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Why is it so difficult to represent stably stratified conditions in NWP models?

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Abstract

In the 1990's scientists at ECMWF suggested that artificially enhancing turbulent diffusion in stable conditions improves the representation of two important aspects of weather forecasts, i.e. near-surface temperatures and synoptic cyclones. Since then, this practice has often been used for tuning the large-scale performance of operational Numerical Weather Prediction (NWP) models, although it is widely recognised to be detrimental for an accurate representation of stable boundary layers. Here we investigate why, 20 years on, such a compromise is still needed in the ECMWF model. We find that reduced turbulent diffusion in stable conditions improves the representation of winds in stable boundary layers, but it deteriorates the large-scale flow and the near-surface temperatures. This suggests that enhanced diffusion is still needed to compensate for errors caused by other poorly represented processes. Among these, we identify the orographic drag, which influences the large-scale flow in a similar way to the turbulence closure for stable conditions, and the strength of the land-atmosphere coupling, which partially controls the near-surface temperatures. We also take a closer look at the relationship between the turbulence closure in stable conditions and the large-scale flow, which was not investigated in detail with a global NWP model. We demonstrate that the turbulent diffusion in stable conditions affects the large-scale flow by modulating the strength of synoptic cyclones and anticyclones, but also the amplitude of the planetary-scale standing waves.

1 Introduction

The model intercomparison studies performed in the context of the GEWEX Atmospheric Boundary Layer Studies (GABLS) showed that operational numerical weather prediction (NWP) models are less skillful in reproducing features of stably stratified boundary layers than research models when compared to large-eddy simulations (*Cuxart et al.*, 2006; *Beare et al.*, 2006; *Svensson and Holtslag*, 2009; *Svensson et al.*, 2011). This is mainly because turbulence closures used in operational NWP models maintain stronger mixing in stable conditions than closures typically used in research models, and than what can be justified from large-eddy simulations (*Svensson and Holtslag*, 2009) or observations (*McCabe and Brown*, 2007; *Mauritsen and Svensson*, 2007; *Brown et al.*, 2008). This enhancement of turbulent diffusion in stable conditions has repeatedly been shown to be detrimental to the representation of stable boundary layers (STBLs): their depth is overestimated, the low level jets are too weak and located too far from the surface, the near-surface ageostrophic wind-angles are too small, hence the wind turning between the surface and the top of the boundary layer is underestimated (*Bosveld et al.*, 1999; *Brown et al.*, 2005; *Cuxart et al.*, 2006; *Brown et al.*, 2008; *Bosveld et al.*, 2008; *Svensson and Holtslag*, 2009). Moreover, given that the free-troposphere is mostly stably stratified, enhancing the diffusion in stable conditions can affect the atmospheric flow, well beyond the STBL. For example, it can lead to weaker upper tropospheric jets or weaker inversion layers. The weakening of the inversions capping the boundary layer can further result in a decrease of the stratocumulus cover, and thus be partially responsible for the underestimation of low-level cloud amount ubiquitous to global models (*Koehler et al.*, 2011).

It is therefore now well-known that enhancing the diffusion in stable conditions beyond what can be supported by observations or large-eddy simulations may be detrimental for the representation of STBLs and of stratocumulus clouds. Yet, this approach has been a fairly common practice in the past 20 years in operational models. To date, the diffusion in stable conditions is still enhanced, to various degrees, in world-leading operational weather forecast systems such as the ECMWF Integrated Forecast System (IFS), the MetOffice Unified System or the NCEP Global Forecast System (GFS). 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, or meso-scale variability that are not explicitly represented in models. But it is difficult to demonstrate that such effects explain the enhancement of the diffusion that is imposed in certain operational NWP models (*McCabe and Brown*, 2007). In practice, this approach is attractive because the degree of turbulent diffusion used in stable conditions has proven to be a powerful tuning knob for adjusting key aspects of weather forecasts. Scientists at ECMWF showed, for example, that maintaining more diffusion in stable conditions represents an effective way to reduce the cold near-surface temperature biases frequently encountered in STBLs and to improve the representation of synoptic cyclones (*Beljaars and Viterbo*, 1998; *Viterbo et al.*, 1999).

