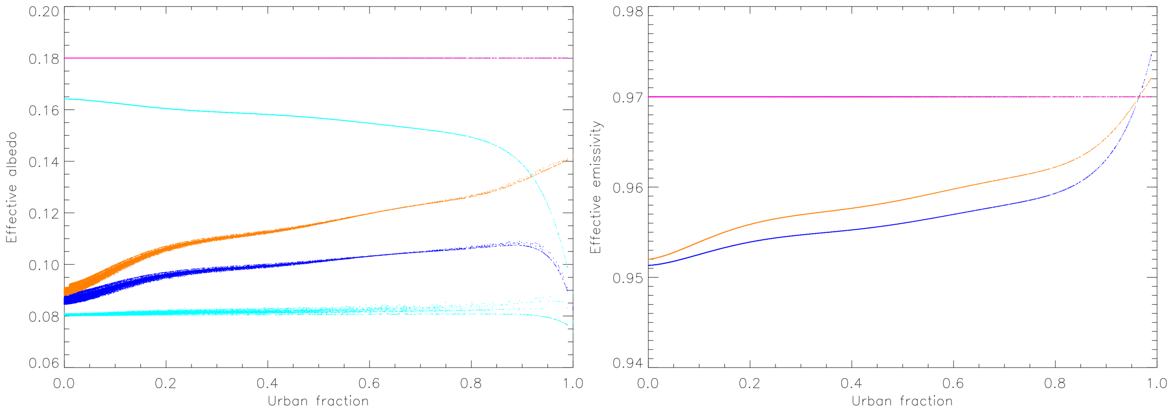


Figure 4.2: Similar to Figure 4.1 with effective albedo (left) and emissivity (right). The albedo depends on the solar zenith angle and so has a spread of values unlike the other parameters. The cyan locus is the maximum and minimum values and the blue is the average over the sunlit hours. The urban-1t (black) and roof (pink) albedo and emissivities are identical.

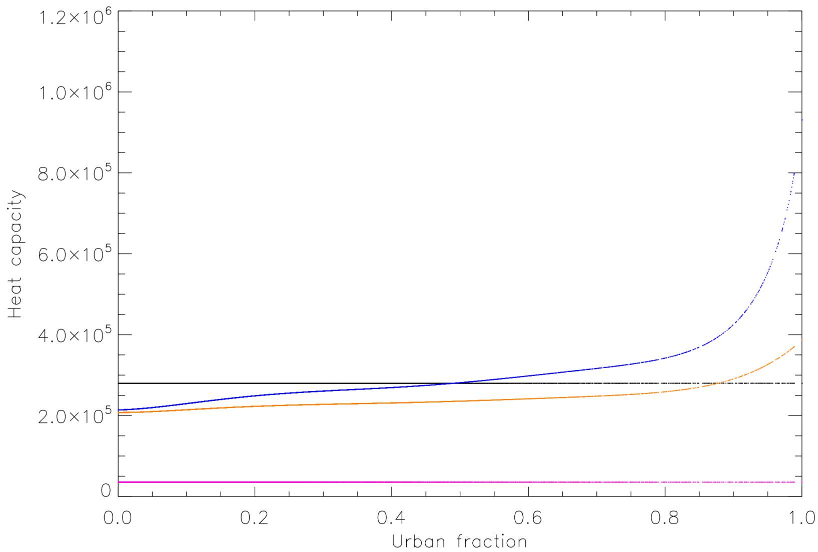


Figure 4.3: Similar to Figure 4.1 for heat capacity.

Coupling with the soil

The roof tile in MORUSES has a very small thermal inertia, since the assumption is made that roofs in the UK are very thin. Consequently, the surface temperature of the roof tile shows a large diurnal cycle; it cools down quickly during the evening transition and equally warms up quickly during the morning transition. In some cases the fast cooling rate might lead to the formation of ice on the roof. The timescale of changing the roof temperature is determined by the heat capacity of the roof. A weak radiative coupling of the roof to the underlying soil and its impact on the overall sensible heat flux and air temperature was tested in order to reduce the diurnal amplitude slightly without making the roof artificially thicker.

The 25th July was chosen as a case study to test the impact of a radiative coupling on the model performance. Figure 5.1 shows four difference plots for screen level temperatures at 2, 15, 18 and 21 UTC for the UKV domain. Differences in screen level temperature are up to 1–1.5 K in the larger cities such as London, Paris and Birmingham with warmer temperatures during the night for the radiatively coupled roof. Slightly lower temperature differences of the order of 0.5 K are simulated during the afternoon when the boundary layer is deep and heat is mixed over a larger volume. Overall, the case study shows that the radiative coupling leads to a smaller diurnal amplitude of the screen level temperature.

Figure 5.2 shows the corresponding diurnal cycle of the sensible heat flux and screen level temperature at King's College London (KCL), in central London, for the urban-1t configuration, the MORUSES configuration without radiative coupling and the MORUSES configuration with radiative coupling against observations taken on the roof of KCL. The diurnal cycle of the sensible heat flux shows a reduced sensible heat flux around noon by about 60 Wm^{-2} and is about 30 Wm^{-2} higher after the evening transition when the roof is radiatively coupled to the underlying soil. The radiative coupling further leads to a phase delay of the sensible heat flux; due to the radiative coupling between the roof and the underlying soil the roof heats up and cools down slightly more slowly than without radiative coupling. This in turn delays the change in temperature of the roof compared to the air and therefore delays the sensible heat flux. The corresponding screen level temperature for the KCL location shows that the radiative coupling delays the increases in the daytime temperatures marginally. However, the most noticeable impact of the radiative coupling is the increase in the night time temperatures by about 0.5 K leading to a better agreement with the observations. Due to the radiative coupling more energy is available from the roof/soil to maintain roof temperatures at a higher level. This in turn leads to the overall larger and positive sensible heat flux at night, the roof drops its temperature at a slower rate and maintains a slightly positive sensible heat flux during the night for about 3 to 4 hours longer.

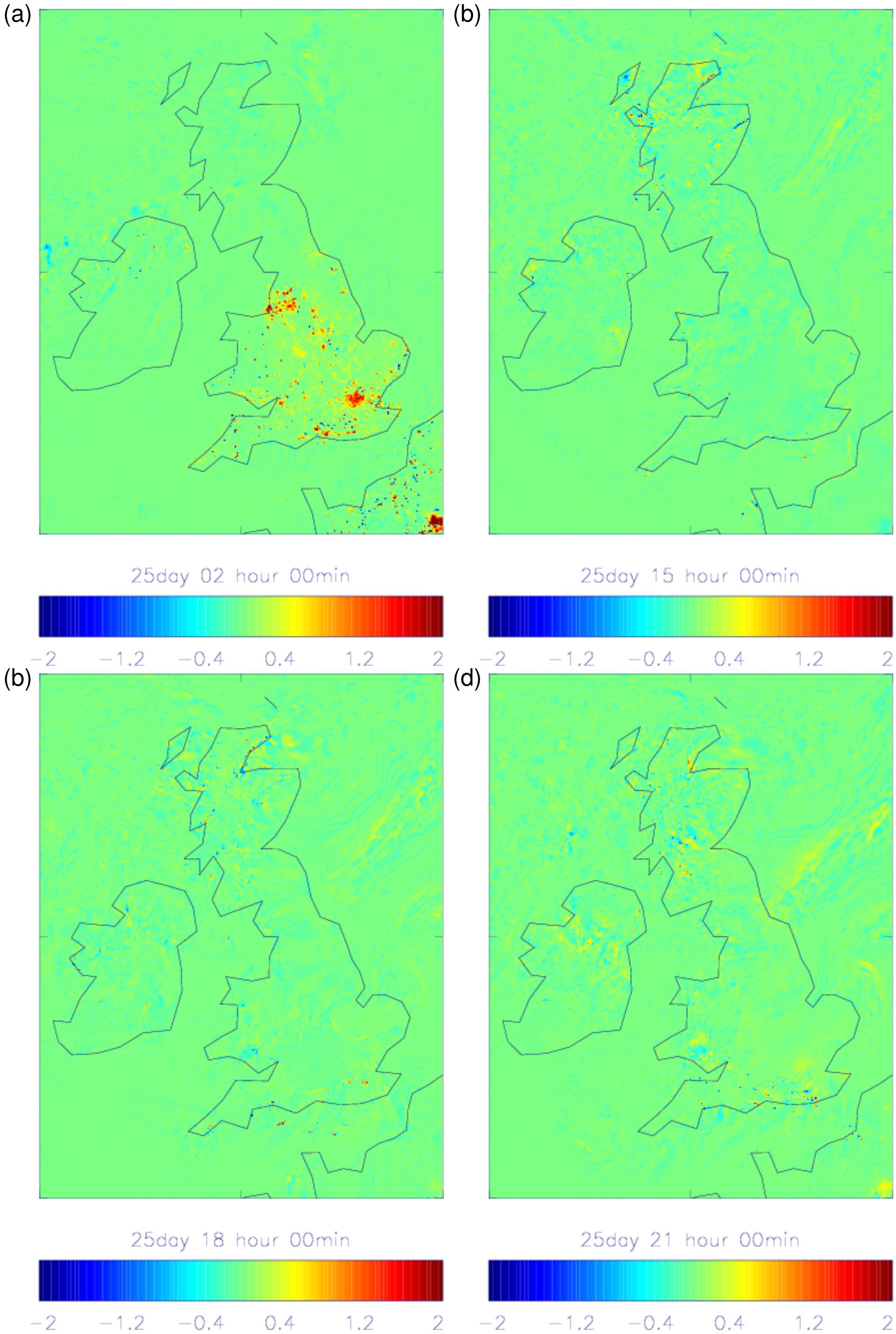


Figure 5.1: Differences in screen level temperature between MORUSES with radiatively coupled roof and without radiatively coupled roof at (a) 2 UTC, (b) 15 UTC and (c) 18 UTC and (d) 21 UTC.

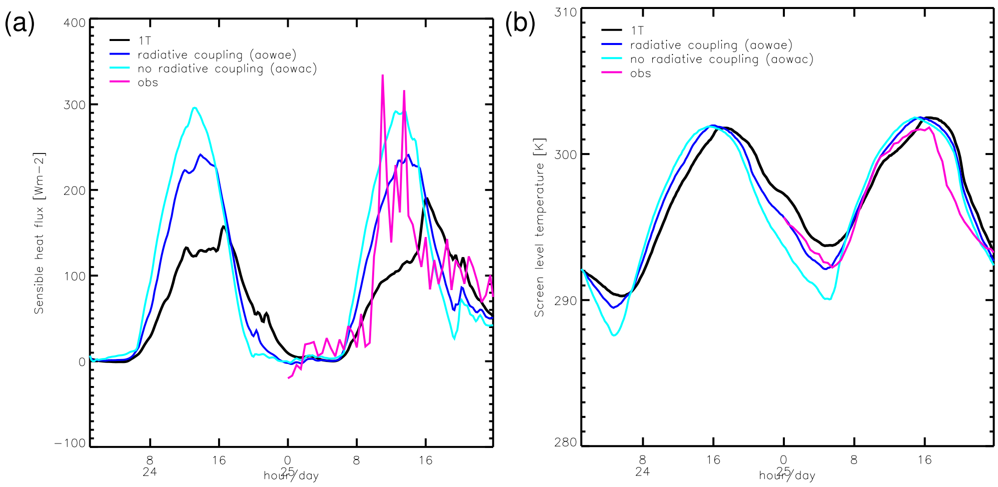


Figure 5.2: Diurnal cycle of (a) sensible heat flux and (b) screen level temperature at KCL for UKV urban-1t (black), UKV MORUSES with radiative coupling (blue), UKV MORUSES without radiative coupling (turquoise), observation (magenta).

