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ORIGINAL PAPER

Upgrades to the Boundary-Layer Scheme in the Met Office Numerical Weather Prediction Model

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Abstract Recent upgrades to the boundary-layer scheme in the UK Met Office operational global Numerical Weather Prediction model are documented. These comprise a reduction in turbulent mixing in stable conditions over the sea, and the inclusion of non-local momentum mixing in convective conditions. The dependence of low-level winds on changing stability is shown to have been significantly improved. Crucially, it is also found that these improvements in local performance have been achieved without degrading the model skill in terms of synoptic evolution—something that has proved difficult to achieve in the past in many operational models. In fact some aspects of the large-scale flow (e.g. zonal mean winds) have been slightly improved.

Keywords Momentum mixing · Numerical weather prediction · Parametrization · Wind turning

1 Introduction

The boundary-layer parametrization used in the UK Met Office Unified Model for Numerical Weather Prediction (NWP) and Climate Prediction is essentially a two-part scheme 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. Before the recent upgrade, a non-local (or non-gradient) component was applied only to the sensible heat flux. For the stable boundary layer a simple down-gradient formulation dependent on local stability (via the Richardson number that measures the stability of the atmosphere to turbulent mixing) is used.

Although used successfully for a number of years, a number of problems have been identified, in particular with regard to the response of the low-level winds to changing stability (e.g. Brown et al. 2005, 2006). The purpose of this paper is to document the changes

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made to the scheme to address these issues, and to show evidence of their adoption leading to improved performance. It is pleasing to be able show that the improvements in local performance have been obtained without degrading the synoptic evolution. Furthermore, the original errors are common to a number of independent NWP models, and it is therefore believed that the results are of relevance for developers of other models.

Section 2 details the changes to the boundary-layer parametrization and the motivation for them. Section 3 describes the testing strategy and results are shown in Sect. 4. Finally conclusions are given in Sect. 5. A Cartesian (x, y, z) co-ordinate system is used throughout, with the z direction normal to the surface, and the velocity vector has components (u, v, w). T + xx refers to an xx hour forecast.

2 Boundary-Layer Scheme Changes

2.1 Modification of Stable Boundary-Layer Turbulent Mixing Over the Sea

The diffusivities (for momentum and scalars) in the stable boundary layer 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 is a function of Ri, the local gradient Richardson number. Until the March 2006 upgrade, the global operational NWP model used, for all stable boundary layers,

$$f = f_{\text{long-tails}}(Ri) = \frac{1}{1 + 10Ri}. \tag{2}$$

This 'long-tails' function decays only slowly with increasing Ri, and gives significantly more mixing at high stabilities than indicated by observations or large-eddy simulation (LES) (e.g. Beare et al. 2006). Other NWP models also typically use formulations that give apparently excessive mixing (e.g. Cuxart et al. 2006). Their use is very likely to be responsible for systematic errors in operational forecasts of near-surface winds. For example, Brown et al. (2005) showed systematic errors in surface wind direction over the sea in stable conditions, which appeared to be at least in part due to excessive mixing leading to stable boundary layers that were too deep and had insufficient wind turning across them. Furthermore, Brown et al. (2006) showed excessive wind speeds and systematic direction errors at nighttime over land in the UK Met Office and ECMWF models.

Unfortunately, past tests of functions that give less mixing in stable conditions have given disappointing results, typically resulting in excessive cooling at the surface and reduced skill in predicting the synoptic evolution (e.g. Viterbo et al. 1999; Beljaars and Viterbo 1998). One possibility is that the traditional functions are effectively parametrizing the effects of heterogeneity leading to some mixing within a grid box even when the grid box mean is very stable (Mahrt 1987). However, it is difficult to see how this effect can justify the use of functions that enhance the mixing as much as is commonly done (e.g. see discussion in McCabe and Brown 2007), and another possibility is that the functions are simply compensating for errors elsewhere in the surface energy balance.

In the absence of a complete solution to these problems, we have adopted the pragmatic approach (originally suggested by Anton Beljaars, private communication, 2007) of implementing a function giving less mixing only over the sea. Here the heterogeneity argument is not applicable, and the fixed sea surface temperature boundary condition in any event prevents any problems with excessive cooling. The function implemented is the 'sharp' function of King et al. (2001)

$$f = f_{\text{sharp}}(Ri) = \begin{cases} (1-5Ri)^2 & 0 \le Ri < 0.1, \\ \left(\dfrac{1}{20Ri}\right)^2 & Ri \ge 0.1, \end{cases} \tag{3}$$

which is much closer to Monin-Obukhov similarity than the long-tails function that it replaces over the sea (and that is still used over land). This change will be referred to as SHARP_SEA. Some results will also be shown from separate tests (SHARP_ALL) of applying the sharp function everywhere.

2.2 Introduction of Non-Local Momentum Mixing

The vertical turbulent momentum fluxes (τ_x and τ_y) in the model are parametrized through

$$(\tau_x, \tau_y) = -\rho K_m \left(\frac{\partial u}{\partial z}, \frac{\partial v}{\partial z}\right) + (\tau_x^{NL}, \tau_y^{NL}) \tag{4}$$

where ρ is the density, K_m is the eddy diffusivity for momentum, and τ_x^{NL} and τ_y^{NL} are the non-local stresses. Until the recent upgrade, the non-local stresses were set to zero. However, Brown and Grant (1997) showed that without a parametrization of non-local stresses, a one-dimensional model produced wind profiles in the convective boundary layer that were less well-mixed than predicted by LES, and underestimated the near surface wind. Inclusion of a non-local stress parametrization (building on one originally proposed by Frech and Mahrt 1995) improved the agreement with LES. Furthermore, Brown et al. (2006) showed that the operational verification statistics indicate a slow bias in the 10-m wind over land by day, especially in spring and summer. The ECMWF model (which also does not allow non-local mixing of momentum in the convective boundary-layer) was found to show a similar bias. Brown et al. also performed further comparisons between a one-dimensional model and LES, again highlighting the benefits of a non-local stress parametrization.

