Stable boundary layer modelling at the Met Office

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A snapshot is given of current stable boundary layer research and modelling at the Met Office. Substantial progress has been made in recent years with, for example, the introduction of a new means of interpolating the near surface air temperature, a parametrization for mixing induced by unresolved drainage flows in complex terrain and a representation of suppressed aerosol activation in fog. A persistent bias in clear sky temperatures remains, though, with nights too warm and days too cold, that appears common to all configurations. Ongoing research is focused on the near-surface structure and coupling with the surface, as well as continued work on fog and stable boundary layers in complex terrain.

1 Operational models at the Met Office

The Met Office Unified Model (MetUM) has been highly successful for nearly twenty years in providing weather forecasts and climate simulations from the same technical infrastructure, dynamical core and atmospheric parametrization code, now at resolutions from 1.5km to 300km. Whilst being beneficial in terms of reducing duplication of common programming tasks, for example, it presents the challenge of needing to perform well across a wide range of time and space scales. However, with climate models being required to provide ever more local detail and predictions of weather impact, and NWP forecast ranges being extended into seasonal timescales, the requirements of both communities are converging. There is also the significant benefit of examining climatalogical errors alongside observationally constrained case study performance that allows, for example, a physical interpretation of significant regional biases to be identified and addressed (such as the improvements to the boundary layer mixing formulation in cold-air outbreaks described in Bodas-Salcedo et al, 2012).

Although many aspects of the MetUM used in different applications are indeed identical, some differences in details have developed over the years. For the reasons alluded to above, the strategic decision has been made recently to merge these differences into single “Global Atmosphere” and “Global Land” configurations (for the atmospheric and land surface components), as described in Walters et al (2011). These configurations, labelled GA3.0 and GL3.0 (and GA/L3.0 when combined), are a common choice of scientific options that will be applied to all of the Met Office’s global components, from NWP to climate simulations. GA/L3.0 gave acceptable performance for seasonal and climate versions but, pragmatically, it was found necessary to create “branch configurations”, GA3.1 and GL3.1, for global NWP. These retained a limited number of global NWP physics options that, although thought to be less scientifically justifiable, continued to give improved overall NWP performance. This is of particular relevance here because the most significant are aspects of the stable boundary layer and land surface formulations, as described in section 2.

In addition to the global models, the MetUM is used operationally at 1.5km resolution over the UK, the model being known as the “UKV”. Although not strictly considered under the GA/GL configuration management process, the UKV parametrization options are very similar to those in GA/L3.0, where applicable (for example the UKV does not currently have any convection parametrization but the surface and boundary layer vertical mixing schemes are very similar). The UKV also uses a Smagorinsky-type scheme for horizontal diffusion where the coefficients are dependent on the three-dimensional flow. In addition to higher horizontal resolution, the UKV also has somewhat higher vertical resolution in the boundary layer and lower troposphere, see Fig 1, including the lowest grid levels which are at 2.5m for horizontal winds and 5m for scalars and vertical wind component in the UKV, compared to 10m and 20m in the global model. Fig 1 also shows a levels set (L140) roughly double the resolution of the UKV levels ($L70_{UK}$) that is currently being used for research purposes. Increasing the resolution to the $L70_{UK}$levels demonstrated significant improvement in boundary layer cloud and near-surface temperature forecasts in the 4km resolution forerunner to the UKV and the potential for further benefit from further enhancement is currently being evaluated.

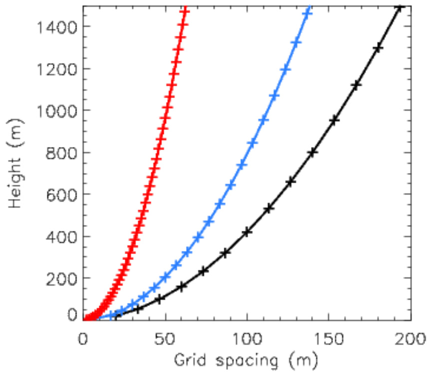

Figure 1: Vertical grid spacings over the lowest 1500m of the atmosphere from GA3.0 (black), UKV (blue) and L140 (red).

