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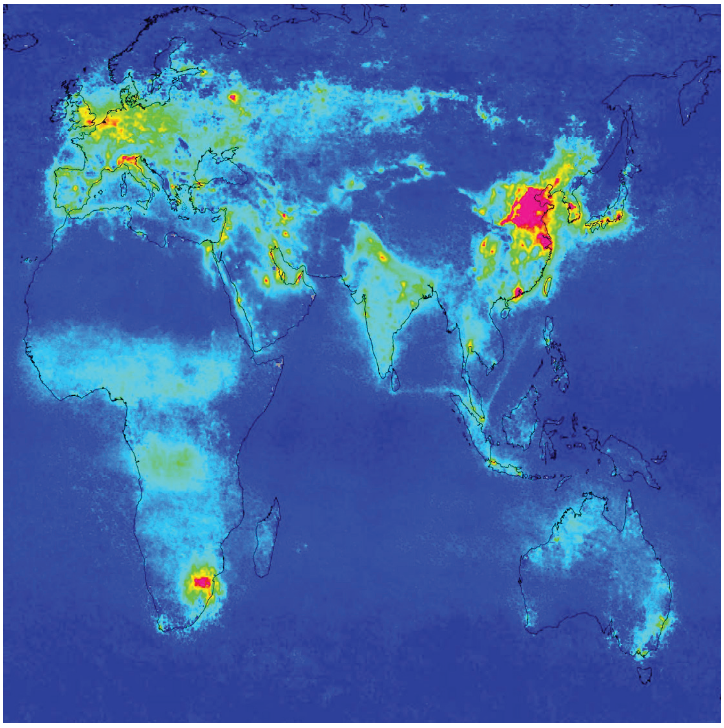
METEOROLOGY

Improving the representation of stable boundary layers



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Improving the representation of stable boundary layers

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High-quality near-surface wind forecasts are particularly valuable for wind energy applications. As more and more forecast users are becoming interested in providing services for such applications, considerable efforts were made in the past three years to improve the representation of stable boundary layers in the ECMWF forecasts. The forecast errors in such conditions, encountered typically over land during night or in winter time, are among the most systematic and longstanding errors of global weather forecasts. The representation of the wind is perhaps the most problematic in terms of both wind speed and wind direction in the first hundreds of metres above the surface.

A revision of the parametrization of turbulent diffusion (or vertical mixing) in stable conditions was recently implemented in cycle 40r1 (November 2013) of the Integrated Forecasting System (IFS). This revision has been combined with changes to the representation of surface drag (or friction) in regions with orography and to the strength of the heat exchange between the land surface and the atmosphere. This set of changes improves the forecasts of near-surface winds in stable boundary layers, but also leads to better forecasts of the large-scale circulation patterns during autumn and winter in the northern hemisphere.

Background

In the framework of GEWEX Atmospheric Boundary Layer Studies (GABLS, *Holtslag et al*., 2013) it has been demonstrated that most operational global NWP models are less skilful in representing the key features of stably stratified boundary layers than limited area or research models. In global NWP forecasts:

- Stable boundary layers are often too deep.
- Low-level jets are too weak and located too high above the surface.
- Near-surface ageostrophic wind angles are too small, so that the wind turning between the surface and the boundary layer top is underestimated.

The cause of these errors is well-known: most of them stem from the fact that the operational NWP models in question use turbulence schemes which maintain more turbulent diffusion in stable conditions than justified by observations or very high resolution simulations. To date, the turbulent diffusion in stable conditions is still excessive to various degrees in world-leading operational weather forecasting systems such as those run by ECMWF, Met Office, National Centers for Environmental Prediction (NCEP) and Japan Meteorological Agency (JMA). It is often argued that the artificial enhancement of the mixing in stable conditions is needed to account for contributions to vertical mixing associated with surface heterogeneity, gravity-waves and mesoscale variability which are not explicitly represented in models. But it is difficult to estimate by how much the mixing in stable conditions should be enhanced.

