Report on JULES and UM changes to improve the clear sky diurnal cycle of temperature and winds, based on comparisons with Cardington observations

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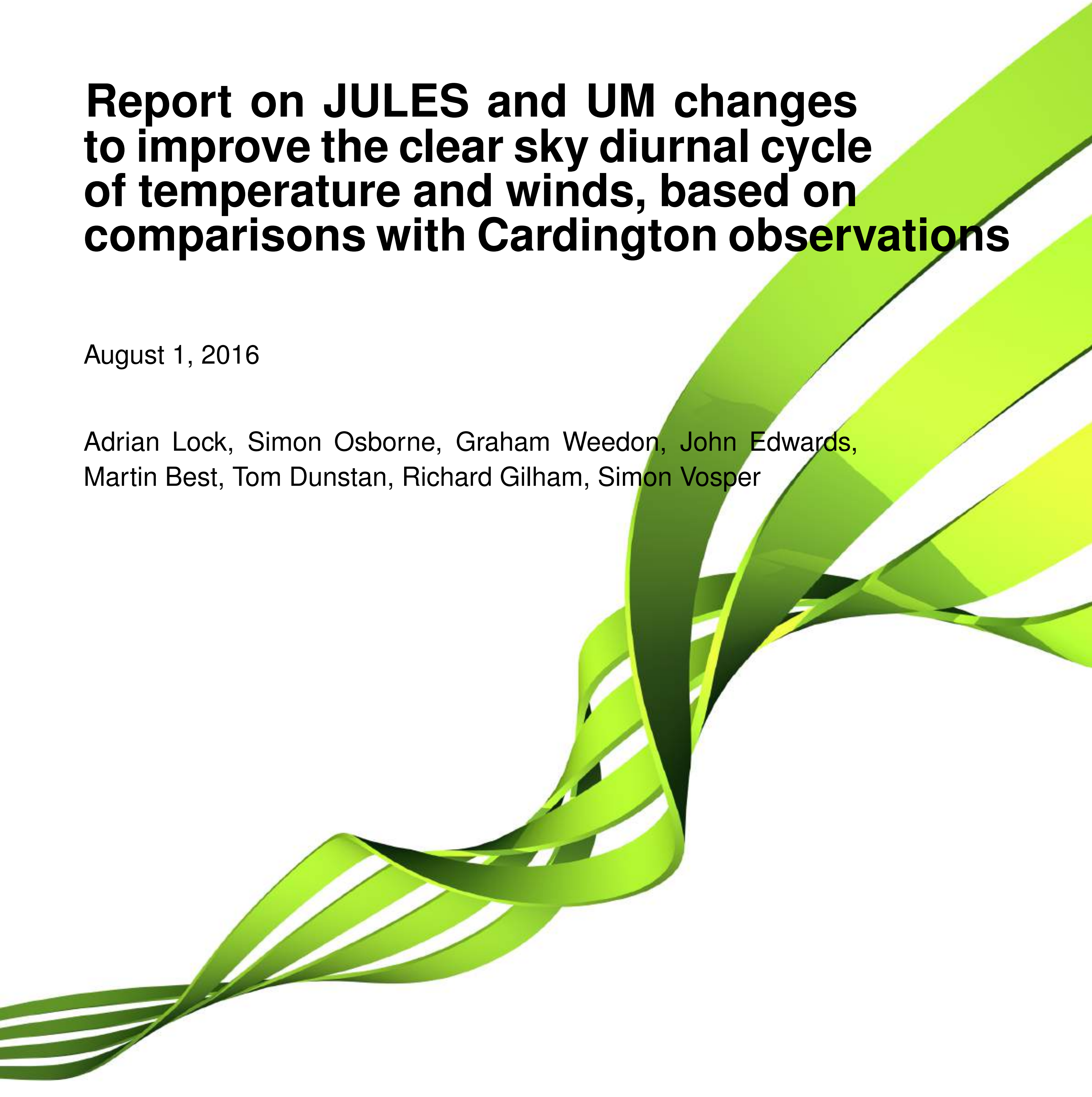

Abstract

Detailed studies have been conducted into the the nature of the systematic diurnal errors in near-surface temperatures and winds in MetUM forecasts over the UK. These studies have included off-line JULES simulations, case studies with the UKV and month-long DA-trials, and detailed comparison has been made with both the operational network of surface sites and the Met Office Observational Research site at Cardington. While the issues involve complex interactions between the land surface representation, the boundary layer turbulence scheme and their interaction with the resolved scale flow, some proposed changes to the model configuration will be taken forward into testing for possible inclusion in RA1 (for example, improvements to parameters representing the properties of vegetation and stable boundary layer turbulence). Key recommendations for further work are:

- more realistic UKV surface characteristics (tile fractions, canopy height, albedo and LAI) are urgently required with suggestions made for relatively simple short term improvements
- longer term, the choice of vegetation tiles should be reviewed (what what are the important differences between vegetation types that require separate tiles? How is small-scale heterogeneity (such as hedges and scattered trees) to be represented in JULES?)
- detailed work is required to understand and improve the representation of vegetation canopies in JULES (we are very grateful to have Hiroshi Kusabiraki, visiting Scientist from JMA, working with us for the next two years on this)
- there are several outstanding questions regarding the representation of soils in JULES that impact on temperature forecasts, both through the thermal conductivity and also via the soil moisture and its impact on surface evaporation (soil vertical resolution and soil tiling play a role as does the specification of root depth; the sensitivity of evaporation from bare soil to the soil moisture content also appears insufficient)
- a detailed study of the surface momentum budget is needed, including the effects of subgrid orography even at UKV resolution on both the low-level wind and temperature profile, as well as better characterisation of the surface roughness

1 Introduction

There are long-standing errors in the diurnal cycle of near-surface temperature and wind speed forecasts in the UM, with both variables exhibiting a suppressed diurnal range compared to observations (so too warm and windy at night, too cold and calm by day), especially under cloud-free skies. Some improvements were reported in Brown et al (2008) after the introduction of non-local stress profiles and a stronger reduction of turbulent mixing with increasing stability over sea, and further reductions in stable turbulence and surface emissivity were made in PS31 for UKV (Jan 2013). However, recent example verification over the UK of global and UKV forecasts in Figs. 1 and 2 suggests these problems remain (other verification plots are available from `http://www-nwp/~fprc/UKV/Verification/Daily` The following discussion of these errors will focus on "inland sites" (dashed lines) as they are likely to give a more representative comparison than "coastal" or "mountain".

There is a persistent fast wind speed bias at night of almost 0.5 ms^{-1} in UKV (1 ms^{-1} in GM) that is associated with equally persistent direction errors of 5 (and 10) degrees. As discussed in Brown et al (2008), these errors are suggestive of excessive vertical turbulent mixing of momentum in nocturnal boundary layers and, consistently, this is also configured to be somewhat stronger in GA6 ("Mes"-tail") than current UKV ("SHARPEST"). By day the winds are consistently too weak in the UKV, although the magnitude of the bias is smaller than by night, while the GM still has winds that are consistently too strong but less so than at night. The picture is complicated further by the issue of subgrid orographic drag which is currently switched on in GM (both gravity wave and form drag) but is not used in the UKV. Despite the latter's significantly higher resolution it is not clear that subgrid orography might not still make a significant contribution to overall drag. Quite why the GM winds are systematically stronger over UK land than UKV is not clear and may warrant further investigation. There is also some evidence from verification of winds of the sea (and the performance of the wave model around the UK) that here the reverse is true, with GM have slower winds over the sea than UKV. Tests of using consistent sea-surface exchange formulations in UKV and GM are planned for the coming year (current the details differ).

The near-surface temperature verification in Fig. 1 shows the daytime cold bias is much more seasonally persistent (at around 0.5 K) than the nighttime warm bias, which was not seen at all in the past two winters. However, these two seasons were marked by being particularly stormy and lacking in the lighter wind conditions which case study evaluation, such as is shown in this report, still shows lead to very significant warm biases (of several degrees) developing. It is not clear whether efforts to improve the nocturnal cooling on clear calm nights (by reducing turbulent mixing, for example) would have a detrimental effect on temperature errors under last winter's weather regimes.

Some progress was made in PS37 UK LAMs to reduce the average daytime error in screen temperature, see Fig. 3, reducing the daytime cold bias almost by half (from around 0.8 K to 0.5 K). The dominant contribution was to include the interactive aerosol-dependent parametrization of droplet

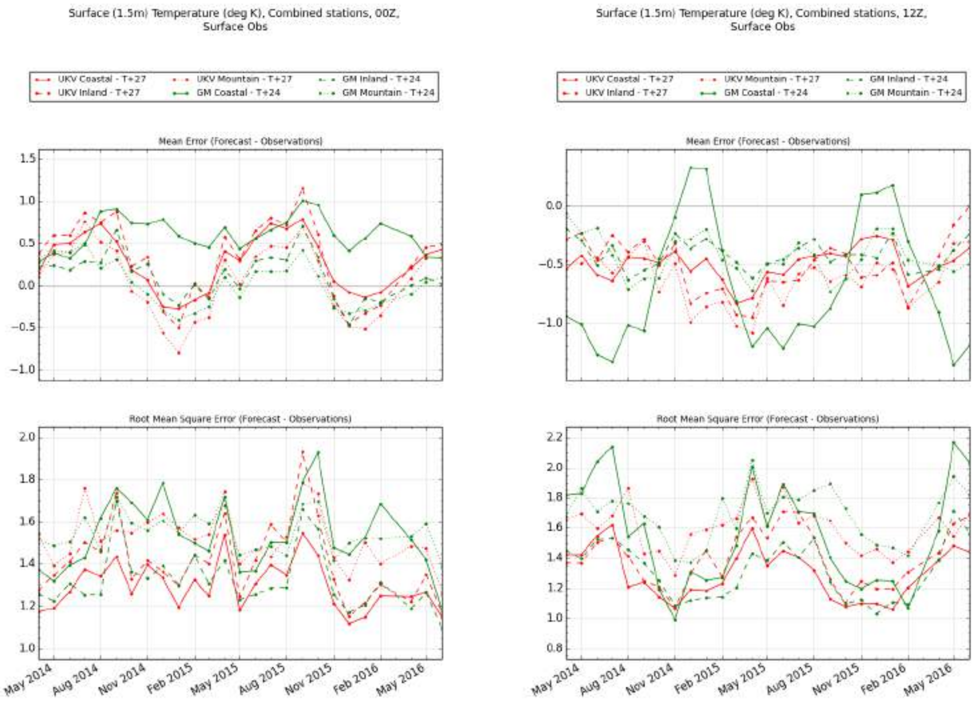

Figure 1: Verification over the UK at 00z (left) and 12z (right) for screen-level temperature

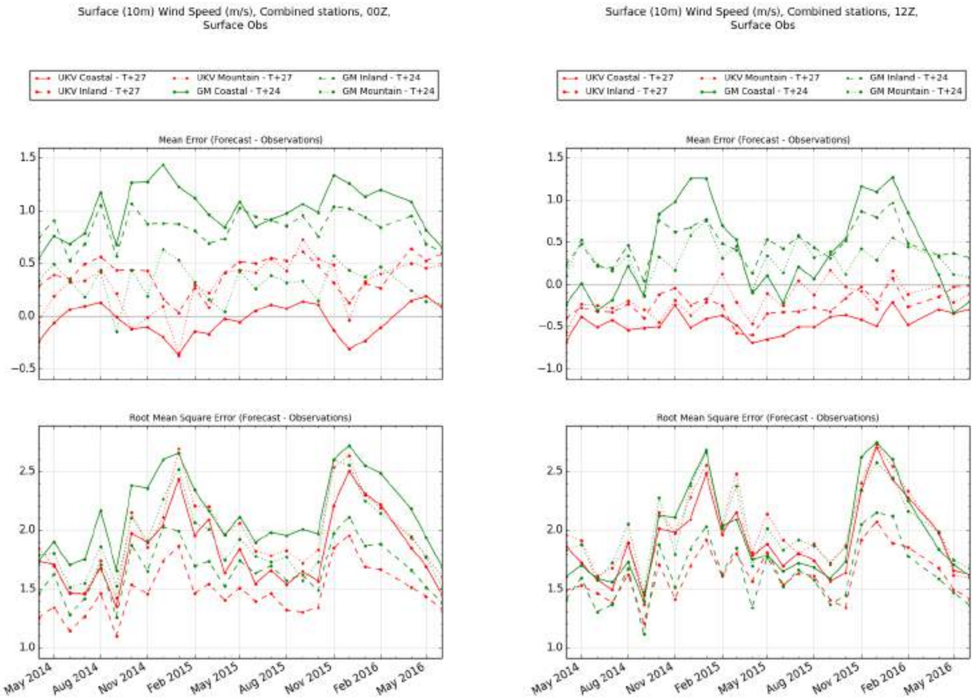

Figure 2: Verification over the UK at 00z (left) and 12z (right) for 10m wind speed

size in the radiative transfer calculation (the so-called first indirect effect of aerosols on atmospheric radiation) that, on average, reduced the reflectivity of clouds resulting in enhanced downwelling shortwave radiation at the surface (and verification for the solar power industry has previously highlighted lack of incoming SW radiation as a significant bias in UKV). Since PS37 became operational (15 March 2016) Fig. 1 suggests some encouraging improvement in the operational UKV daytime temperature biases (being close to neutral on average in May and June, and distinctly warmer than GM).

Bohnenstengel and Hendry (2016) report on the impact of the implementation of the MORUSES urban scheme, also in PS37 UKV. A systematic reduction in roughness length was shown to lead to a small increase in mean wind speed (although at 0.1 ms^{-1} small compared to monthly variability in Fig. 2). There was also a small beneficial nocturnal cooling seen in urban areas, also connected to the reduced surface roughness (driving weaker near-surface turbulence).

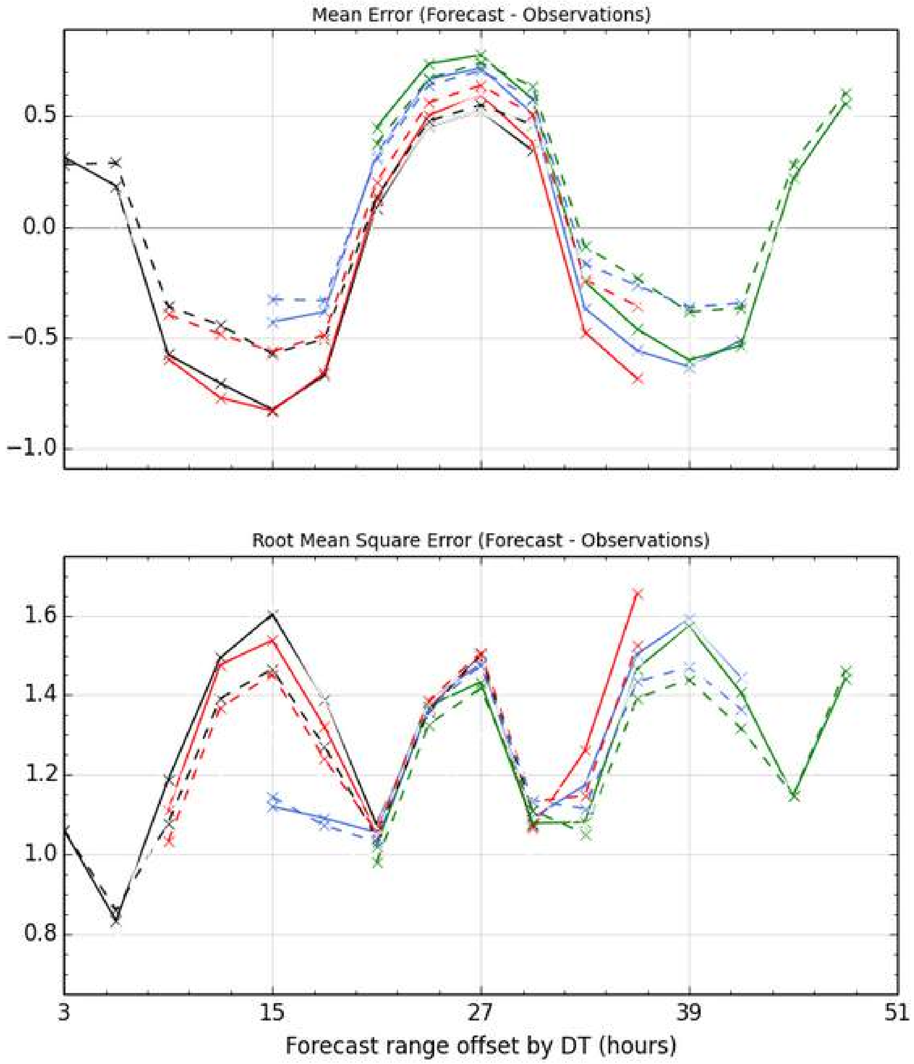

Figure 3: Diurnally sampled verification over the UK for the UKV summer trial of the PS37 upgrade (dashed lines) compared to the operational control (solid lines)

The MORUSES study serves to highlight the importance of surface drag in the performance of the UKV, something that has motivated some of the studies in this report. The report is set out as follows. First, two studies in sections 2 and 3 investigate the performance of stand-alone JULES, driven by observations from the Met Research Unit at Cardington, and its sensitivity to a wide range of science choices, parameter settings and ancillary data. Section 4 then studies the impact of including the orographic drag parametrizations and making changes to the surface vegetation characteristics in the UKV. Finally, conclusions are drawn in section 5.

2 JULES sensitivity studies for single-site JULES runs based on the Cardington field site

2.1 Introduction

Various sensitivity studies have been performed using offline JULES Version 4.4 for the grass site of Cardington, Bedfordshire. As near-surface air temperature is one of the necessary driving variables for JULES, our overall aim is improve the prediction of skin temperature, whilst also being wary of the various components of the energy balance, soil temperature and momentum fluxes. JULES runs have been carried out with operational UKV settings for the plant functional type (PFT) of C3 grass, and then modifications have been made to the canopy parameters and the soil layer resolution. An additional study is also shown on the shortwave albedo of grass.

The modifications made for C3 grass are shown in Table 1. The PFT parameters are fixed whilst the prescribed dataset of observed albedo is allowed to vary with time during the simulation. These modifications have been included in simulations either separately or collectively as a ‘real grass’ configuration.

parameter	type	UKV	realistic
$canht$	PFT	1.46m	0.1m
$kext$	PFT	0.5	1.0
$z0hm$	PFT	0.1	0.01
$rootd$	PFT	0.5m	0.175m
LAI	PFT	0.78–2.39	2.0
albedo	prescribed	0.18	observed

Table 1: JULES parameters modified to create a real grass configuration.

Reducing $canht$ to a value comparable to the manicured grass site at Cardington (5–8cm height all year round) is an obvious modification to test the physics of JULES when driven by the site meteorology. Forcing the shortwave albedo is another constraint based on real-world data. LAI

is hard to estimate but it is reasonable to assume that its value would not change appreciably throughout the year for the grass at Cardington (compared to the LAI of C3 grass in the ancillaries which varies between 0.78 and 2.39). A $rootd$ value of 0.5 is arguably suitable for long grass, but the short grass at Cardington would tend to have shortened roots. The ratio of roughness lengths $z0hm$ ($= z_{0h}/z_{0m}$) depends in part upon leaf area index and friction velocity and our estimate for short grass is taken from figure 3 of Duynkerke (1992). Increasing the absorption coefficient $kext$, used as a Beer's law exponent for the transmission of radiation through the canopy in an analagous manner to optical depth, implies a denser grass canopy with less implicit bare soil. This was deemed more realistic for grass than a value that is meant to represent crops too.

Given the importance of assessing the momentum flux, we start by correlating observed and simulated friction velocity for a moderate length dataset which highlights some of the practical issues of measuring turbulence at Cardington.

2.2 Effect of wind direction on correlation of observed and simulated U_* and 10-m winds using a 16-month dataset

Fig. 4 shows scatter plots of JULES surface friction velocity (U_*) against observed U_* at the 10m height. Each panel shows the same observed data but different JULES configurations as labelled. The data is coloured according to 30° wind direction bands. All plots show a distinct limb of data for wind directions roughly in the 350 to 110° sector which contains the airship hangars (150m away from the 10-m mast) and the a cluster of single-story buildings (40m away). Both the $ukvgrass-canht$ ($canht$=0.10m) and $realgrass$ runs show good, and similar, correlations of U_* for the bulk of the points not affected by local buildings. As the effective fetch of the 10m turbulence can vary significantly depending on stability conditions, we have also driven JULES with 10m and 25m data in addition to 2m. But it can be seen that the correlation becomes poorer as the drive height increases because the JULES U_* values tend to increase away from reality and become noticeably non-linear. 50m drive height data is not shown here due to significant data loss in the period under scrutiny. $realgrass-tiles$ shows another run containing the UKV mixture of tile fractions for the Cardington grid box instead of 100$\%$ C3 grass. This also increases turbulence in JULES and pushes U_* to unrealistic values.