In view of this evidence, the recent upgrade included a parametrization (referred to as UWNL) of non-local stresses very similar to that proposed by Brown and Grant (1997). From $z = 0.1z_i$ to $z = z_i$ (where z_i is the boundary-layer depth) they are written

$$\left(\tau_x^{NL}, \tau_y^{NL}\right) = \left[\frac{\rho}{\rho_s}\right]\left[\frac{2.7w_*^3}{(u_*^3 + 0.6w_*^3)}\right]\left[\left(\frac{z'}{z_i'}\right)\left(1 - \frac{z'}{z_i'}\right)^2\right](\tau_{xs}, \tau_{ys}), \tag{5}$$

where ρ_s is the density at the surface, w_* is the convective velocity scale, u_* is the friction velocity, $z' = z - 0.1z_i$, $z_i' = z_i - 0.1z_i$, and τ_{xs} and τ_{ys} are the surface stresses. The term involving u_* and w_* is as proposed by Brown and Grant (although note that their Table 3 contains a typographical error), and ensures that the non-local stress is zero in neutral conditions but asymptotes to a stability-independent fraction of surface stress in convective conditions. The shape function has been modified slightly from that proposed by Brown and Grant, as they used $z' = z$ and $z_i' = z_i$ and applied non-local stresses from the surface to z_i. Here we apply non-local stresses only between $0.1z_i$ and z_i. The motivation for this change was to ensure that the match to surface-layer similarity was maintained below $0.1z_i$ (although separate tests suggested that the impact of this change is small).

3 Testing Strategy and Operational Model Upgrade

The boundary-layer changes (SHARP_SEA, UWNL) proposed for operational implementation were first tested individually, and then together (SHARP_SEA+UWNL), in 10 case study (forecast only to 6 days) tests at N216 resolution (longitudinal spacing of 0.83° and latitudinal spacing of 0.56°). These tests used 38 vertical levels, with 12 levels in the bottom 2 km (lowest level at 10 m for wind and 20 m for heat and moisture) and the model top at 39 km. Five of the cases were in the period December 2003–February 2004, referred to as DJF, and 5 in the period June–September 2003, referred to as JJAS. The dates chosen were all at least two weeks apart in order that they were synoptically independent of one another.

For further testing, as is common practice in operational model upgrades, these changes were packaged together with other changes (which themselves had also been tested individually in case studies). The combination of all the changes will be referred to as PACKAGE, and consists of UWNL, SHARP_SEA plus:

- Changes to the surface scalar transfer over the sea to bring its dependence of wind speed more in line with recent observations. At the same time, the effects of salinity in reducing the saturation vapour pressure (previously neglected in the model) have been included. Details are given in Edwards (2007).
- Changes to the convection parametrization, including the adoption of a new detrainment formulation resulting in a smoother decay of convective mass flux with height.

Trials of PACKAGE were run for a summer and winter month using 4D-Var data assimilation (Rawlins et al. 2007). These tests used the operational resolution: N320 (longitudinal spacing of 0.56° and latitudinal spacing of 0.38°) and a vertical grid as that used in the case studies in the troposphere, but with an extra 12 levels taking the model top to 63 km. Finally PACKAGE ran in a parallel suite (N320 4D-Var) for a month, prior to its becoming the operational suite on 14 March 2006.

The surface transfer and convection changes had some important beneficial impacts in the tropics. However they will be reported separately and are not the focus of this paper, which concentrates on the impact of the boundary-layer changes. To isolate these, a number of results will be shown from the clean case study tests of these changes. Results will also be shown from the 4D-Var trials and operational verification statistics where changes can be clearly ascribed to the introduction of SHARP_SEA and UWNL.

4 Results

The primary aim is to show that the boundary-layer parametrization changes have led to the expected improvements of the response of the near-surface winds to stability changes. However, the wind changes in turn lead to surface stress changes, and hence potentially impact on the atmospheric angular momentum budget. For this reason, Section 4.1 first looks at the size of the stress changes and for evidence of impacts on large-scale evolution. Sections 4.2 and 4.3 then examine the impacts of the boundary-layer changes on the near-surface winds over land and sea.

4.1 Effects on Surface Stress and Large-Scale Evolution

Figure 1 shows the impact of some of the parametrization changes on the zonally averaged zonal component of boundary-layer surface stress ($\langle \tau_{xs} \rangle$) after 24 h, averaged across the 5