Evaluation

The UKV was run at PS36 including the MORUSES PS37 configuration for the whole month of April 2015. Rob King generated comparison plots during his secondment in Reading between the UKV urban-1t parametrisation and KCL data as well as BT Tower data and he summarises his results in King (2015). In the following we compare diurnal cycles of screen temperatures and sensible heat fluxes with the UKV-MORUSES set-up against observations made on top of KCL in central London and at 190 m height on top of BT Tower.

6.1 Screen level temperature and sensible heat flux

We compared the screen level temperatures and sensible heat fluxes (Figures 6.1–6.8) averaged over 3×4 grid boxes against observations on top of KCL roof taken by Sue Grimmond and Simone Kotthaus for the whole month of April on a daily basis. The observed sensible heat fluxes and temperatures for KCL roof are 30 minute averages. Since comparing simulated variables against observations in complex urban terrain raises the question of representativity spatially and vertically we added fluxes and temperatures measured at 190 m on top of BT Tower to the diurnal cycles to get an idea of the vertical change over the lowest 200 m. MORUSES gives surface fluxes and temperatures at screen level height above roughness length and displacement height and it is difficult to establish the exact height at which an observation would need to be sited to be comparable. The BT observations give the sensible heat flux, sonic temperature which includes the impact of humidity and WXT temperature which does not account for the impact of humidity on the measured temperature (Personal communication Dr. Christos Halios, University of Reading).

In order to take into account different meteorological conditions days were categorised into 'cloudy and windy', 'cloudy and calm', 'clear and windy' and 'clear and calm' with Figures 6.1–6.8 being organised in this way. Cloudy days were characterised as having greater than 50% total cloud cover at least 50% of the time over an 24 hour period. When comparing urban-1t and MORUSES against observations we expect to see the largest impact of the urban parametrisation during clear and calm conditions, especially at night when the surface temperature is decreasing via long wave radiative cooling. Under such conditions the urban heat island is usually very pronounced with the larger urban thermal inertia offsetting the radiative cooling in urban areas. During cloudy and windy conditions we hypothesise that the local surface energy balance has a smaller impact on the urban boundary layer structure due to overall increased turbulent mixing. This may lead to smaller differences between urban-1t and MORUSES with regards to simulated air temperatures.

Figures 6.1–6.7 (even numbers) compare the diurnal cycle of the surface sensible heat flux for the UKV with MORUSES and the UKV with urban-1t against observed heat fluxes at KCL. In addition we added observed heat fluxes on top of BT Tower to demonstrate how they change over the lowest 200 m of the urban boundary layer. The MORUSES configuration leads to a larger sensible heat flux during day and often a slightly larger heat flux during the night than the urban-1t configuration. The sensible heat flux starts to increase between 1 and 2 hours earlier in the morning with MORUSES than with urban-1t and shows a larger amplitude during the day. The MORUSES sensible heat flux peaks about 1 hour earlier than the urban-1t heat flux. The amplitude simulated by MORUSES is considerably larger and peak values around noon are higher. MORUSES also simulates slightly larger heat fluxes during the night than urban-1t which helps to maintain slightly higher surface skin temperatures and maintain the urban heat island. The reason for the different behaviour in amplitude and phasing between MORUSES and urban-1t is caused by the two sub-grid-scale land-use tiles MORUSES uses. The grid box averaged sensible heat flux is a surface fraction weighted flux consisting of the roof fraction and the canyon fraction and any other surface tiles within the tiling scheme. The roof fraction has a small thermal inertia and favours a larger diurnal amplitude of the sensible heat flux, while the canyon fraction has a large thermal inertia with a smaller diurnal amplitude. The phasing of the sensible heat flux is delayed for the canyon compared to the roof due to the difference in thermal inertia. The fraction weighting of the tiled sensible heat fluxes within MORUSES then allows to change the phasing and the amplitude of the grid box averaged heat flux as a function of the canyon geometry at each grid point. The larger amplitude and earlier phasing at KCL are caused by the roof fraction within MORUSES for the KCL location. In contrast, urban-1t does not account for the changing geometry and uses the same urban parameters for the whole domain. Urban-1t is prescribed with a larger thermal inertia; this in turn leads to a smaller amplitude of the diurnal sensible heat flux and a phase shift of the peak by about 1-2 hours compared to MORUSES. MORUSES captures the timing and amplitude of the diurnal cycle well, while urban-1t shows a delayed increase and a too low amplitude especially during the day.

The differences between MORUSES and urban-1t in the sensible heat flux translate into smaller differences in the screen level temperatures (see Figures 6.2–6.8, odd numbers) compared to the KCL measured temperatures. Overall temperatures between the two schemes differ by only about 1 K. However, MORUSES' temperatures increase between 30 to 60 minutes earlier than urban-1t due to the earlier increase in the sensible heat flux. On occasions MORUSES and urban-1t sometimes overestimate and sometimes underestimate the night time screen level temperatures by 1 K, which is within the measurement uncertainty. Overall, the sensible heat fluxes and screen level temperatures show good agreement with KCL data on different days.

Cloudy and windy conditions were identified on five days (see Figures 6.1 & 6.2 for sensible heat flux and screen level temperature respectively). Observations for air temperature and sensible heat flux at KCL were only available on four of those days. This gives us a very small sample to draw any conclusions. Overall, simulated sensible heat flux and temperatures follow KCL observations very closely. The difference in the phasing during the morning transition for temperatures between MORUSES and urban-1t appears less pronounced for 'cloudy and windy' conditions (Figure 6.2) than for 'clear and calm' conditions (Figure 6.8). This is despite a similar phase difference for the surface sensible heat flux between MORUSES and urban-1t in both meteorological situations. This is an indication that the higher wind speeds lead to enhanced mixing throughout the urban boundary layer thereby reducing the local impact of the surface energy balance on the screen level temperatures and hence leading to smaller differences between both schemes on near surface temperatures under windier meteorological conditions.

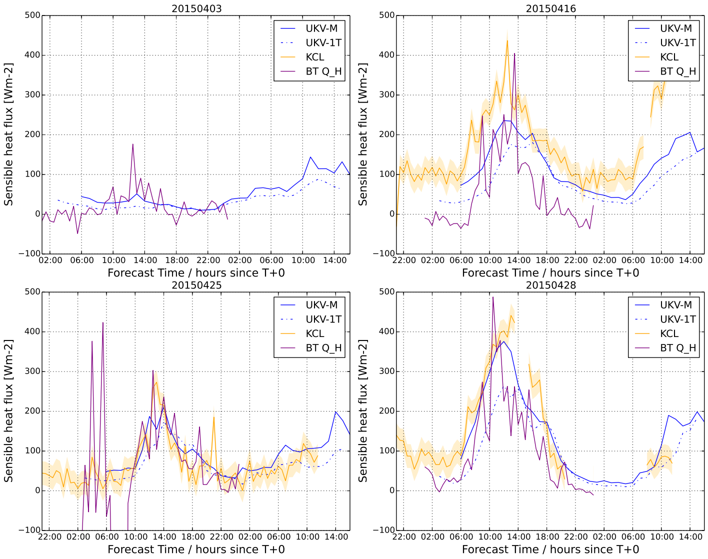


Figure 6.1: Surface sensible heat flux in cloudy and windy conditions for UKV-MORUSES (blue solid line), UKV-urban-1t (blue dashed line), KCL observations (orange solid line) and BT Tower (purple solid line). Orange shading depicts the desired accuracy range.

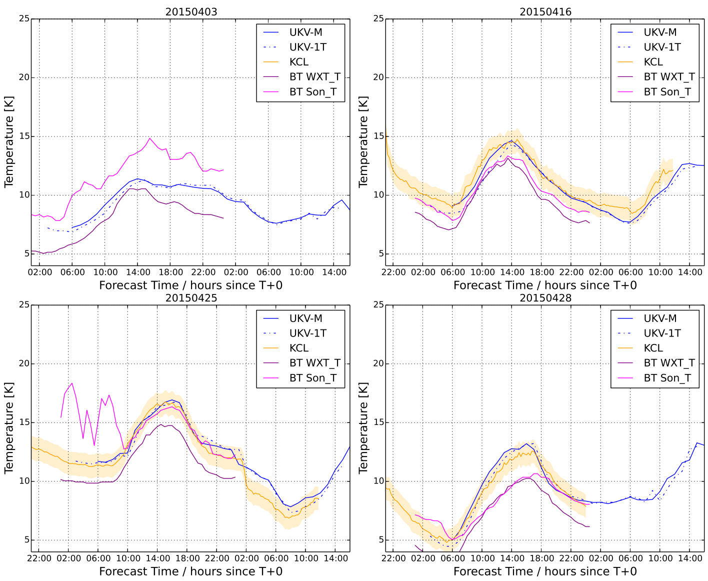


Figure 6.2: Like Figure 6.1, but for screen level temperature in cloudy and windy conditions. BT Son_T refers to sonic temperature on top of BT tower and BT WXT_T refers to WXT temperature on top of BT tower.

Cloudy and calm conditions were identified on six days (see Figures 6.3 & 6.4 for sensible heat flux and screen level temperature respectively). On these days MORUSES simulated a larger sensible heat flux than urban-1t. It increases earlier in the morning and maintains a slightly larger sensible heat flux at night. Observations of the sensible heat flux were available on three out of six days. MORUSES captures the daytime heat flux better than urban-1t. During the night both are underestimating it on one occasion, simulate it well on another and urban-1t performs better on one night. Overall differences in temperatures between MORUSES and urban-1t are small and both capture temperatures just within the uncertainty range, but underestimate temperatures during day on one occasion and underestimate the night time temperatures on the same day.