In conclusion, the optimum JULES simulations of U_* (or momentum flux) are based on shortened ($canht$=0.10m) C3 grass when driven from the lowest available measurement level for winds (2m). The diagnosed 10m wind speed from JULES (not shown) responds in a similar manner to U_*, with the best agreement occurring for a short $canht$=0.10m when JULES is driven by the screen-level observations. As the MetUM in general assimilates screen-level network observations of the state parameters, it makes sense to optimise off-line JULES with the Cardington screen-level data too. Please also refer to section 3 for optimisation of momentum flux and wind speed from an extended

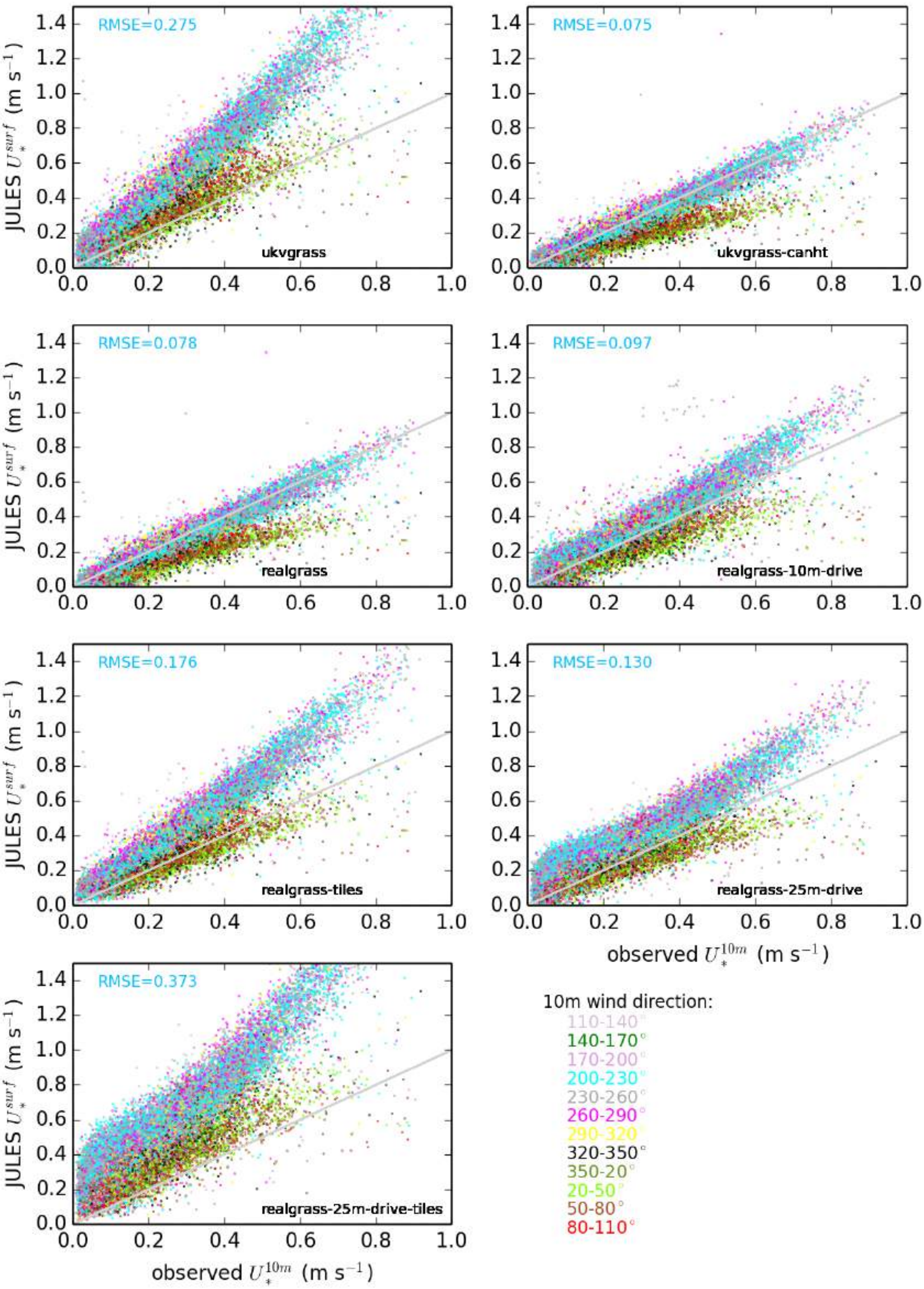

Figure 4: JULES simulated surface friction velocity (U_*) against observed U_* at 10m. Each point represents 30 min covering the period May 2014–August 2015.

dataset.

2.3 Effect of increasing the number of soil layers

We have increased the number of soil layers from 4 to 6 and 9 using the thickness definitions of Edwards *et al* (2011) whilst keeping all other settings unchanged. These runs were performed using the UKV settings for C3 grass. The thicknesses are summarised in Table 2.

no. of layers	thicknesses (cm)
4	10, 25, 65, 200
6	1.46, 5.41, 16.2, 44.9, 100.1, 186.9
9	1.63, 2.92, 6.43, 14.15, 28.3, 49.2, 78.5, 116.0, 164.0

Table 2: Three sets of soil layer thickness used in the JULES sensitivity runs

For the 6 and 9 level runs, the JULES time step (*timestep_len* in `timesteps.nml`) had to be reduced from 30 mins to less than 15 mins (10 mins was chosen) to remove some spurious oscillations in soil temperature in the top shallow layer (and hence other parameters too).

The effects of running JULES with 6 and 9 soil layers compared to the normal 4-layer scheme are shown in the monthly mean plots for April and August 2015 in Figs 5 and 6. We can treat these months as ‘transitional’ and ‘dry’ in terms of soil moisture: the 10cm measurement shows soil moisture above the critical point in April, and between the wilting and critical points in August. The JULES data for these two example months were extracted from 16-month simulations that are initialised with the correct soil conditions and left to free-run for the period. The JULES moistures tend to be too low, especially in the top soil layer as seen here, because JULES tends to evaporate too readily.

Daytime soil temperatures are warmed markedly in the 6 and 9 layer schemes, giving better agreement with the 1cm observations, in particular with the phasing of the diurnal cycle, although the nights are now too cold. Ground heat fluxes during the day in April are increased, probably too much, with the daytime peak occurring too early in general in JULES. The August ground heat does not change by much with soil resolution. The effect on latent heat is somewhat haphazard from month to month, perhaps reflecting changes in soil moisture. August shows quite a dramatic reduction in latent heat with increasing soil resolution that is not seen in April. Sensible heat likewise varies greatly from month to month, although it naturally tends the opposite way to latent heat, but is overestimated in general for both months shown here. There is a small increase in daytime skin temperature in August for the 9-layer scheme (and decrease at night), which is beneficial as regards correcting the model temperature bias (note the blue data conceals the orange here).

Fig 7 shows comparisons of JULES and observations over a two-day clear-sky period between 15–16 April 2014. JULES runs were carried out at 4, 6 and 9 levels. The soil schemes are identical to those used in the monthly mean runs. The JULES soil temperatures alone are shown in panels (f),

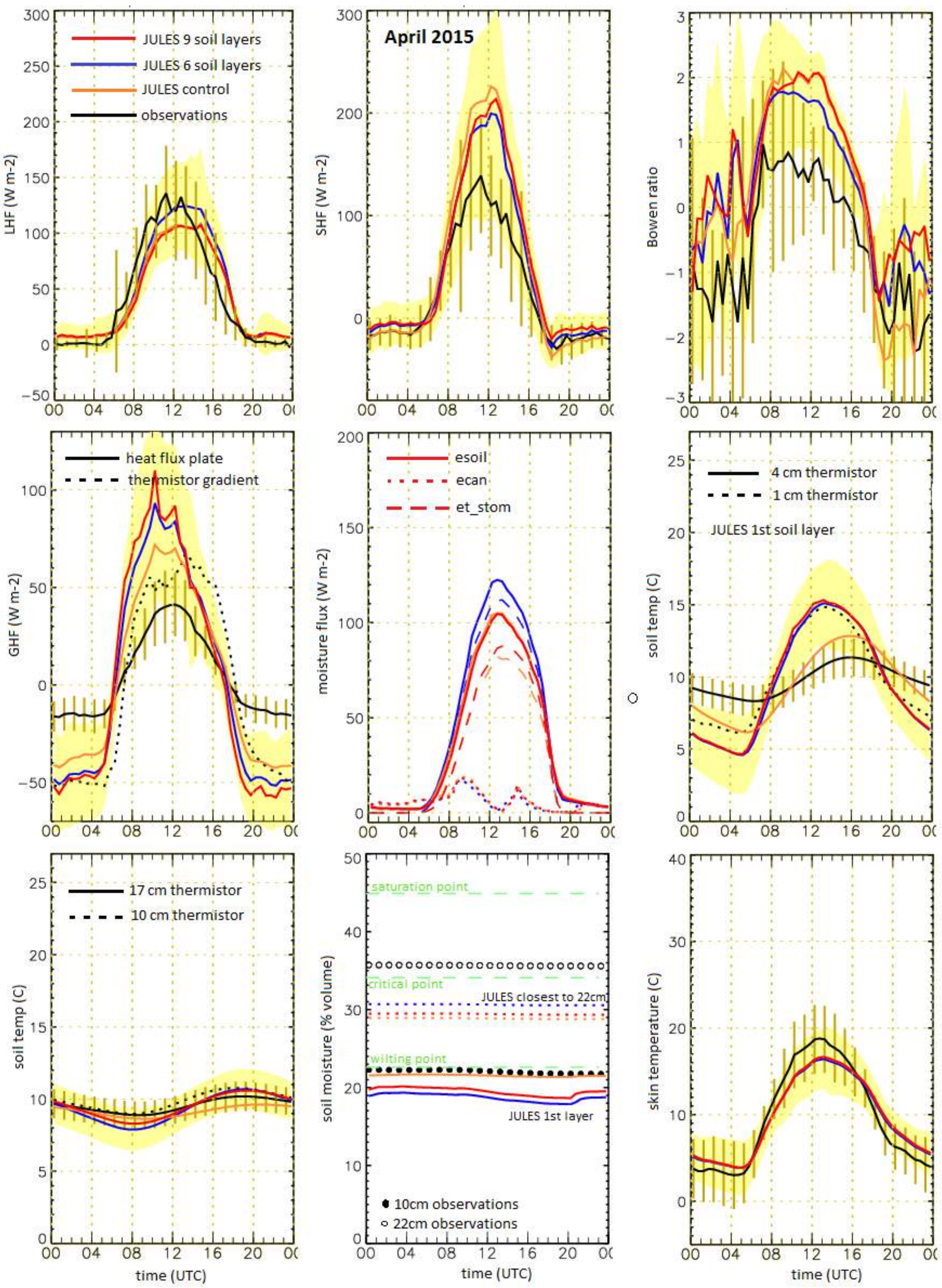

Figure 5: April 2015 monthly means for various air and ground parameters from observations (black with vertical +/- 1 standard deviation bars) and JULES simulations (coloured lines with yellow shading representing JULES control +/- 1 st dev).

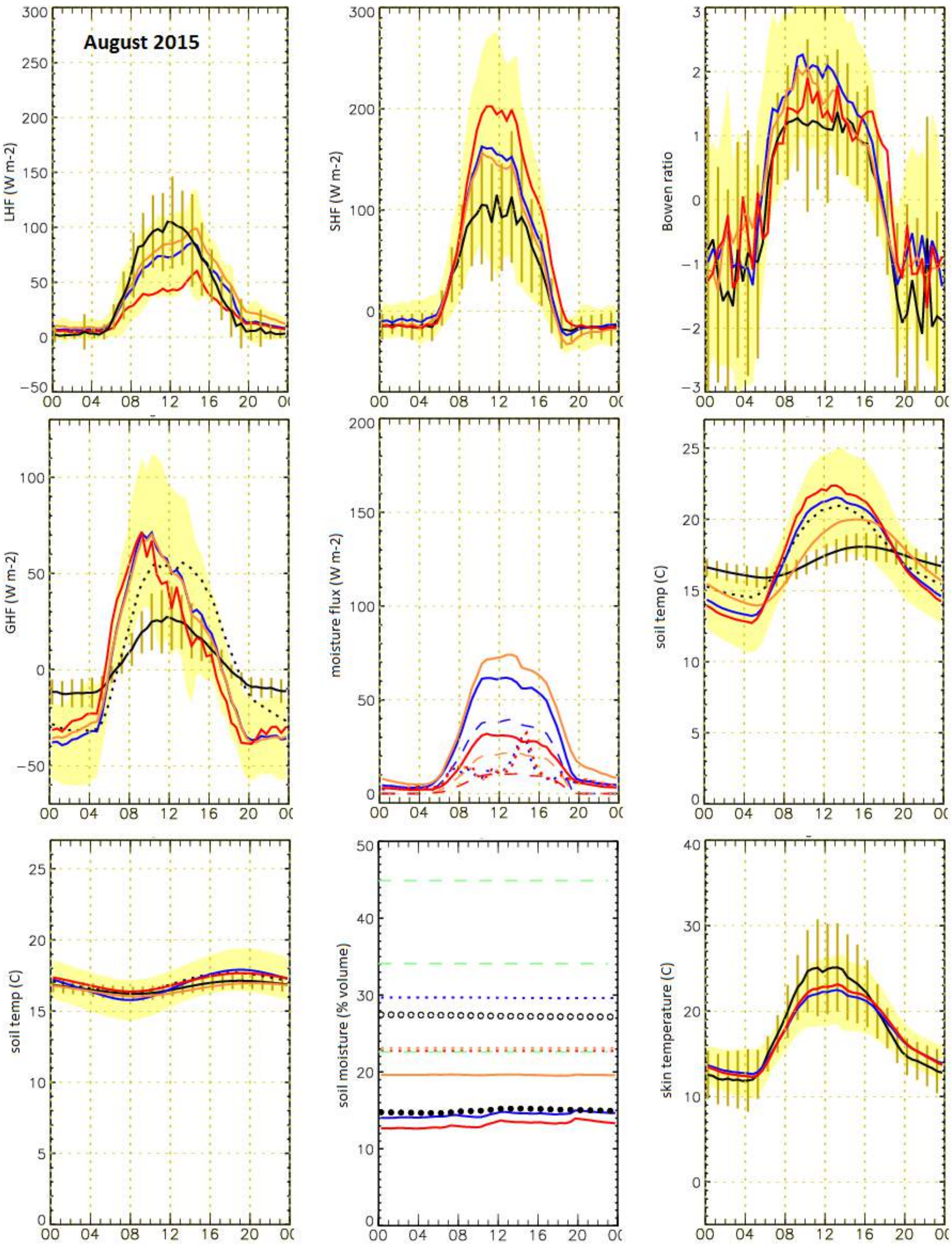

Figure 6: August 2015 monthly means for various air and ground parameters from observations (black with vertical +/- 1 standard deviation bars) and JULES simulations (coloured lines with yellow shading representing JULES control +/- 1 st dev).

(g), and (h) where the warmer near-surface soil layers can be seen in the 6 and 8 layer schemes. Finer-scale variations in the first two layers can also be seen that correlate with skin temperature and downwelling radiation variations: however, such variations are not seen in the 1cm soil temperature observations in panel (b).

The 6 and 9-layer near-surface soil temperatures are now too warm during the day by 1-2°C and too cold at night by 2-3°C (panel b), similar to the August 2015 means in Fig 6. Smaller magnitude differences are also seen deeper in the soil (panel c). Ground heat fluxes are also increased in magnitude relative to the 4 layer scheme, again with early diurnal peaks. The magnitudes of the sensible and latent heat fluxes in the higher resolution schemes remain largely unchanged here. The skin temperatures at night are warmed by a small amount (less than 1°C) and unchanged during the day. So the effects of increasing soil resolution are not consistent if we consider the monthly means shown above. These effects can probably be reconciled through the available soil moisture and its effect on latent heat flux, hence knock-on effects on sensible heat and skin temperature.

Although the 6 and 9 layer soil schemes show warmer skin temperatures at night, the morning transition period shows a slightly slower growth in skin temperature (with the energy going into the soil instead) which matches the observed gradient. The time of the skin temperature minimum is also slightly later in the modified soil schemes and now matches the observations (but again, the soil temperatures are now poorer in this respect). The time of the transition in the sensible heat flux (from around zero to positive values) and its increase during the morning are also improved (but with a very sharp increase in the ground heat flux during the transition).

In summary, increasing soil resolution increases the diurnal range in soil temperature. Night minima tend to be too cold, however, and day maxima too warm when soil moisture is driest in late summer. For case studies under stable conditions, the soil temperature range can be overestimated by 5–7°C with the higher resolutions. The response of the energy components depends in part on the soil moisture, with the turbulent heat fluxes being sensitive in summer when the soil moisture is close to the wilting point and relatively insensitive in April when the soil is wetter. The diurnal range in skin temperature is increased in the driest months by 1°C, although for our case study in April when soil moisture was above the critical point there was a slight decrease in the diurnal range of skin temperature.

2.4 Comparisons of observations and JULES simulations using improved grass configurations

2.4.1 Reducing *canht*

Chopping $canht$ to more realistic heights has the most profound impact of all the canopy parameters in Table 1, not only on the daytime skin and soil temperatures but the turbulent fluxes too (sensible,

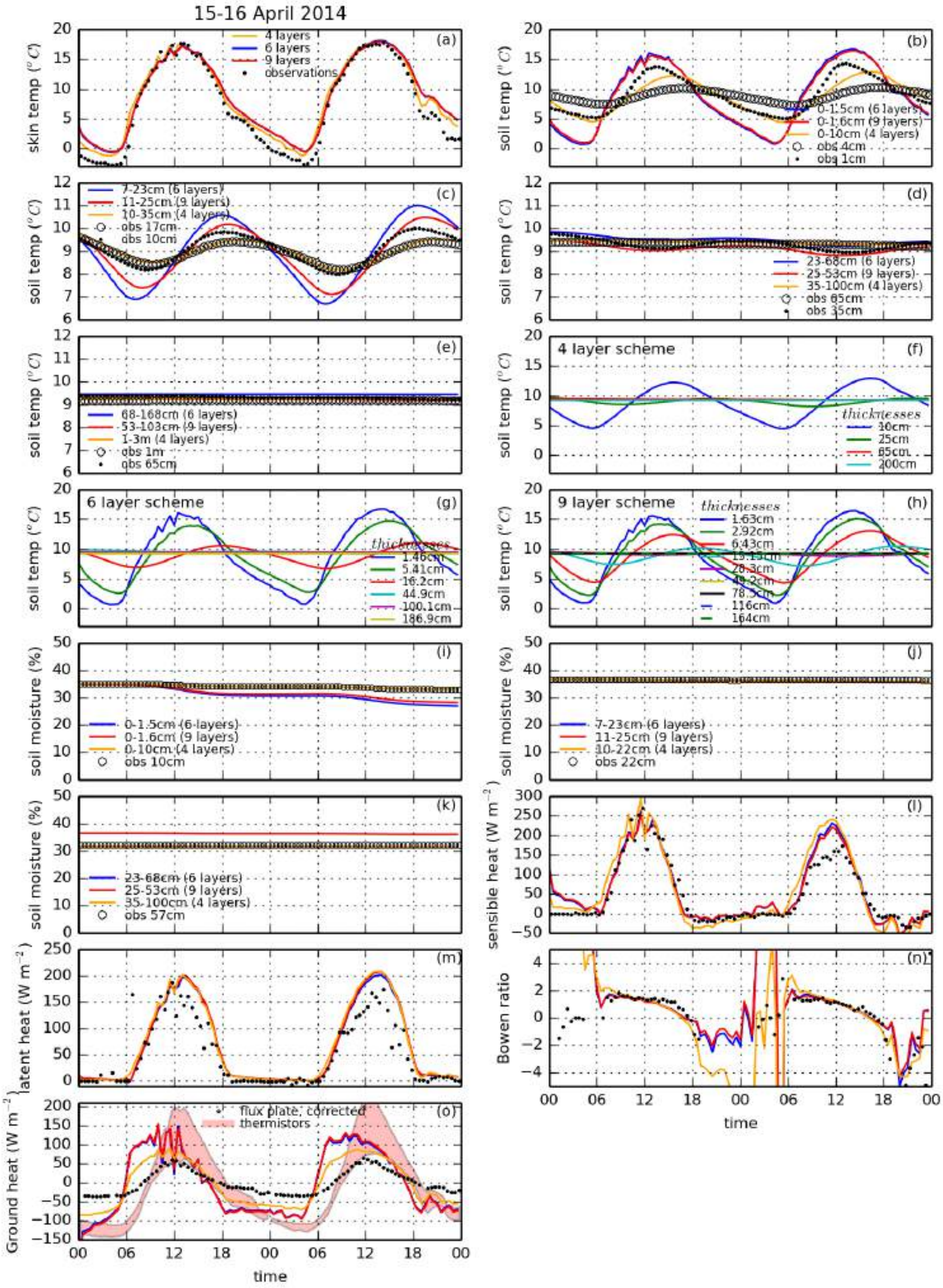

Figure 7: Observations and JULES simulations for the largely cloud-free 48-hour period between 15–16 April 2014. JULES runs are shown at three different soil layer resolutions: 4, 6 and 9 layer schemes.

latent and momentum), which often show better agreement when $canht$=0.1m. The nighttime skin temperatures are not affected by changes in $canht$, so the warm bias at night which is arguably more important than the daytime cold bias, e.g. for predicting overnight frosts, still needs to be addressed.