In theory, reducing the degree of mixing should lead to better forecasts of the key features of stable boundary layers. However, in practice it is difficult to make such a change in a global NWP model. At ECMWF, all previous attempts to use a less diffusive turbulence scheme in stable conditions have been unsuccessful. Back in the 1990s, scientists at ECMWF showed that maintaining more mixing in stable conditions represents an effective way of (a) reducing the cold near-surface temperature biases that are frequently encountered in stable boundary layers and (b) improving the representation of synoptic cyclones (*Beljaars & Viterbo*, 1998; *Viterbo et al*., 1999). At that time, artificially enhancing the diffusion appeared to be the best compromise for improving the quality of medium-range weather forecasts. Thereafter, attempts were made to get back to mixing levels which are closer to observational evidence and would allow a better representation of stable boundary layers. Unfortunately, such attempts were not successful because they degraded the large-scale performance of the forecasts, especially in the northern hemisphere in winter (*Brown et al*., 2005).

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The way forward

A detailed investigation was conducted in 2011/2012 at ECMWF (*Sandu et al*., 2013) in order to understand whether artificially enhancing the diffusion is still necessary, despite the numerous model improvements and increase in resolution that have occurred in recent years. The study explored the effects of reducing the mixing in stable conditions on the quality of the forecasts produced with the latest version of the IFS.

It was demonstrated that reducing the mixing in stable conditions improves, as expected, the quality of the wind forecasts in stable boundary layers. But, at the same time, it deteriorates to some extent the prediction of near-surface temperatures. Perhaps even more importantly, it also impacts on the atmospheric flow by leading to deeper low pressure systems and stronger high pressure systems. These effects were apparent both at the scale of individual synoptic cyclones and anticyclones and in the mean state. This implies that reducing the diffusion in stable layers near the surface has a direct effect on the amplitude of the stationary planetary-scale waves. For some regions and seasons these effects are detrimental for the quality of the forecasts. The most important drawbacks are similar to those found with previous attempts to reduce the mixing in stable conditions: a deterioration of the geopotential height scores during winter in the northern hemisphere and an increase of the near-surface night-time cold biases, especially over Europe and North America.

The boundary layer winds, which arguably depend primarily on the representation of turbulence, thus benefit from reduced mixing in stable conditions, while other features (e.g. the large-scale flow and the 2-metre temperatures) sometimes deteriorate. This suggests that excessive mixing is still needed in stable situations, as it has been for more than 20 years, to compensate for errors in other processes that play a role in the evolution of the large-scale flow and 2-metre temperatures. Therefore, a less diffusive turbulence scheme for stable conditions can still not be implemented as a stand-alone change in the IFS.

Sandu et al. (2013) also explored possible strategies for mitigating the detrimental impacts of reducing the turbulent diffusion in stable conditions to more realistic levels. It was found that (a) adjusting the strength of the drag over orography can help improve the representation of the large-scale flow and (b) adjusting the strength of the land-atmosphere heat exchange can be used to compensate for the near-surface cooling induced by reducing the diffusion in stable conditions. These processes are among the most uncertain processes that need to be parameterized at current resolutions, with observational evidence being scarce.

Turbulent diffusion in a nutshell

A

SA first order local turbulence closure is used in the IFS to parametrize the diffusion in stable layers. Such layers are found close to the surface in stable boundary layers and in most parts of the free-troposphere.

For each stable layer, the flux $F\varphi$ of a quantity ϕ (temperature, moisture or wind) is parametrized with a K-di usion approach:

$$F_\varphi = K\frac{\partial\varphi}{\partial z}$$

The diffusion coefficients K are proportional to the wind shear across the layer, a mixing length scale l and an empirical function depending on stability through the Richardson Number R_i:

$$K = \left|\frac{\partial u}{\partial z}\right| l^2 f(R_i)$$

The mixing length l is proportional to the height above the surface when the stable layer is in vicinity of the surface, and is bounded by an asymptotic value in stable layers situated far away from the surface. Two types of empiric stability functions of $f(R_i)$ are used in atmospheric models:

- Long tail functions, which maintain a certain degree of mixing in very stable layers with $R_i > 1$.
- Short tail functions, for which there is virtually no mixing in such layers.