2 Stable boundary layer parametrization sensitivities

The turbulence, or boundary-layer, parametrization is essentially a two-part first-order turbulence closure, split by boundary-layer stability (Lock et al, 2000). For the unstable boundary layer it uses a K-profile closure (diffusion coefficients that are scaled functions of height within the boundary layer) with an explicit entrainment parametrization at the boundary-layer top. For the stable boundary layer (SBL) a simple down-gradient formulation dependent on local stability (via the Richardson number, Ri, that measures the stability of the atmosphere to turbulent mixing) is used. In the stable regime, the diffusivities (for momentum and scalars) are set through

$$K = \lambda^2 S f(Ri) \tag{1}$$

where S is the vertical wind shear, λ is the mixing length, and f introduces a dependence on stability.

igure 2 plots the stable stability functions, $f(Ri)$, used in the MetUM. Over land, GA3.0 uses what is known as the “Mes tail” (after the mesoscale model in which it was first used), which is a linear interpolation with height between the Louis (1979) function (in red) at the surface and sharp (in blue) at 200 m and above. As discussed in Brown et al (2008), the global NWP configuration has for many years used the “long-tail” stable stability functions over land, together with adjustments to the mixing lengths, that combine to give significantly more mixing than the GA3.0 setup (and than indicated by observations or large-eddy simulation, e.g. Beare et al. 2006) and these remain key differences in GA3.1. Subsequent to Brown et al, though, GA3.1 also reduces mixing smoothly with height but in this case the reduction is from long-tails below 500m to sharp above 2km. Note that all MetUM configurations use the sharp functions at all heights over the sea, Fthereby restricting enhanced mixing to near the surface over land. Although the argument can be made that this enhancement is parametrizing the effects of surface heterogeneity, studies suggest that the GA3.1 enhancement is excessive (e.g. see discussion in McCabe and Brown, 2007) and even the GA3.0 enhancement is not currently related to any quantitative measure of the heterogeneity. Hence there remains a concern that this may be used as a means of compensating for errors elsewhere in the surface energy balance.

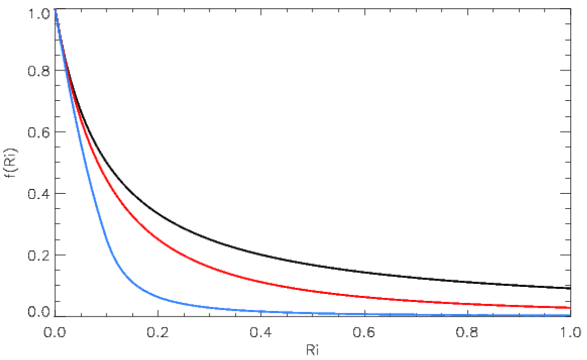

Figure 2: Stability functions used in the MetUM: long-tail (black), Louis (red) and sharp (blue).

A closely related difference between GL3.0 and 3.1, therefore, is that GL3.0 performs its land surface calculations on each of the 9 surface tiles separately and aggregates surface fluxes, while GL3.1 amalgamates the properties of each surface type, weighted by their grid-box fraction, into single, representative parameter values. As well as being only an approximation of a truly heterogeneous surface, this choice means that GL3.1 must also compromise improvements to the treatment of individual surface types (such as the fraction of snow stored on or below tree canopies and the thermal capacity of deep but sub-grid lakes). As discussed in Walters et al, the GL3.1 surface representation gives a systematically cooler land surface while the enhanced SBL mixing will tend to warm under stable conditions by a similar magnitude, although with far from universal geographical or temporal cancellation! This can be seen in figure 3 where GA/L3.1 reduces the cold bias at midday over northern Africa and more generally at high latitudes (mainly due to the enhanced SBL mixing) whilst cooling many other, primarily forested, land areas (e.g., Amazonia, western China and a band around 60N). The latter is due to the use of aggregated surface properties and is particularly beneficial in the south east USA. Understanding and improving this coupled land-atmosphere system is a key challenge for making improvements in GL4.0 and GA4.0.

However, these problems are far from dominating the main biases in the near surface temperatures in the MetUM, as illustrated in Fig. 4 with the northern hemisphere winter temperature biases from the operational NWP forecasts at 0 UTC and the diurnal mean biases from a climate simulation. Despite the differences in resolution and timescale, and that the former uses GA/L3.1 physics, the latter GA/L3.0, the patterns are remarkably similar, suggesting the stable boundary layer tail or surface aggregation differences are only perturbing a bias arising from some other aspect of the model simulation. The NWP biases are also visible (albeit at smaller magnitude) from day 1 of the forecast suggesting the main issue is with the local physics.

Further detail and more evidence of the consistency of model temperature biases can be seen in Fig. 5 for MetUM forecasts from various versions of the global NWP model together with higher resolution forecast configurations over the UK. While the former would be consistent with a positive bias in cloud cover, the latter have been sampled only for clear sky conditions and yet show a very similar signal. This suggests there is an underlying diurnal variation in the MetUM temperature bias under clear sky of up to 1K that acts to suppress the diurnal temperature range (i.e., the MetUM is robustly too cold by day, too warm by night). As in Fig. 3, the systematic cooling arising from the GL3.1 aggregated surface properties is visible (particularly by night), and this dominates any nocturnal cooling that would be expected from the much reduced turbulent mixing in GA3.0. Further reduction in the mixing, by using the sharp tail instead of the Mes tail, does give some nighttime cooling but, being at most 0.2K, is a small fraction of the bias. Further geographical sampling of the UK verification shows the diurnal biases are not related to significant orography either and so the main errors are occurring under the relatively idealised conditions of clear skies over largely flat terrain. Improving these errors is an area of active research and, perhaps not surprisingly, many contributory factors have already been identified, including:

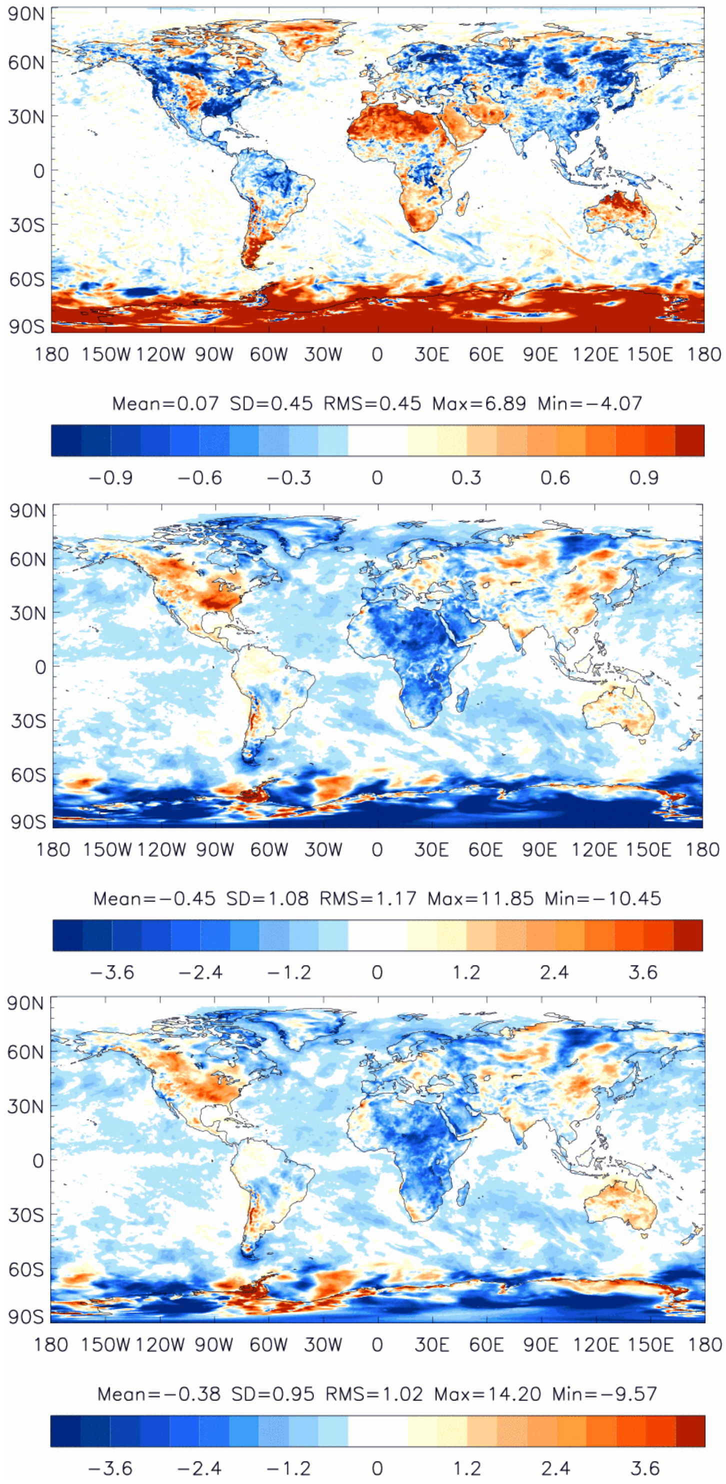

Figure 3: Mean 5 day forecast 1.5 m temperature differences at 12 UTC during 10 case studies from June to August. The top panel shows GA/L3.1 minus GA/L3.0; the middle and bottom panels show, respectively, the GA/L3.0 and GA/L3.1 biases against Met Office operational analyses.