We show the effect of reducing $canht$ to 10 and 5cm for monthly means data from July 2015 in Fig 8 for a selection of pertinent parameters. There is an improvement in the daytime sensible heat (in fact a general reduction in the turbulent fluxes) and 10m wind speed, although friction velocity has been decreased too much. Skin temperatures are greatly improved (during the day only), but the soil temperatures are arguably too warm with the JULES 0–10cm soil layer now as warm as the 1cm observations.

Adjusting $canht$ for the optimum friction velocity and 10m wind speed from a long-term dataset is shown in section 3: an indicative value of about 0.45m is given when driving JULES with 25m level observations. Our drive data is from screen-level unless otherwise stated (e.g. Fig 4), which means 1.2m for air temperature and humidity and 2m for winds. The 2m wind data is available from April 2011 and so does not cover the longer time range in section 3, so 10m winds were the lowest level used in that study. Further JULES simulations using the 2m wind data should be carried out for the past 5 years; our study here is limited to 16 months. The fetch represented when driving at 25m will include surrounding fields, hedges, small trees and a bit of urban, and so a $canht$ of 0.45m could be deemed appropriate for rural and semi-rural terrain in general. See section 5 for further discussion.

2.4.2 Individual canopy modifications

Monthly mean results for individual canopy changes other than $canht$ (plots not shown) as described in Table 1 are summarised thus:

- Reducing $rootd$ to 0.175m can give a dramatic decrease in the daytime latent heat flux (except in winter when the ground is approaching saturation much of the time), which can be beneficial but can be too much reduction. Sensible heat increases to balance this to some extent. The resultant slightly warmer skin temperatures during the day are barely significant.
- Decreasing $z0hm$ increases skin temperature during the day (2°C achievable as a monthly mean value for $z0hm$=0.001); there is also a small beneficial increase in soil temperatures and a decrease in sensible heat which is largely helpful.
- Increasing $kext$ decreases skin temperature at night (up to 1.5°C for $kext$=2), which is beneficial, but the denser canopy means soil temperatures are decreased at night by probably too much.
- The effect of forcing albedo to match the observations is to increase the albedo, which results in a cooling of the skin temperature during the day (< 1°C) and a decrease in the sensible

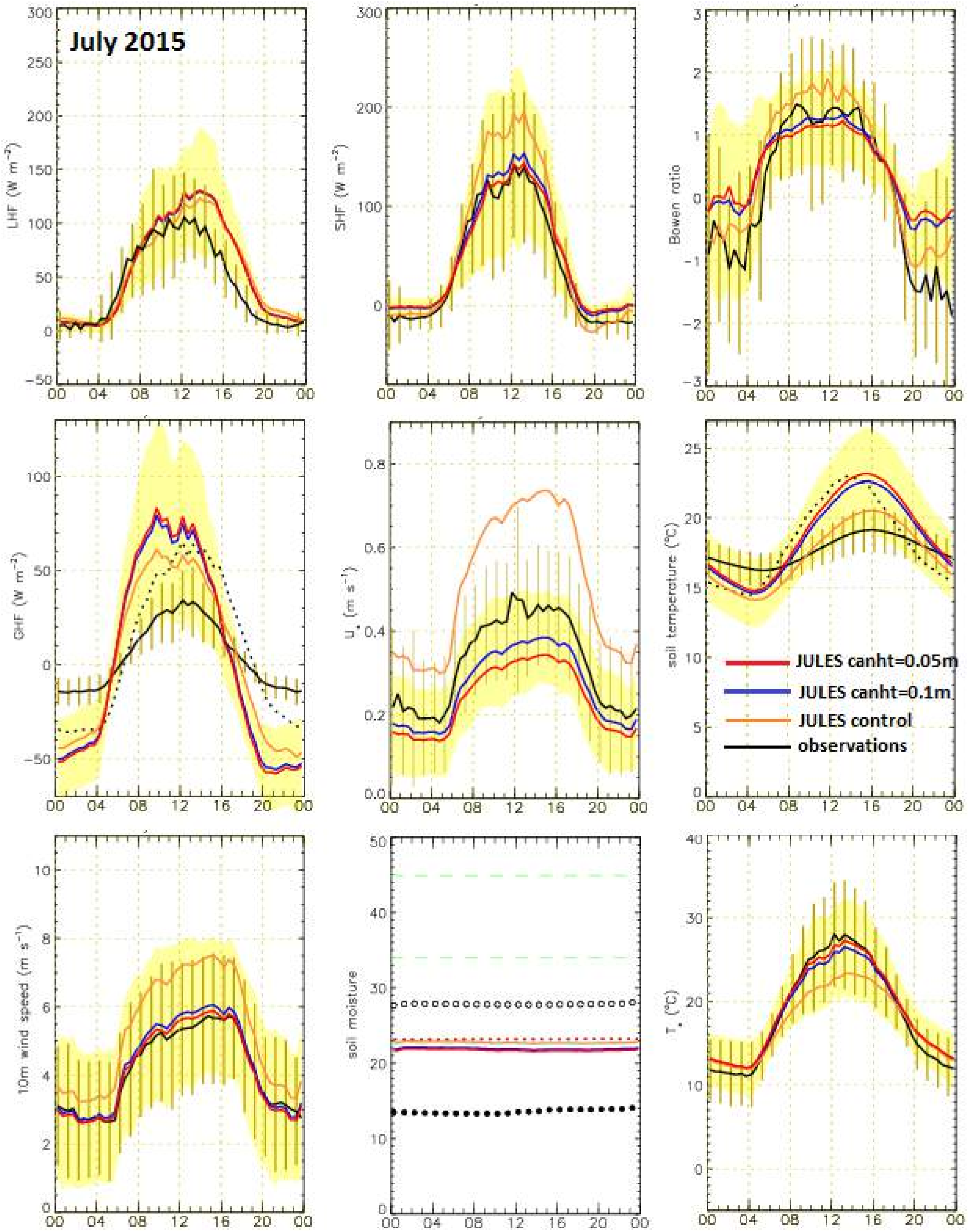

Figure 8: Monthly mean observations (black) and JULES simulations (colours) are shown for July 2015 of the effects of reducing C3 grass canopy height $canht$ from 1.46m (JULES control in orange) to 0.1 (blue) and 0.05m (red) heights.

heat.

2.4.3 'Real grass'

All the modifications listed in Table 1 together make up our 'real grass' scenario. Results using the 16-month dataset organised into monthly means are shown in Figs 9–13, allowing seasonal differences to be analysed. The reduction in the turbulent fluxes for real grass is largely similar to that due to decreasing $canht$ alone and is almost often beneficial. As $canht$ likewise dominates friction velocity and the diagnosed winds, the real grass results for these parameters essentially resemble the example month shown in Fig 8.

Skin temperatures are greatly improved both at night and day, although spring and early summer shows the daytime real grass JULES temperatures to be too warm, sometimes by a few degrees. This is during less cloudy conditions on average, and it is noted that the our real grass settings for JULES clear-sky case studies (not shown) tends to produce slightly too cold temperatures at night ($\approx$ 1°) as well as too warm during the day ($\approx$ 1–2°), so the diurnal range in temperature swings from our initial problem of being too small to being too large. The effect of setting $kext$=1.0 has a bigger cooling effect on the skin temperature on a clear radiation night relative to monthly-averaged weather conditions. Although a $canht$ of 0.45m was derived for a drive height of 25m (section 3), its use produces daytime skin temperatures for clear-sky conditions that are in good agreement with observations and therefore seems a good compromise.

The real grass ground heat fluxes are increased in spring and early summer, although not excessively, when skin temperatures are likewise warmed. Soil temperatures in the first soil layer are warmed in the spring and summer, which depending on the month is probably better at night but too warm during the day, given we should expect the JULES first soil layer to best match the 4cm observations. During the winter months when the soil is near-saturated, JULES real grass data is universally too cold by 1-2°C.

In summary, the 'real grass' package shows an overall improvement compared to setting $canht$=0.1m alone. Skin temperature minima are colder and the turbulent heat fluxes are decreased with good agreement through the year, especially for sensible heat. The impact on latent heat is a bit more mixed, although its asymmetrical decrease during the day when using real grass means the late afternoon and evening period is now often improved where before the overestimate by JULES was particularly noticeable. July 2014 (Fig 9) is a good example of such an improvement where the morning transition remains unchanged but the midday and afternoon latent heat is decreased to much nearer the measurements.

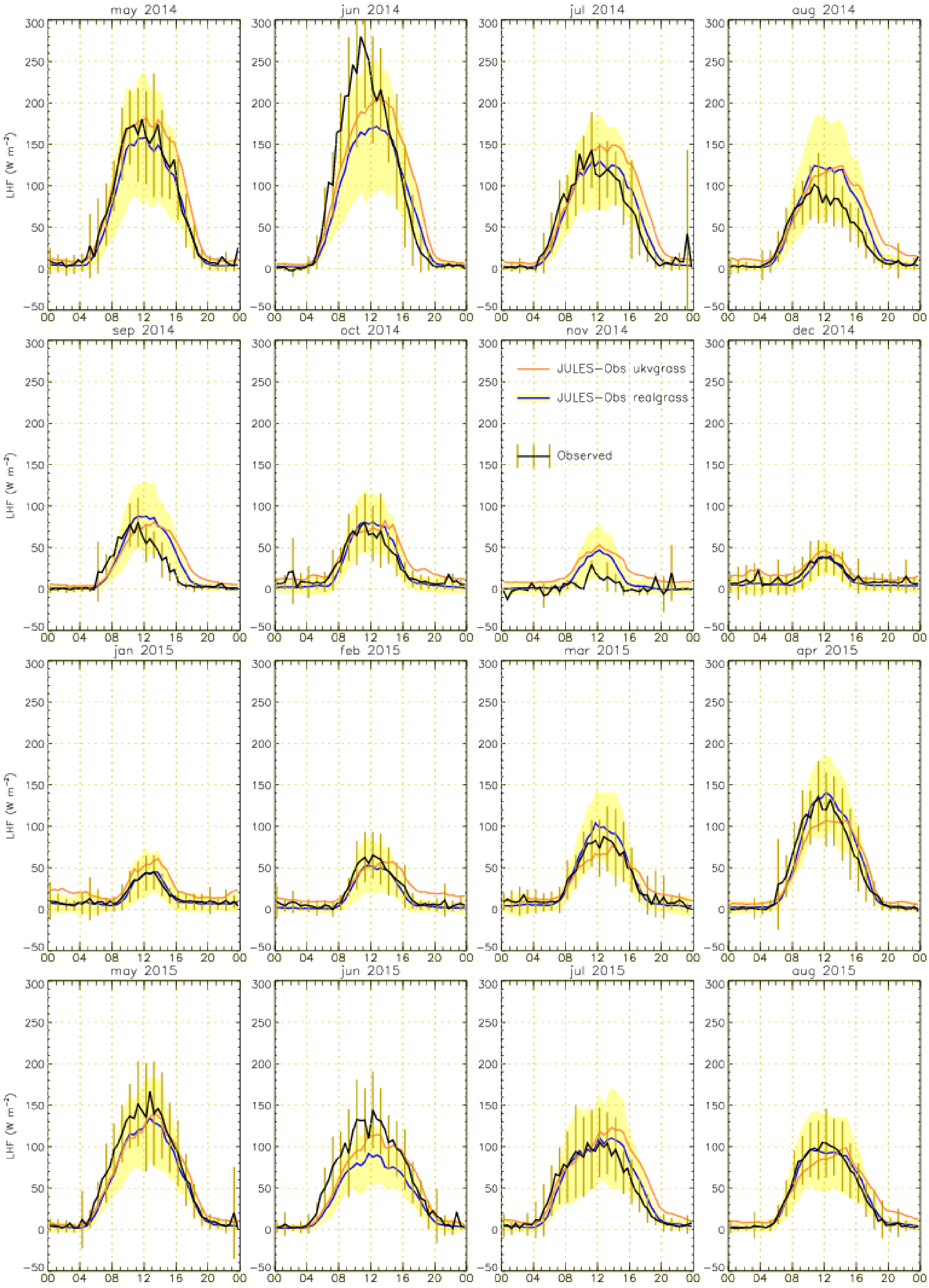

Figure 9: Monthly mean observations (black) and JULES simulations (colours) of latent heat flux are shown for all months between May 2014–August 2015. Orange is the UKV settings control, blue is the ‘real grass’ configuration

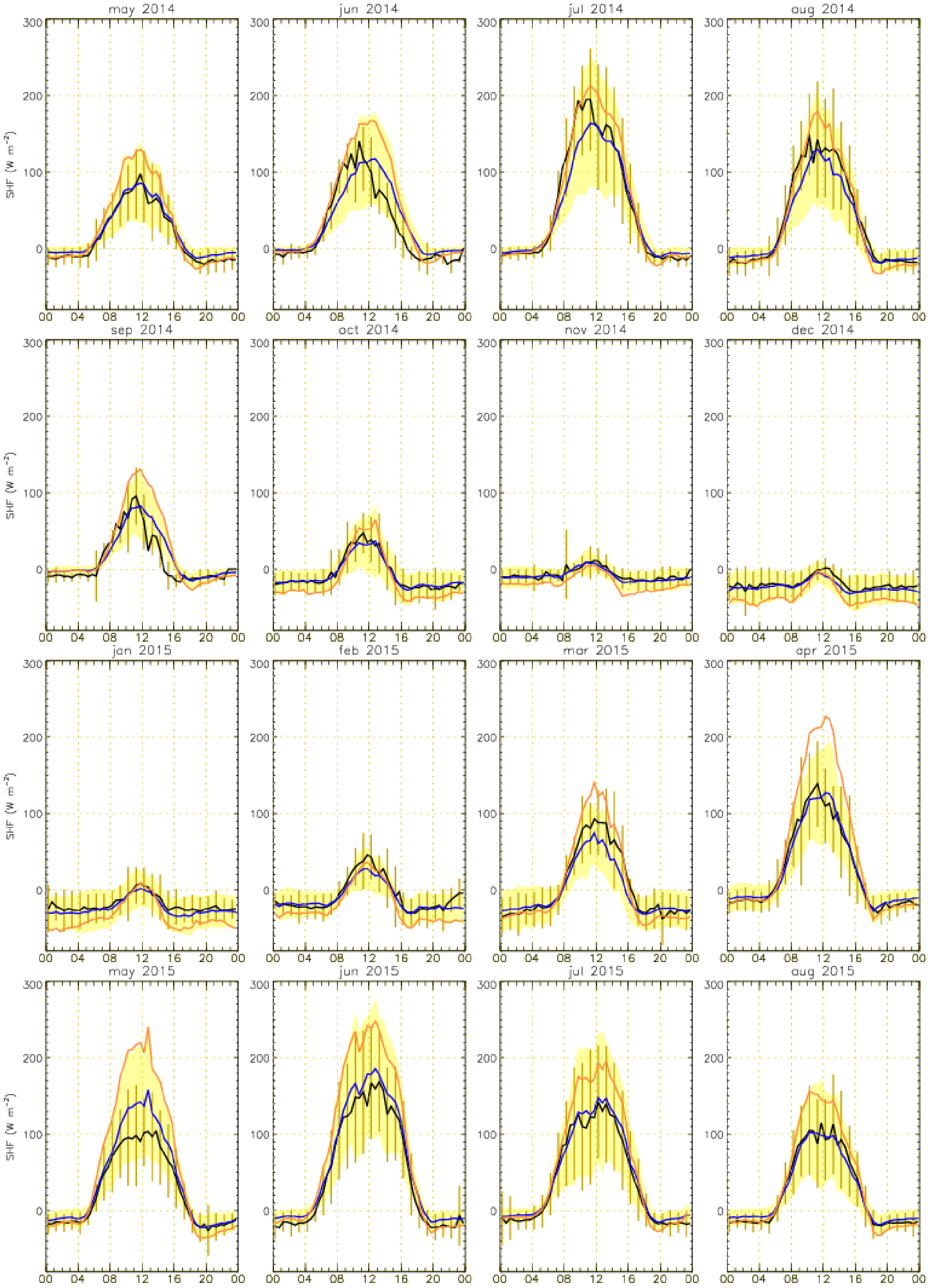

Figure 10: Monthly mean observations (black) and JULES simulations (colours) of sensible heat flux are shown for all months between May 2014–August 2015. Orange is the UKV settings control, blue is the 'real grass' configuration

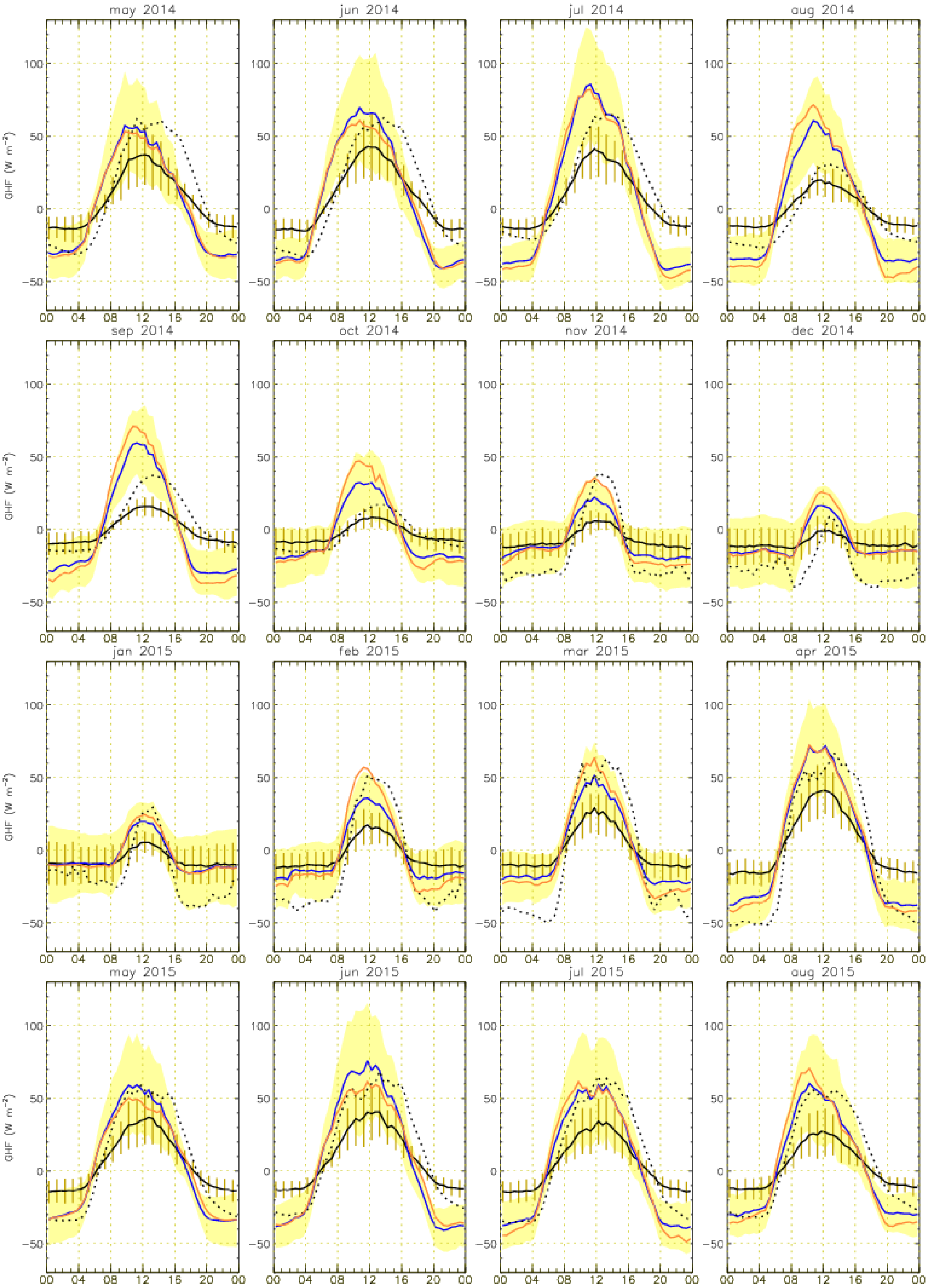

Figure 11: Monthly mean observations (black) and JULES simulations (colours) of ground heatflux are shown for all months between May 2014–August 2015. Orange is the UKV settings control, blue is the 'real grass' configuration