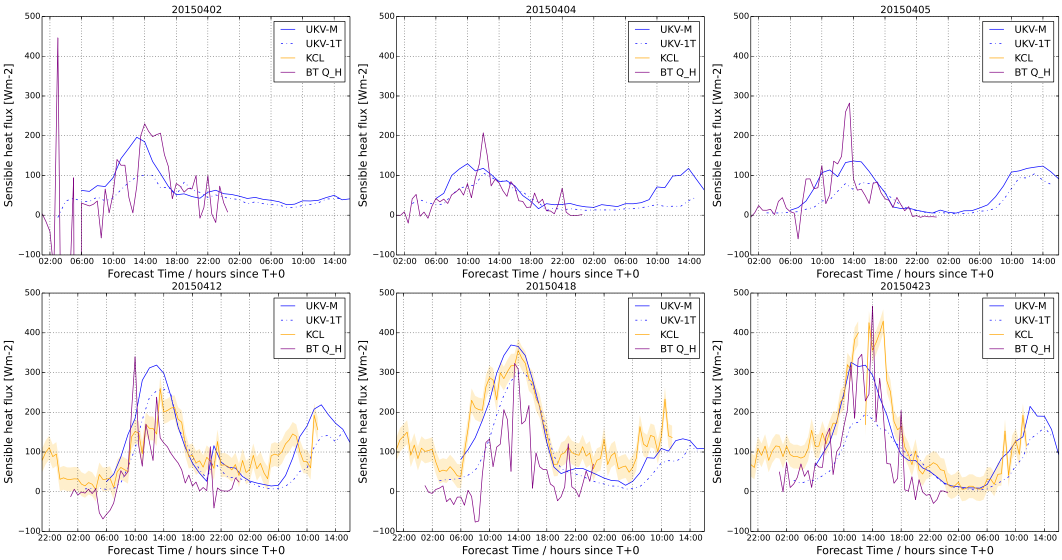


Figure 6.3: Like Figure 6.1 for surface sensible heat flux, but for cloudy and calm conditions.

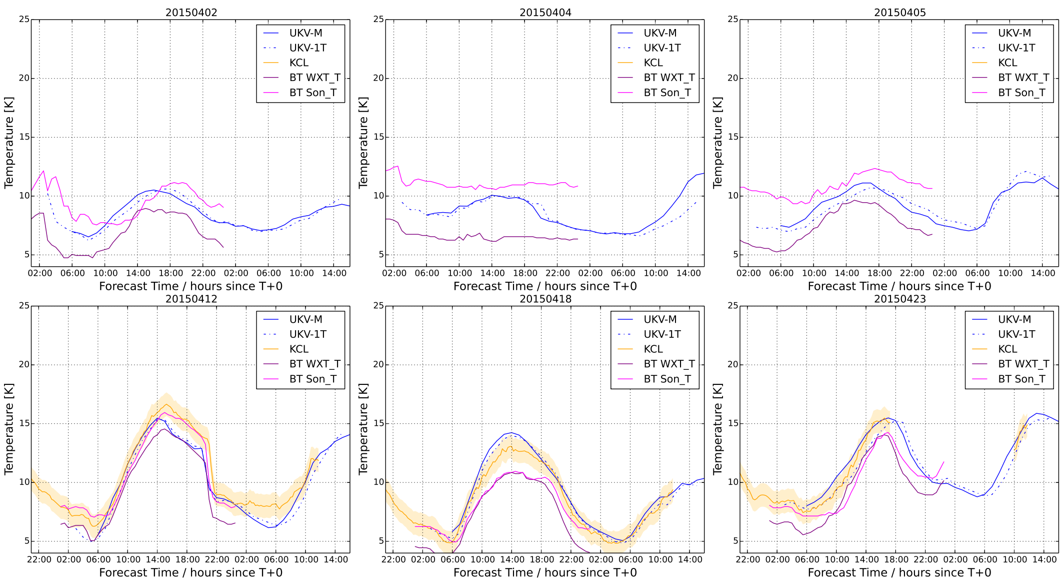


Figure 6.4: Like Figure 6.1, but for screen level temperature in cloudy and calm conditions.

Clear and windy conditions were identified on nine days (see Figures 6.5 & 6.6 for sensible heat flux and screen level temperature respectively). On these days the differences between MORUSES and urban-1t become very obvious in the sensible heat flux. MORUSES starts to increase earlier in the day and maintains a larger sensible heat flux at night. MORUSES simulates the observed sensible heat flux well and especially outperforms urban-1t during the morning transition. Again differences in temperatures are small, but MORUSES temperatures increase slightly earlier than those of urban-1t. On occasions both schemes slightly overestimate the daytime maximum temperatures.

Clear and calm conditions were identified on eight days (see Figures 6.7 & 6.8 for sensible heat flux and screen level temperature respectively). The differences in the phasing of the sensible heat flux between MORUSES and urban-1t are significant again with the peak in the sensible heat flux simulated up to 3.5 hours later than with MORUSES and a significantly lower amplitude. Compared to KCL data MORUSES performs better than urban-1t. As a result MORUSES captures the screen level temperatures slightly better than urban-1t. However, on two occasions we are under- as well as overestimating the peak temperatures around noon. This might be caused by different cloud cover between simulation and observations or local effects such as anthropogenic heating near the observation site.

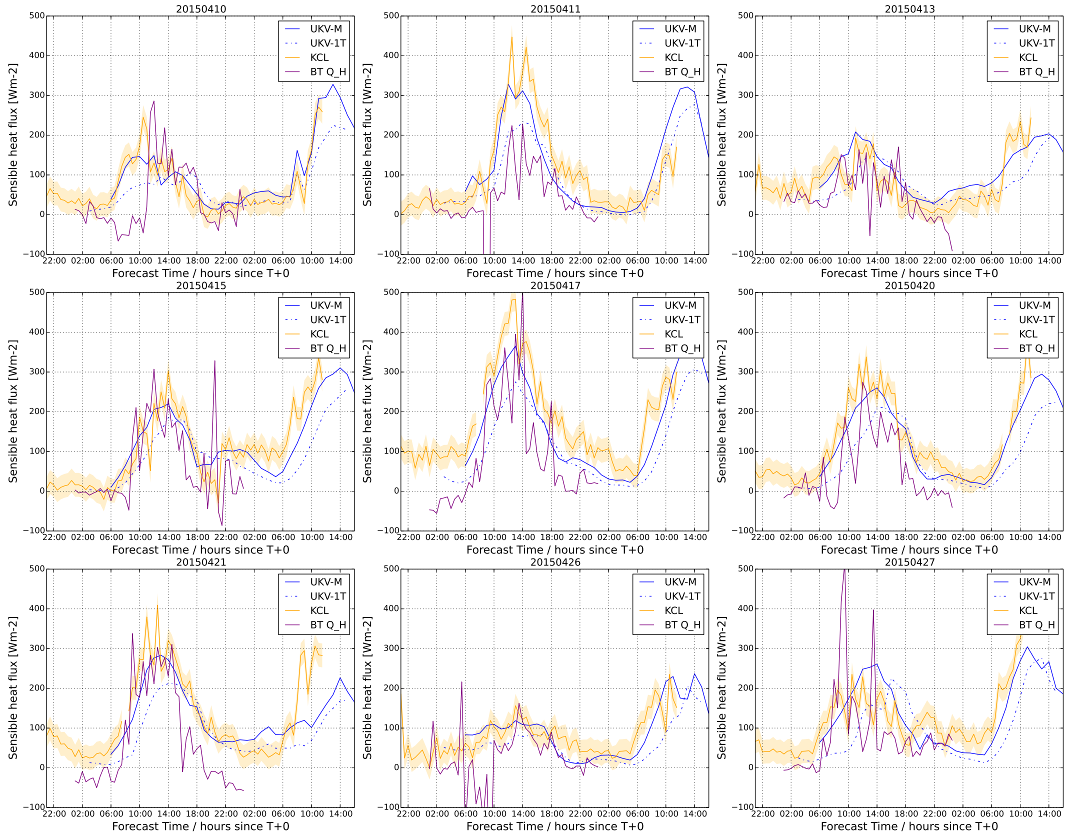


Figure 6.5: Like Figure 6.1 for surface sensible heat flux, but for clear and windy conditions.

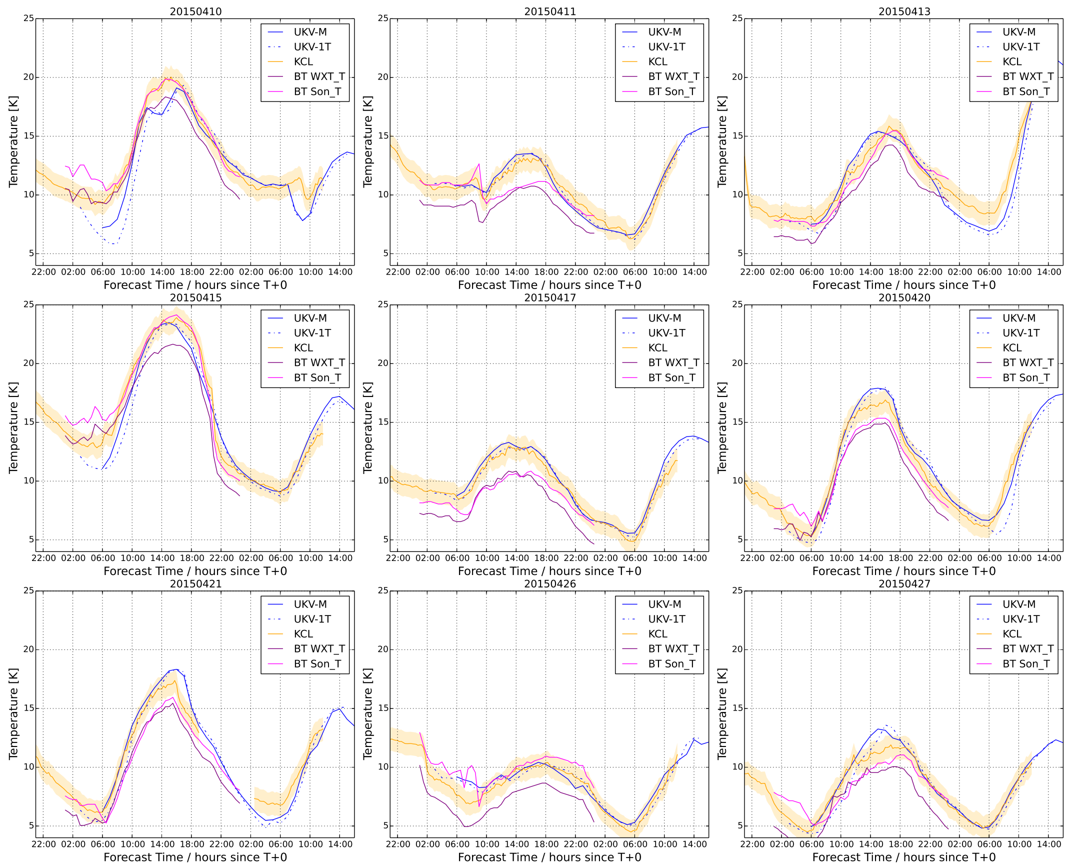


Figure 6.6: Like Figure 6.1, but for screen level temperature in clear and windy conditions.