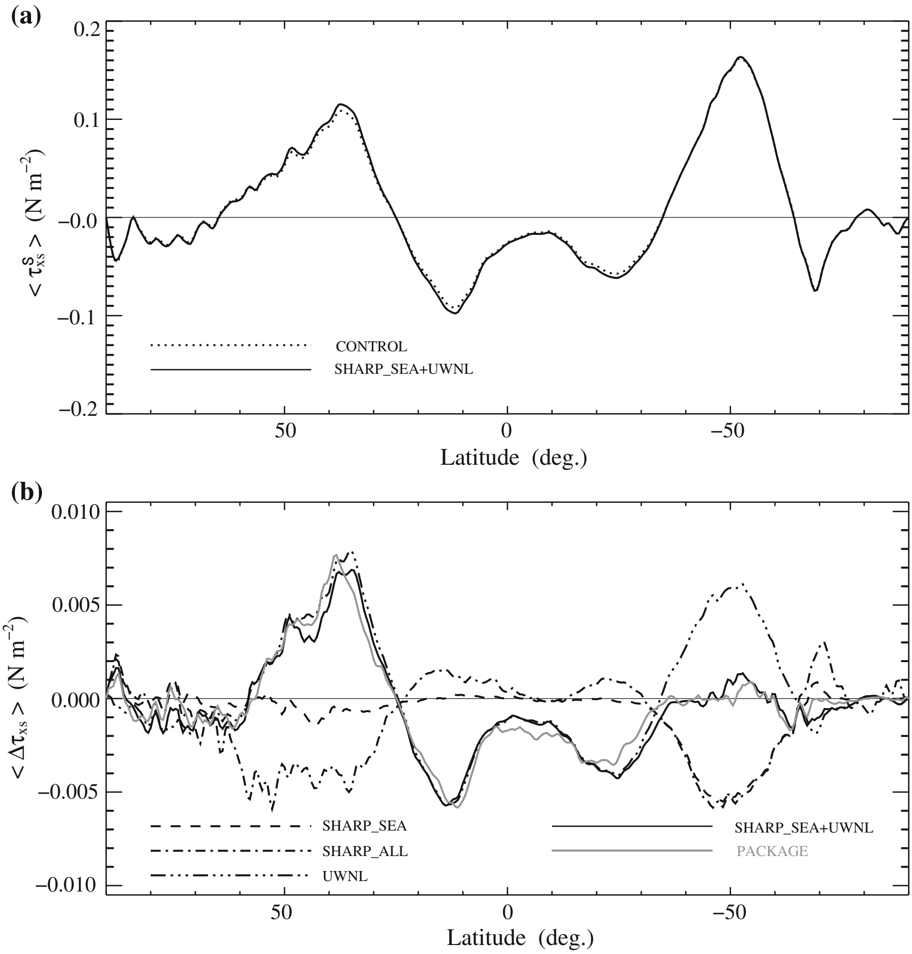


Fig. 1 Zonally-averaged zonal component of boundary-layer surface stress in 24 h forecasts valid at 1200 UTC, averaged over 5 DJF cases, as a function of latitude. (**a**) Full fields; (**b**) change from CONTROL. Note that the SHARP_SEA and SHARP_ALL results are almost identical at mid-latitudes in the Southern Hemisphere

DJF cases. The full fields (Fig. 1a) show that the changes between SHARP_SEA+UWNL and CONTROL are relatively small, although in the Northern Hemisphere (NH) and tropics (TROP) the magnitudes are systematically increased. To show the impact more clearly, Fig. 1b shows the changes ($\langle \Delta\tau_{xs} \rangle$) relative to CONTROL. SHARP_SEA+UWNL gives positive values (of up to 0.008 N m^{-2}) in Northern Hemisphere mid-latitudes, and negative values in TROP. In both regions these changes amount to an approximately 7% increase in the magnitude of $\langle \tau_{xs} \rangle$.

In order to understand these changes, Fig. 1b also shows changes relative to CONTROL seen in the separate tests of the individual components, SHARP_SEA and UWNL. The SHARP_SEA+UWNL stress changes are close to being a linear superposition of the SHARP_SEA and UWNL ones (and the PACKAGE results are very similar, implying that the surface transfer and convection changes in PACKAGE have relatively little impact on this statistic). UWNL is the dominant contributor in the Northern Hemisphere and TROP (although there is a small loss from SHARP_SEA in the Northern Hemisphere). Note that the Northern Hemisphere changes in zonal mean stress are dominated by changes in stress over the sea, even at latitudes where the land fraction is high. This is because the boundary layer over land in winter is typically stable or only very weakly unstable and so UWNL has little impact over land. In the Southern Hemisphere from around 40–60°S, it can be seen that the approximately zero values of $\langle \Delta \tau_{xs} \rangle$) from SHARP_SEA+UWNL are in fact made up of non-zero opposing contributions from SHARP_SEA and UWNL, with the former decreasing and the latter increasing stress (each by around 4–5% of the CONTROL value).

Figure 2 is as Fig. 1, except showing results from the JJAS case studies. SHARP_SEA+UWNL here gives a small increase in the magnitude of $\langle \tau_{xs} \rangle$ at almost all latitudes, typically by between 3 and 5% in the Southern Hemisphere, by around 6% in the band of easterlies in TROP, and by around 7% (of relatively small CONTROL values) in the Northern Hemisphere. The Southern Hemisphere increase arises from the positive contribution from