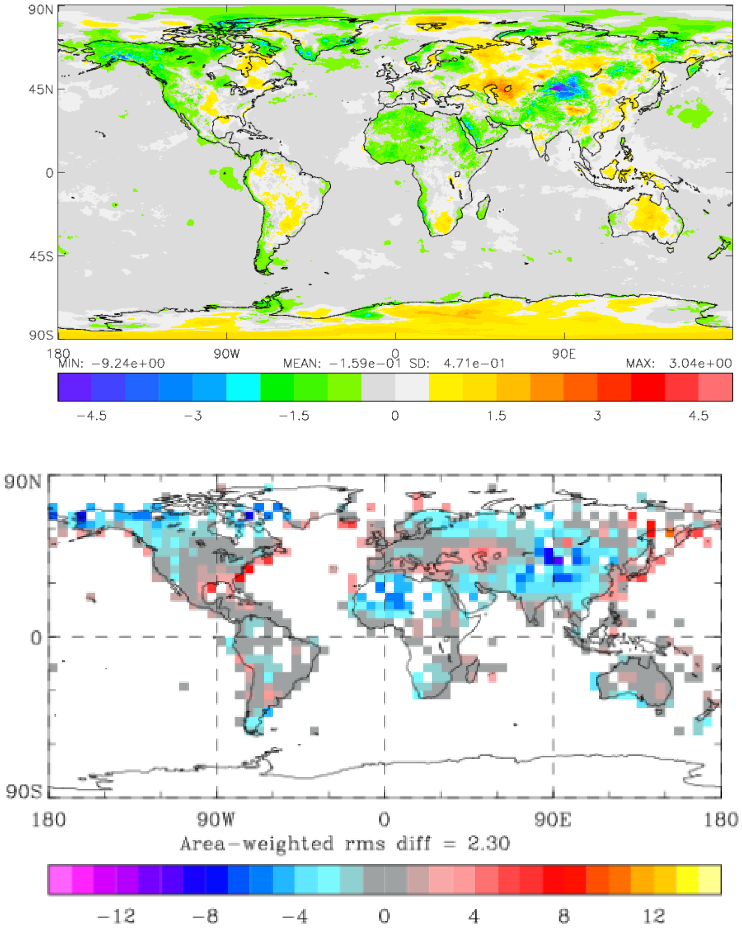

Figure 4: December to February mean 1.5 m temperatures: top operational NWP (run at N512, or approximately 24km resolution in the mid-latitudes, with GA/L3.1 physics) day 5 0Z forecast difference from Met Office analyses; bottom: 10 year N96 atmosphere/land only climate simulation (at N96, or 135km, with GA/L3.0 physics) diurnal mean difference from CRUTEM3 observations (Brohan et al., 2006)

- excessive turbulent mixing under stable conditions, contributing to the nocturnal warm bias
- biases in the climatological aerosol profiles that restricts downwelling SW radiation at the surface (and thence daytime warming)
- surface emissivities (fixed at 0.97) are too large for bare sandy soils (which therefore cools dessert areas too strongly)
- errors in the interpolation of 1.5m temperature between the surface skin temperature and lowest atmospheric model level (e.g., Edwards et al, 2011) showed this can give cold biases in stable conditions under light winds. Verification of this diagnostic currently uses the grid-box mean value and yet observations tend to be made over grass surfaces.
- comparisons with observations of the surface energy budget from the Met Office research site at Cardington (Edwards et al, 2011) suggest the thermal roughness length in the model may be too large for short grass. This study also indicated excessive daytime evaporation and suppressed sensible heat fluxes.
- potential biases in the diurnal cycle of ground heat flux (i.e., too much heat absorbed during the day that is then emitted at night) which might reflect a lack of resolution in the soil (the highest level is currently 0.1 m thick in all configurations) and/or biases in soil hydrology