The near-surface temperature cold biases encountered in STBLs, i.e. typically over land during night or in winter time, can have various causes, such as the strength of the energy exchange between the land and the atmosphere, an overestimation of the radiative loss at the surface caused by biases in the water vapor path or the surface skin temperature, errors related to the vertical turbulent mixing, the horizontal advection, or the representation of clouds. Irrespective of their cause, a simple cure for such cold near-surface biases is to use a turbulence closure that maintains more diffusion in stable conditions. More diffusion means the cooling due to the radiative loss at the surface is distributed in a deeper layer, so that the near-surface temperature drops less and the cold biases are reduced. Moreover, it also prevents entering a so called runaway cooling regime that may occur in models that use weak turbulent diffusion in stable conditions. Such a problem arises due to an interaction between the radiative cooling at the surface and the turbulence closure scheme. When the surface starts to cool the stratification close to the ground increases. If the turbulence closure prescribes a strong diminution or even a ceasing of mixing for stronger stabilities, the increase in stratification leads to a reduced downward heatflux and a further cooling of the ground. The resulting positive feedback loop, which leads to increasingly colder temperatures near the surface, can ultimately be ceased only if the large-scale geostrophic forcing is sufficient to restore the turbulent mixing within the thinning boundary layer (*Mauritsen*, 2012; *Van de Wiel et al.*, 2012).

Another prominent model caveat palliated by enhancing the diffusion in stable conditions is related to the development of synoptic-scale cyclones. At high horizontal resolution, the large-scale performance of NWP models (e.g. expressed by the root mean square of the geopotential height at 500hPa) is sensitive to changes in the surface drag. It has been noticed that imposing more diffusion in stable conditions, hence more drag close to the surface, helps damping the weather systems, and improving thus the large-scale performance of the model (*Beljaars and Viterbo*, 1998). The impacts of the degree of mixing maintained in stable conditions on the strength of the weather systems, in particular of synoptic cyclones, are often explained through the modification of the Ekman pumping. But support for this hypothesis is poor, except for an idealized case study of an extratropical cyclone performed by *Beare* (2007). The idea that arises from theory (*Holton*, 2004) and from this idealized case study is that more diffusive turbulence closures produce more drag close to the surface, but also maintain more turbulent mixing in the boundary layer. They therefore lead to reduced ageostrophic wind angles at the surface and in the same time to deeper turbulent layers (*Svensson and Holtslag*, 2009). The frictional cross-isobaric (ageostrophic) flow becomes thus weaker, but takes places over a deeper layer, so that overall the integrated cross-isobaric flow increases. This reinforces the secondary circulation which acts to spin-down the synoptic-scale cyclones, by replacing high-vorticity air within the cyclone with low-vorticity air, and hence contributes to their decay (*Holton*, 2004; *Beare*, 2007).

Artificially enhancing the diffusion in stable conditions proves thus useful for offsetting biases in operational NWP models. However, such a practice leads to a number of other issues related to the representation of STBLs. This motivates efforts to reduce the degree of mixing in stable conditions in NWP models. A first step in this direction is taken in this study by investigating whether such a compromise is still needed in the ECMWF IFS. This investigation builds on previous tests carried at different stages with the ECMWF model in order to examine how a reduction of the degree of diffusion maintained in stable conditions affects the model behaviour (*Brown et al.*, 2005). The question we want to address is whether the other components of the model have improved enough in the recent years, or the increase in resolution has helped to overcome the need for using an artificially enhanced diffusion in stable conditions. Particular attention is given to the impacts of the turbulence closure used in stable conditions on the large-scale dynamics and therefore on the large-scale performance of the model, which are often invoked, and yet poorly documented in the literature (*Beljaars and Viterbo*, 1998; *Svensson and Holtslag*, 2009).

Our approach consists in performing a set of sensitivity (forecast) experiments in which we reduce to certain degrees the turbulent diffusion in stable conditions (Section 3). The results were used to understand how such a model change affects the flow near the surface and in the free-troposphere (Section 4), and how it impacts the atmospheric circulation at synoptic and planetary scales (Section 5). The experiments were also used to assess whether a less diffusive turbulence closure for stable conditions could be implemented at present as a stand alone change (Section 5), or whether changes to other parameterizations would be necessary in order to improve, or at least to preserve the large-scale performance of the model. A number of supplementary sensitivity experiments helped identifying parameters and parameterizations that affect the atmosphere in a similar manner as the turbulence closure scheme for stable conditions (Section 6).