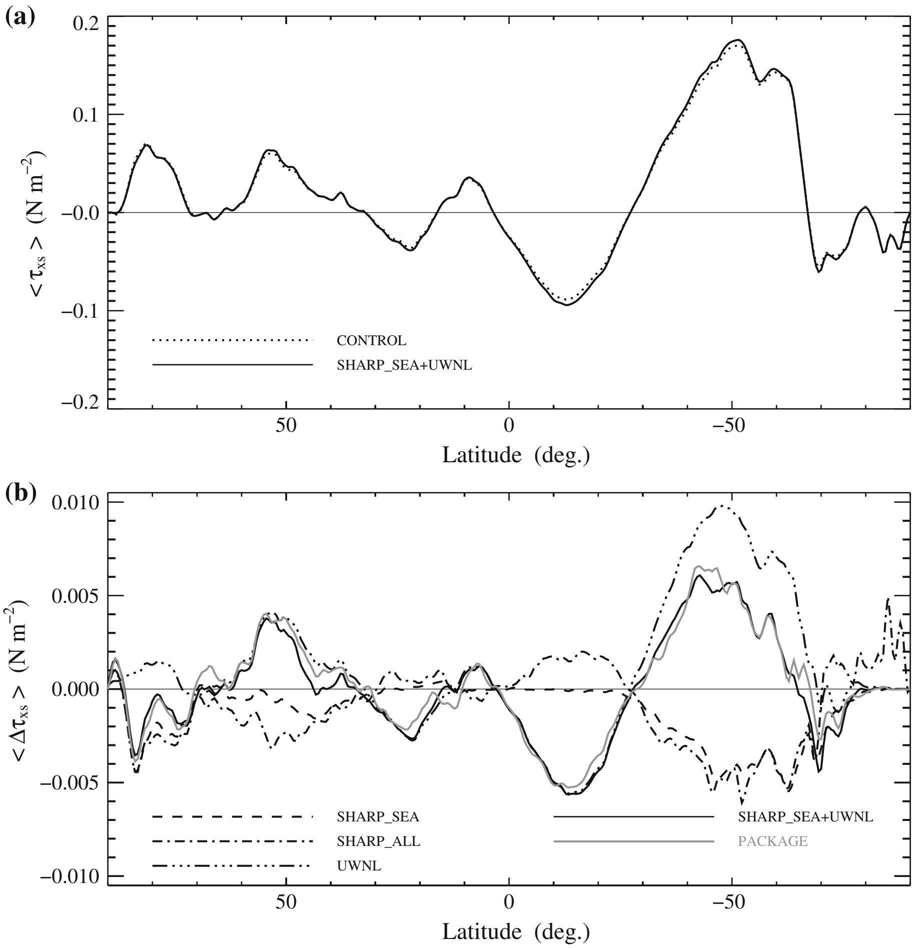


Fig. 2 As Fig. 1, except results averaged over 5 JJAS cases

UWNL outweighing the negative contribution from SHARP_SEA (as it also did, although still more clearly, in the Northern Hemisphere winter). In the Northern Hemisphere, the contributions from the stresses over sea are relatively small (although SHARP_SEA at least cancels out any increase from UWNL, as it also did in the Southern Hemisphere summer) and the positive values of $\langle \Delta\tau_{xs} \rangle$ arise primarily from the effects of UWNL over land. The increased impact of UWNL over land relative to that obtained in winter is consistent with a greater fraction of the stress coming from points with boundary layers unstable enough for the UWNL parametrization to have a significant impact. The PACKAGE results are again very similar to those from SHARP_SEA+UWNL.

As an aside, Figs. 1b and 2b also show $\langle \Delta\tau_{xs} \rangle$ obtained with SHARP_ALL in order to help understand whether any problems associated with the use of that parametrization are associated with a loss of stress. The use of this parametrization does indeed give much more negative values of $\langle \Delta\tau_{xs} \rangle$ in the Northern Hemisphere than obtained with SHARP_SEA (and positive values of $\langle \Delta\tau_{xs} \rangle$ are also seen in TROP). However, the decreases in stress magnitude are typically still comparable to or smaller than the increases brought about through UWNL. This suggests that loss of drag, at least in a zonal mean sense, is unlikely to lead to significantly degraded results with SHARP_ALL. However, the DJF case-study tests with SHARP_ALL showed the well-known temperature biases over land (cooling by 2–3 K over large areas by T+120), and hence this option was not pursued further in assimilation trials at this point.

Figure 3 shows the DJF and JJAS case study T+72 average differences in zonal mean zonal winds between CONTROL and analysis and between SHARP_SEA and CONTROL, UWNL and CONTROL, SHARP_SEA+UWNL and CONTROL. Again the SHARP_SEA+UWNL results are to a good approximation a linear summation of those from SHARP_SEA and UWNL, and they are consistent with the surface drag changes. In the DJF cases, the extra drag from UWNL leads to a general deceleration of the westerlies between 30 and 60°N (although only typically of 0.1–0.2 $\mathrm{m\,s^{-1}}$). Reference to the CONTROL to analysis differences suggests that this change is of mixed benefit. It should also be noted that comparison with Northern Hemisphere sondes generally suggests that the model winds are low (by around 0.4 $\mathrm{m\,s^{-1}}$) and that the changes slightly increase this discrepancy. However, the deceleration by UWNL of the low-level easterly flow in the tropics is clearly beneficial, and the deceleration of the westerlies at around 45°S is also largely good, particularly when considered in conjunction with the acceleration further south that is given by SHARP_SEA.

In the JJAS cases, UWNL gives a clearly beneficial westerly tendency at low levels centred on around 10°S. Further south, westerly tendencies (at all levels) at around 25 and 67°S and an easterly tendency in between are all very largely beneficial. SHARP_SEA also contributes some beneficial acceleration of the westerlies at around 60°S.

Changes in the zonal mean flow in the 4D-Var trials of PACKAGE also show consistent signals in the extra-tropics and at low-levels in the tropics. The impacts of PACKAGE on verification scores (for a range of standard statistics including pressure at mean sea level, heights, winds, temperatures and relative humidity at various pressure levels) versus both observations and analysis were found very largely to be positive, especially in the Northern Hemisphere summer trial. In this trial almost all scores in the Northern Hemisphere and Southern Hemisphere were improved to some extent, and large improvements were seen in many of the tropical scores. These will not be presented in detail as it is not possible to decouple the impacts of the boundary-layer changes on the verification scores from those of the other components of PACKAGE. However, given past difficulties with implementing boundary-layer changes of the sort discussed here, it is noteworthy that it is clearly possible to do so while still maintaining an acceptable large-scale evolution.