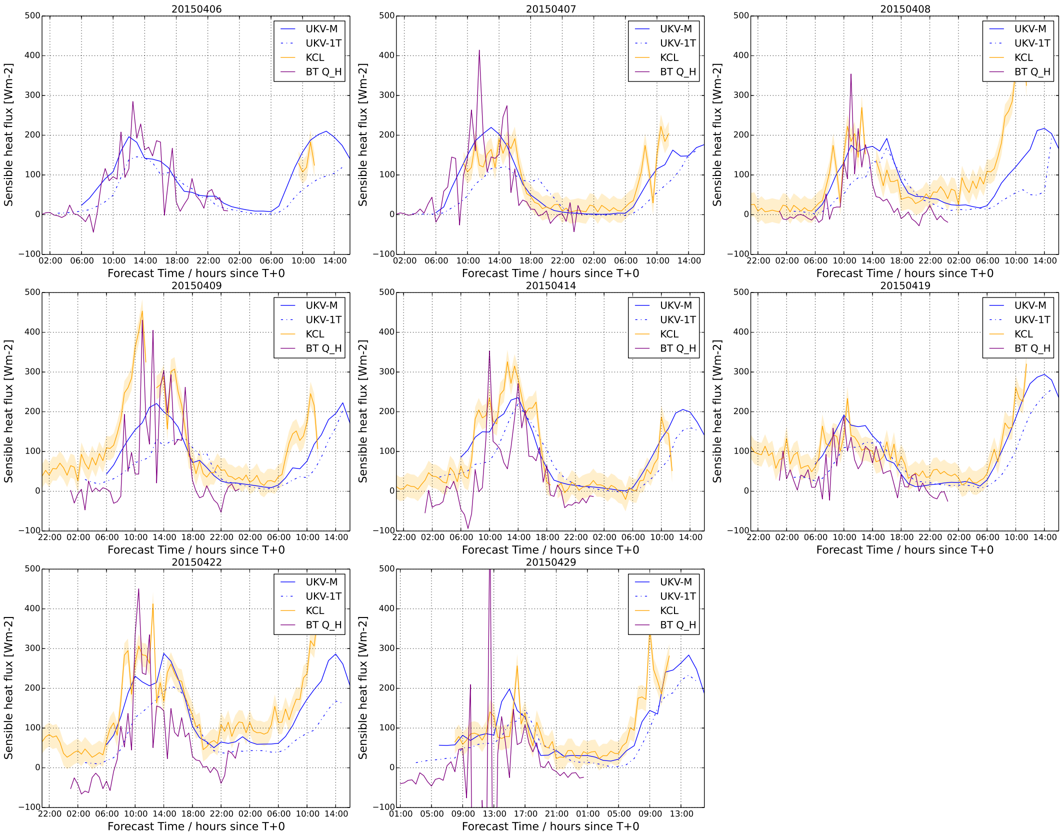


Figure 6.7: Like Figure 6.1 for surface sensible heat flux, but for clear and calm conditions.

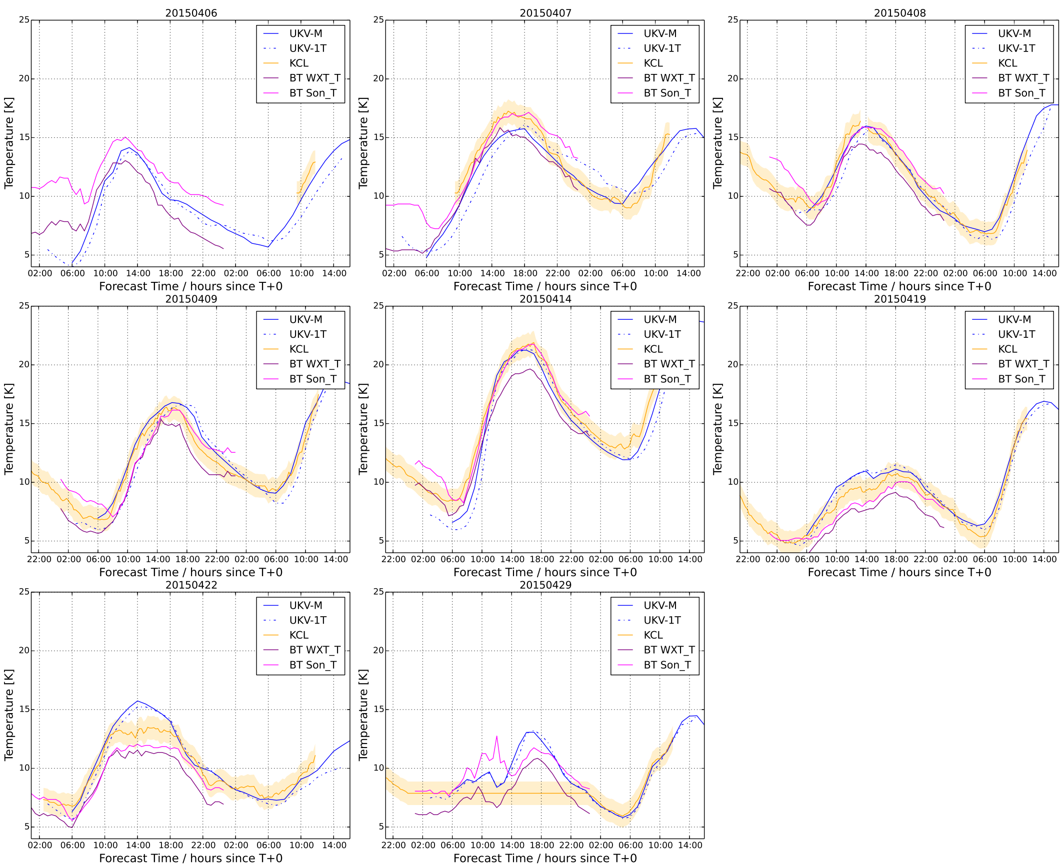


Figure 6.8: Like Figure 6.1, but for screen level temperature in clear and calm conditions.

6.2 Wind speed and direction

The PS37 trials showed a small impact of MORUSES on the rural wind speed (see Figure 7.1) where it led to a slight increase in wind speed compared to the UKV urban-1t scheme. In addition we compared 10 m wind speed and direction on the B grid for April 2015 against observations taken at KCL and added the wind speed measured on top of BT Tower to show the range of change of wind speed over the lowest 200 m of the urban boundary layer (see Figures 6.9–6.12). The desired accuracy for wind speed was set to 1 ms^{-1} and added as shading to the KCL observations to account for measurement uncertainty and model uncertainty. Overall, MORUSES produces slightly higher wind speeds than urban-1t. Figure 7.1 (right) shows evidence that the increase observed in the trial was caused by the reduced roughness length for momentum. However, not all changes to the wind speed can be accounted for by the reduced roughness length and it needs to be checked whether the remaining differences are caused by the surface energy balance and its impact on the boundary layer properties. The increase in wind speed is mostly less than 0.25 ms^{-1}. Overall wind speeds calculated from both urban-1t and MORUSES compare well against measured wind speeds at KCL.

The desired accuracy for wind direction was set to 22.5° and added to the KCL observations. Overall both urban-1t and MORUSES follow the observed wind direction closely (see Figures 6.13–6.16). Differences between urban-1t and MORUSES are negligible on most days. Only on two clear and calm days MORUSES and urban-1t behave more erratically and show differences (see 20150407 and 20150408, Figure 6.16). The remaining clear and calm days show slightly larger differences between the wind direction than any of the other less clear and calm days. These differences are most pronounced at night time and we speculate that the boundary layer depth and structure differ between urban-1t and MORUSES. This is subject to further research.

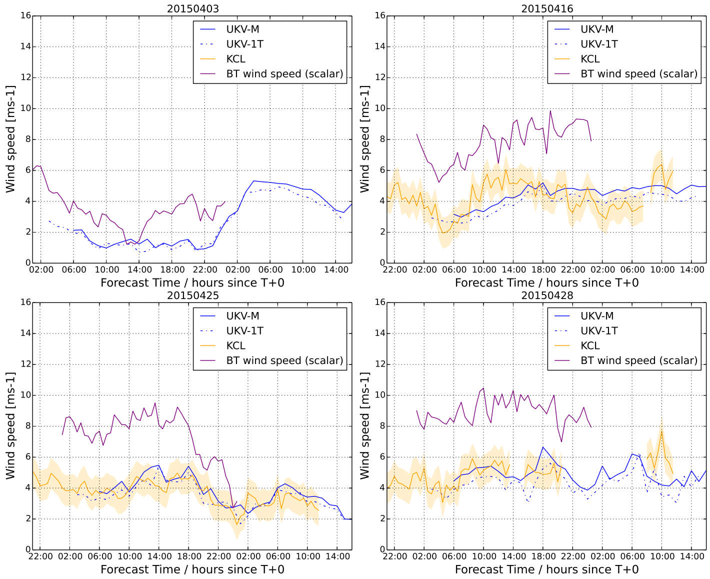


Figure 6.9: Wind speed in cloudy and windy conditions for UKV-MORUSES (blue solid line), UKV-urban-1t (blue dashed line), KCL observations (orange solid line) and BT Tower (purple solid line). Orange shading depicts the desired accuracy range.

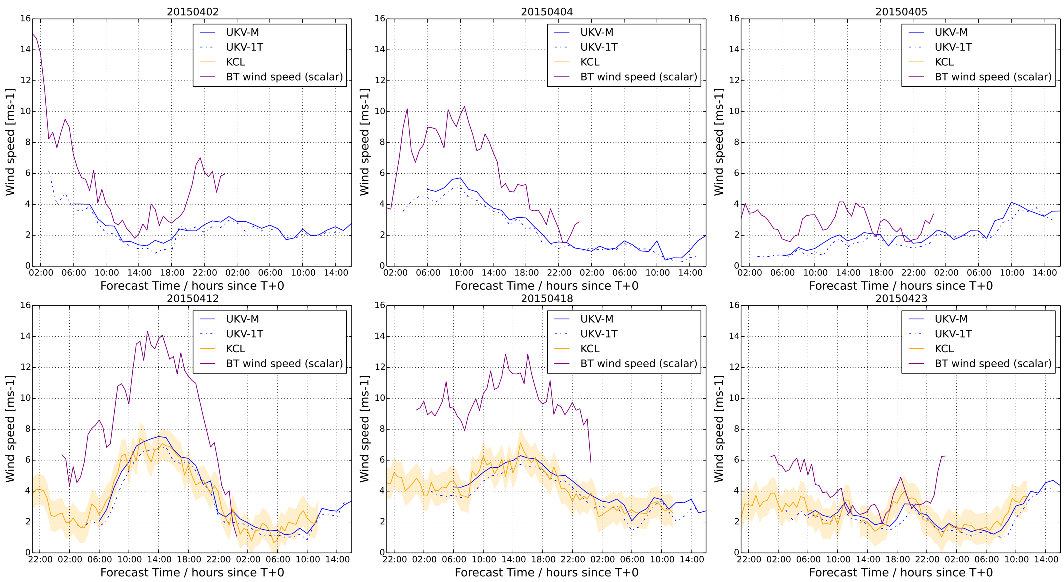


Figure 6.10: Like Figure 6.9, but for cloudy and calm conditions.