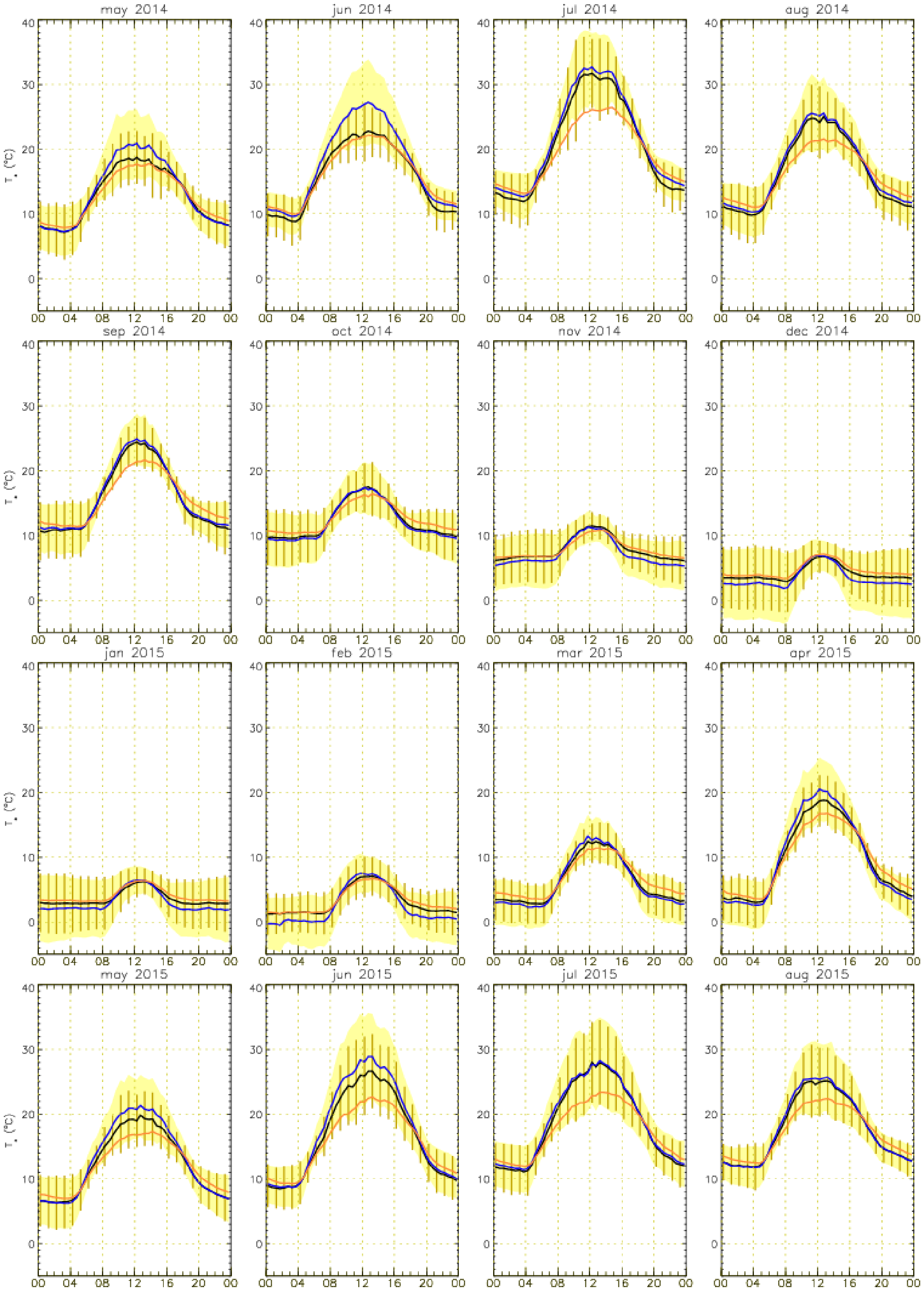

Figure 12: Monthly mean observations (black) and JULES simulations (colours) of skin temperature are shown for all months between May 2014–August 2015. Orange is the UKV settings control, blue is the 'real grass' configuration

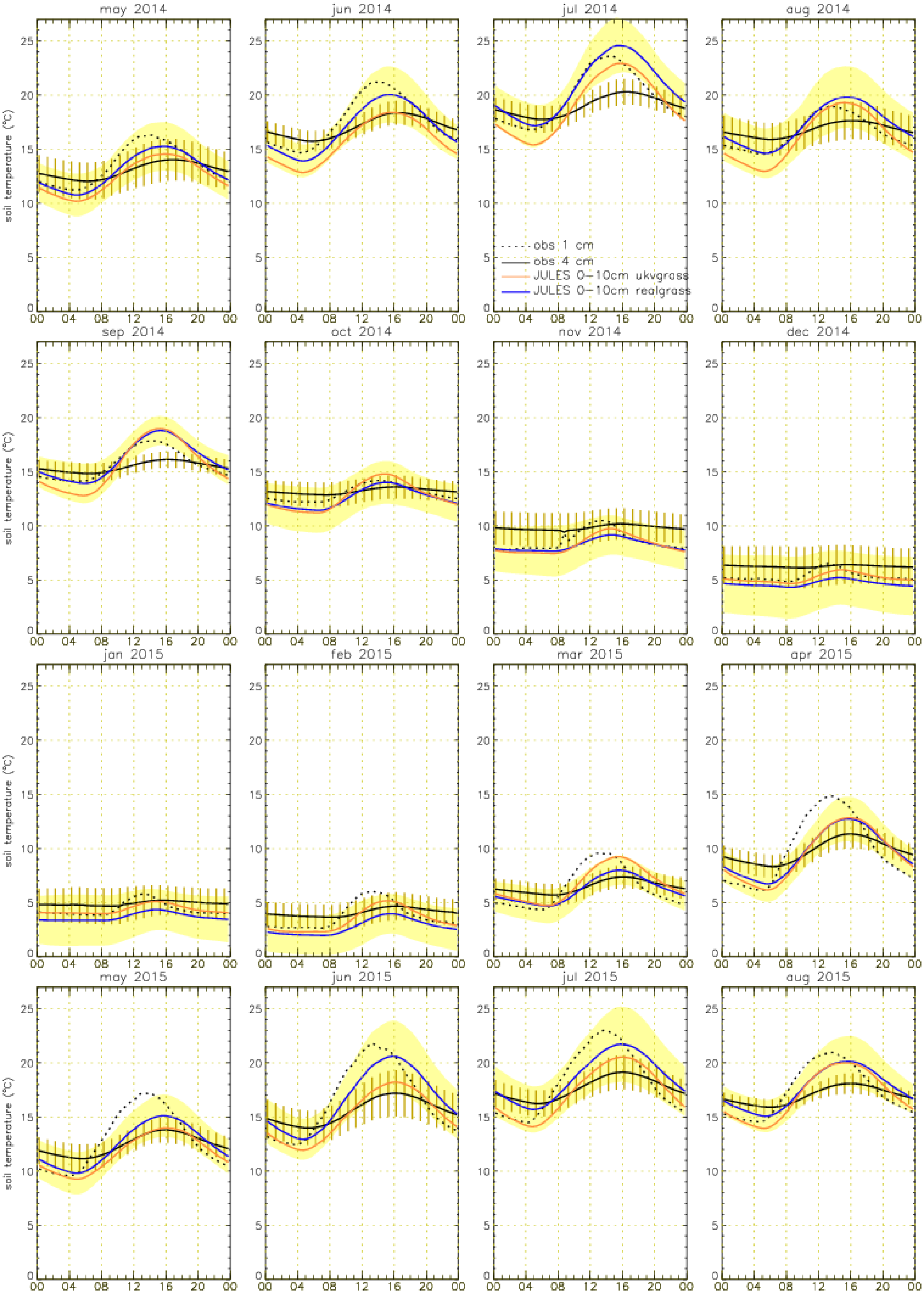

Figure 13: Monthly mean observations (black) and JULES simulations (colours) of soil temperature are shown for all months between May 2014–August 2015. Orange is the UKV settings control, blue is the 'real grass' configuration. JULES data is for the first soil level (0–10cm depth). Observations are from 1 and 4cm thermistors.

2.5 Investigation into the shortwave albedo of grass

It is known that the JULES (hence the UKV) shortwave albedo over grass is too dark. The "excess" energy at the surface is seemingly converted into turbulent heat fluxes that tend to be too large. There is a zenith-angle dependence in the real-world albedo, dominated by the direct beam, with higher values when the sun is low in the sky, so JULES needs to separate direct and diffuse albedos to match the observations. The operational UKV has recently implemented zenith-angle dependence as part of PS37.

The namelist `jules_radiation.nml` has the logical switch l_spec_albedo (turns on the spectral albedo model for VIS and NIR components) and l_cosz (calculates solar zenith angle); the JULES defaults for these are False. We have turned these switches to True as part of the tests, together with changing the relative fractional weightings of the direct and diffuse components called $wght\_alb$ in `~/control/shared/jules_radiation_mod.F90`, and labelled "wghts" in Fig 14. The default setting in JULES assumes diffuse skies (i.e. cloudy), such that if l_spec_albedo=TRUE but the direct and diffuse weightings remain at the default settings, then very little change is seen in the output. Therefore l_spec_albedo=TRUE and revised $wght\_alb$ values need to be applied together for this clear-sky case study. The default values of $wght\_alb$ are `[0, 0.5, 0, 0.5]` for VIS direct, VIS diffuse, NIR direct, NIR diffuse. The revised values tested here, computed using the Edwards-Slingo radiation code for Rayleigh skies, are `[0.4387, 0.0686, 0.4876, 0.0051]`.

We also change the leaf reflection ($alnir$, $alpar$) and scattering coefficients ($omega$, $omnir$) within `pft_params.nml`, called the "optical coefficients" in Fig 14. These have been deemed inappropriate for grass, i.e. in particular they are too bright in the NIR, and more up-to-date values have been taken from the literature (table 3.1 of Oleson et al 2010), as shown in Table 3.

The spectral albedo for vegetation canopies invoked by l_spec_albedo=TRUE is based on the two-stream model of Sellers (1985). Since the direct-beam single scattering albedos is this paper apply to isotropic surfaces only, non-isotropic scattering is applied in JULES by way of a correction. A revised formulation of this correction has been devised and a final test here was to apply this revised, expanded bi-Lambertian correction to the surface albedo in `albpft.F90`.

Fig 14a shows the JULES albedos are in general too dark. Invoking the l_cosz dependency produces diurnal albedo curves whose shapes look reasonable. The splitting of the JULES radiation into VIS and NIR components using l_spec_albedo (Fig 14b) shows quite dramatic differences in the two albedos, with the NIR components being much brighter. Whilst we expect the VIS and NIR albedos in JULES to be broadly correct given that the visible radiation is readily absorbed by leaves for photosynthesis, we have never made spectral irradiance measurements at Cardington to allow verification in this report.

We are planning to deploy some new red-domed pyranometers at Cardington, so that we will have VIR and NIR diffuse and direct albedos over grass. At present we can only produce full solar

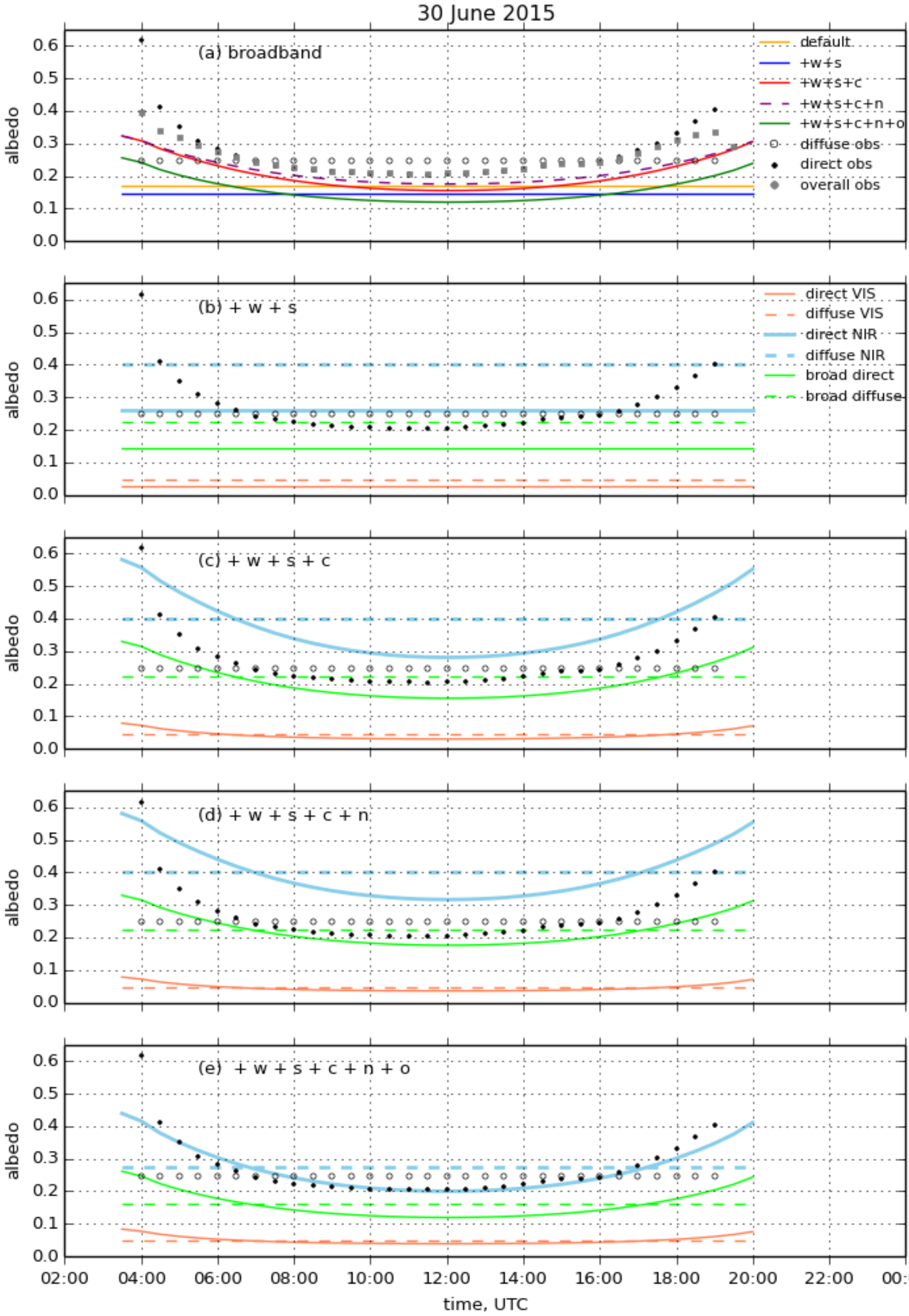

Figure 14: JULES simulations of shortwave albedo over C3 grass compared to Cardington observations. Key w: revised $wght\_alb$ values for Rayleigh skies (see text), s: $l\_spec_{a}lbedo$=True, c: l_cosz=True, o: revised optical coefficients, n: revised non-isotropic correction. (a) broadband solar spectrum albedo with overall, direct, and diffuse observations; (b) JULES spectral and direct–diffuse splits, together with direct and diffuse observations; (c) JULES albedos as b but with cosz diurnal curves; (d) JULES albedos as c but with non-isotropic correction subtle brightening; (e) as d but with optical coefficient not-so-subtle darkening.

spectrum diffuse and direct albedos (as shown distinct from the global albedo in Fig 14a), with the diffuse albedo calculated from a near-by overcast day when the pyranometers are only measuring diffuse radiation. This diffuse albedo is then assumed to be the same on a sunny day and to be constant throughout the day (open circles in all panels in Fig 14). Red dome data would allow us to split these direct and diffuse albedos into VIS and NIR components like JULES does. An even better approach, and maybe something to consider for future deployment, would be to measure solar irradiances (global downwelling, diffuse downwelling and upwelling) at hyperspectral resolution.

The diffuse and direct JULES albedos in Fig 14b show that the diffuse albedo fares best, albeit a bit too dark. There is more of an issue for the overall direct beam albedo (solid green in panel c) which is quite dark around noon, but even poorer at low sun angles. The revised non-isotropic surface increases the JULES albedos by a small amount, but the new optical coefficients (Table 3) darken the overall albedo markedly for C3 grass. Even though the visible albedo brightens very slightly here (Fig 14e), the NIR albedo darkens significantly for both direct and diffuse radiation and dominates the overall value. Given the evidence in the literature, the JULES grass spectral properties are too bright in the NIR and need to be darkened, although the operational revision is still under review. New red-dome pyranometer data will help constrain the NIR albedo, albeit just for a single site.

In summary, we have investigated and identified some theoretical improvements to the JULES albedo. We still do not understand why we cannot match the observed albedo; indeed the updated leaf optical properties have made the diagnosed NIR albedo, therefore the overall albedo, darker. That said, we also realise that brightening the grass albedo to observed levels will not improve the cold temperature bias during the day.

3 Sensitivity of JULES with UKV configuration to meteorological forcing height and JULES parameters

UKV forecasts have known errors in surface temperature and near-surface air temperature and wind speed. Such errors could conceivably arise from modelling of the boundary layer, the parameter settings used within JULES and/or land-surface ancillary data. In order to investigate the potential impact of changing JULES parameter settings on UKV function, an offline Rose JULES v4.4 suite (u-aa242) was designed to be as close as possible to the UKV land surface C3-grass tile configuration, including the specification of time-varying LAI. This offline suite is referred to here as “JULES-UKVconfig” and was forced using MRU Cardington half-hourly meteorological observations.

Gap-filling was required in order to force JULES-UKVconfig with the observed continuous meteorological forcing variables (wind speed, near-surface temperature (Tair), surface pressure, specific humidity (Qair), surface downwards longwave flux, surface downwards shortwave flux). The procedure adopted was to process each half-hour interval of a meteorological variable independently. When a half-hour gap in observations was part of a total gap length of less than three hours, linear interpolation between the previous and next observed values was applied. For gaps of three hours or longer, the gap was filled by finding the average value from exactly the same half-hour interval of the other available years (i.e. between 1st January 2005 and 31st July 2015). These methods guarantee that JULES is forced with variable values that lie within the range of observations over the ten and a half year interval. In particular, these methods ensure that there is preservation of the diurnal and annual cycles in each continuous variable. In the case of precipitation, as a discontinuous variable, either linear interpolation or using averages across years would have resulted in potentially inappropriate drizzle-like rates. Instead gaps in the precipitation observations were treated as having a zero precipitation rate.

The gap-filled meteorological data were converted to the NetCDF format suitable for running JULES and a series of sensitivity runs were designed to investigate the modelled surface temperature (Tstar), sensible heat flux and latent heat flux. This was achieved by varying independently: a) the meteorological forcing heights and b) changes of selected JULES parameters away from the UKV values. At MRU Cardington the Tair and relative humidity (converted to specific humidity for JULES forcing) are observed at 1.2 m, 10 m, 25 m and 50 m. Relative humidity is, from 2015 onwards, also observed at 0.01 m above the grass canopy. Similarly wind speed is observed at 10 m, 25 m and 50 m. Investigations were targeted at two short intervals that were known to include precipitation events and periods of overnight stable conditions: 14–21 April 2015 and 29 June–6 July 2015. Due to the range in soil moisture conditions and their effect on model biases, the summer time period is discussed here.

As shown in Fig. 15 the differences in air temperature between the 1.2 m and 50 m reveal the overnight establishment of stable conditions – as indicated by the coloured infills of the Tair time series. A major precipitation event overnight on 3–4 July led to a substantial increase in observed soil saturation at 22 cm depth. Note that the overnight differences in relative humidity between the canopy top and 50 m disappeared during and just after the overnight rain while canopy evaporation saturated the atmosphere (Fig. 15). This event led to a change in the performance of JULES versus observed energy fluxes because the rainfall had the effect of switching the saturation of the top two model soil layers from below to above the wilting point.