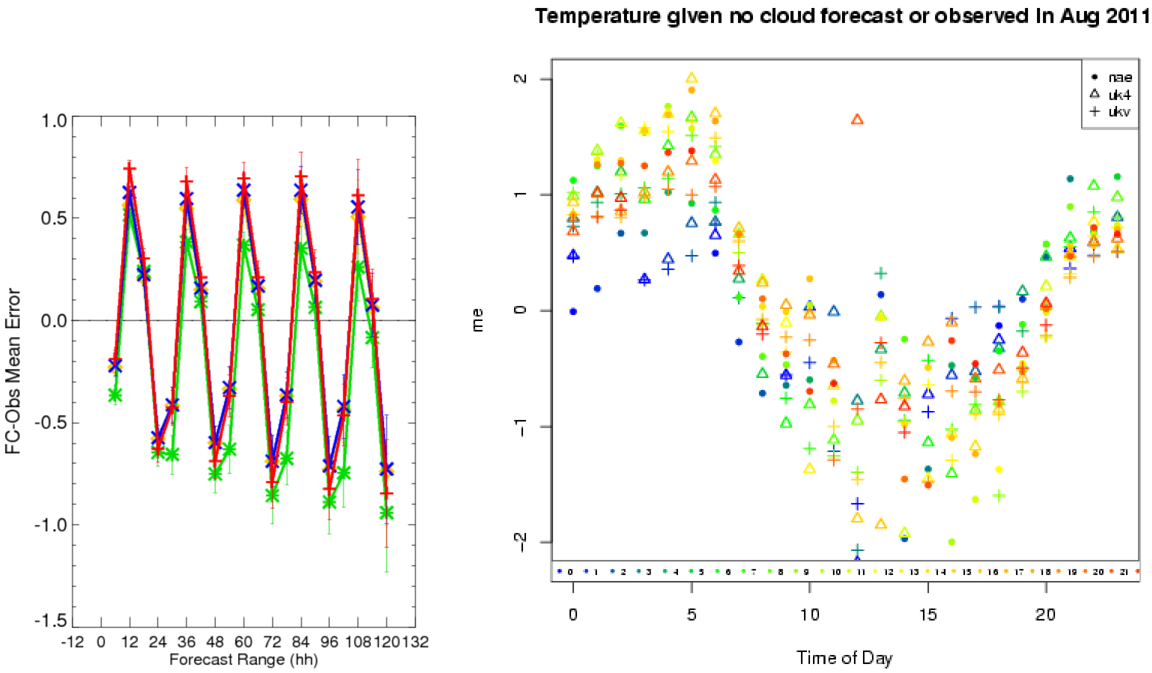

Figure 5: Mean forecast 1.5m temperature errors (a) as a function of forecast range for the global MetUM against European stations, for 10 case studies initialised at 12Z during June to August, for GA/L3.0 (red), GA/L3.1 (green), an updated version of GA/L3.0 (blue) and GA3.0 with sharp-tailed stability functions (orange); and (b) as a function of time of day against UK stations for August 2011, for times when there was no cloud in either model or observations, for limited area versions of the MetUM (nae is at 12km, uk4 at 4km and ukv at 1.5km resolution), with the colours denoting forecast range, as given at the bottom of the panel (from blue for the analysis to red for T+21).

It should be noted that the above tests, changing the stability dependence of stable boundary layer mixing, show almost negligible impact on the synoptic scale flow, e.g., for 500 hPa height or 850 hPa wind verification. Only through its cooling effect on North American lower level temperatures in summer does GA/L3.1 show a measurable benefit for mean sea level pressure, for example. This lack of sensitivity appears very different from the experience at ECMWF. One speculative suggestion arising from discussions at this ECMWF-GABLS workshop was that, until as recently as 2009, the boundary layer turbulence parametrization in the MetUM only operated over the lowest 3km of the atmosphere. Hence other parametrizations, in particular those acting on momentum fields, such as orographic form drag, gravity wave drag and convective momentum transport, were developed over many years in a very different context to those at ECMWF (where the turbulence parametrization has always operated over the whole troposphere). It would be interesting, therefore, to compare the magnitudes and geographical distribution of the different terms in the momentum budget.

3 Stable boundary layers in complex terrain

This section focuses on the role played by small scale hills in modulating the nighttime boundary layer structure. Especially under light winds, valleys are more sheltered, colder and more prone to fog than hill tops. This poses direct forecasting challenges where the topography is unresolved by NWP models and much work has focused on understanding how cold pools form (Vosper and Brown, 2008) and how to add local topographic detail to coarse scale NWP temperature forecasts (Sheridan et al, 2010). This subgrid variability also has implications for parametrization of grid-scale turbulent fluxes. McCabe and Brown (2007) investigated this using a 1km version of the MetUM and found that area-averaging simulations of stable boundary layers in complex terrain could imply vertical mixing that was enhanced over what would be expected over a flat surface. Motivated by these studies, a parametrization for unresolved drainage flows has been developed, as described below, and is now operational in the UKV. Further developments in these areas will be informed from a field and numerical modeling campaign, COLPEX (COLd-air Pooling EXperiment), and some initial results are given in section 3.2

3.1 Parametrization of unresolved drainage flows

The motivation for including the effects of unresolved complex terrain actually came from the development of serious cold biases in Scottish valleys during the initial trialling of the UKV. During this period the winds were, in fact, relatively strong but cold and generally from the north. While observed temperatures at low elevations hovered around 0C, as shown in Fig. 6, the UKV temperatures fell to below -20C in several valleys, where the winds also decoupled leaving largely stagnant cold pools. The MetUM grid-scale orography is smoothed using a Raymond filter that suppresses 2 grid-length scales completely but 6 grid-lengths hardly at all (Webster et al, 2003) and the cold valleys were found to be predominately close to 6 grid-lengths across. Rather than further smooth the resolved orography (which did remove the problem but would also reduce skill in forecasting orographic precipitation, for example), the following hypothesis was developed.