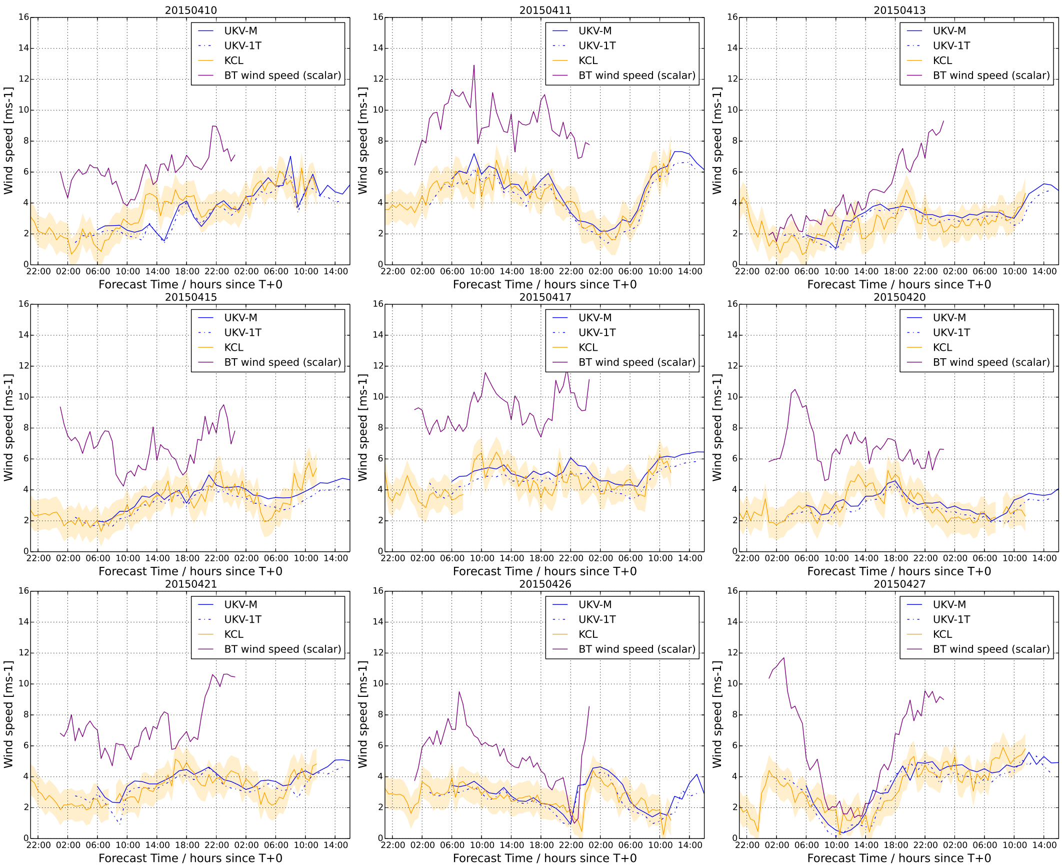


Figure 6.11: Like Figure 6.9, but for clear and windy conditions.

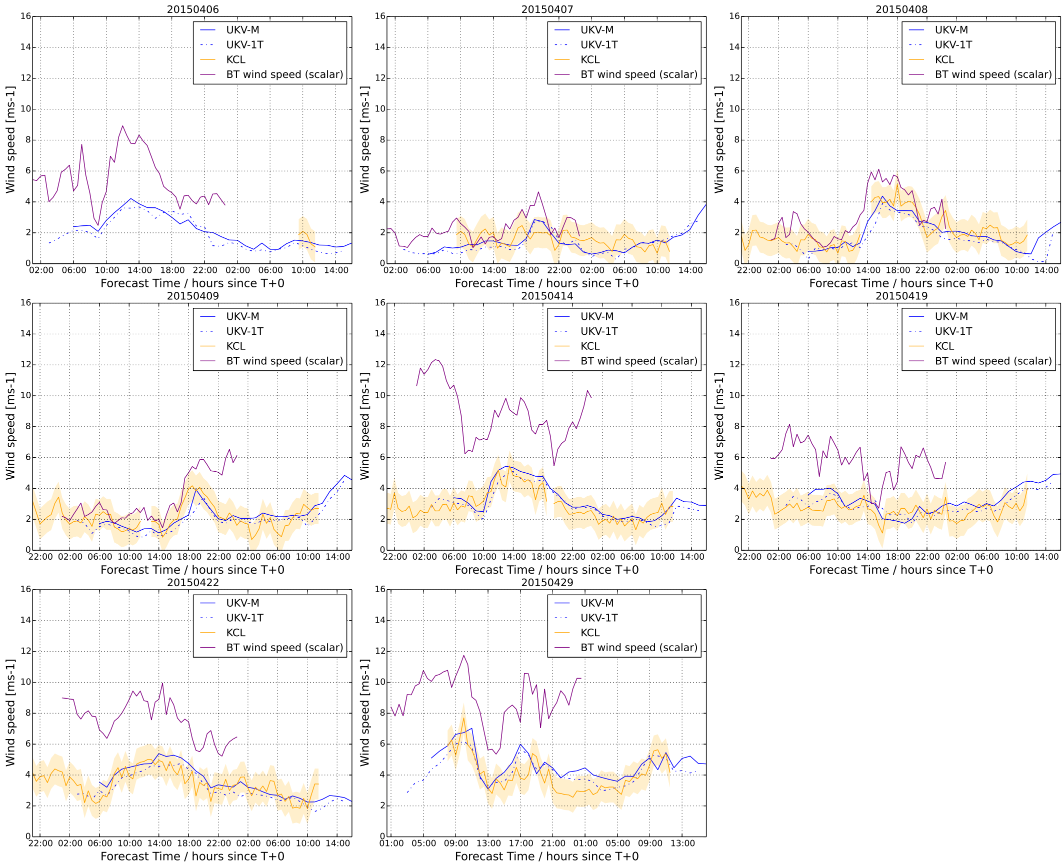


Figure 6.12: Like Figure 6.9, but for clear and calm conditions.

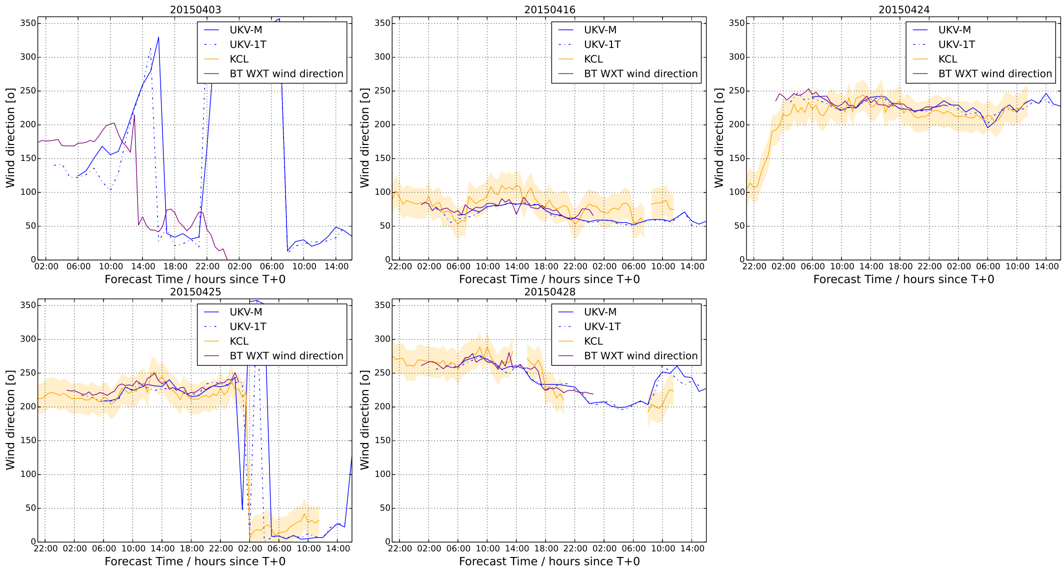


Figure 6.13: Wind direction in cloudy and windy conditions for UKV-MORUSES (blue solid line), UKV-urban-1t (blue dashed line), KCL observations (orange solid line) and BT Tower (purple solid line). Orange shading depicts the desired accuracy range.

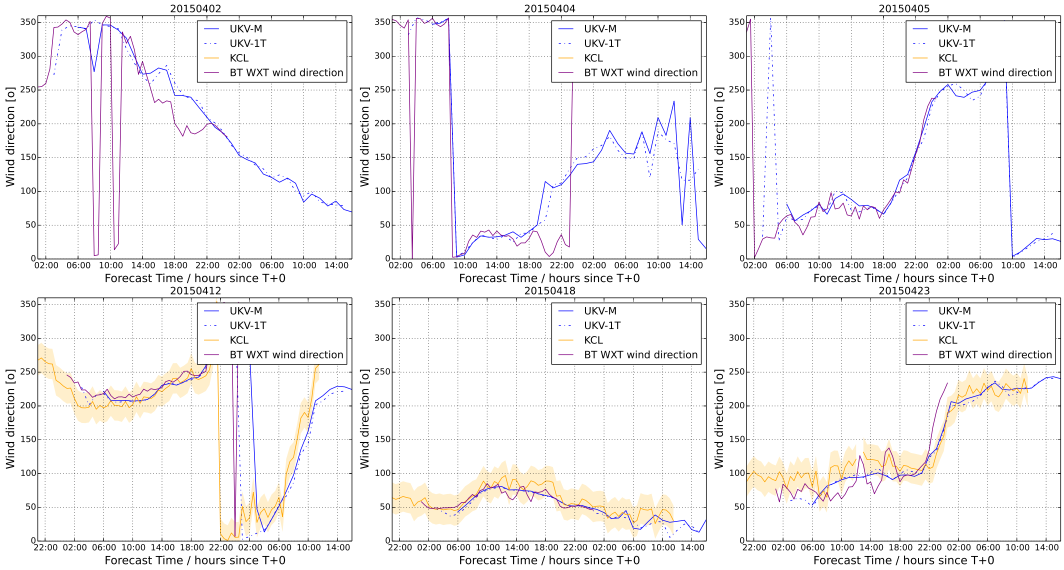


Figure 6.14: Like Figure 6.13, but for cloudy and calm conditions.