Infra-red temperature (IRT) at Cardington has a known bias of about +1 K for surface temperatures of 2.0 to 14.0° C rising to about +2 K for surface temperatures of 20.0° C (Edwards et al., 2011). Nevertheless, these observational biases are small compared to the biases in JULES-UKVconfig when the IRT measurements are compared to the modelled surface temperature (Tstar). In Fig. 16 the observed IRT measurements are shown as black lines with crosses. When JULES-UKVconfig is forced with 1.2 m Tair and Qair plus 10 m wind speed, the model underestimates midday surface temperatures by about 5 K (red lines below black in the third panel). This pattern is repeated for the

Table 3: Old and new (Oleson et al 2010) leaf optical properties contained within pft_-params.nml

coefficient		BL tree	NL tree	C3	C4	shrub
alnir	old	0.45	0.35	**0.58**	0.58	0.58
	new	0.45	0.35	**0.35**	0.35	0.45
alpar	old	0.10	0.07	**0.10**	0.10	0.10
	new	0.10	0.07	**0.11**	0.11	0.10
omega	old	0.15	0.15	**0.15**	0.17	0.15
	new	0.15	0.12	**0.16**	0.16	0.15
omnir	old	0.70	0.45	**0.83**	0.83	0.83
	new	0.70	0.45	**0.69**	0.69	0.70

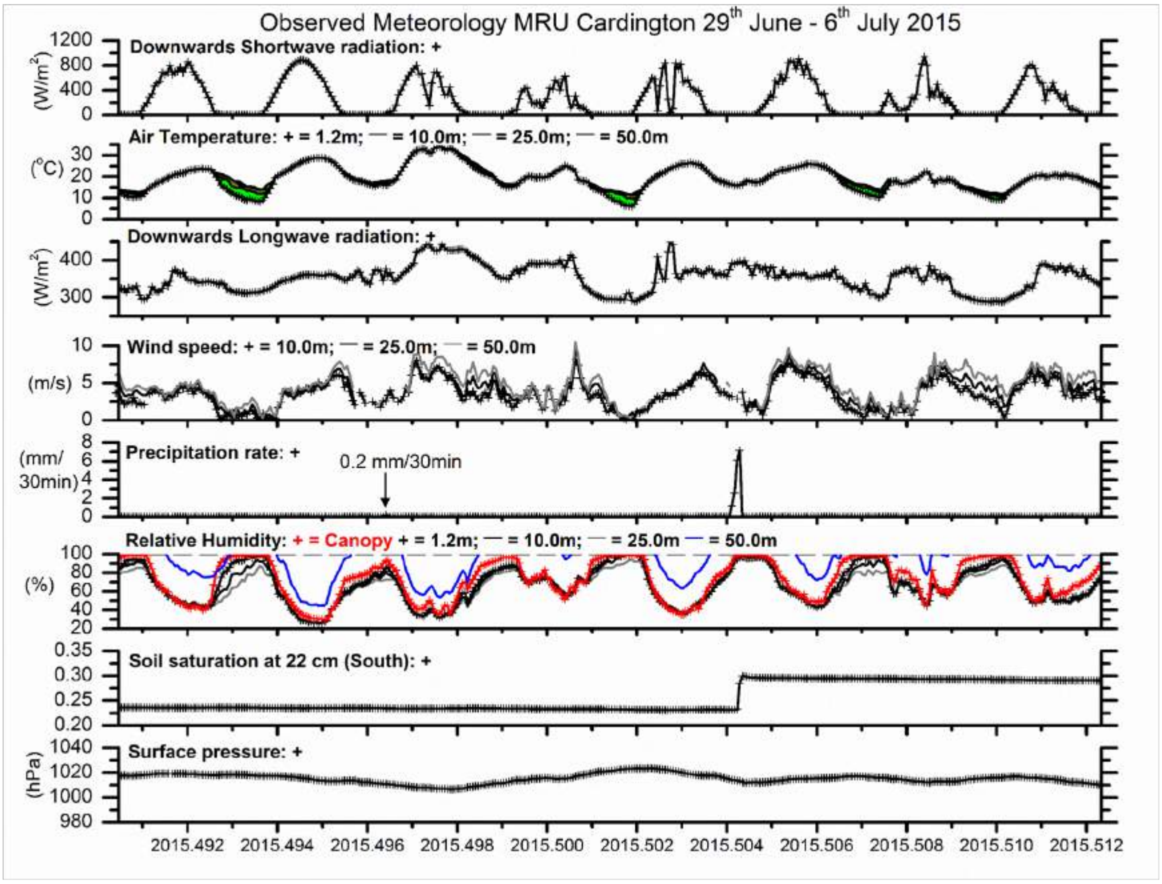

Figure 15: Observed meteorology at Cardington June 2015

other meteorological forcing heights (10, 25 and 50 m). However, when using 50 m meteorology, in addition Tstar is severely overestimated during the night (by up to 10 K, Fig. 16). On the other hand, changing the canht_ft_io parameter (subsequently referred to here as “canht”) from the UKV specification of 1.46 m to 0.1 m profoundly improves the midday estimate of Tstar (i.e. blue lines overlying black pluses and lines). The change in “canht” does not improve the positive bias in overnight surface temperature with the 50 m meteorological forcing (Fig. 16).

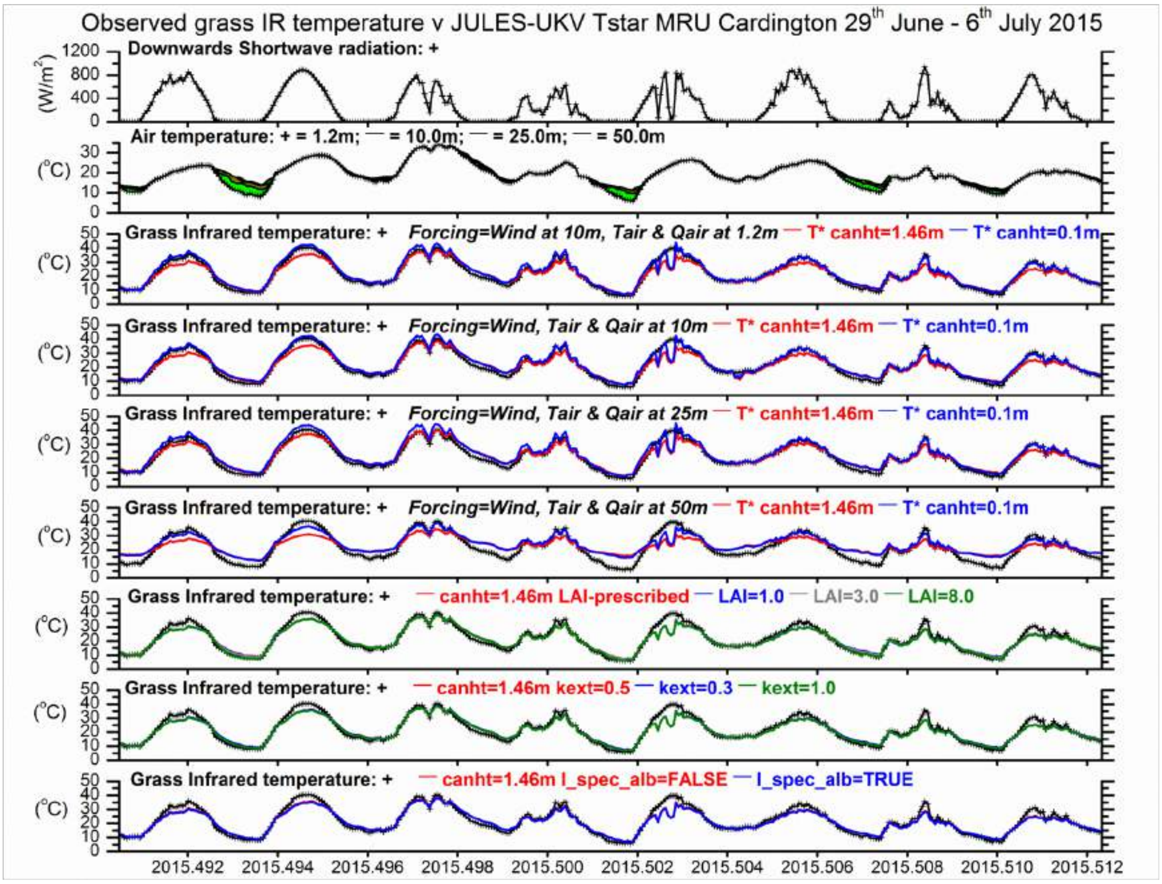

Figure 16: Sensitivity of JULES-UKVconfig Tstar to forcing height and parameters

Running JULES-UKVconfig with a fixed LAI of 1.0, 3.0 or 8.0 has no noticeable effect of modifying the differences between Tstar and the IRT data. Similarly changing kext from the UKV value of 0.5 down to 0.3 or up to 1.0 has no noticeable effect on Tstar and this is also the case if l_spec_alb is changed from false to true (Fig. 16).

The differences between JULES-UKVconfig sensible heat fluxes and the observations depend on the soil saturation conditions. When JULES models the upper soil layers as having a saturation below the wilting point the midday sensible heat is overestimated in the middle of the day by up to 150 Wm^{-2} (Fig. 17). However, after the rainfall raises the soil moisture concentrations above the wilting point this June midday overestimate of sensible heat flux drops to about 100 Wm^{-2}. Reducing the canht from 1.46 m to 0.1 m approximately halves the positive bias after the rainfall event. As for Tstar, prescribing fixed LAI or changing kext have no effect on sensible heat flux bias. Changing l_spec_alb to true produces a modest reduction in bias (Fig. 17).

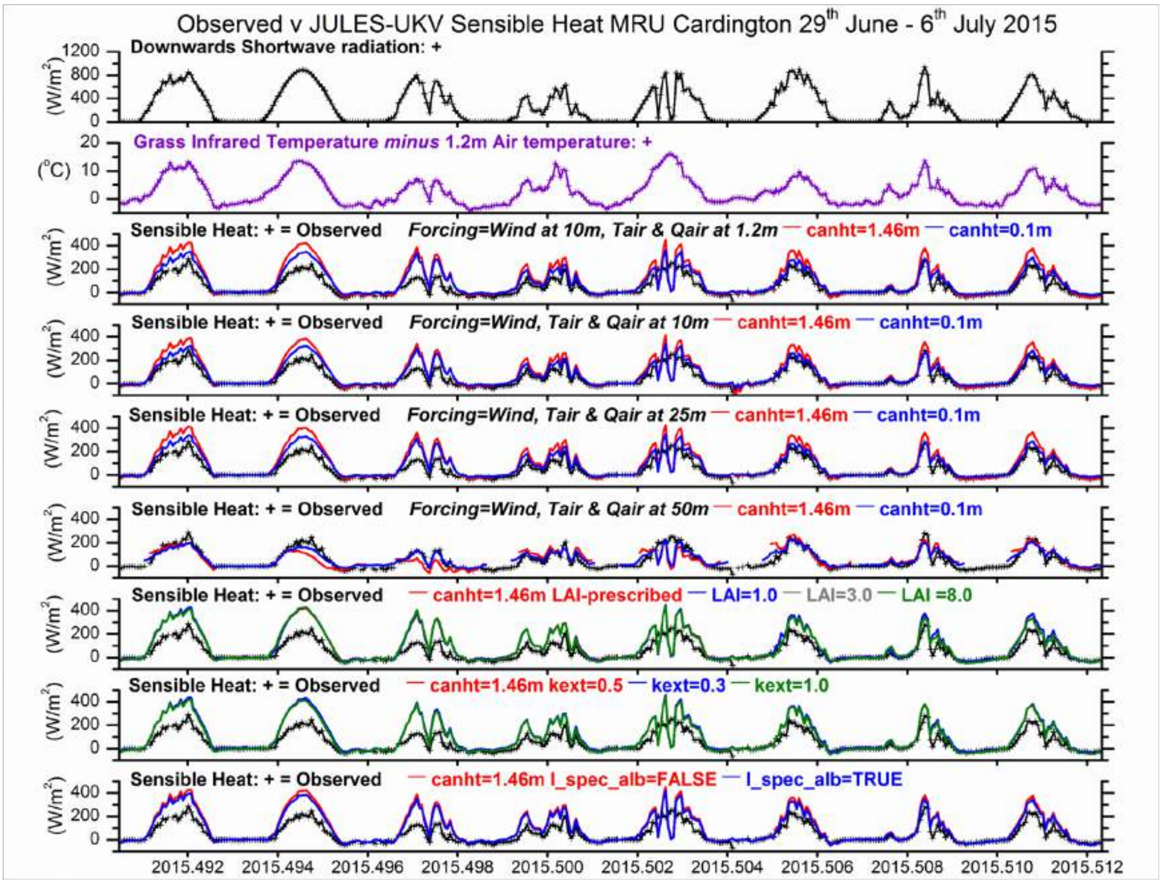

Figure 17: Sensitivity of JULES-UKVconfig sensible heat flux to forcing height and parameters

As for sensible heat the bias in latent heat fluxes from JULES-UKVconfig depend on the saturation conditions of the modelled upper soil layers. When the soil saturation is below the wilting point midday latent heat fluxes are underestimated by up to 150 Wm^{-2} (Fig. 18). When soil saturation is modelled as above the wilting point latent heat fluxes are only underestimated by a few tens of Wm^{-2}. Note the small overnight peak in latent heat flux as observed and modelled when canopy evaporation is occurring during and just after the rainfall. Changing canht to 0.1 m leads to slightly improved biases in latent heat flux after the rainfall, but when the meteorological forcing is applied from 50 m there are substantial improvements using canht $= 0.1$ m before the rain. However, the bias in sensible heat and latent heat flux using forcing at 50 m is the opposite from that at lower level forcing (Figs 17 and 18). The observed humidity from just above the canopy to 25 m follows a consistent trend, but the humidity at 50 m does not fit in with this trend (Fig. 15). Hence problems with measurement of the humidity at 50 m may explain the different direction in the JULES bias in sensible- and latent-heat flux compared to lower level forcing. Fixing the LAI has a modest effect on the modelled latent heat fluxes whereas varying kext and l_spec_alb have no effect (Fig. 18).

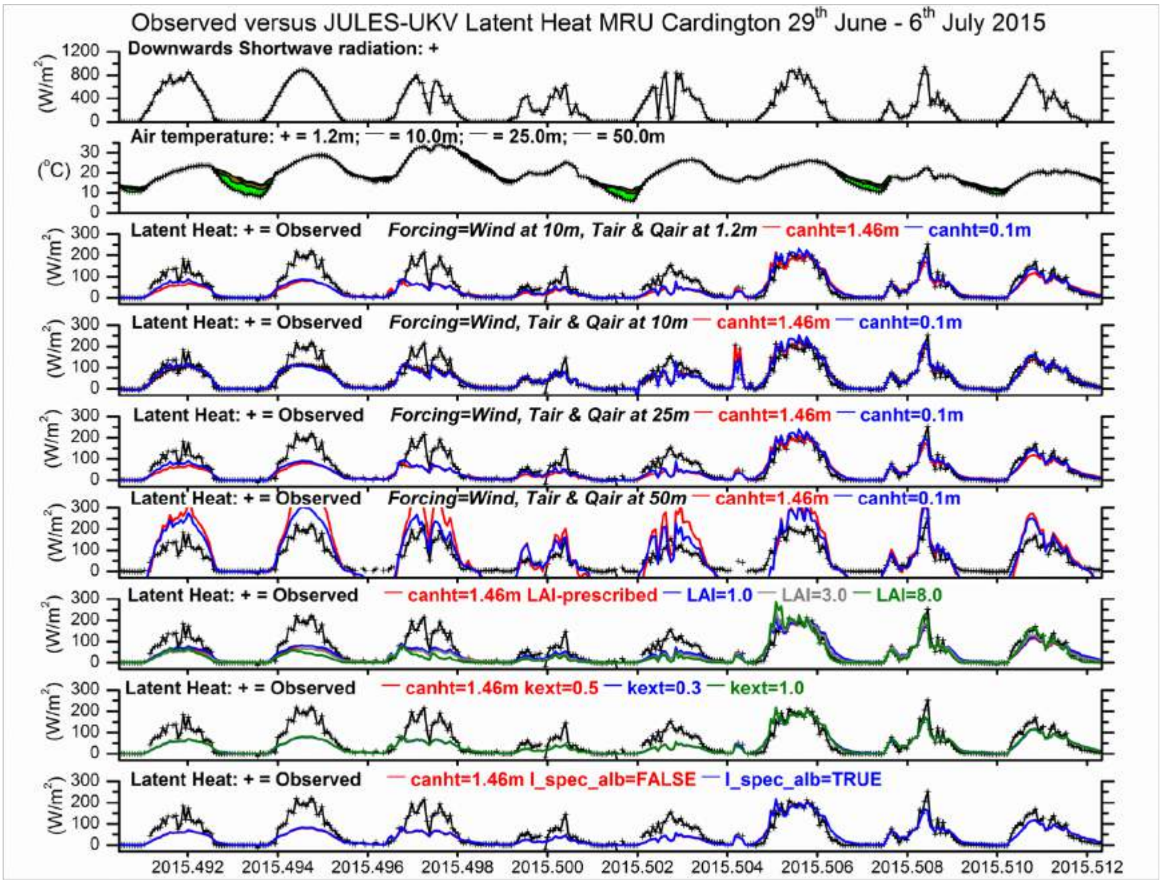

Figure 18: Sensitivity of JULES-UKVconfig latent heat flux to forcing height and parameters

This exercise demonstrated that overall the bias in JULES-UKVconfig when modelling surface temperature and energy fluxes is somewhat sensitive to the meteorological forcing height, LAI, kext and l_spec_alb. On the other hand, changing canht can lead to significant improvement in the performance of the model. This suggested that it is worth trying to optimize the canht prescribed within UKV.

3.1 Optimizing canht_ft_io for JULES-UKVconfig

Momentum flux is of fundamental importance for modelling the surface energy fluxes. Consequently, optimization of "canht" for JULES-UKVconfig has targeted the MRU Cardington "observations" of momentum flux. Observed momentum flux was calculated from the January 2005 to July 2015 half-hourly observations of 10 m Tair, relative humidity, horizontal wind covariance, vertical wind covariance and surface pressure. JULES-UKVconfig was run repeatedly using the four different forcing heights of Tair, Qair and wind speed observations and for a wide range of canht. Thus for the runs using the 50, 25 and 10 m forcing canht was varied from 1.46 m (the UKV configuration) down to 0.1 m. For the 1.2 m forcing canht was varied between 1.46 m and 0.01 m.

The "optimum" canht value according to each forcing height was judged using both the mean bias error (MBE) and the root mean square error (RMSE) for January 2005 to July 2015. Figure 19 shows that for all forcing heights the optimum canht for JULES-UKVconfig as judged against observed 10 m momentum flux is far smaller than the current UKV configuration value. For each forcing height the optimum canht value is associated simultaneously with the MBE closest to zero and the smallest RMSE. For forcing heights between 10 m and 50 m the optimum canht value ranges from 0.40 and 0.55 m varying in a near-linear manner. However, below 10 m there is a discontinuity in a plot of optimum canht and forcing level against the optimum value dropping to just 0.05 m with forcing at 1.2 m. The discontinuity is present whether either the optimum-canht axis or the forcing-level axis or both axes are plotted using logarithmic scales. The interpretation of the discontinuity is that it results from non-linear changes in the effective roughness length with height associated with the effects on wind turbulence of trees, fencing, bushes and buildings around the MRU Cardington site. At the height of 1.2 m the momentum flux is dominated by the local grass roughness length, whereas at heights from 10 m upwards, these larger roughness elements impact on the flux.