2 Historical Perspective on the Turbulence Closure in Stable Conditions in IFS and the Associated Longstanding Biases

In the ECMWF model the turbulent diffusion in stable conditions is parameterized with a first order closure based on local stability (*Louis*, 1979). The exchange coefficients for momentum and heat K_M, K_H depend on a mixing length l, the gradient of the horizontal wind U and stability functions $f_{M,H}$:

$$K_{M,H} = l^2 \left|\frac{\partial U}{\partial z}\right| f_{M,H} \tag{1}$$

The mixing length $l = kz$ used in the surface layer is bounded above this layer by introducing an asymptotic length scale $\lambda = 150m$: $1/l = 1/kz + 1/\lambda$ (*Blackadar*, 1962). Some studies suggest that the mixing length should be flow depedent (*Rossby and Montgomery*, 1935; *Mauritsen and Svensson*, 2007; *Mauritsen and Enger*, 2008). Such formulations are however difficult to implement in first order closures and therefore the asymptotic mixing length is often considered to be constant in these schemes, albeit the evidence regarding the values it should take is poor. The constant λ-value used in IFS is substantially higher than the ones used in other NWP models with a similar first-order closure (e.g. UK MetOffice use 40 m and the NCEP use 30 m) and that suggested by observations in neutral free-shear layers (*Tjernstrom* (1993) found a value of 23 m).

Concerning the stability functions, they differ in the surface layer, taken to be the layer between the surface and the lowest model layer, and above, i.e. within stable boundary layers, inversions capping the boundary layer and the free troposphere. In the surface layer, the stability functions are empirical functions of z/L, z being the height above the surface and L the Monin-Obukhov length, derived from the stability functions proposed by *Holtslag and Bruin* (1988). The $f_{M,H}$ functions used in the surface layer are in agreement with the Monin-Obukhov theory in the sense that at large Richardson numbers (R_i) they allow for virtually no turbulent transport ($K_{M,H}$ tend to zero, blue lines in Fig. 1) and enter the category of the so called short-tail stability functions. Above the surface layer, $f_{M,H}$ are a function of the local Richardson number R_i. As in other operational models, long-tail functions are used above the surface layer in order to maintain diffusion at large R_i numbers. As explained in the introduction this offsets model biases such as run-away surface cooling and too active synoptic cyclones.

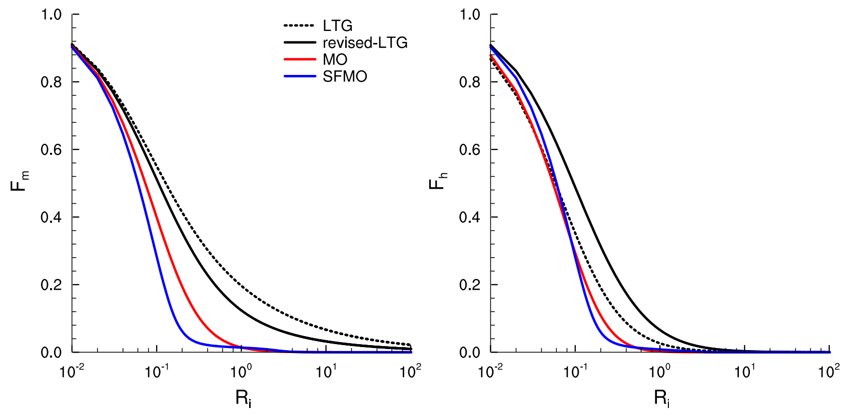

Figure 1: Stability functions for momentum and heat: original Louis functions (black dotts), Monin-Obukhov functions used in the surface layer (blue), revised Louis functions used close to the surface (full black) and Monin-Obukhov functions used further away from the surface (red).