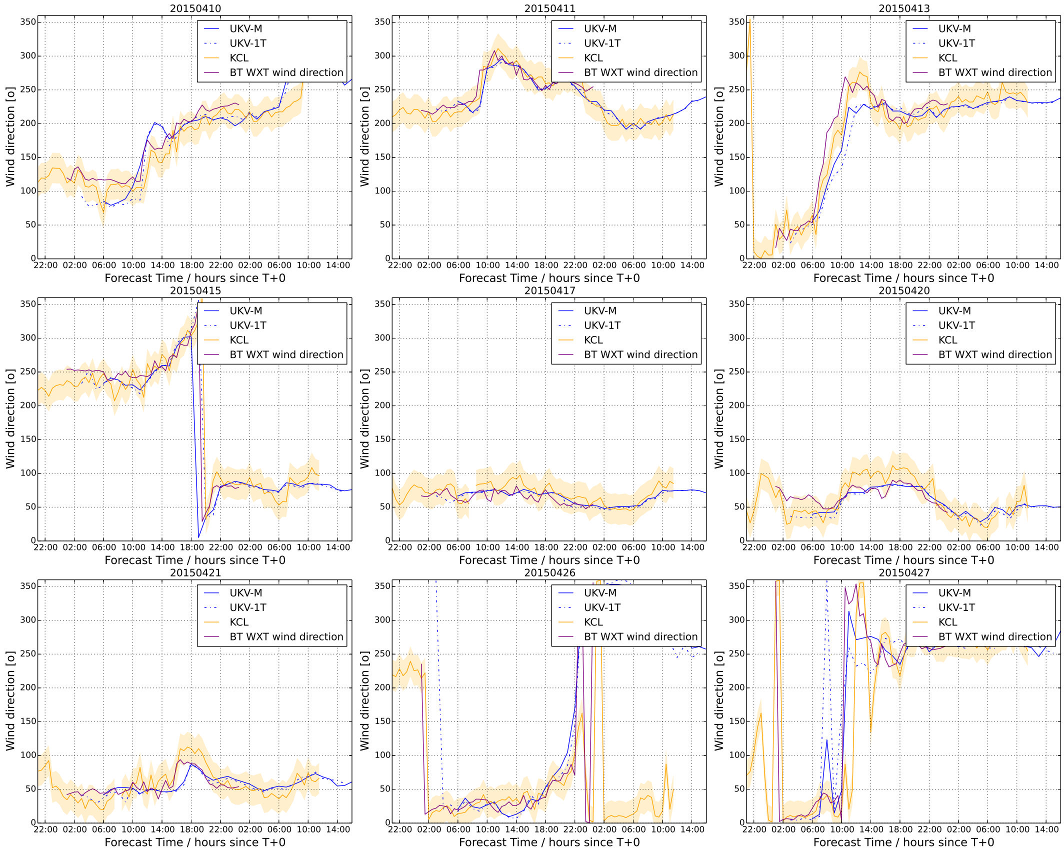


Figure 6.15: Like Figure 6.13, but for clear and windy conditions.

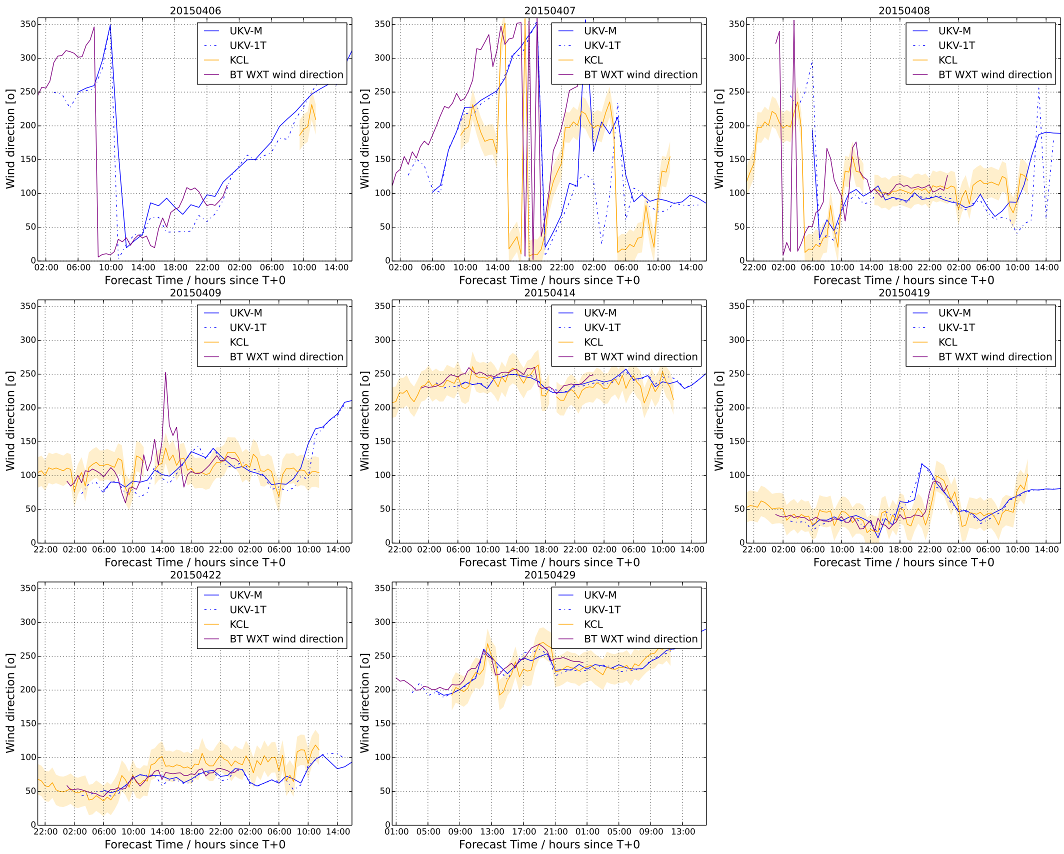


Figure 6.16: Like Figure 6.13, but for clear and calm conditions.

PS37 trials

MORUSES was tested as part of the PS37 UKV trials as an upgrade to the operational urban scheme (see opchange:#466). MORUSES was tested both individually and packaged in the PS37 final stretch package and the full trial verification results can be found via UKVPS37Testing. Trial periods run for MORUSES individually were: Summer 2014 (5th–30th June) and Winter 2013 (22nd January–26th February). The UK index showed improvement for both trials with 0.75% in the summer and 0.14% in the winter. WGOS accepted the recommendation of the final stretch package and currently MORUSES is being run live in PS37. This section will summarise the UK wide verification results of the Summer 2014 individual trial.

7.1 Wind speed & relative humidity

The most notable impact of MORUSES on the UK wide verification, as previously mentioned in Section 6.2, was an increase in wind speed (see Figure 7.1 right). As MORUSES is a scheme affecting urban areas only, this was initially surprising as it was expected that MORUSES would have a negligible impact on the UK verification as the synop stations are not in urban areas and is thus more of a rural verification. However, in the UKV surface fraction ancillary 25% of urban points have an urban fraction of less than or equal to 0.5%. The extent of the urban can most easily be seen in the building height (stash code 494) in Figure 3.4a where areas with zero fraction are blue. The MORUSES roughness length for momentum is calculated using the MacDonald *et al.* (1998) parametrisation given the urban morphology and reduces the roughness length for all urban fractions when compared to urban-1t, currently operational (see Figure 4.1, top left). A short trial was run with all parametrisations turned off apart from the roughness length, which effectively gives an equivalent of the urban-1t scheme with the roughness length parametrisation. Figure 7.1 (left) shows that after only three days, urban-1t plus the MacDonald *et al.* (1998) roughness exhibited a clear signal of the rise in wind speed so we can safely attribute this increase to the reduction in roughness length, although not all differences in wind speed can be attributed thus. Also probably linked to the decrease in the roughness length for momentum is a slight increase in the relative humidity, which improves a slight dry bias in the Summer 2014 trial (see Figure 7.2, left), whereas in the winter it makes the bias slightly worse (not shown). Figure 7.2 (right) shows a similar trend with the roughness length for momentum change only, although again it cannot explain the whole difference.

7.2 Temperature

MORUSES had very little impact on the 1.5 m temperature in both the Summer 2014 and Winter 2013 trial as we would expect from a rural verification. Figure 7.3 (left) shows the verification from the whole trial, while Figure 7.3 (right) shows the diurnal cycle verification. The diurnal cycle shows that MORUSES slightly improves the cold bias by day and warm bias by night. As MORUSES would be expected to have the largest impact in urban areas, a Station Based Verification (SBV) was done for the London area as part of the trial verification for the WGOS report[3] by Jorge Bornemann using OpenRoad data. WGOS report Figure 11 plots the T+24 mean error at 03 Z over the Winter 2015 trial and Figure 12 similarly plots the same for 15 Z for the Summer 2014 for the Control, Basic and Stretch packages. The Stretch package is the Basic plus MORUSES and some DA changes, so the differences cannot be attributed entirely to MORUSES. In the Winter 2015 trial most stations had a warm bias in the control and the Stretch package provided additional improvement when compared to the Basic package, although there was a small detriment to one station. The Summer 2014 SBV showed that the impact of MORUSES was negligible. A more in-depth study using urban OpenRoad data needs to be carried out to build up a better picture of how MORUSES is performing over a larger sample of stations including stations in other UK cities.