3.2 Optimization of other parameters

Investigation of the optimum value of parameters z0hm_pft_io, kext and LAI involved forcing JULES-UKVconfig with meteorology from the 25 m height and using the associated optimum value for canht_ft_io of 0.45 m. For each run the MBE and RMSE across 2005 to July 2015 was assessed against observations of 10 m momentum flux, wind speed, sensible heat, latent heat (when soil saturation was above the wilting point only), near-surface air temperature, surface temperature and

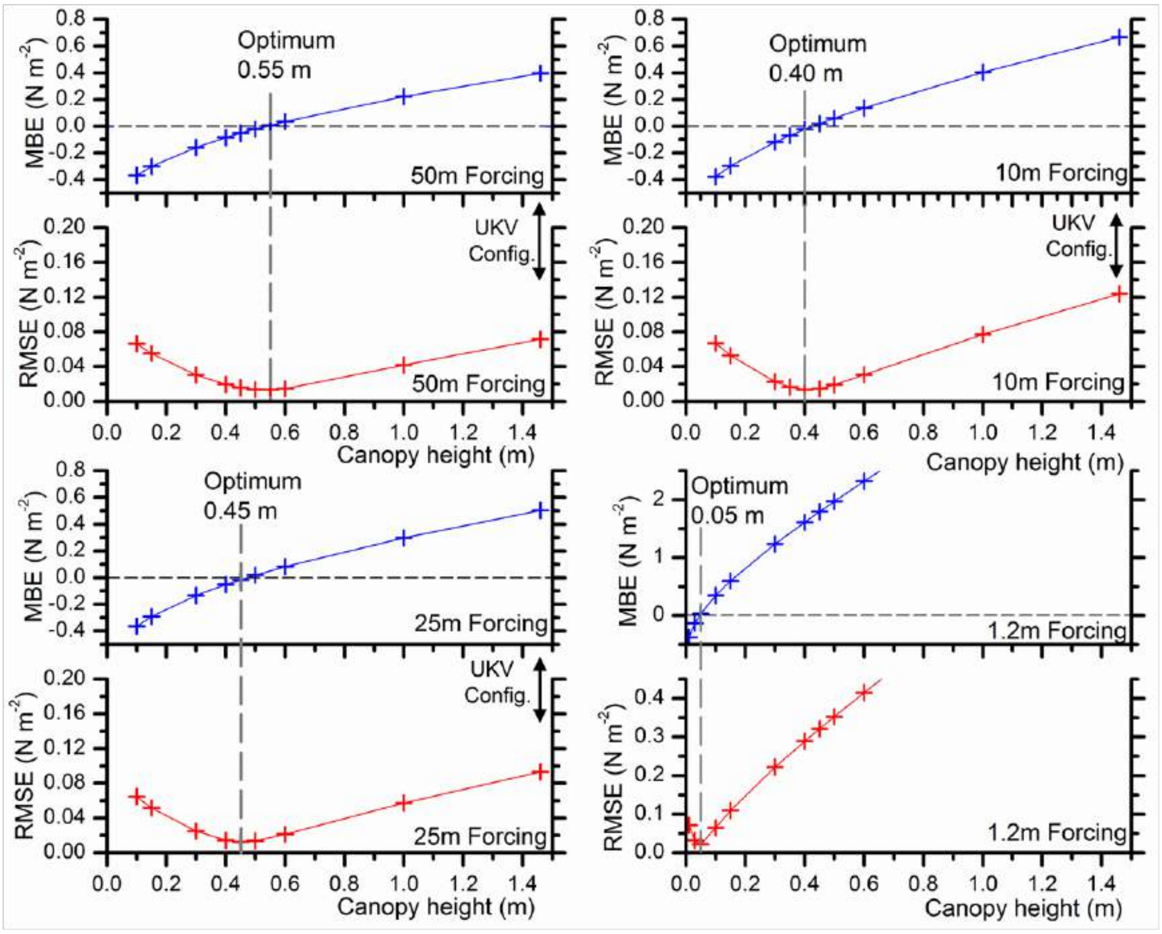

Figure 19: Estimation of optimum canht for JULES-UKVconfig for different meteorological forcing heights

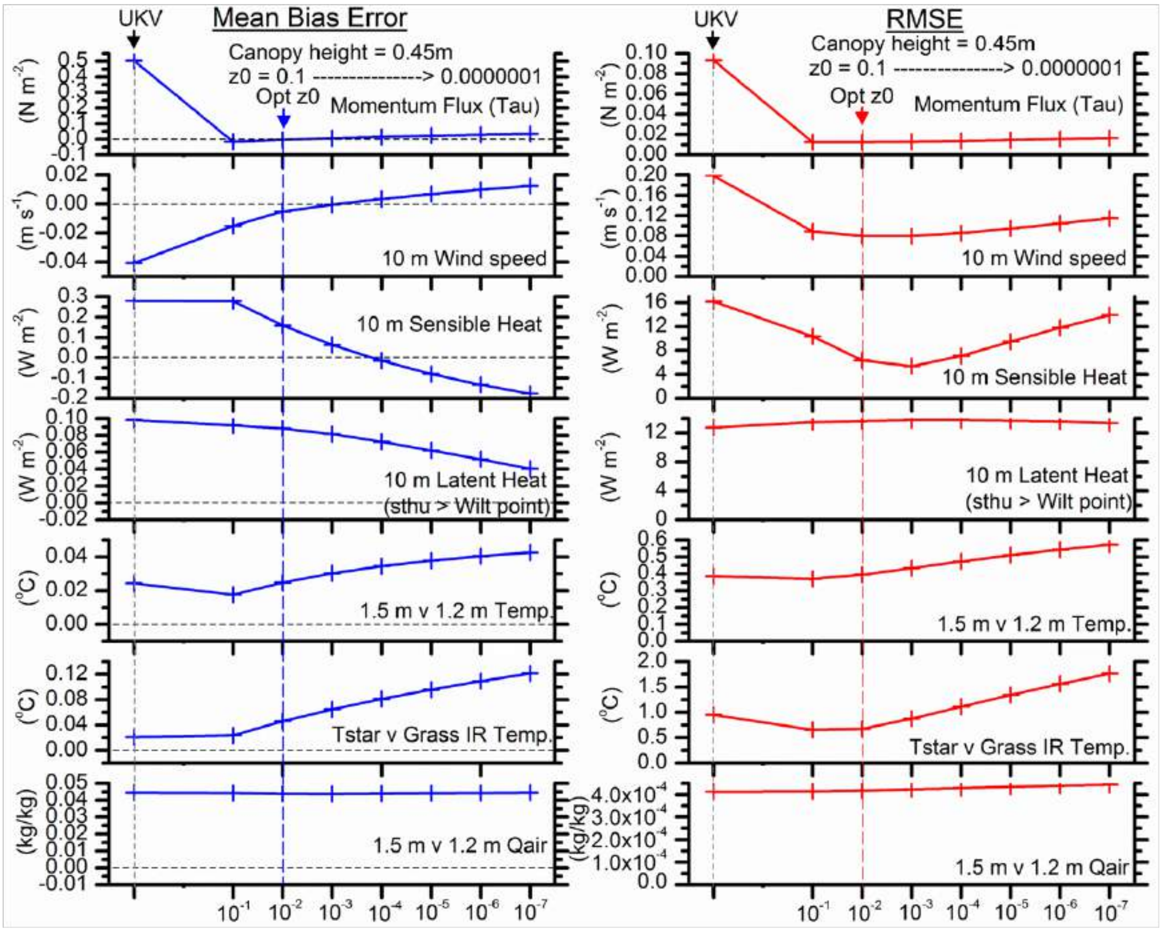

Figure 20: MBE and RMSE for z0hm_pft_io according to parameter values for 25 m forcing of JULES-UKVconfig

specific humidity. In this exercise the “optimum” parameter value requires a compromise in terms of minimizing the MBE difference from zero and finding the minimum RMSE for all the observed variables. For example, in Fig. 20 reducing the z0hm_pft_io value of the UKV configuration value below 0.1 initially improves the MBE and the RMSE for most comparison variables. However, when values of less than 0.01 are used the MBE and the RMSE of Tair and surface temperature become worse than using the standard UKV configuration. Hence the optimum value was chosen as 0.01. Similarly, for kext the optimum compromise value was identified as 1.0 (UKV value = 0.5). Using a fixed LAI of 2.0 instead of a UKV prescribed time-varying LAI led to improvements in all comparison variables (not shown). Independently, the seasonal variation of LAI in UKV ancillaries has been noted as rather strange (there is a secondary maximum in November/December, for example) which might explain why a simple constant value of 2 works better for Cardington.

For illustration purposes, for each calendar month the mean diurnal cycle was calculated for the comparison variables across 2005 to July 2010 together with 95% confidence intervals of the means. Average diurnal cycles $+/-$95% CIs are plotted for January, April, July and October to represent different seasons. Figure 21 shows how for momentum flux the biggest improvement derives from changing canht to 0.45 m whereas z0hm_pft_io, kext and LAI have little impact. For surface temperature the change in canht to 0.45 m has the biggest impact in improving April and July diurnal cycles. Switching z0hm_pft_io to 0.01 improves the April and July midday values whilst switching kext to 1.0 further improves the night time values (Fig. 22). The results for near-surface air temperature show the same pattern of improvements as surface temperature. Since it is related to both variables, sensible heat flux also shows the same pattern of improvements as surface and near-surface temperature.

On the other hand, latent heat flux when soil saturation is above the wilting point, shows virtually no improvement across seasonal and day or night regardless of changes to canht, z0hm_pft_io or kext (Fig. 23). These fluxes are overestimated significantly in spring, summer and autumn in the middle of the day, but underestimated at night in spring and summer. Note that this is in contrast to the situation in June 2015 shown in Fig. 18 when latent heat flux is slightly underestimated by JULES-UKVconfig. It appears that conditions at that time lead to results that are not representative of the average latent heat flux errors. Specific humidity is overestimated in July especially at night, but the errors are also only marginally influenced by the changes to the parameters investigated.

4 UKV tests

Detailed case study evaluation by Lock et al (2015) identified a package of changes, the "RealGrass" package, that improved particularly the nocturnal warm bias in stand alone JULES simulations and also UKV case studies. This package comprised the following changes:

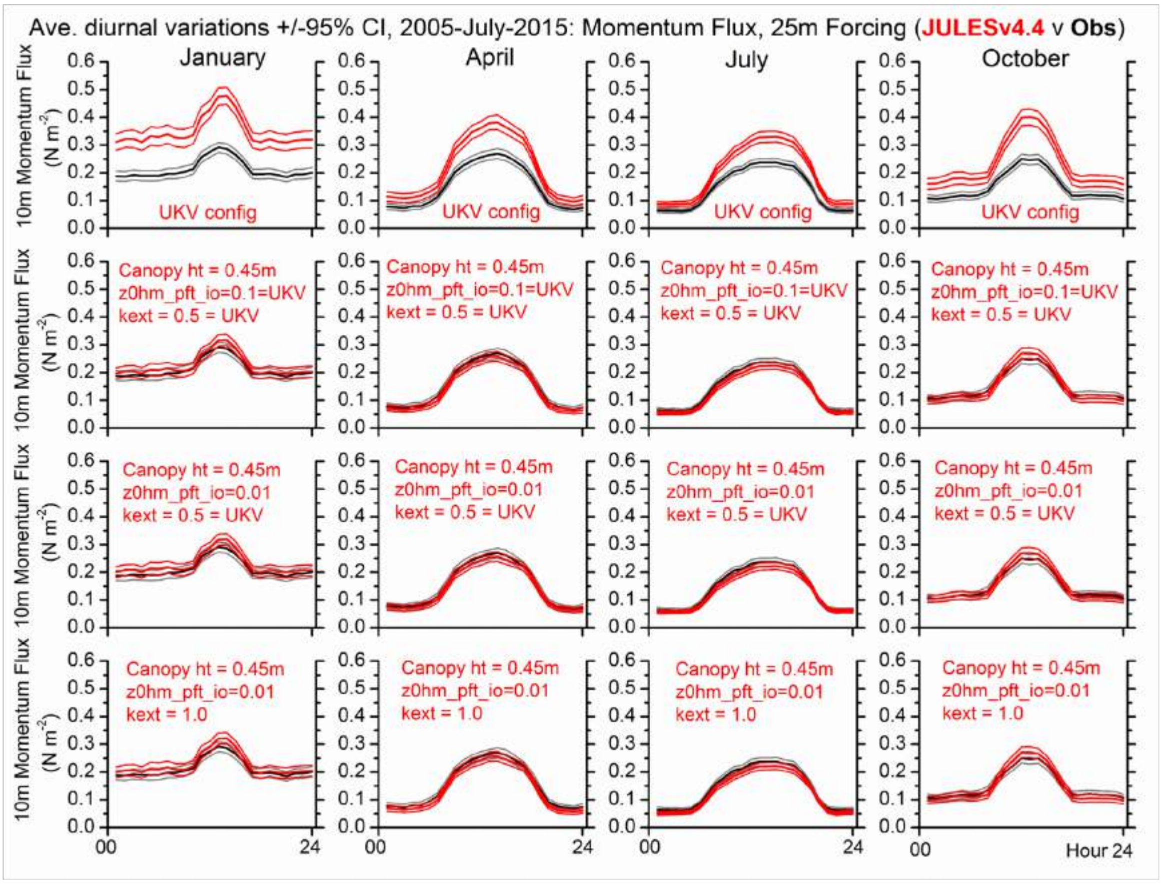

Figure 21: Average diurnal cycles in observations and JULES-UKVconfig for 10 m momentum flux with 25 m forcing

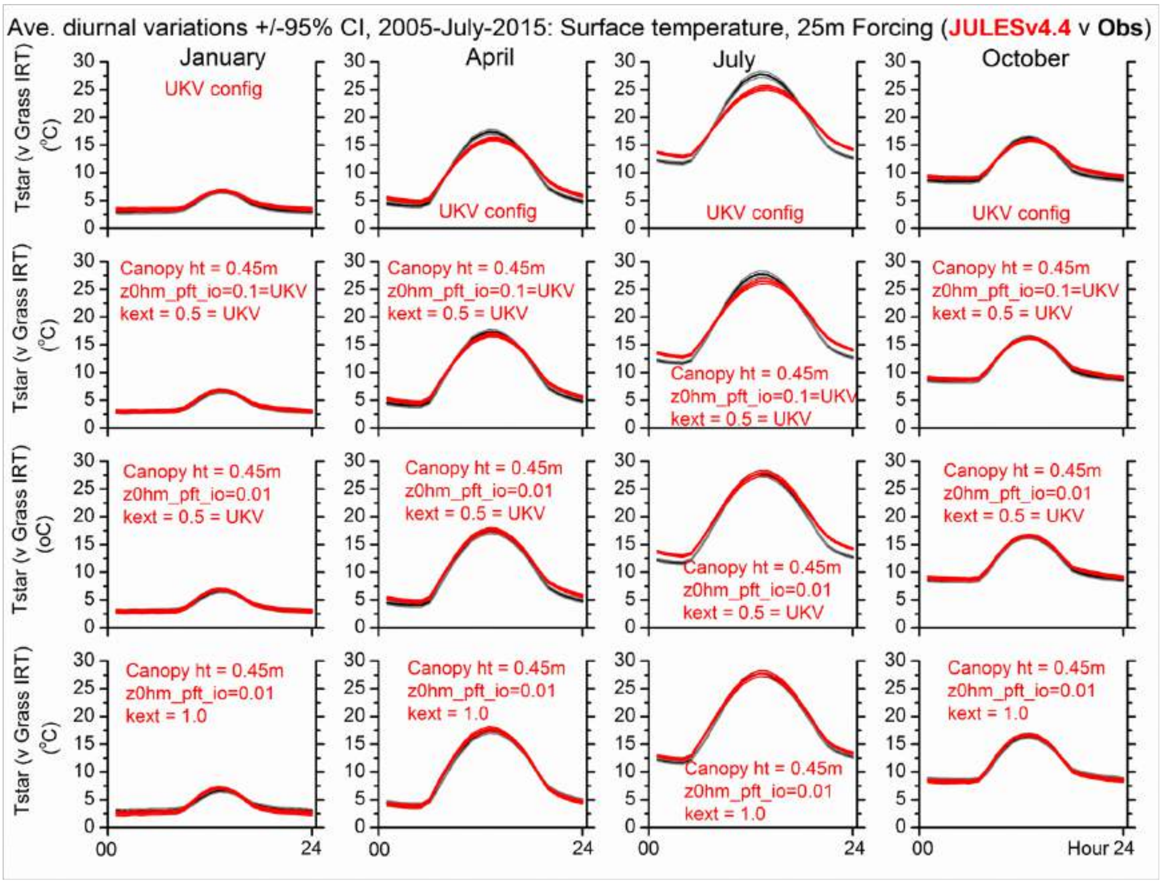

Figure 22: Average diurnal cycles in observations and JULES-UKVconfig for surface temperature with 25 m forcing

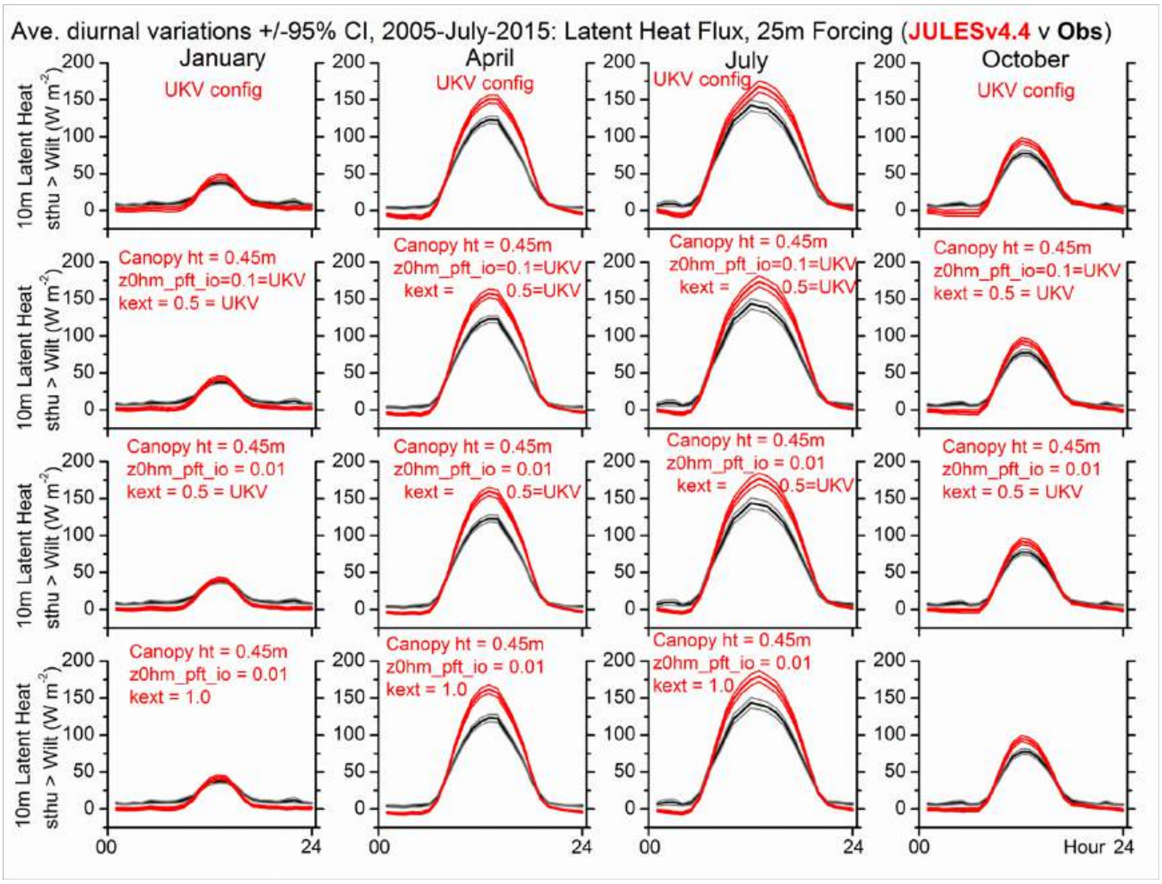

Figure 23: Average diurnal cycles in observations and JULES-UKVconfig for latent heat flux with 25 m forcing

- JULES parameter changes
  - set the albedo for tiles C3 and C4 grass and shrubs to 0.25 (the observed grass albedo at Cardington, cf 0.2)
  - set kext=2 for tiles C3 and C4 grass - this greatly reduces the bare soil fraction of these tiles, which is where the soil is turbulently coupled to the atmosphere rather than radiatively coupled to the canopy
  - set $z_{0h}/z_{0m} = 0.01$ for C3 grass (cf 0.1)
- JULES ancillary changes (note these have been crudely implemented via code changes for simplicity)
  - Canopy height for C3 grass set to at most 10cm, and C4 grass at 30cm (because of the different source data Ireland and France have a lot of C4 grass while the UK has none)
  - bare soil tile fraction reduced (where < 0.5) to at most 0.02, converting excess to C3 grass
- UM boundary layer parametrization changes
  - Minimum asymptotic mixing length, λ_0 reduced from 40 m to 5 m (recall $\lambda = \max[0.15z_h, \lambda_0]$): this change allows the mixing length to reduce for boundary layers of depth, z_h, less than 266m which in principle should be more realistic
  - sharper than "Sharpest" stable stability functions ($Ri_{\mathrm{trans}} = 0.19$ instead of 0.1)
  - Ri in the lowest grid-level calculated using the surface skin temperature. With the Charney-Philips grid staggering Ri must be calculated on θ-levels which is done by interpolating static stability at all levels except level 1, where the stability between levels 1 and 2 is used. In stable conditions this will significantly underestimate the true stability and so here the surface skin temperature is used to calculate the static stability between level 1 and the surface

The RealGrass package has been tested here in two month-long UKV trial periods (February and June 2015) on top of the near-final PS37 package (control suites are mi-ah847 and mi-ah871, resp., which are OS37 without the multi-level snow scheme).