The CTL and NEW diffusion closures are summarized below.

Up to Cy38r2

- Asymptotic mixing length: 150 m.
- Long tail function close to the surface and short tail functions far away from the surface.
- The shear consists of resolved shear and subgrid shear, parametrized as a height dependent term with a maximum around 850 hPa.

From Cy40r1

- Asymptotic mixing length: 10% of the boundary layer height in stable boundary layers; 30 m in free-shear layers.
- Long tail functions in all stable layers.
- Only resolved shear is considered.

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The changes to the forecasting system

An optimal set of changes to the IFS was found which combines a revision of the turbulence closure (see Box A) with an increase in the drag over orography and a strengthening of the land-atmosphere heat exchange for forested areas. The revised turbulence closure leads to less diffusion in stable boundary layers and in the inversions layers capping boundary layers situated around 850 hPa, while not changing too much the diffusion above this level.

These combined changes were tested for a six month period (January to March and June to August 2012) in a T511 configuration (grid spacing of 39 km) with 137 levels in analysis mode. This means 10-day forecasts were initialized daily at 00 UTC from their own analysis (i.e. analysis performed with the same version of the forecasting system). Hereafter, we will focus on either the June to August or the January to March results of the control (CTL) and of the NEW T511 experiments, depending on which ones are more relevant for the features we want to highlight. Shorter experiments performed at T1279 (grid spacing of 15.6 km) confirmed that the impact of these changes is consistent across resolutions.

Impacts on near-surface winds

In the northern hemisphere the wind generally turns clockwise with height throughout the boundary layer; the opposite being true for the southern hemisphere. In the IFS, the modelled surface wind directions are generally rotated clockwise with respect to surface observations in the northern hemisphere, while in the southern hemisphere they are rotated anticlockwise (*Brown et al*., 2005, Figure 1 and Figure 2a). The model therefore underestimates the wind turning within the boundary layer. These biases are increasingly pronounced in stable conditions (*Brown et al*., 2005), where they are amplified by the too strong mixing maintained in such conditions. The bias of the near-surface wind direction predicted for night-time over land clearly illustrates the systematic nature of these biases in stable boundary layers. Indeed, this bias varied only a little over the past 20 years with values ranging between 15° and 10° (Figure 1).

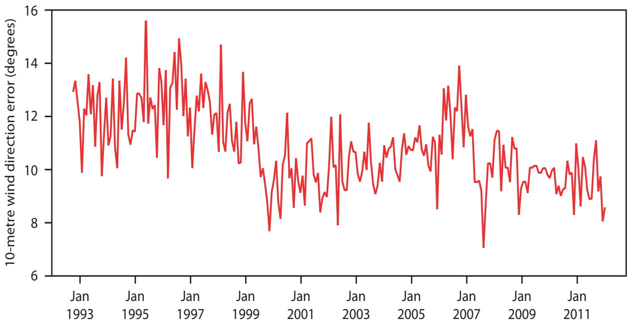

Figure 1 Historic evolution of 10-m wind direction errors of the IFS. These are monthly values of mean errors at a lead time of 60 hours of the daily forecasts initialized at 12 UTC (verifying time 00 UTC). The verification includes 800 SYNOP stations over Europe (30°–72°N, 22°W–42°E).