Over the years, the formulation used in IFS for $f_{M,H}$ above the surface layer has seen a number of modifications that had noticeable impacts on the model performance. Until 1996, $f_{M,H}$ were set to the *Louis et al.* (1982) long-tail functions (Fig. 1). In 1996 these functions were revised (revised LTG, Fig. 1) in order to enhance the turbulent mixing for heat and to decrease the one for momentum. This change, together with the inclusion of the soil moisture freezing in the surface scheme (*Viterbo et al.*, 1999), significantly reduced the nighttime cold bias in 2m temperature over land (Fig. 2). Since 2007, $f_{M,H}$ are given by an interpolation between the revised LTG stability functions near the surface and a less diffusive short-tail form of the Monin-Obukhov stability functions (Fig. 1) far away from the surface (typically in the inversions capping the boundary layer and in the stable parts of the free-troposphere):

$$f(R_i) = \alpha f_{LTG}(R_i) + (1-\alpha) f_{MO}(R_i) \qquad (2)$$

where $\alpha = exp(-z/\beta)$, with $\beta = 150\,m$. This interpolation was somewhat detrimental for the near surface temperature bias (Fig. 2), but it limited the erosion of stratocumulus clouds. This was far too pronounced when the revised LTG functions were used to describe the inversions capping the boundary layer (*Koehler et al.*, 2011), because the enhanced diffusion leads to excessive entrainment of warmer and drier free-tropospheric air at the cloud top.

In 2007, a new parameterization of non-resolved shear was introduced by adding a height dependent term with a maximum around 850 hPa to the shear, and thereby to the Richardson number used to compute the diffusion coefficients in IFS. This change, motivated by the lack of meso-scale vertical wind-shear in the ECMWF model, resulted in an increase in the diffusion coefficients, which improved the representation of the tropical winds, in particular around 850 hPa (M. Koehler, personal communication). Nevertheless, the formulation of this non-resolved shear parameterization is theoretically not very satisfactory as it remains unclear how it scales with wind speed and model resolution, and how it should vary vertically (*Mahrt and Vickers*, 2006).

The representation of turbulent diffusion in stable conditions used currently in IFS is one way of dealing with the need for more diffusion close to the surface and less diffusion in the inversions capping the boundary layer in NWP models. In the UK MetOffice Unified Model, long-tail stability functions are