Effectively the only source of drag in the UKV is the roughness of the surface tiles (proportional to the canopy height for vegetated tiles). There are two subgrid orographic drag parametrizations in the UM that are not currently used: the "gravity wave drag" scheme that represents the effects of both gravity waves and flow blocking, and the turbulent form drag scheme (to represent the pressure effects of small scale hills) which is traditionally implemented (e.g., in GA) through enhanced "effective" surface roughness. The use of effective roughness lengths to represent the integrated pressure drag on the resolved flow has the unfortunate side effect of giving spuriously slow near-surface wind speeds. Consequently an alternative implementation (Wood et al, 2001) applies the form drag as a non-local stress profile, leaving the surface stress and scalar exchange to be determined in terms of the surface (vegetative) roughness lengths only.

While there are good reasons for including these drag parametrizations even at UKV resolution (Vosper et al, 2016), and the new "5A" GWD scheme and the distributed version of the form drag schemes are the obvious starting points, there are still choices to be made within those implementations. For example, the GWD scheme settings are those in GA6 while Vosper et al (2016) recommend alternatives based on high resolution model comparisons; the form drag scheme has optional stability dependence (not currently implemented in GA in order to avoid a temporal oscillation in drag and thence wind speed over resolved slopes); the orographic drag parameter, $C_{D(orog)}$, has been tuned down in GA from its "typical" value of 0.3 that we will initially test here; and the distributed version uses a reference height (currently a third of the PBL depth, but rather tightly constrained to be between 100 and 300m) that gives both the height of the wind speed and direction used in the surface stress calculation and also the scale for the exponential decay of the stress with height. Wood et al found the decay scale to be relatively insensitive but the role of the reference wind has not been investigated. In stable PBLs this could be an important parameter but the stability dependence on the form drag is also an important open question. Furthermore, others (e.g., Steeneveld et al, 2008 and Lapworth et al, 2015) have argued for the inclusion of gravity wave effects in stable boundary layer (SBL) mixing, while Boutle et al (2015) found evidence for enhanced SBL mixing from small scale orography in UM simulations with a 333m horizontal grid.

Results are presented here from the following tests of changes to the parametrized drag in UKV trials from 5 February to 5 March 2015:

- ah847 = PS37 control
- al959 = PS37 + GWD (UKV SSO)
- al983 = PS37 + GWD (NAE SSO)
- aj315 = PS37 + "Real Grass"
- aj447 = PS37 + "Real Grass" + form drag (NAE SSO)
- am836 = PS37 + "Real Grass" + form drag (UKV SSO)
- an063 = PS37 + "Real Grass" + form drag (UKV SSO) + stability dependence (stopped after 15 February)

where "UKV SSO" means the subgrid orographic fields were at the highest resolution available from the CAP, on the UKV grid itself, while "NAE SSO" use reconfigured NAE (12km) subgrid orographic fields. Recall that the form drag tests here all use $C_{D(orog)} = 0.3$ rather than the GA-tuned value of 0.15.

4.1 Impact of changes to drag

First, the impact of the GWD scheme on 10m wind speeds can be see from Fig.24 to be very much localised to the mountainous areas of the UK, as might be expected. These results use the UKV SSO but the NAE SSO gave very similar results. Fig.24 is a daytime average but the nighttime average impact is also very similar (not shown). Fig.25 shows a time series of the impact on the 10m winds from various drag changes averaged over the Scottish highlands. It is interesting how the GWD scheme has a much more significant impact over the first week of the trial period (up to 15 February) than after. The early part of the period was characterised by high pressure with a strong low-level inversion (around 1km above ground level) while after 15 February the weather became much more mobile with predominately westerly winds. It seems likely that the flow blocking part of the scheme was much more active in the early part and that that scheme has the biggest influence on the 10m wind speeds (but unfortunately the necessary diagnostics were not generated to know this for sure). Given the size of the UKV domain (even after PS38) and the constraint that the lateral boundary forcing imposes on the large-scale flow, it is unlikely that drag from propagating gravity waves will have much impact on the evolution of low level winds, or indeed other weather aspects for which the UKV is intended to be used.

The impact of the "RealGrass" package and the distributed form drag scheme (without stability dependence), on top of "RealGrass", is shown in Fig. 26. The impact of "RealGrass" itself is widespread and rather uniform (reflecting the geographical distribution of the grass tiles) while the impact of form drag is again largely tied to orography but is significantly more widespread than that of the GWD scheme. There is also an apparent enhancement of impact at night, potentially reflecting the stress being applied over a shallower depth. The time series of average wind speed over Scotland in Fig. 25 reflect these differences but also show that the impacts here are much more invariant through the trial than for GWD, and so presumably less dependent on weather regime. Also shown is a trial including the stability dependence of form drag which makes remarkably little difference. Finally, Fig. 27 shows the impact on average wind speeds over central England. Although the changes are small compared to over Scotland, there is a systematic increase from reducing the canopy height in the RealGrass package, and a reduction from form drag, with the UKV SSO giving much more drag than NAE SSO. Again the stability dependence makes negligible difference even though there is a very clear diurnal variation in the impact of form drag (particularly clear in the fractional impact), with nightime interestingly having stronger impact than daytime. This possibly reflects the shallower layer over which the stress is deposited.

4.2 Verification results

Standard verification against surface observations has been carried out for these trials with the temperature and wind verification shown in Fig. 28. Consistent with the impact maps above, and given

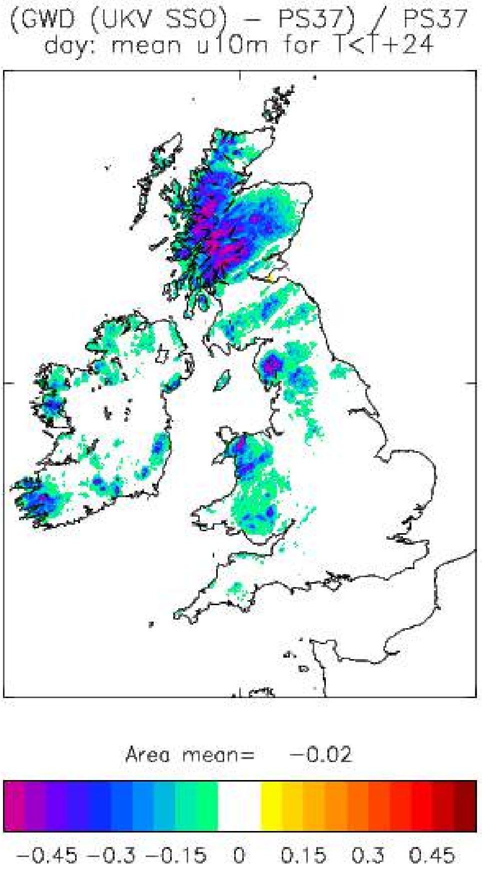

Figure 24: The fractional impact on 10m wind speed from the GW drag scheme on top of PS37, for UKV trials from 5 February to 5 March 2015, averaged over daytime hours only (6–18 UTC)

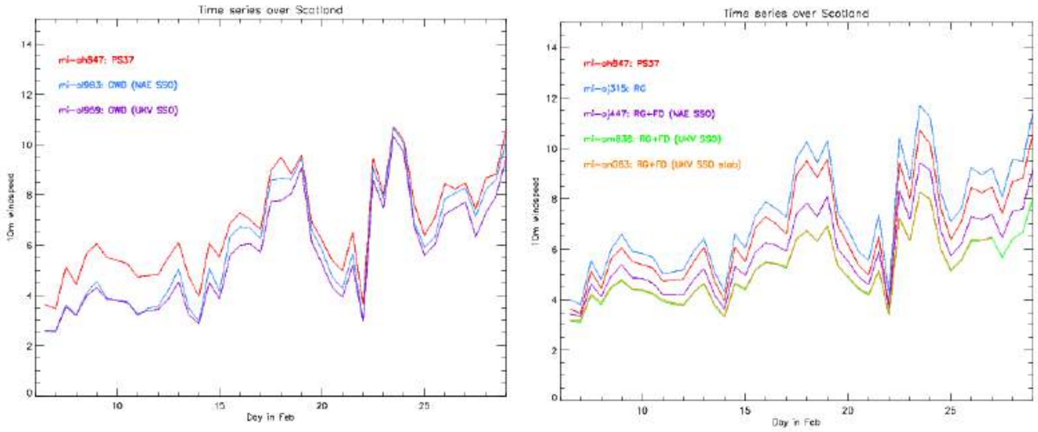

Figure 25: Time series of 10m wind speed averaged over Scotland (6W-2W, 55.5N-58.5N) for trials from 5–28 February 2015: left shows tests of GWD, right of form drag

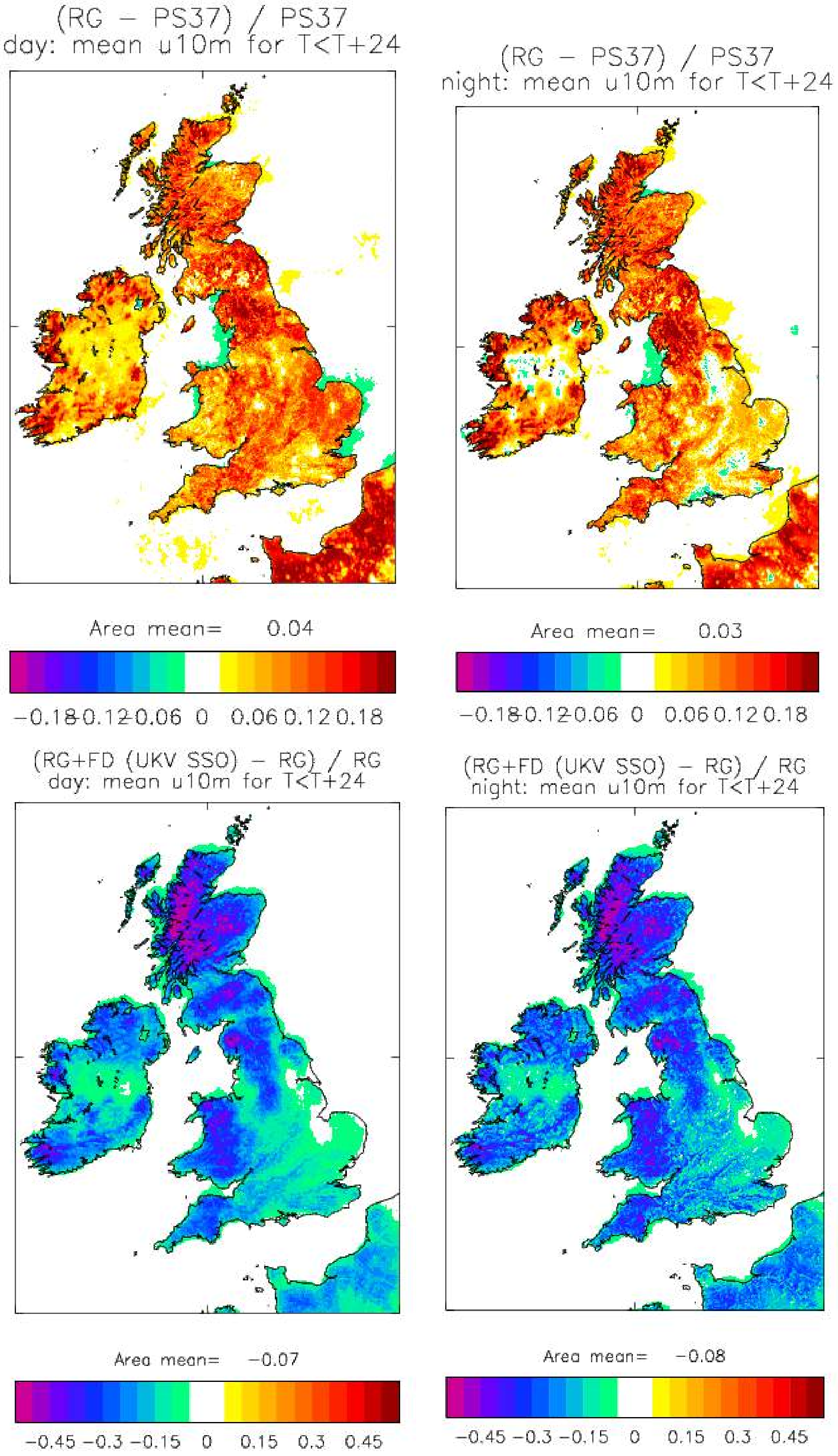

Figure 26: The fractional impact on 10m windspeed for UKV trials from 5 February to 5 March 2015, averaged over daytime (6–18 UTC, left) and nighttime (18–6 UTC, right) for "RealGrass" (top) and distributed form drag (bottom)

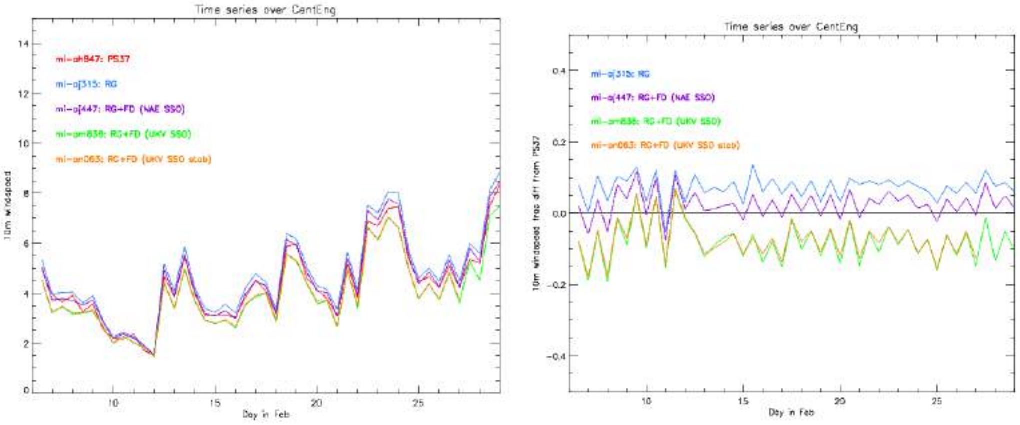

Figure 27: Time series of 10m wind speed (left) averaged over central England (2.5W-0.5E, 51N-53N) for trials from 5–28 February 2015. Right is the fractional difference from the left shows tests of GWD, right of form drag

a lack of sites in the most mountainous regions, GWD has little impact on winds but does introduce a slight cooling on average that also increases the rms error. RealGrass gives significantly faster winds (by reducing surface roughness), with much worse rms error, and also colder temperatures (several factors contribute but the reduction the fraction of bare soil and SBL turbulent mixing are the most significant) which are not beneficial on average, increasing both the existing cold bias in this period and the rms error. It should be noted that although there is some compensation on average between RealGrass increasing wind speed and form drag reducing it (and with NAE SSO these two almost balance), the rms error is always worse suggesting the balance is not happening locally.

The diurnal cycle of the temperature errors in Fig. 29 shows the impact of RealGrass is, as expected, mostly to cool the nighttime temperatures and these are cooled further when the form drag is added. It remains strange that the inclusion of a stability dependence in the form drag (that cuts off the drag as the stability measured by the level 1 to surface Richardson number increases) makes so little difference, even at night (not shown).

The significant degradation in the rms error for winds from adding orographic drag (Fig. 28) is disappointing but closer examination of the geographical distribution of the errors in Fig. 30 shows there are particularly significant degradations in a handful of sites in complex terrain (e.g., Capel Curig in north Wales and a site in northern Scotland). The Capel Curig site lies in a narrow (3km across) east-west valley in Snowdonia that is not well resolved in the model. The mean error at this site is very slow suggesting that in reality locally strong winds are funnelled along the valley, especially in the dominant westerly flow regime, a process that will be poorly represented in the model and will be made worse when parametrized orographic drag is added and slows the grid-box mean wind profile further. It is not clear that anything other than post-processing will allow meaningful validation in this sort of location but lack of an objective measure of where site-specific

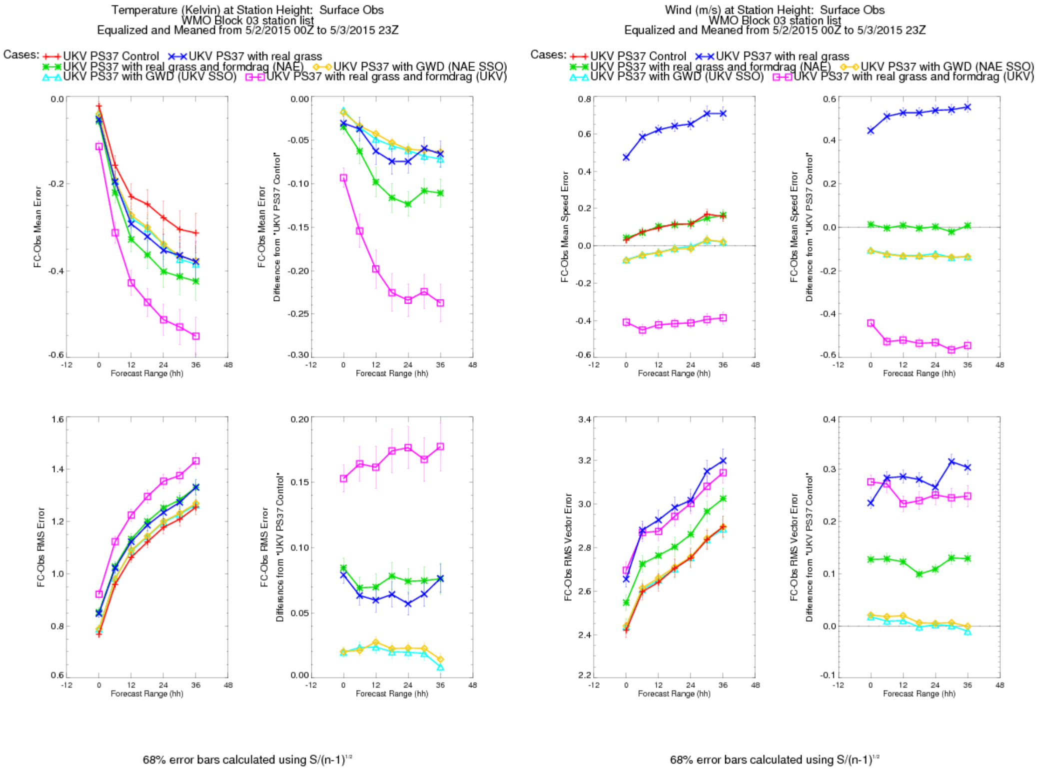

Figure 28: Verification of near surface temperature (left) and wind speed (right) from PS37-based trials of changes to drag, turbulent mixing and land surface properties, as described in the text

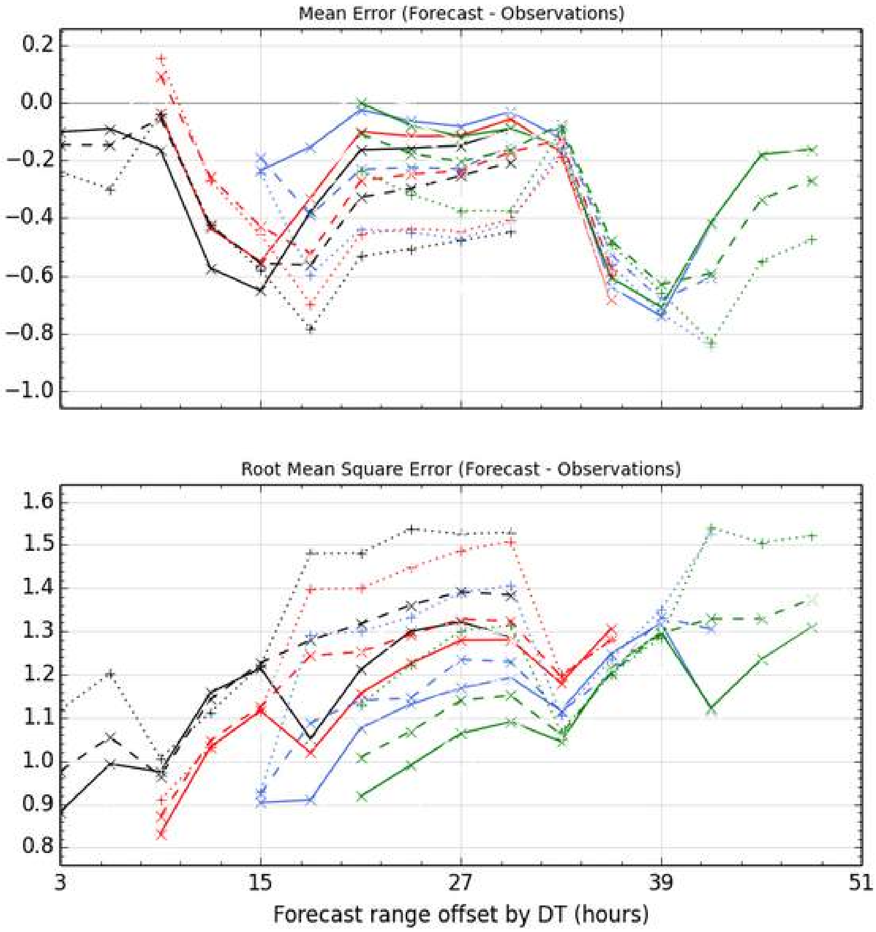

Figure 29: Diurnally-sampled near surface temperature errors (K) against WMO surface sites in the UK, from UKV trials of PS37 (solid), RealGrass (dashed) and RealGrass plus UKV SSO form drag (dotted)

validation *is* appropriate would be needed to allow any objective verification of raw model data.