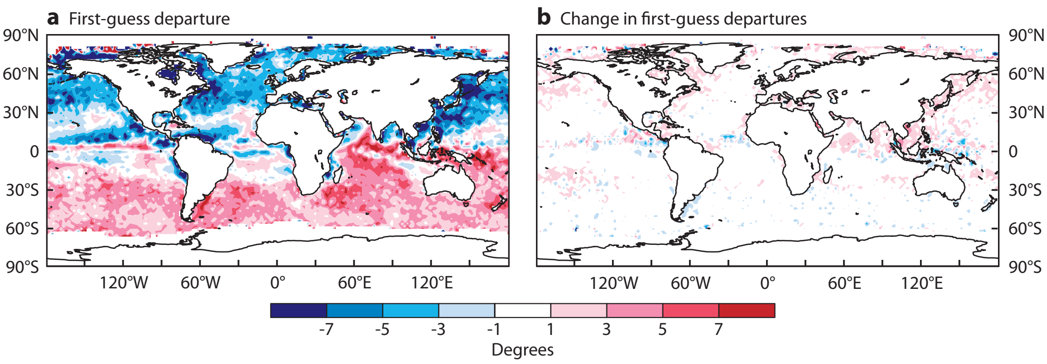

Figure 2 (a) Mean first-guess departure (observations minus model) of wind direction at the surface (degrees) with respect to ASCAT scatterometer observations in the CTL analysis run and (b) the mean change in these first-guess departures in the NEW experiment with respect to the CTL. These quantities represent the average over the 00 and 12 UTC analyses. Results shown here are for June to August when the stable regions over the oceans are more extended than in January to March.

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The revision of the turbulence closure significantly reduces these biases in wind direction. Thus, the wind direction bias at the surface, which approaches 10° over Europe for night-time conditions in the CTL experiments, is reduced on average by 3° in winter and by 1° in summer in the NEW experiments. A similar positive impact can be seen for oceanic regions where stable boundary layers prevail (i.e. where warm air is advected over a cold sea surface). This is inferred from the first-guess departures with respect to scatterometer observations of the wind direction at the surface. In the NEW experiments these first-guess departures are reduced in both hemispheres with respect to the CTL runs (Figure 2b) over the regions where the boundary layer is stably stratified.

The revision of the turbulence closure also diminishes the longstanding biases in near-surface wind speeds. To evaluate the impact of these model changes on the near-surface winds, model results from the CTL and NEW experiments were compared with observations obtained at three sites with differing characteristics: Cabauw (open pasture), Hamburg (urban area) and Falkenberg (rural landscape, open pasture around the site, forest patches in the surroundings). The data was kindly provided by KNMI (Netherlands), University of Hamburg and DWD (Germany).

The observed wind speeds have at night a minimum at 10 m and a maximum at approximately 200 m. This maximum, also known as the nocturnal low-level jet, is a distinct feature of stable boundary layers. In the CTL experiment the model underestimates the wind speed at night in the upper part of the boundary layer. Therefore the amplitude of the diurnal cycle of the wind speed at these levels is too small (Figure 3). The reason is that the strong mixing applied in stable conditions has a tendency to smear out the nocturnal low-level jet by excessively transporting momentum towards the surface. As expected, the low-level jets are strengthened when the turbulent diffusion in stable boundary layers is reduced in the NEW experiment. The improvement in the upper part of stable boundary layers can be seen in terms of both the mean wind speed and root-mean-square error (Figure 4).

At 10 m, the model appears to reproduce well the mean wind speed at night but to underestimate it during daytime at the towers situated in the countryside (Cabauw and Falkenberg); for Hamburg, which is in a strongly urbanized area, it is the opposite. This points to uncertainties in the representation of the roughness length for momentum, which may not be representative of the respective sites.