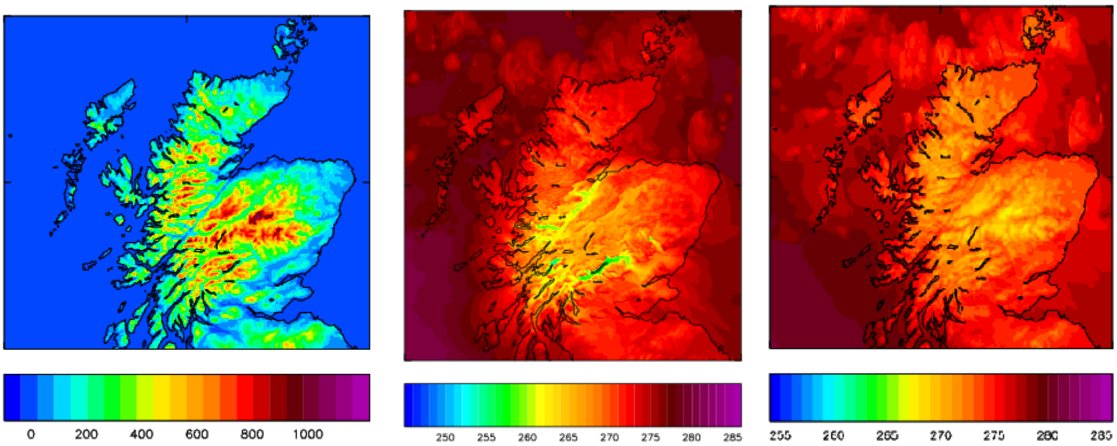

Figure 6: UKV (a) orographic height (in metres) over Scotland; forecasts of 1.5m temperature for 12 UTC on 2 Feb 2010 from (b) the original UKV and (c) UKV with subgrid drainage shear included as in (3)

In reality, under such decoupled conditions, significant drainage flows would develop with associated turbulent vertical mixing. For resolved hills on scales of 6 grid-lengths, the MetUM dynamics will not explicitly resolve these flows and so they should be parametrized within the boundary layer scheme. Following Derbyshire and Wood (1994) and Porson et al (2011), we consider an idealised two-dimensional regime where uniform surface cooling leads to the generation of static stability (with buoyancy parameter N^2) over a slope of gradient α. This drives a horizontal pressure gradient given by

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = \frac{g}{\theta_v}\left(\theta_v(z) - \theta_{vs}\right)\alpha$$

where θ_{vs} is the virtual potential temperature at the surface. Substituting this pressure gradient into the horizontal momentum equation and differentiating with respect to height then gives

$$\frac{\partial}{\partial t}\left(\frac{\partial u}{\partial z}\right) = N^2\alpha$$

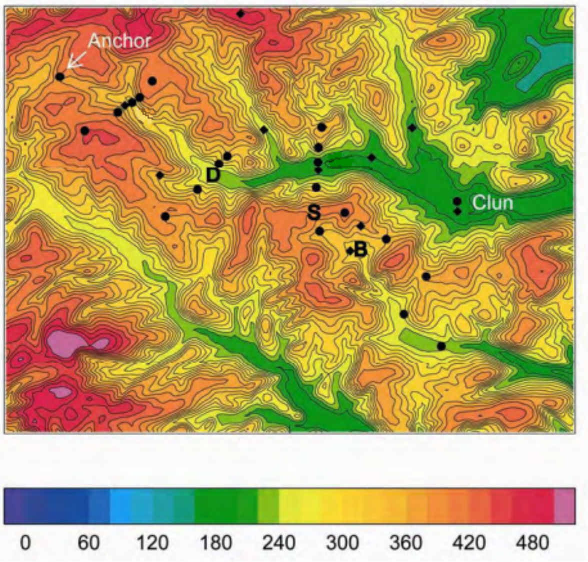

Figure 7: Map of the terrain in the COLPEX area (showing height above sea level for 13 km north-south by 18km west-east) and locations of the main observation sites (letters D, S and B) and additional weather stations (circles and diamonds).

After a time t, therefore, the hydrostatic imbalance will generate a drainage flow with associated wind shear, S_d, given by:

$$S_d = N^2 \alpha t \beta \left(\frac{z}{\sigma_h} \right) \tag{2}$$

where a height-dependent factor, β, has been included that limits the vertical extent to be below approximately one standard deviation of the subgrid orographic height, σ_h. Note that σ_h and α are taken as the averages over the 12 km surrounding each grid box, in order to be representative of the local area over which such flows will be underresolved. Finally, this drainage wind shear is included in the turbulent mixing parametrization by rewriting (1) as:

$$K = \lambda^2 (S + S_d) f(Ri) \qquad \text{with} \qquad Ri = \frac{N^2}{(S + S_d)^2} \tag{3}$$

In this initial implementation, t in (2) has been taken as a fixed timescale of 30 minutes, for simplicity. So, for example, taking typical values for cold pools forming in the Scottish Glens, of $\partial\theta_v/\partial z \sim 1$ K per 100 m and $\alpha = 0.15$, gives $S_d \sim 0.1\text{s}^{-1}$, or a realistic drainage flow of 1ms^{-1} at 10m. This then implies $Ri \sim 0.04$ (instead of $>> 1$) which, from Fig. 2, can be seen to imply very significant enhancement of turbulent mixing, and gives $K \sim 1\ \text{m}^2\text{s}^{-1}$.