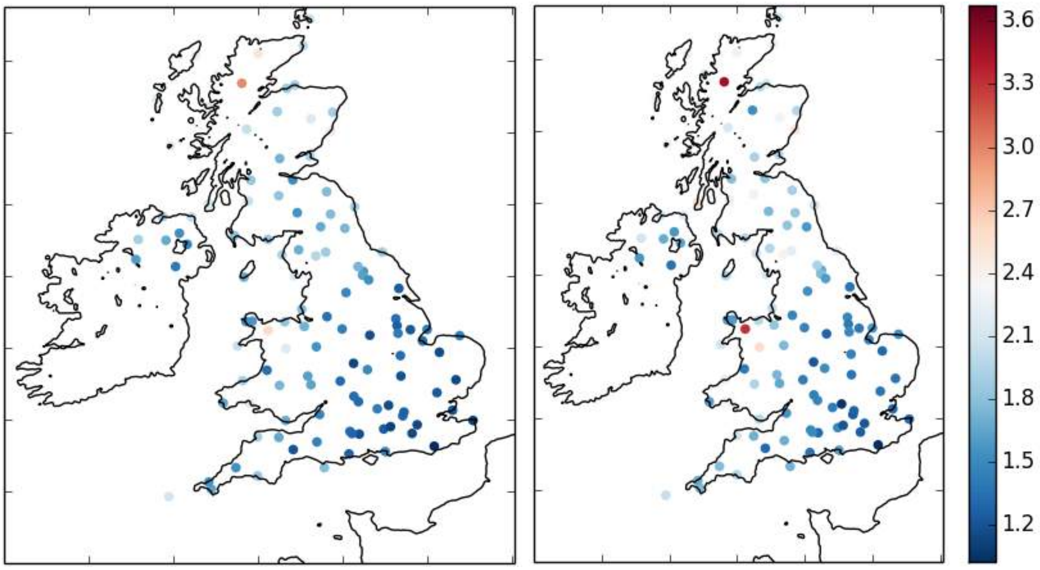

Figure 30: Average RMS error in near surface daytime wind speed against WMO surface site observations in the UK, from PS37 (left) and RealGrass plus form drag (right) trials from 5 February to 5 March 2015

4.3 UKV case study tests

Given the rather disappointing impact of these changes in the trial verification, here results from a single case study (the first LANFEX IOP, based at Cardington, on the night of 24 November 2014) are presented, to illustrate the impacts in more detail. In this case the standard RealGrass package is tested on its own and then combined with both GWD and form drag parametrizations. The typical warm bias on such a clear calm night is clearly visible in the Cardington time series of screen temperature in Fig. 31, with PS38 too warm by up to 3 K. The RealGrass package greatly improves the forecast temperatures, matching the observed screen level (and skin, not shown) temperatures very well. The impact of adding orographic drag is small but enhances the cooling in the evening transition even more, and beyond that observed. As seen before, the impact of including the stability dependence of the form drag is minimal. Also shown in Fig. 31 is the time series for the Bedford synop site (actually on an airfield near Thurleigh a few miles to the north of Bedford and on a low wide ridge). Here the situation is almost reversed, with PS38 being only a little too warm while RealGrass gives a distinct cold bias of up to 2 K (and orographic drag here makes almost no difference).

The wider impact of these changes is illustrated in by the screen temperature maps in Fig. 32 which show distinctly colder temperatures over much of the central UK with RealGrass, but also further, locally very significant, cooling from the drag parametrizations over Wales and the Pennines. The verification for this case study against synop observations in Fig. 32 shows that, while PS38 clearly

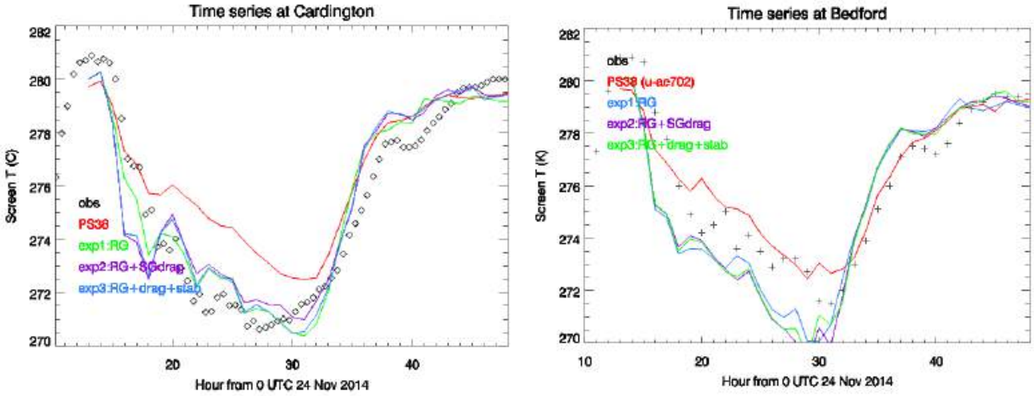

Figure 31: Time series of screen temperature from Cardington (left) and Thurleigh (north of Bedford, right)

has a widespread warm bias, the combined RealGrass and drag package has developed more serious cold biases over much of the country, apart from the south-west.

4.4 UKV trial of combined drag changes only

To separate the impact of the drag changes from those to the land surface, a drag package trial based on PS38 UKV has been run comprising GWD (GA6 set-up with UKV SSO) + form drag (distributed drag profile without stability dependence and $C_{D(orog)} = 0.15$) + canopy height for grass tiles set to 10cm. An initial test was attempted with $c_{D(orog)} = 0.3$ and canopy heights of 0.45 m (as recommended from standalone single-tile JULES testing in section 3) but these gave very poor wind verification with a very slow bias. The reduced value for $c_{D(orog)}$ is then the same as that used in GA while use of a shorter canopy height can be motivated through the heterogenity seen with higher level forcing in JULES being represented in UKV through the other tiles. These settings then give roughly neutrally biased wind speeds on average across the UK, although the rms error is still increased from PS38 by around 5%, as before suggesting these drag changes don't combine particularly effectively.

The screen temperature verification in Fig. 33 shows benefit from the drag package in the first few days of the trial period, warming the model's cold bias and reducing the rms error. However, after 17th January the drag changes introduce an average cooling and a significant increase in rms error. The first few days of the trial are dominated by strong westerly winds and the passage of fronts leading to significantly overcast conditions. For the first time on the night of 16–17 January there is a slackening in the gradient wind combined with predominately clear skies, conditions which then occur more frequently in the trial. In this regime adding parametrized orographic drag dramatically slows the winds leading to strong surface cooling in the Scottish Highlands particularly, but also other regions of complex terrain as can be seen in Fig. 33 (the worst cold bias at this time is -9.3K compared to -3.3K in PS38). Much more detailed investigation is required to determine if any of this

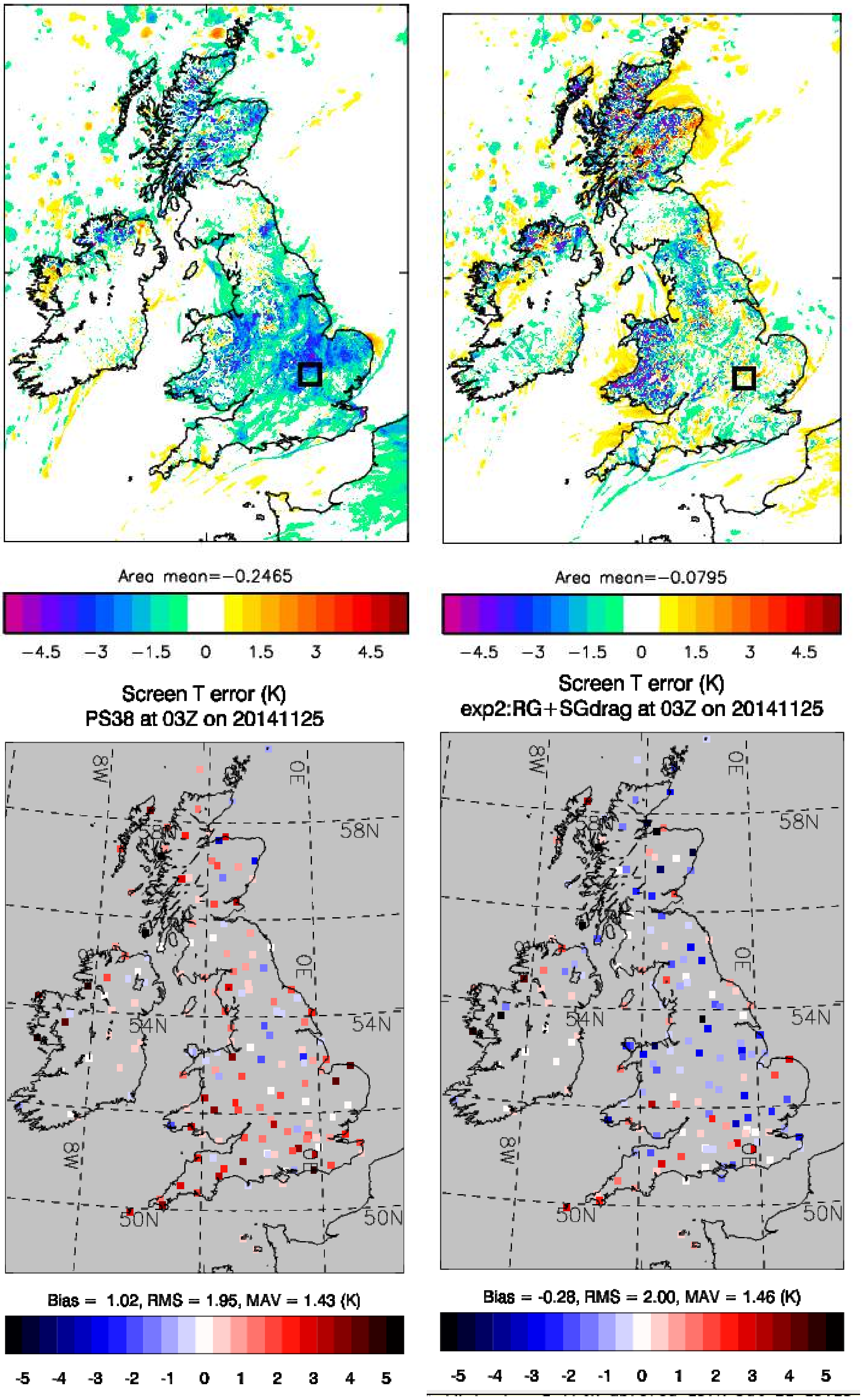

Figure 32: Near surface temperatures from UKV case studies initialised at 12 UTC on 24 November 2014. Top row show the impact at 6 UTC of the "RealGrass" package (left) and of subgrid orographic drag (right); bottom row shows errors at 3 UTC for PS38 (left) and RealGrass plus orographic drag (right)

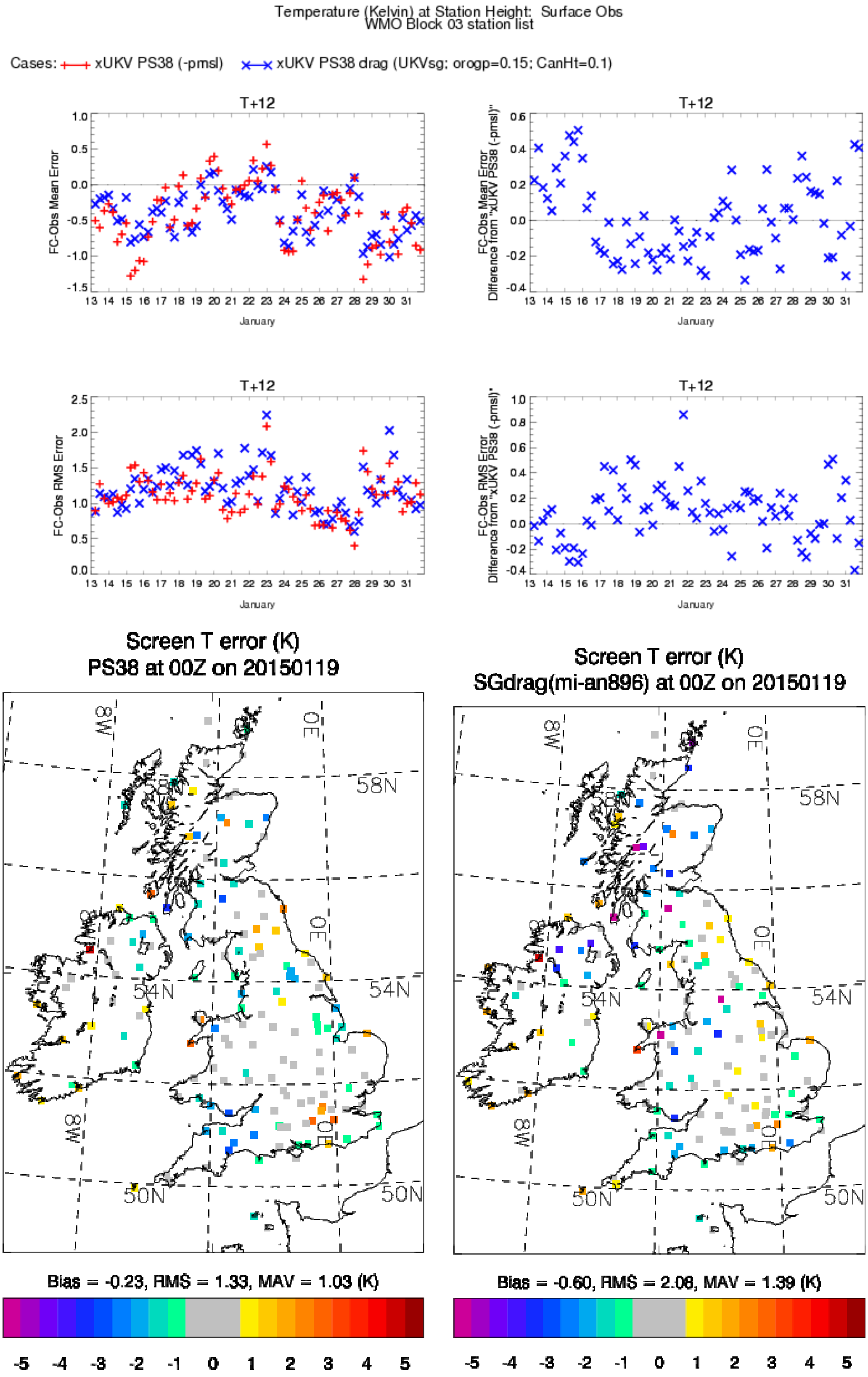

Figure 33: Time series of screen temperature verification for T+12 forecasts from the drag package trial (top) and example verification of T+12 forecasts for 0z on 19 January 2015 for PS38 (left) and the drag package (right)

local cooling could be realistic formation of cold pools in valleys, or whether it is indicative of not correctly coupling the turbulent mixing of momentum and heat generated by subgrid hills (as was suggested by Boutle et al, 2016).

5 Summaries and recommendations

Detailed studies have been conducted into the the nature of the systematic diurnal errors in near-surface temperatures and winds in MetUM forecasts over the UK. These studies have included off-line JULES simulations, case studies with the UKV and month-long DA-trials and detailed comparison has been made with both the operational network of surface sites and the Met Office Observational Research site at Cardington. While the issues involve complex interactions between the land surface representation, the boundary layer turbulence scheme and their interaction with the resolved scale flow, the following changes to the model configuration should be taken forward into testing for possible inclusion in RA1 (subject to revision following some of the shorter term more detailed studies recommended below). Note that these are rather more conservative than the RealGrass settings described in section 4 (with less dramatic changes to kext and SBL turbulent mixing, for example) but especially without reduction of the canopy height for the grass tiles — reductions even only to 0.45m, as recommended from the Cardington studies discussed in this report, have been found to lead to serious degradation in UKV wind speed verification.

- include surface temperature in lowest level Ri (but leave the rest of the SBL mixing as operational, given still unquantified impact of subgrid orography on vertical mixing)
- fix grass LAI at 2
- set canopy height for trees to a lower value (14m)
- kext=1 for grass tiles (c3 and c4)
- $z_{0h}/z_{0m} = 0.01$ for grass tiles (c3 and c4)
- improved specified spectral albedos for direct and diffuse radiation on plant tiles (currently under development in GA)
- reduce bare soil tile fraction to 0.1 (more conservative than value of 0.02 tested already and is roughly the maximum over the UK in GA)

Areas for further work

- More realistic UKV ancillaries of tile fractions, canopy height and LAI are urgently required
  - are some simple short term improvements possible (e.g., implementing the observed surface albedo via an ancillary, as used in GA; would fixing the grass LAI at 2 be better than the current seasonal variation?)
  - further work on the spectral albedo scheme is needed, not least to understand continuing differences from what is observed at Cardington. Very recent enhancements to the

surface observations at Cardington to include red-domed pyranometers should be very helpful but hyperspectral observations may ultimately be required

- Longer term, the choice of vegetation tiles should be reviewed
  - this has not been done since seasonally and spatially-varying ancillaries were introduced and so, most obviously for example, the bare soil tile fraction appears to represent an annual mean impact from ploughing that would be better represented by seasonally varying LAI and canopy height
  - what are the important differences between vegetation types that should require separate tiles? For example, it is likely impossible to generate a map of root depth, and crops and grass fields have very different seasonal variability
- How is small-scale heterogeneity (such as hedges and scattered trees) to be represented in JULES?
  - the tile fractions rather suggests the UKV C3-grass tile includes hedges and scattered trees (the tree and shrub tile fractions are very small in Devon, for example) and so ought(?) C3-grass to be rougher than simple grass to reflect that? Is this "aggregate" approach the best we can do? What are the implications for the tile fractions and associated ancillary data?
- detailed work is required to understand and improve the representation of canopies in JULES (e.g., is there a need at least for separate canopy top and base temperature?; how should bare soil within plant tiles couple to the atmosphere?)
  - more detailed validation studies using the dew meter data from Cardington are planned in order to understand why JULES appears reluctant to form dew
  - we are very grateful to have Hiroshi Kusabiraki, visiting Scientist from JMA, working with us for the next two years on the representation of canopies
- there are several outstanding questions regarding the representation of soils in JULES that impact on temperature forecasts, both through the thermal conductivity and also via the soil moisture and its impact on surface evaporation
  - the current representation of evaporation from bare soil appears insufficiently sensitive to the soil moisture content, underestimating evaporation from moist soils and overestimating evaporation from dry soils
  - concerns have been raised (?ref??) about the response of JULES soil moisture following rainfall on dry soil, with the subsequent dry-down being far too rapid, which will have implications for UK summertime forecasts

    - the current minimum of 0.5m for the e-folding root depths makes it much easier for plants to keep accessing soil moisture (thereby maintaining surface evaporation at the expense of surface heating), and instinctively feels too deep for short grass, but how can more realistic root depths be quantified?
    - tests with higher soil vertical resolution have suggested there may be benefits for summertime drying of near-surface soil and thence surface fluxes, and also with potential to improve the diurnal temperature range
    - the tiling of the underlying soil profile has been shown to have a significant impact on surface evaporation, via the evolution of the soil moisture available to plant roots, which raises question on how best to represent this heterogeneity in JULES

- a more detailed study of the momentum budget is needed, to include the effects of subgrid orography
    - why does reducing the canopy height (and thence surface roughness length) in the UKV to optimal values from off-line JULES studies give degradation in 10m wind speed verification?
    - what is the impact of current subgrid drag parametrizations, including on vertical mixing of heat as well as momentum?
    - would new ancillaries for subgrid orographic fields, especially for form drag, improve the model's skill in complex terrain?
    - would including directional dependence in the form drag parametization help?
    - Comparisons with very high resolution simulations and possibly in an idealised framework, including stable stratification, would almost certainly be illuminating, and the LANFEX and COLPEX observations could serve as a valuable truth

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