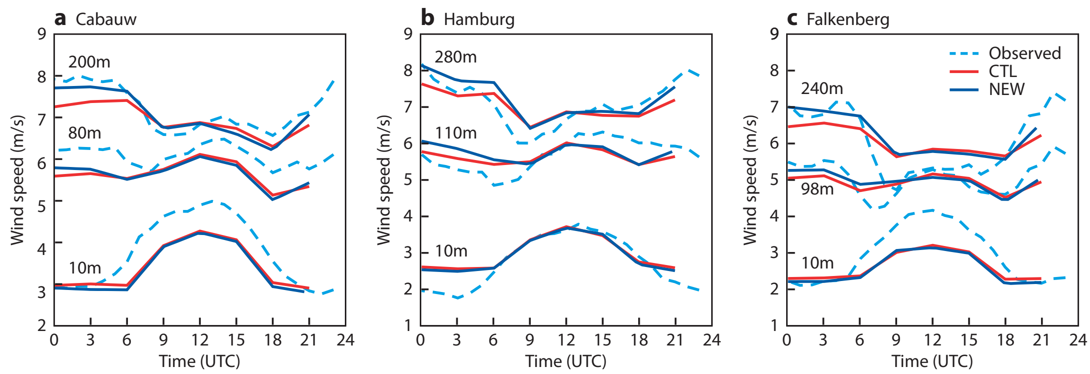

Figure 3 Averaged diurnal cycle of wind at (a) Cabauw, (b) Hamburg and (c) Falkenberg from forecasts produced in the CTL and NEW experiments (lead times 24 to 42 hours) compared to observations. Note that for Falkenberg the jump around 100 metres is due to the data below 100 metres coming from tower measurements and above 80 metres from sodar. Results are shown for June to August when the diurnal cycles are the most pronounced.

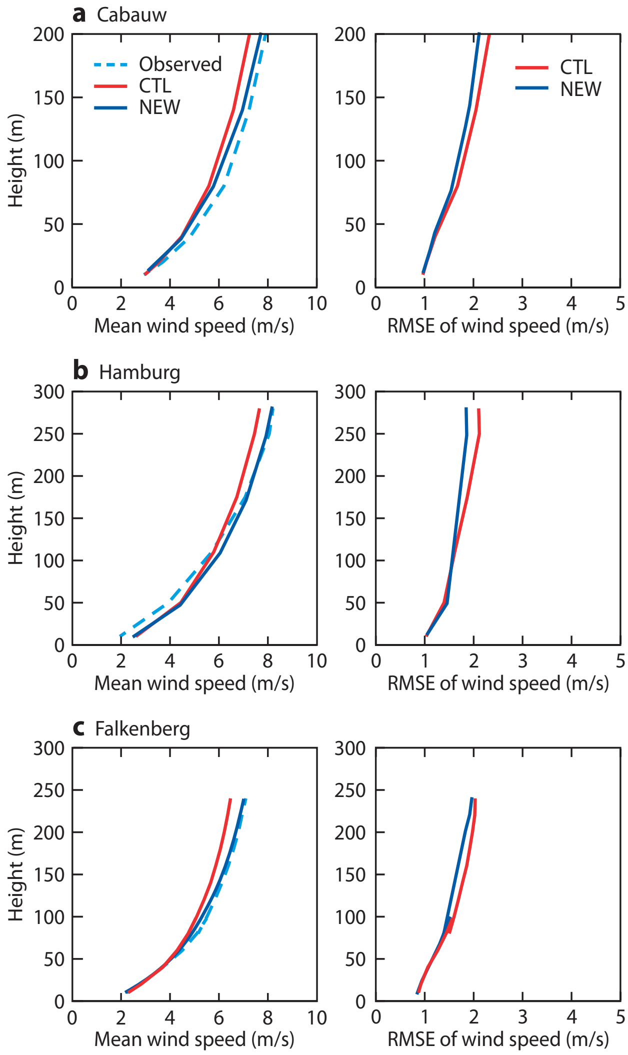

Figure 4 Mean wind speed (left) and root-mean-square error (RMSE) of wind speed (right) from forecasts produced in the CTL and NEW experiments with respect to the observations from the towers at (a) Cabauw, (b) Hamburg and (c) Falkenberg. The modelled profiles correspond to lead time 24 hours of the daily 00 UTC forecasts (verifying at 00 UTC). Results are shown for June to August when the low-level jets are the most pronounced. Note that for Falkenberg the jump around 100 m is because the data below 100 m comes from tower measurements and above 80 m from sodar.