The impact on UKV temperatures in these valleys is very dramatic, see Fig. 6c, bringing them back within the range of observations (not shown). Moreover, subsequent routine verification, sampled on orographic regions of the UK only, shows no sign of any warm bias at night (above that seen across all areas of the UK, as in Fig. 5).

3.2 COLPEX observations and modelling

An introduction to the observations and modeling studies that comprise COLPEX is given in Price et al (2011). The field campaign ran for 15 months in Shropshire, UK, with many observation sites set up

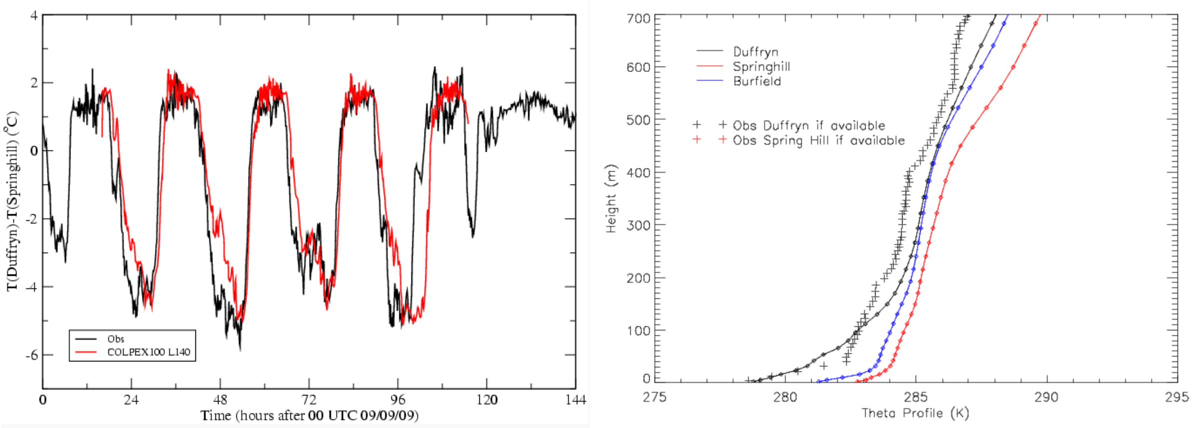

Figure 8: a) time series of 1.5m temperature difference between Duffryn and Springhill sites (marked by the "D" and "S" in Fig. 7) from the observations (black) and the MetUM 100m L140 simulation (red) and (b) potential temperature comparison with sonde (plusses) at 22 UTC on 9th September 2009 at the valley site, Duffryn

in a region of small hills and valleys, as shown in Fig. 7. The MetUM is being run at 100m horizontal resolution and with 140 levels (see Fig. 1) over a 30km square domain covering this area. Generally it does a very good job with the evolution of temperatures, including the relative near surface cooling seen in the valleys over night shown in Fig. 8a. Of direct relevance to future operational NWP configurations, the higher vertical resolution with L140 reproduces the observed shallow cold near-surface layers significantly better than $L70_{UK}$, although the SBL top remains apparently somewhat too diffuse, see Fig. 8b. These simulations are currently being used in combination with the observations to understand how the cold pool forms and what factors control cold pool depth and strength. Also, in a similar way to McCabe and Brown, the profiles and fluxes will be area-averaged to inform parametrization development for complex small scale terrain, such as that for drainage flows described in section 3.1.

4 Fog

Fog remains a particularly important forecast challenge that is intimately connected to the representation of stable boundary layer mixing but also on many other aspects of the model physical parametrizations. It is an area of active research at the Met Office, including field observations (Price, 2011) and comparisons with large-eddy simulation (Porson et al, 2011). Much improvement in operational forecast skill has come in recent years from improved representation of soil hydrology and cloud microphysics, in particular from including the gravitational settling of cloud water droplets and with a (specified) droplet number appropriate for stable fog layers with reduced aerosol activation (Wilkinson et al, 2012).

Further work is still required to improve the structure of the nocturnal (cloud-free) boundary layer (such as the warm bias noted in section 2) that is crucial to fog formation, without generating excessive fog. For example, the MetUM COLPEX simulations discussed in section 3.2 show similar skill in the near-surface temperature profile for a case when fog was observed to form in the early morning. In both the model and reality the formation of the cold pool in the early evening led to very high relative humidities (RH) in the lowest 100m as can be seen in Fig. 9. In the MetUM, cloud is diagnosed by assuming symmetric variability of subgrid moisture around the grid box mean with the cloud given by the part of the distribution that exceeds saturation. As a result, the model *must* form cloud as RH approaches 100% and yet no fog (or any other cloud) was observed until several hours later. Related to this, Fig. 10 shows