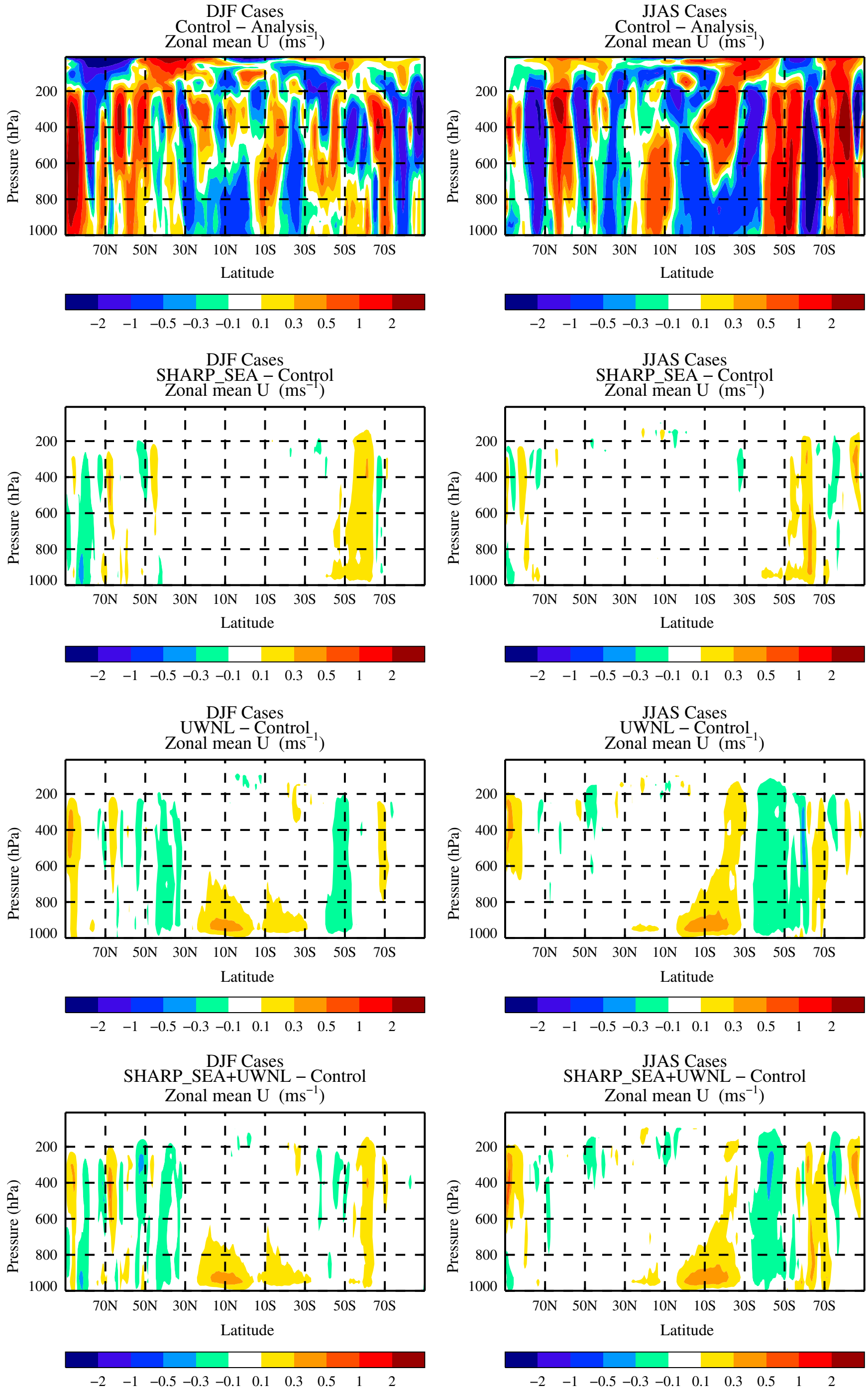


Fig. 3 Average zonal mean zonal wind differences at T+72 from case studies. Top row: CONTROL minus analysis; second row: SHARP_SEA minus CONTROL; third row: UWNL minus CONTROL; bottom row: SHARP_SEA+UWNL minus CONTROL. Left column: DJF: right: JJAS

While the 4D-VAR trials were not designed to give a breakdown of the impacts of the different parts of PACKAGE on the verification scores, month long (July) N216 trials using 3D-Var (Lorenc et al. 2000) were run for some of the separate components. One of these gave a clean test of the impact of UWNL. It showed the same mean wind improvements as seen in the case studies. UWNL also gave a 4% reduction in root-mean-square 850 hPa wind vector error at T+48 in the tropics, and reductions in root-mean-square error in pressure at mean sea level versus observations in the Southern Hemisphere (2% at T+48, increasing to 4% by T+96).

Analysis of energy spectra did not suggest that the drag changes were large enough to have a significant impact on the energy levels in the model. Some small reductions in the T+120 kinetic energy levels at 200 hPa at mid-latitudes in the winter hemisphere were noted. These slightly exacerbated an existing tendency for the model to lose energy relative to analysis in the Northern Hemisphere, but brought the forecasts in closer agreement with analysis in the Southern Hemisphere.

4.2 Surface Winds Over the Sea

Figure 4 shows an example from one of the case study tests of the impact in 24 h forecasts of the boundary-layer changes on the surface winds over the North Atlantic. The top panels show the pressure at mean sea level (PMSL), 10-m winds and surface buoyancy flux from CONTROL, in order to give an idea of the synoptic situation. A low pressure system is centred at around 34°W, 60°N. A cold front (visible as a marked change in wind direction) runs from some distance east of the low centre back towards Newfoundland, and a warm front is aligned approximately north-south at around 20°W. Between the two fronts the surface buoyancy flux is negative (i.e. a stable boundary layer) but elsewhere it is predominantly positive (i.e. an unstable boundary layer). The remaining panels show the impact (relative to CONTROL) of the parametrization changes on the 10-m wind direction (negative values indicating an anticlockwise turning i.e. a backing in the Northern Hemisphere) and speed. The results are very much as anticipated. The largest impacts of SHARP_SEA are in the warm sector, where reduced stable boundary-layer mixing leads to a systematic backing and slowing of the 10-m wind. Some acceleration is also seen ahead of the warm front and in a narrow strip to the east of Newfoundland, possibly related to changes in mixing in the inversion region above the unstable boundary layer or a non-linear response to changes elsewhere. Conversely, UWNL has little impact or no impact in the stable warm sector, but increases wind speeds (typically by around 5%) elsewhere (without having much impact on wind direction). The results obtained with SHARP_SEA+UWNL appear to a reasonable approximation to be a linear summation of those from UWNL and SHARP_SEA individually.

To quantify the surface wind changes the changes in wind speed and direction at sea points in various latitude bands were averaged over unstable and stable points from all 10 case studies. As an example, Table 1 shows the results for the 50°S–30°S and 30°N–50°N bands. Once again it can be seen that SHARP_SEA gives a deceleration and backing (a clockwise rotation in the Southern Hemisphere) in stable boundary layers, and that UWNL gives a speed increase in unstable boundary layers. The PACKAGE results (both in this Table and in Fig. 4) are close to being the sum of those from SHARP_SEA+UWNL. This confirms that it is these boundary-layer changes that dominate the surface wind changes (and not the surface transfer or convection changes).

In order to verify the effects of the changes, comparisons are made with surface wind data from QuikSCAT. For technical reasons, this can only be done with the operational forecast model, and so we have to compare results from before and after the operational upgrade.