Impacts on near-surface temperatures

Near-surface temperature cold biases are often found in stable boundary layers that typically occur over land at night or in winter (Figure 5a). They may result from errors in the representation of various processes, such as energy exchange between the land and the atmosphere, radiative loss at the surface, turbulent diffusion, horizontal advection or clouds. Nevertheless, these biases are very sensitive to the degree of turbulent diffusion in stable conditions. Indeed, less diffusion means the cooling due to the radiative loss at the surface is distributed in a shallower layer, so there is a drop in near-surface temperature and the existing cold biases increase. This was one of the main factors that have prevented the reduction of the turbulent diffusion in stable conditions in the past.

The revised turbulence closure leads as well to a cooling at the surface. However, the magnitude of this cooling is modulated by the dependence of the diffusion coefficients on the stability of the boundary layer (through the new formulation of the asymptotic mixing length described in Box A). Consequently, the induced cooling is more pronounced in strongly (hence shallower) boundary layers than in weakly stable (hence deeper) ones. Moreover, the increase of the heat exchange between the land surface and the atmosphere for areas where high vegetation is present leads to a warming during night-time. So, it partially outweighs the cooling induced by the revision of the turbulence closure. It follows that the combined changes included cycle 40r1 of the IFS lead to only relatively small changes in near-surface temperatures (Figure 5b).

Figure 5a illustrates the patterns of the 2-metre temperature forecast biases occurring over continental areas during night-time in the winter season. These biases are complicated and not understood – they are positive in some areas and negative in others. Consequently the near-surface cooling associated with our changes (Figure 5b) leads to an improvement in some areas and to a slight deterioration in others. The improvement (deterioration) in forecast performance is indicated by a decrease (increase) of the mean absolute error in 2-metre temperature in the NEW versus the CTL experiments (Figure 5c).

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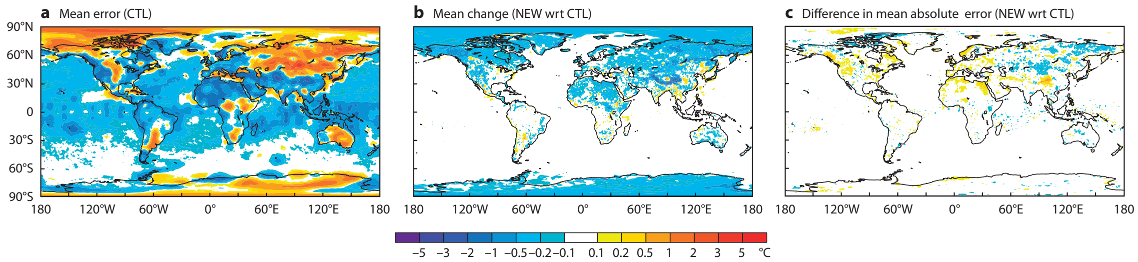

Figure 5 (a) Mean 2-metre temperature error (°C) for the CTL daily forecasts performed for January–March 2012 with respect to the analyses from which the forecasts were initialized. (b) Mean change in 2-metre temperature in the NEW experiment with respect to the CTL. (c) Difference in mean absolute error in the 2-metre temperature in the NEW experiment with respect to the CTL. The plots correspond to the time of the minimum of the diurnal cycle in 2-metre temperature derived from the lead times 24 to 42 hours of the daily 00 UTC forecasts.

Impacts on large-scale circulation

Sandu et al. (2013) demonstrated that changes made to surface drag, by modifying either the diffusion in stable boundary layers or the drag over orography, affect the large-scale circulation through their impact on the synoptic systems and on stationary planetary waves. To illustrate these impacts, Figure 6 shows how the changes to the turbulent closure in stable conditions and to the drag over orography discussed here modify the mean of the 1000 hPa geopotential height during a winter month when these impacts are the most pronounced. To emphasize the changes affecting the weather systems, in the figure the regions of mean low sea-surface pressure (lows) are indicated by dashes and the regions of high sea-surface pressure (highs) are indicated by full lines.