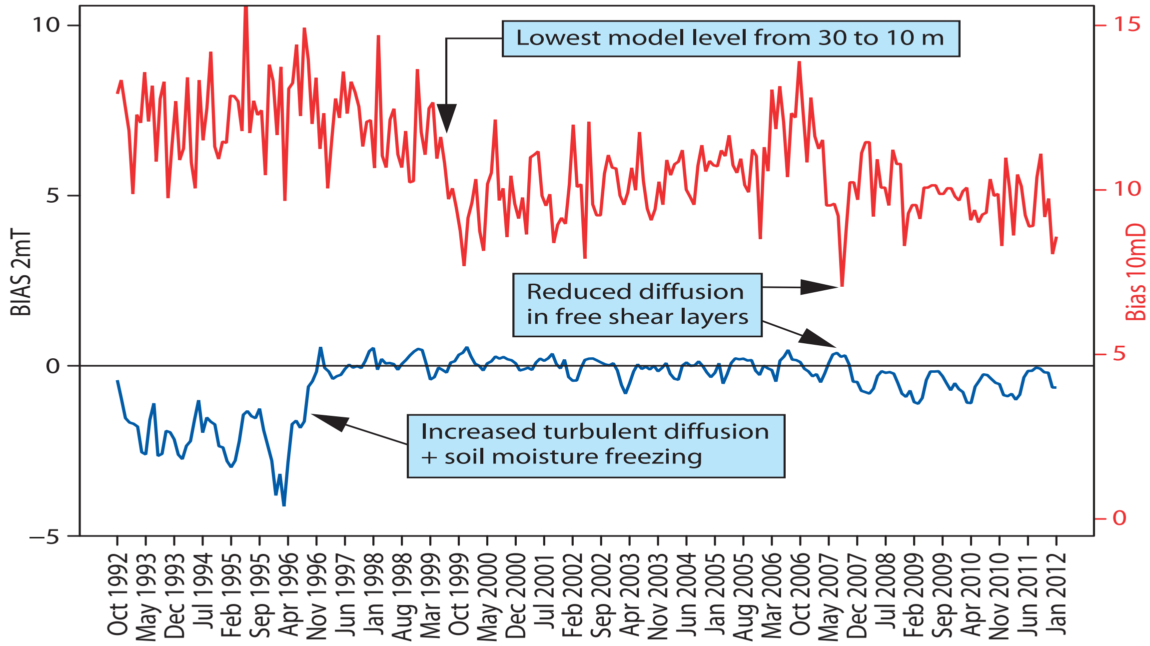

Figure 2: Historic evolution of 2m temperature and 10m wind direction errors of the operational ECMWF IFS. These are monthly values of mean errors at a lead time of 60 h of the daily forecasts initialized at 12 UTC (verifying time 00UTC). The verification includes 800 SYNOP stations over Europe (30-72N, 22W-42E).

used close to the surface over land and short-tail functions are used over oceans (*Brown et al.*, 2008). At NCEP the GFS model applies long-tail stability functions, while adding a background diffusivity with different values for heat and momentum, respectively. For heat, the background diffusivity exponentially decreases with height from 1.0 m^2s^{-2} at the surface, while for momentum is constant and equal 3.0 m^2s^{-2}. To avoid excessive erosion of stratocumulus clouds, the background diffusivity for heat is reduced to 30 percent of that at the surface in the lower inversion layers (*Han and Pan*, 2011).

Although enhanced diffusion is still applied in IFS close to the surface in stable conditions, the near-surface nighttime temperatures forecasted with the most recent model versions remain generally too cold over land, especially during wintertime and at high latitudes where the stable conditions are most frequently encountered (Figs. 2 and 4). The large scale patterns of the mean nighttime 2 m temperature forecast errors with respect to the ECMWF 2 m temperature analyses, which are very close to routine observations, are however complicated and not well understood. They suggest that the representation of turbulent diffusion in stable conditions is not the only process responsible for near-surface nighttime temperature biases. An example supporting this idea will be given in Section 6.

The choice of the turbulence closure in stable conditions affects not only the representation of near-surface temperatures but also that of near-surface wind speed and direction. In the Northern Hemisphere (NH), the modeled surface wind directions are generally veered (rotated clockwise) with respect to observations both over land (Fig. 2) and over the oceans (*Brown et al.*, 2005), while in the South Hemisphere (SH) they are backed (rotated anticlockwise) with respect to observations. Although systematic, these biases are more pronounced in stable conditions (*Brown et al.*, 2005), where they are amplified by the increase in surface drag associated with the enhancement of turbulent diffusion. In the NH the surface wind is generally backed relative to the geostrophic wind, so that the wind veers with height throughout the boundary layer (the opposite being true for the SH). This implies that the model biases in wind direction at the surface translate into an underestimation of the wind turning within the boundary layer. The surface wind-direction biases, and consequent biases in wind turning, were reduced on two occasions: in 1999, when the lowest model level was lowered from 30 to 10 m, and in 2007 when the turbulent diffusion was reduced in free shear layers away from the surface. The bias, though, still remains significant (Fig. 2).

The enhanced diffusion prescribed in stable conditions also leads to biases in the representation of the diurnal cycle of wind in the boundary layer. The observed diurnal cycle of wind speed presents a minimum at night 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 the STBL. The ECMWF model operational in 2011 reasonably represents this diurnal cycle of wind, but underestimates its amplitude both at the surface and at 200 m (Fig. 3). The reason is that the strong mixing applied in stable conditions has the tendency of smearing out the low-level jet by excessively transporting momentum towards the surface.