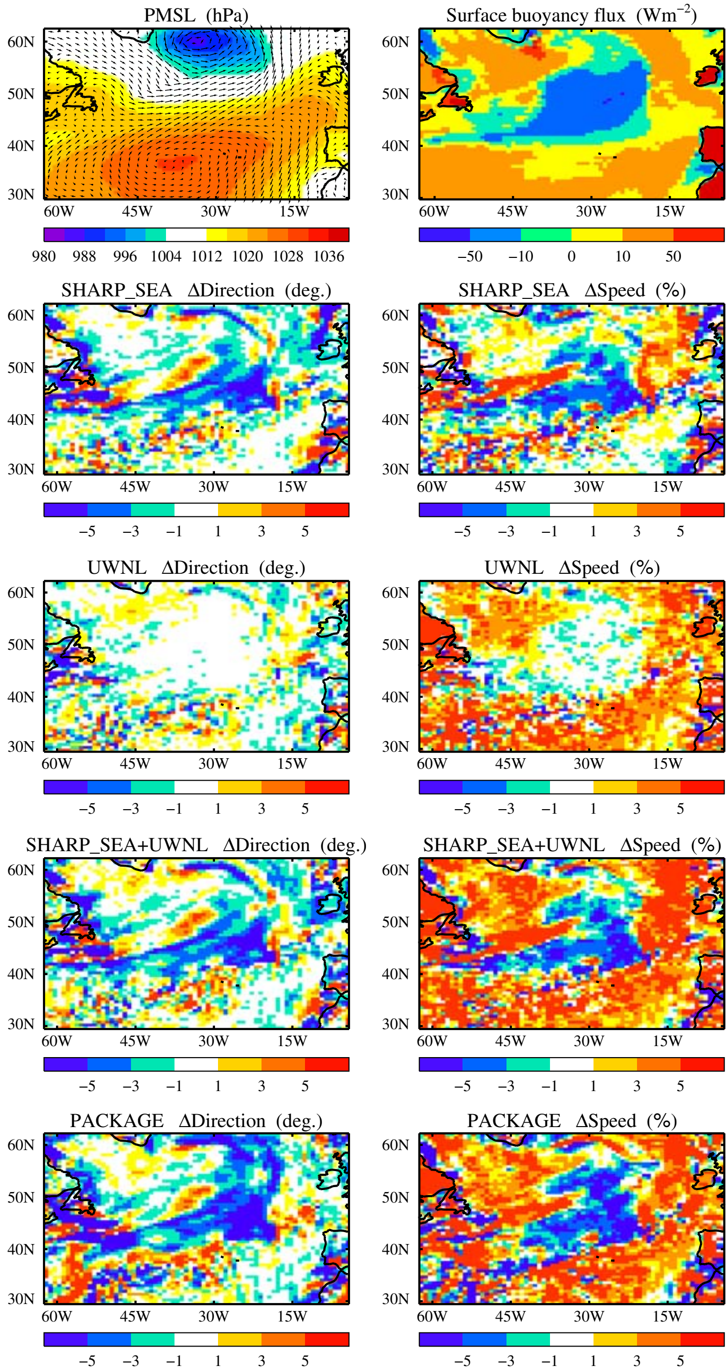


Fig. 4 Results from T+24 forecasts from 1200 UTC on 29 July 2003. Top row: CONTROL results for PMSL and 10-m winds (left) and surface buoyancy flux (right). The remaining rows show the changes in wind direction and speed relative to CONTROL from simulations with SHARP_SEA, UWNL, SHARP_SEA+UWNL and PACKAGE

Table 1 Average changes in T+24 10-m wind direction and speed relative to CONTROL from simulations with UWNL, SHARP_SEA, UWNL+SHARP_SEA and PACKAGE

	ΔDirection (°)				ΔSpeed (m s^{-1})			
	Unstable		Stable		Unstable		Stable	
	S	N	S	N	S	N	S	N
SHARP_SEA	+0.1	−0.1	+2.2	−2.7	+0.01	+0.03	−0.22	−0.17
UWNL	−0.1	+0.1	+0.1	−0.3	+0.24	+0.21	−0.03	−0.03
SHARP_SEA+UWNL	+0.0	+0.0	+2.4	−2.9	+0.25	+0.24	−0.26	−0.19
PACKAGE	+0.0	−0.1	+2.5	−3.2	+0.22	+0.22	−0.26	−0.22

The results have been averaged over all 10 cases studies and over all sea points in the 50°S–30°S latitude band (indicated by S) and in the 30°N–50°N band (indicated by N)

Although this is not a traditional 'clean' test (in which the same period is simulated with different formulations), as will be shown below, long-standing errors are clearly reduced, and in a way entirely consistent with the changes expected from the boundary-layer changes.

At the UK Met Office, surface wind data from QuikSCAT is extracted from the SeaWinds Scatterometer Real-Time BUFR Geophysical Data Product. Pre-processing is applied (e.g. to select only observations in the instrument's sweet zone, and to exclude data likely to be contaminated by land, sea-ice or rain). A variational technique (Candy 2001) is then used to select which of the four possible QuikSCAT wind vectors to use. Figure 5 shows time series of daily average differences over two latitude bands between the resulting QuikSCAT wind directions and the global model background. Separate averages have been made over cases for which the observed wind was within 60° of northerly and southerly. Similar results were obtained when the split into northerly and southerly categories was made on the basis of the modelled (rather than of the observed) wind. This confirms that the differences seen between the northerly and southerly results are not an artefact of the method of sampling.

Prior to the operational upgrade, significant direction errors were seen for the wind direction that will typically be associated with warm advection—northerly winds in the Southern Hemisphere, and for southerly winds in the Northern Hemisphere. This error is entirely consistent with the errors previously found in both the UK Met Office and ECMWF models in the Northern Hemisphere winter (Brown et al. 2005). Here it can additionally be seen that there is an annual cycle in the magnitude of the error, with the largest errors occurring in the summer hemisphere. In contrast, the average errors for the wind direction associated with cold advection (southerly in the Southern Hemisphere, northerly in the Northern Hemisphere) are small.