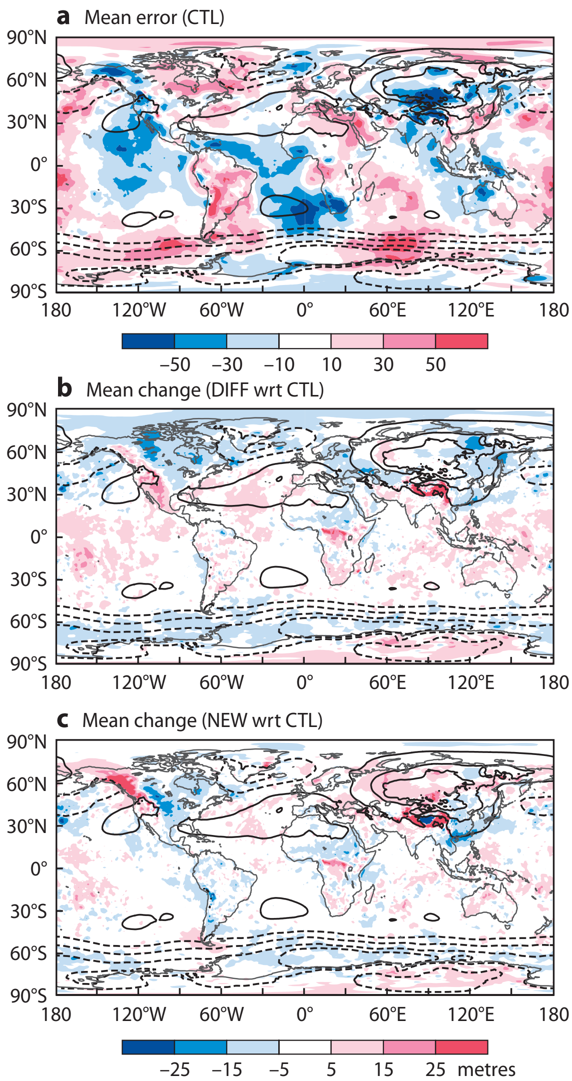

Figure 6 (a) Mean error of the 1000 hPa geopotential height of the CTL experiment for January 2012, with respect to the analyses from which the forecasts were initialized, at forecast lead time of 24 hours (verifying at 00 UTC). (b) Change in mean of the 1000 hPa geopotential height in an experiment where only the changes to the turbulence closure in stable conditions are tested (experiment DIFF) with respect to the CTL run. (c) Same as (b) but for the NEW experiment where the changes to the turbulence closure are combined with the ones to the surface drag (all in metres). The low pressure systems (dashes) and high pressure systems (full lines) are defined from the monthly mean analyzed fields of 1000 hPa geopotential height.

The mean bias of the 1000 hPa geopotential height suggests that in the short range of the CTL forecasts the highs are on average too weak (i.e. the geopotential is too low). Meanwhile, the lows are either relatively well represented or not deep enough (i.e. the geopotential is too high), especially in the storm track region in the southern hemisphere (Figure 6a). The reduction of the diffusion in stable boundary layers (experiment DIFF) leads to an increase of the geopotential height at 1000 hPa in the highs and decrease in the lows from the beginning of the forecasts (Figure 6b). This corroborates the idea that a reduction in surface drag strengthens the pressure systems, most likely by diminishing the integrated cross-isobaric flow (*Beare*, 2007; *Svensson & Holtslag*, 2009). When this change is combined with the increase in the drag over orography (Figure 6c), the highs strengthen even more and the lows deepen less with respect to the CTL compared to when the turbulence changes were tested individually (Figure 6b).