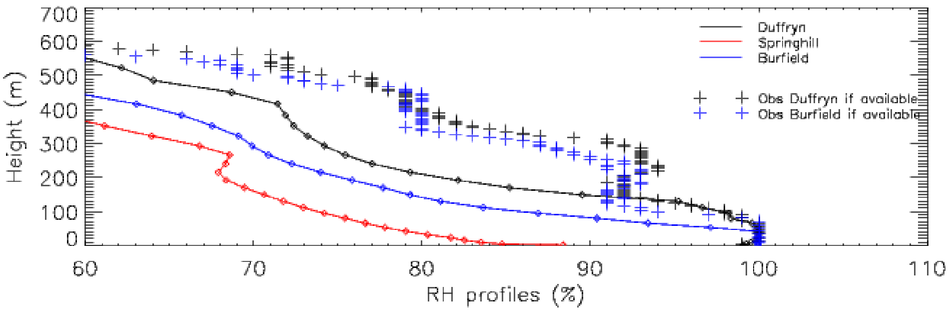

Figure 9: Relative humidity comparison with sonde at 20 UTC on 10th December 2009 at the valley site, Duffryn

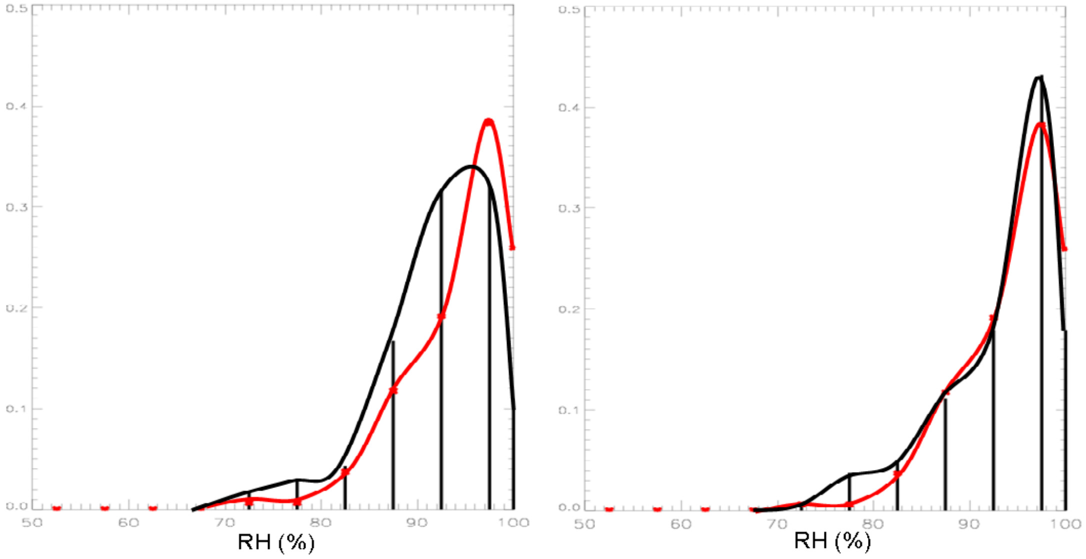

Figure 10: Normalised probability density functions of relative humidity from synop observations over the UK (red) and from the UKV (black). Left-hand panel is from the operational UKV and the right-hand from the UKV with a stability function that reduces to zero at $Ri = 0.25$.

that the operational UKV underestimates the occurrence of high RH while a test with reduced SBL mixing performs much better. This test also reduces the nighttime warm bias. However, it is currently associated with an unacceptable widespread increase in the occurrence of fog. To make progress in this area, then, may require further developments to the cloud scheme and, for example, some form of parametrization of aerosol activation.

5 Summary

A key strategic aim at the Met Office is to harmonise parametrization settings in the MetUM, as far as possible across all time and space scales. To a great extent this has been acheived, although significant differences remain in the global NWP model where enhanced stable turbulent mixing over land and an aggregated land surface scheme are found to give significant benefit. However, despite these differences, there are very similar regional biases in surface temperature between climate and NWP models indicating underlying deficiencies in the local model physics.

To understand and ultimately remove the remaining surface and boundary layer differences between NWP and climate configurations will require further detailed examination of biases in the surface energy budget. Results to date show there is no simple solution, with different regions suffering from a range of different model problems. This highlights the necessity for accurate simulation of all processes (turbulence, radiation, the land surface and coupling, clouds and microphysics) for accurate simulation of the atmospheric boundary layer. The suggestion is that the role of the enhanced turbulent mixing in the NWP model is as much to dampen the near surface response to errors elsewhere in the surface energy budget rather than to represent, for example, the effects of unresolved heterogeneity. These effects are by no means insignificant, but should explicitly be linked to measures of that heterogeneity, as has been illustrated here for mixing from unresolved drainage flows in complex terrain.

Despite significant advances in recent years much remains to be done. Ongoing stable boundary layer research at the Met Office is focussed on the near-surface atmospheric structure and coupling with the surface, processes in fog and stable boundary layers in complex terrain.

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