On the operational implementation of PACKAGE, Fig. 5a shows that an immediate reduction was seen in the magnitude of the average error for northerly winds in the 50°S–30°S band (with little or no change in the already small error for southerly winds). A reduction in the error for southerly winds in the 30°N–30°N band also occurred (Fig. 5b), although the Northern Hemisphere improvement is most apparent when the 2006 Q3 results are compared with those obtained in 2005 Q3 (when the errors were largest). Consistent with the Southern Hemisphere results, the errors for the cold advection wind direction (in this case northerly) remained small.

These improvements are pleasing, and consistent with what could be expected based on the case study tests. As previously noted, these indicate that the direction changes in PACKAGE are almost entirely due to the effects of SHARP_SEA on the surface wind direction in stable boundary layers. Stable boundary layers account for only a low ($\lesssim$20) percentage

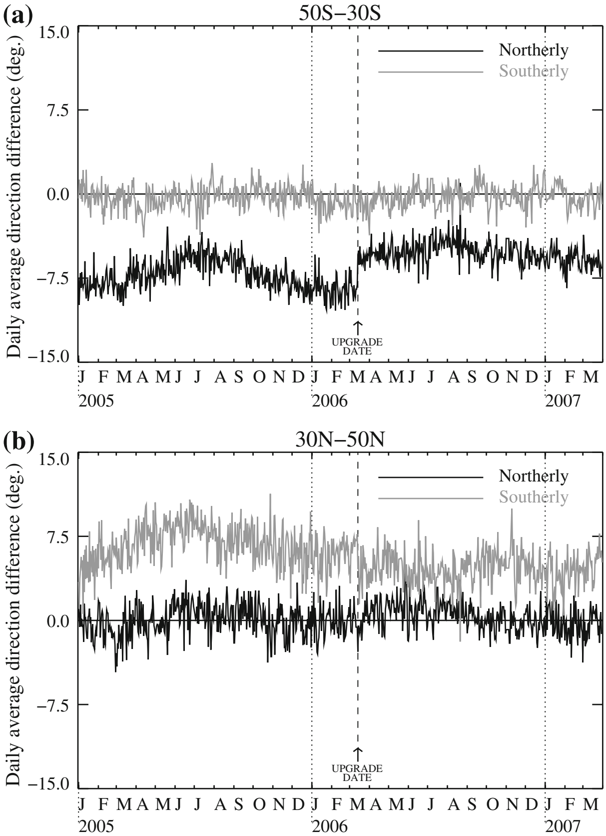
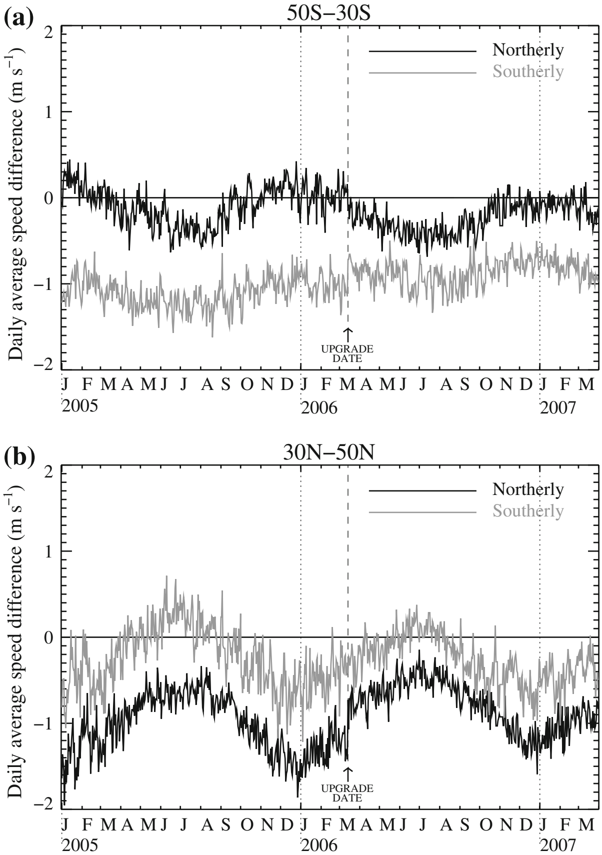


Fig. 5 Difference between global model background and QuikSCAT observed wind direction for cases with observed wind direction within 60° of northerly and southerly. (**a**) Daily averages over the 50°S–30°S latitude band; (**b**) daily averages over the 30°N–50°N latitude band. The dashed vertical line indicates the date of the operational upgrade

of points in the cold advection wind direction categories, and hence the small impact of PACKAGE on wind direction seen in Fig. 5. The warm advection categories are typically 60–70% stable, and therefore show a much bigger impact (although the percentage in the Northern Hemisphere winter drops to around 50, consistent with the smaller impact seen immediately after implementation there).

Figure 6 shows time series of daily average differences between the global model background and the observed QuikSCAT wind speed. Looking first at the pre-upgrade results, there was clearly a tendency for the model to be biased low relative to the QuikSCAT product (especially in the winter hemisphere). Similar behaviour has also been noted for the ECMWF model (Chelton and Freilich 2005). These biases may have been brought about by problems with the QuikSCAT product and or by problems with the model. However, the biases can be seen to be very different in northerly and southerly wind conditions, with much larger negative biases in the conditions associated with warm advection. Again, this is consistent with the results of the ECMWF model. Brown et al. (2006) previously noted that there was no strong dependency on atmospheric stratification in the biases between QuikSCAT and buoy observations. This strongly suggests that, irrespective of any other problems, the differing model biases relative to QuikSCAT in conditions associated with warm and cold advection were indicative of a problem with the response of the model to changing stability.

Fig. 6 Difference between global model background and QuikSCAT observed wind speed for cases with observed wind direction within 60° of northerly and southerly. (**a**) Daily averages over the 50°S–30°S latitude band; (**b**) daily averages over the 30°N–50°N latitude band. The dashed vertical line indicates the date of the operational upgrade



Encouragingly, on operational implementation of PACKAGE, the differences between the magnitudes of the biases in the different advection categories were reduced (although certainly not eliminated). The most marked changes were in the cold advection categories (southerly in the Southern Hemisphere, northerly in the Northern Hemisphere), where the boundary layer are very largely unstable, and UWNL gives a speed increase. In the warm advection categories, the average signals are smaller, as decelerations caused by SHARP_SEA in the stable boundary layer are largely cancelled by accelerations caused by UWNL in the convective boundary layer. On average there is a suggestion of a small deceleration (which further reduces the differences between the biases in the two categories).