The benefit of combining the two changes is clearly emphasized by the changes in the root-mean square error of the geopotential height for the northern hemisphere shown for various levels in Figure 7. The reduction of the root-mean-square error, which is indicative of an improvement in the large-scale forecast performance, is more substantial and becomes significant when the two changes are combined. The combined changes thus lead to a substantial improvement both in terms of mean and root-mean square errors of the geopotential height in the northern hemisphere (especially over Eurasia and North America), but also in the storm track region in the southern hemisphere at all levels (not shown).

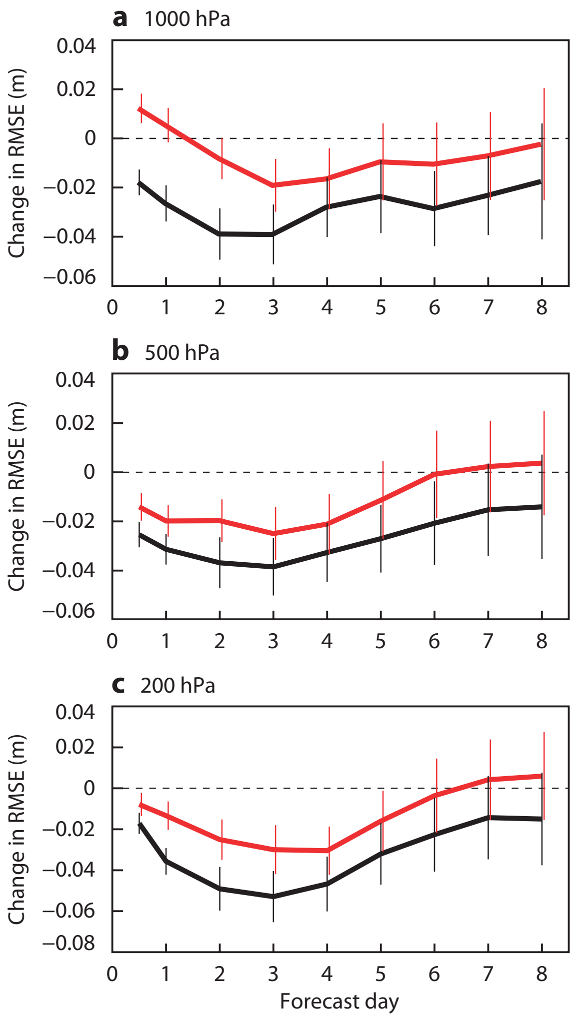

Figure 7 Change in root-mean-square error (RMSE) of the geopotential height for the northern hemisphere extratropics (20°–90°N) at (a)1000 hPa, (b) 500 hPa and (c) 200 hPa in an experiment where only the changes to the turbulence closure in stable conditions are tested (red) and in the NEW experiment where the changes to the turbulence closure are combined with the ones to the surface drag (black), both with respect to the CTL experiment for January to March 2012. If vertical lines do not intersect the 0 line, it means the NEW experiment is significantly better, or worse (95% interval), than the CTL.

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Outlook

Although the solution described here is not entirely satisfactory, it is an important step towards reducing some of the most longstanding errors in ECMWF's parametrization of physical processes – the errors related to the representation of near-surface winds in stable boundary layers. Meanwhile, this work allowed the definition of further research paths that need to be pursued. Namely, it revealed the importance of:

- Improving the representation of drag over orography, which proves to be crucial for the large-scale forecast performance.
- Representing the coupling between the land surface and the atmosphere, which plays a large role in the quality of near-surface temperature forecasts.

The importance of these topics has recently been acknowledged by the research community and two ongoing intercomparison exercises are focusing on these aspects in the frameworks of WGNE (Working Group on Numerical Experimentation), GASS (Global Atmospheric System Studies) and GLASS (Global Land/Atmosphere System Study). These intercomparison studies, in which ECMWF is currently participating, are going to highlight how differently the orographic drag and the land-atmosphere coupling are treated in various NWP models. Hopefully they will stimulate further research on the factors governing land-atmosphere fluxes, the coupling strength, and the representation of drag over orography.

Further reading

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