[3]See `https://code.metoffice.gov.uk/trac/rmed/attachment/wiki/dev/documentation/UKV_PS37_WGOS_Report_final.pdf`

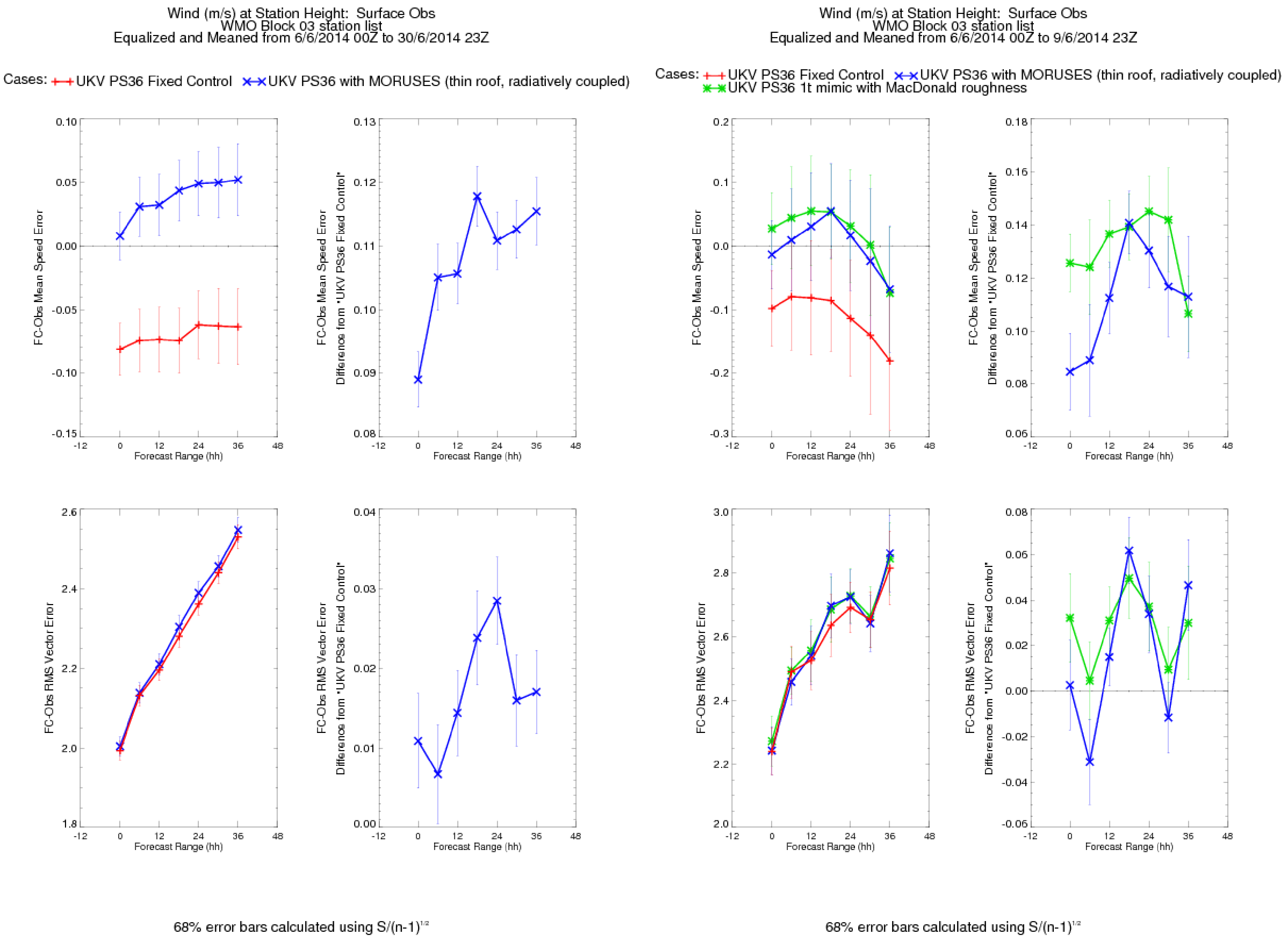
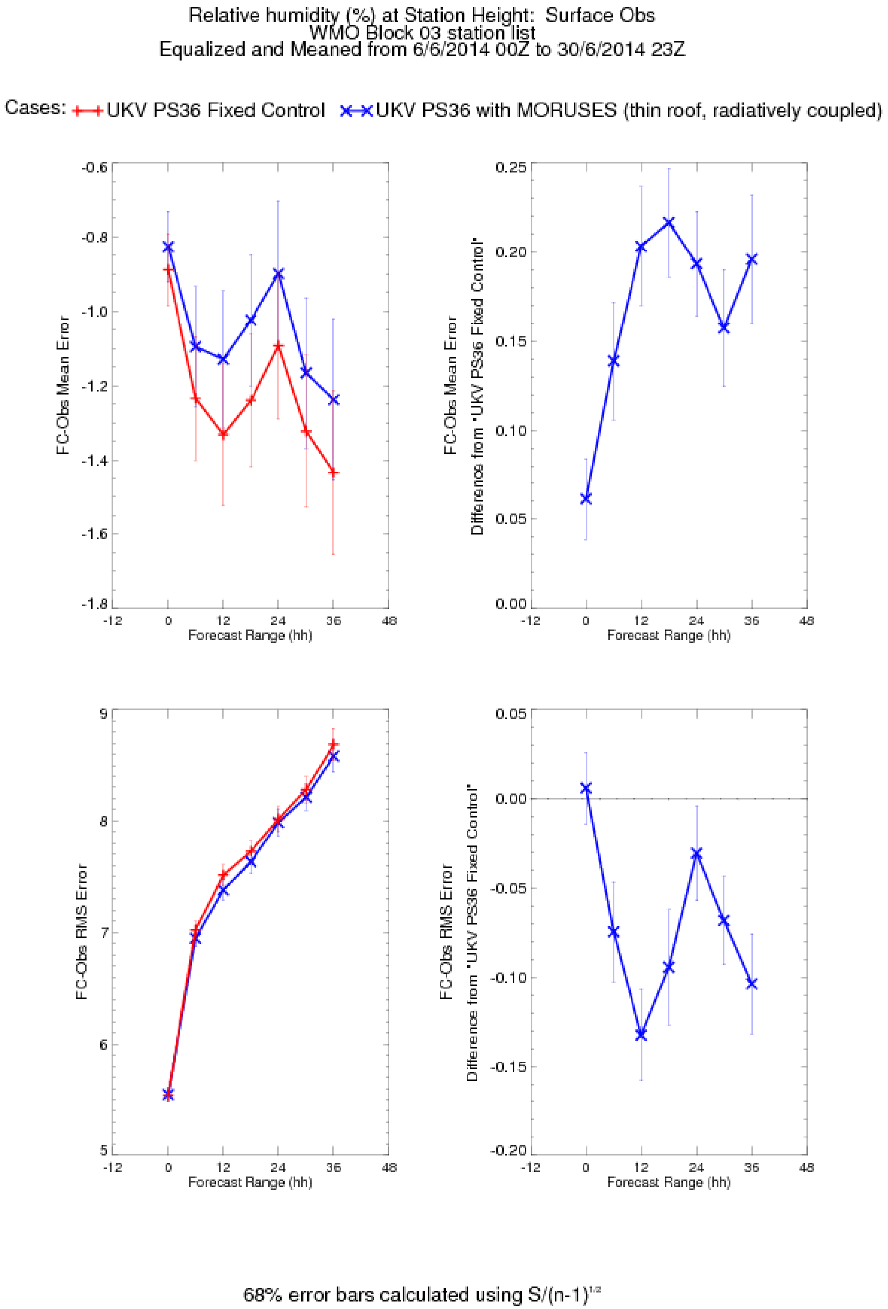


Figure 7.1: Impact of MORUSES on wind speed during the Summer 2014 trial (left) and similarly for the first three days of the same trial including the impact of the MacDonald *et al.* (1998) parametrisation for roughness length for momentum only (right).



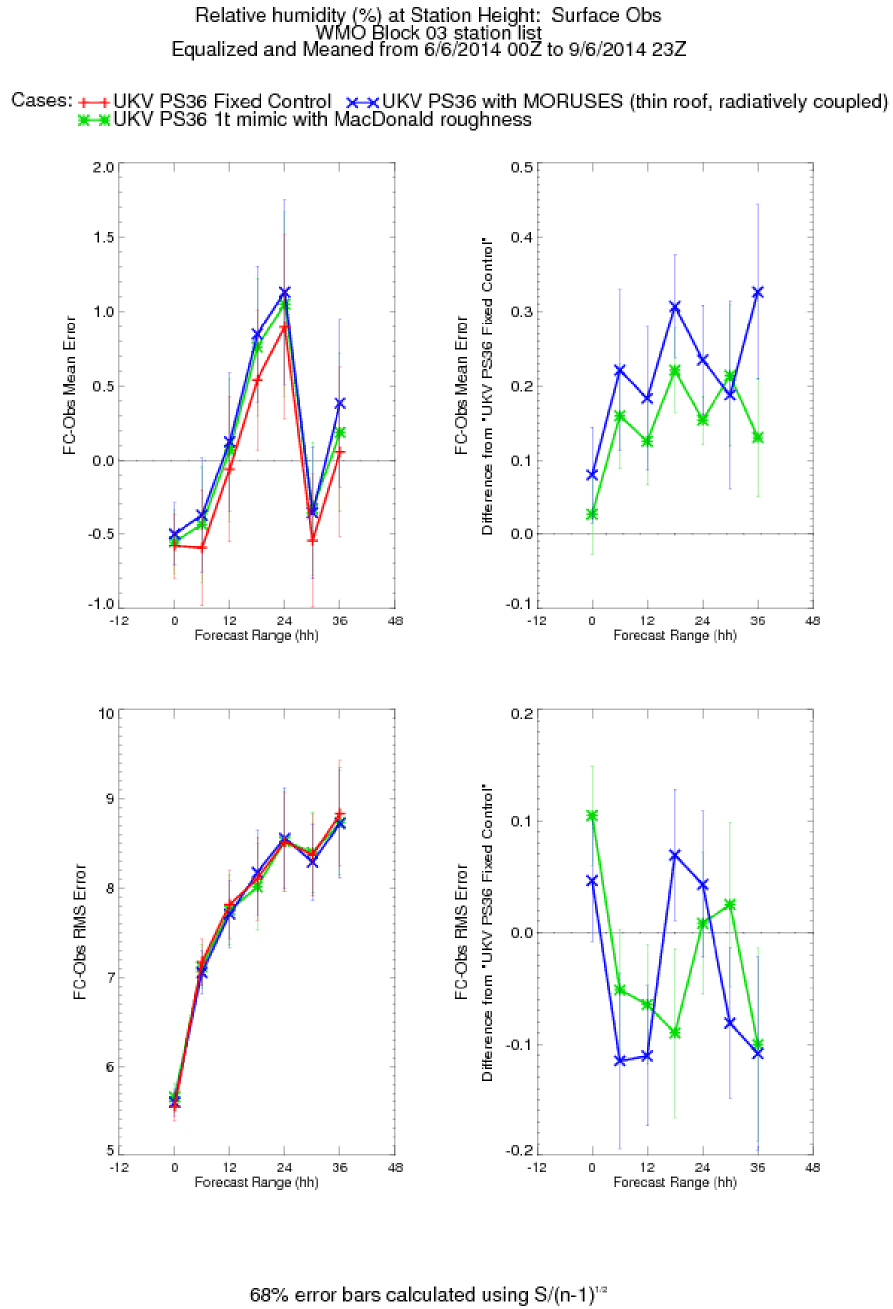


Figure 7.2: Similar to Figure 7.1 for relative humidity.