As an aside, the operational model actually applies a bias correction (not used in Figure 6) to the QuikSCAT winds, which reduces the winds particularly at high wind speeds (Keogh and Offiler 2006). Although this was developed partly through examination of model to QuikSCAT differences (an approach which, on its own, would lead to a rather circular argument if these corrected winds were then used to evaluate model speed errors), some support was also found from QuikSCAT to fixed platform comparisons. Relative to these corrected winds, the biases (not shown) show much less of an annual cycle, and the model cold and warm advection category winds are biased slow and fast respectively. The changes obtained on implementation of PACKAGE in these two categories (acceleration and deceleration respectively) then both appear individually beneficial.

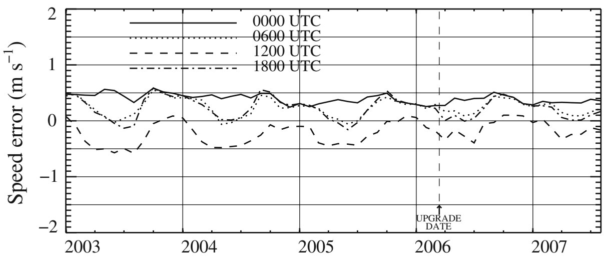


Fig. 7 Time series of monthly averaged 10-m wind speed biases over Europe at T+12. The dashed vertical line indicates the date of the operational upgrade

One minor problem associated with the use of SHARP_SEA should be acknowledged. Although the boundary-layer scheme uses an implicit solver, the diffusion coefficients are calculated explicitly. Over-weighting is used to help retain numerical stability, but the introduction of the stability function that changes more rapidly with stability has made the model more prone to developing spurious two-timestep oscillations in the stable boundary layer. However, tests of a new boundary-layer solver (Wood et al. 2007) suggest that it can remove this instability without otherwise degrading the results.

4.3 Surface Winds Over Land

Figure 7 shows a time series of monthly-averaged bias in 10-m wind speed over Europe at T+12 (similar results are found at other forecast ranges). The results are consistent with past experience with the Met Office and ECMWF models (Brown et al. 2006), with a fast bias of around 0.4 m s^{-1} (giving errors of around 8% of the mean speed in winter, rising to 15% in summer) at night (0000 UTC). By day (1200 UTC), the errors are small in winter, but there is a slow bias in summer. For summers 2003–2005 this reached around 0.5 m s^{-1} (or 10% of the mean wind speed). The summer 2006 and 2007 results, after the implementation of PACKAGE, are a little improved, with the April to August average slow bias reduced to around 0.25 m s^{-1}. Similar accelerations relative to previous summers (of around 5% of the mean value) were seen in daytime wind speeds over Asia and North America. These speed increases are consistent with those that were seen in the case study tests. However, it is worth noting that idealized tests (Brown and Grant 1997; Brown et al. 2006) suggested that implementation of UWNL might be expected to give 10% increases in 10-m wind speed in convective conditions. If such a speed-up had been achieved, the annual cycle in daytime wind biases over Europe would have been almost eliminated (rather than just reduced). The reason that it has not requires further investigation.

As an aside, the case study tests suggest that implementation of SHARP_ALL would significantly reduce the wind speed biases seen by night, with a typical deceleration of 0.2 m s^{-1} seen at stable points. The wind turning across the boundary layer is also increased (by an average of around 4° in the summer cases and 6° in the winter ones). These changes would also reduce the model biases. However, as noted previously, this option was not implemented operationally due to problems with increased temperature biases.

5 Conclusions

This paper has documented changes that were recently made to the boundary-layer scheme in the UK Met Office global operational NWP model. They have contributed to a considerable improvement in operational verification scores that was obtained when they were implemented along with a number of convection changes (to be described separately). It has also been possible to show the expected changes in near surface winds arising from more efficient turbulent mixing in convective conditions, and, over the sea, decreased mixing in stable conditions. These changes have significantly reduced long-standing model errors with respect to observations.

The focus has been on the operational global NWP model. However, it is worth noting that, consistent with the spirit of having a unified model, parallel changes have recently been made to the regional NWP model and also to the latest version of the Met Office Hadley Centre climate model (HadGEM2) that builds on the HadGEM model documented in Martin et al. (2006). All three models now use UWNL (over land and sea), the revised marine surface exchange formulation and the sharp function over the sea. However there are differences in the stability function over land. As previously noted, the global NWP model still uses the long-tails function, while the regional NWP model uses a blend between the long-tails function near the surface and sharp higher up, and the climate model uses the sharp function everywhere. The reason why the climate model has been able to use sharp over land (while the NWP model and other climate models often need more enhanced mixing) is not clear, but may reflect differences in other errors (e.g. in cloud cover). In fact, some signs of a cold bias over winter land are apparent.

Clearly further work is still required on stable boundary-layer mixing over land. Over the sea, further attention to the stable boundary-layer representation would also seem to be justified because, while the switch to SHARP_SEA significantly reduced the errors with respect to QuikSCAT, it did not completely eliminate them. One possibility is to investigate the effects of adopting a stability dependent Prandtl number. Testing of a new higher resolution sea-surface temperature analysis is also planned. Its use is likely to lead to the formation of boundary layers that are more stable (with associated implications for the surface wind strength and direction) when warm air advects across better resolved sea-surface temperature gradients. In weakly convective warm advection conditions, the issue of whether the modelled boundary layer is typically too deep (as speculated by Brown et al. 2006) is worthy of further investigation. Finally, while the introduction of non-local momentum mixing has clearly been beneficial, it would seem to be appropriate to carry out a review of whether the specific implementation is optimal.

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