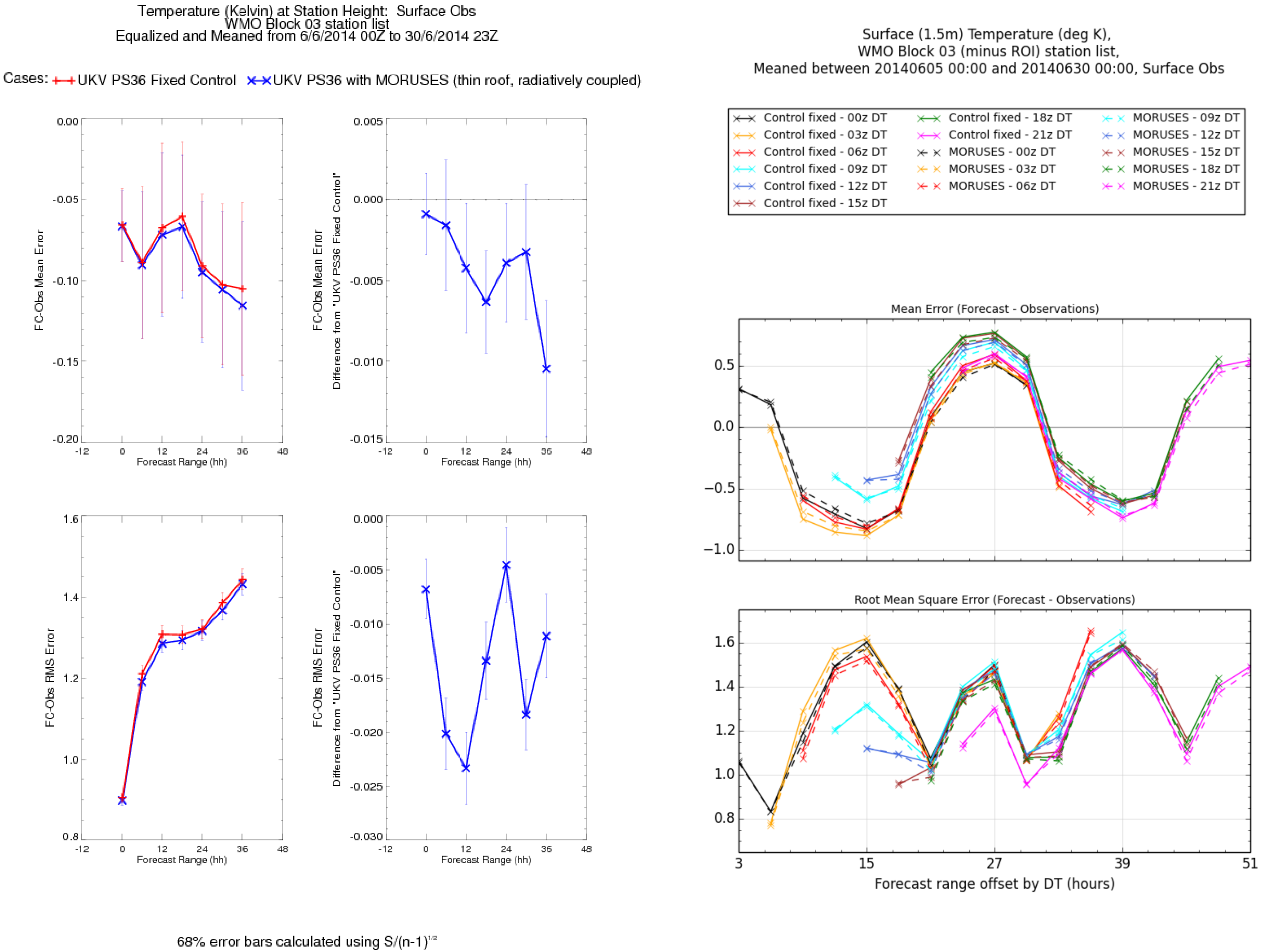


Figure 7.3: Impact of MORUSES on screen level temperature during Summer 2014 trial; whole trial (left) and diurnal cycle (right).

Health advice

The UK wide verification in the PS37 trials show a positive impact, however as already mentioned these are more of a rural based verification. Although a Station Based Verification was performed for the WGOS report, these were for 15 Z in the Summer 2014 and 03 Z in the Winter 2015 trial periods from the T+24 forecast so are limited in their scope. There is still a need to do an SBV analysis using OpenRoad data in more depth specifically looking at maximum and minimum temperatures and their timing for a larger sample of urban areas spanning the range in urban fractions. UKV-MORUSES has been evaluated successfully against observations of surface sensible heat flux, screen temperature and wind for central London, however the performance in the suburbs is an area of further research.

When extending MORUSES to domains with land-use data with coarser or higher resolution than the ITE dataset that is used for the inner UKV domain the morphology datasets need to be carefully checked. On a case study basis we have shown that MORUSES with empirical relationships based on coarser IGBP data still gives better results than urban-1t in dense urban areas. Despite this morphological input data need to be carefully checked, since they are currently coupled to the underlying land-use fraction.

So far MORUSES was evaluated for London at O(1 km) resolutions. It remains open how MORUSES performs at higher or coarser resolution and in urban areas with very tall buildings and a dense urban canopy. However, this is subject to further research within the next years.

Conclusions

This report presents the Met Office Urban Surface Exchange Scheme (MORUSES) that has been recently implemented and tested in the UKV at PS37. MORUSES performance was tested against the operational one-tile scheme (urban-1t) for a case study on 25th June 2012, the whole month of April 2015 and in the two PS37 trials. Performance was evaluated against standard rural observations and shows that the UM-MORUSES performs well. It was further evaluated against observations in central London and showed a good agreement against observations and an improvement in the performance compared to the operational urban-1t surface energy balance parametrisation.

The statistical analysis of the performance in rural areas showed an overall improvement in skill scores for rural areas. The reason that MORUSES had an influence on rural skill scores being that small sub-grid scale urban land-use fractions are present in rural areas and influence the grid box averaged surface energy balance.

Diurnal cycles of surface sensible heat flux during a case study in June 2012 and the month-long simulations in April 2015 demonstrate the improved behaviour of MORUSES over urban-1t in greater detail. The calculation of bulk parameters such as thermal roughness length or emissivity in MORUSES is physically based compared to urban-1t and allows to vary those parameters over a whole urban area as a function of building geometry. The nature of the two-tile scheme in MORUSES and the fraction-weighting of a tile with small thermal inertia (roof) and a tile with larger thermal inertia (canyon) gives more flexibility in the timing and amplitude of the sensible heat flux and storage term. As a result the MORUSES parametrisation improves the timing of the increase in the sensible heat flux in the morning and corrects the timing of the peak of the sensible heat flux. MORUSES also simulates higher peak values in the sensible heat flux during noon and afternoon. This difference has an impact on the timing of the rise in screen level temperature in the morning and brings it forward compared to urban-1t in most cases.

It is very difficult to obtain observations for heterogeneous urban areas that are comparable with simulations. This limits the locations and data available to evaluate urban schemes. So far MORUSES and urban-1t have only been evaluated for densely built central areas in London and it remains open how the scheme performs in the suburbs with higher vegetation fractions and lower buildings. Observational data were chosen from locations that were at some height above roof top to ensure comparability with the simulated variables which are given at screen level above roughness length and displacement height. We would like to emphasise the need for further carefully chosen urban measurement sites in different locations within urban areas and the need for vertical measurements throughout the urban boundary layer to further develop and evaluate urban parametrisations.

Another issue is the accuracy of the morphological input data and the urban land-use data. The report shows that the urban land-use fractions play an important role in setting the urban temperatures. With coarser IGBP datasets used for urban areas in the outer domain of the UKV such as Paris we hypothesise that temperatures are less well simulated than for areas in the inner domain at the moment. The coarser IGBP dataset has an impact on the urban morphology settings favouring taller buildings in the suburbs. Consequently, this leads to a larger thermal inertia for those urban grid boxes and a phase shift of the sensible heat flux towards later in the day. Despite this we showed with a case study for London using IGBP data that MORUSES with coarse IGBP data and an associated set of morphology data still showed a better model performance than urban-1t for London. However, this is an issue that needs to be addressed when the UKV domain gets expanded. A comparison of the IGBP and the ITE dataset for the inner UKV domain demonstrated that the IGBP data underrepresent very small urban sub-grid-scale land-use fractions in rural terrain and hence affect supposedly rural areas with regards to the surface energy balance and temperature as well.

Future research

An area of future research is how MORUSES performs at higher resolutions and in more complex urban areas with single tall buildings and in case of a canopy consisting of taller buildings. A first step will be to develop input datasets for MORUSES at 300 and 100 m resolution and test the model at these resolutions for London. A further step will then be to configure and evaluate MORUSES for areas with isolated tall buildings and a canopy of tall buildings at O(1 km). A NERC-case studentship has been awarded to Grimmond and Bohnenstengel to start investigating the behaviour of MORUSES at higher resolutions and work will be undertaken within the China-CSSP programme to set-up MORUSES for Shanghai and Beijing.

Acknowledgements

We would like to thank Prof. Sue Grimmond, Prof. Janet Barlow, Dr. Simone Kotthaus and Dr. Christos Halios for providing the Met Office with observational data taken within central London. We would further like to thank them for their helpful discussions interpreting the observational data. We would also like to thank Joe Mancell & Ricky Wong with helping to find and fix the bug preventing the UM from reading the MORUSES dump and thus enabling the PS37 work to commence. We would further like to thank Jorge Bornemann for helping to set up the UKV-MORUSES for the PS37 trials, the April 2015 simulations and performing the SBV for the WGOS report. We would like to thank Chloe Eagle for providing us with site-specific data from the observational UM and help with python code. We would like to thank Robert King who worked on the UM-MORUSES simulations for April 2015 during his secondment in Reading.

Bibliography

Bohnenstengel SI, Evans S, Clark PA, Belcher SE. 2011. Simulations of the London urban heat island. *Quarterly Journal of the Royal Meteorological Society* **137**: 1625–1640

Bohnenstengel SI, Hamilton I, Davies M, Belcher SE. 2014. Impact of anthropogenic heat emissions on London's temperatures. *Quarterly Journal of the Royal Meteorological Society* **140**: 687–698

Harman IN, Barlow J, Belcher SE. 2004. Scalar Fluxes from Urban Street Canyons Part II: Model. *Boundary-Layer Meteorology* **113**: 387–410

King R. 2015. Comparison of UKV with MORUSES and JULES in urban areas. *Met Office Internal Report* URL `http://www-nwp/~rking/land_surface/secondment_report.pdf`

MacDonald RW, Griffiths RF, Hall D. 1998. An Improved Method for the Estimation of Surface Roughness of Obstacle Arrays. *Atmospheric Environment* **32**: 1857–1864

Porson A, Clark PA, Harman IN, Best MJ, Belcher SE. 2010a. 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**: 1514–1529

Porson A, Clark PA, Harman IN, Best MJ, Belcher SE. 2010b. 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**: 1530–1542

Porson A, Harman IN, Bohnenstengel SI, Belcher SE. 2009. How Many Facets are Needed to Represent the Surface Energy Balance of an Urban Area? *Boundary-Layer Meteorology* **132**: 107–128

Met Office	Tel: 0370 900 0100
FitzRoy Road, Exeter	Fax: 0370 900 5050
Devon, EX1 3PB	enquiries@metoffice.gov.uk
UK	www.metoffice.gov.uk

Produced with the Met Office LaTeX template v2.0.0