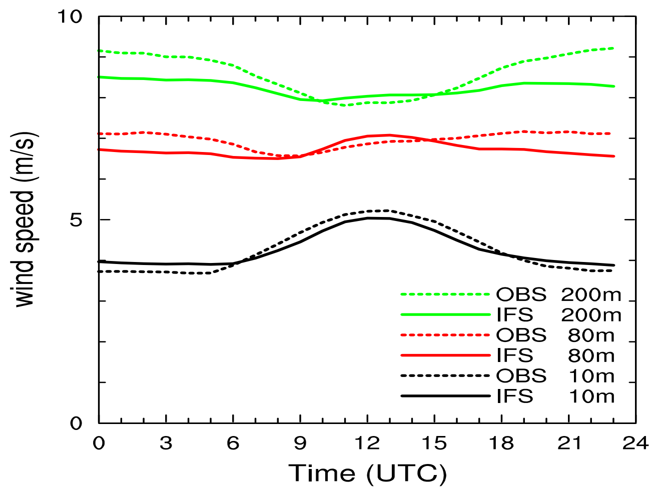

Figure 3: Annually averaged diurnal cycle of wind in Cabauw (Netherlands) at 10, 80 and 200 m of height for 2011. The operational ECMWF IFS (derministic high resolution T1279 L91 run, cycles 37r2 and 37r3) daily 00UTC forecasts (lead times 24 to 42 h) are compared to observations.

3 Experiments

We performed a set of T511L91 ($\approx$ 50 km horizontal resolution and 91 vertical levels) 10-day forecast experiments for a winter (January 2011) and a summer month (July 2010). The most relevant experiments discussed in this paper are summarized in Table 1. For all experiments, 10-day forecasts are initialized daily at 0UTC from the same T511L91 analyses.

The model version used for the control (CTL further on) experiments is IFS model cycle 37r2 (operational from 18-05-2011 to 15-11-2011), with two modifications: (i) we are using the new roughness length table implemented in cycle 37r3 (*Sandu et al.*, 2011/2012), which significantly improves the model 10m wind speed biases over land; (ii) we do not include the term which is currently used in operations in the turbulence parameterization to account for non-resolved shear (see Section 2). This term interacts non-linearly with the formulation of the stability functions via their dependence on the Richard-

Label	Stability functions above the surface layer	Asymptotic mixing length	Other changes
CTL	revised LTG close to the surface, short-tail fct. above (eq. 2.2 and Fig. 1)	150m 150m	
ST	short-tail fct. used in the surface layer (Fig. 1)	150m 150m	- -
LT30	revised LTG (Fig. 1)	30m	-
LT30-SEA	revised LTG over ocean points, CTL formulation over land and sea-ice	30m	-
LT30-TOFD	revised LTG	30m	50% increase in the intensity of TOFD scheme
LT30-BLOCK	revised LTG	30m	50% increase in the intensity of BLOCK scheme
COU	CTL formulation	150m	doubled skin layer conductivity

Table 1: Characteristics of the various forecast experiments.

son number, hence on the shear. As the clarity of our conclusions might have been hampered by such interactions we decided to perform all the experiments discussed in this study without this non-resolved shear term.

Our sensitivity experiments differ from the CTL experiments only through the modifications brought to the turbulence closure in stable conditions or to various parameters indicated in Table 1. The experiments labelled ST and LT30 are used to investigate how the performance of the system is affected if we reduce the degree of turbulent diffusion used in stable conditions near the surface. The changes to the turbulent closure in stable conditions imposed in these experiments lead to a reduction of the diffusion coefficients close to the surface, because either the stability functions are replaced with less diffusive ones (blue lines in Fig. 1, ST runs), or the asymptotic mixing length is reduced from 150 m to 30 m (LT30 runs). In the free-shear layers, the changes imposed by replacing the short-tails currently used in these layers (red lines in Fig. 1) with the short-tails used in the surface layer in the ST runs (blue lines in Fig. 1), or with the revised LTG functions (black lines in Fig. 1) combined with a smaller asymptotic mixing length in the LT30 runs, lead generally to a reduction of the diffusion coefficients for momentum. However, the diffusion coefficients for heat can either increase or decrease depending on stability.

The LT30-SEA experiments investigate whether the impacts on the large-scale circulation obtained in the LT30 runs are predominantly due to changing the diffusion over land or over sea (Section 5). The last three pairs of experiments in Table 1 help illustrating that other parameters might impact the model performance, at least as significantly as the formulation of turbulent diffusion in stable conditions (Section 6). The LT30-TOFD and LT30-BLOCK experiments demonstrate that the large-scale circulation is also affected by changes to the parameterizations used to represent surface drag over orography, namely: TOFD - the turbulent orographic form drag (*Beljaars et al.*, 2004), and BLOCK - the low-level blocking part of the subgrid orography scheme (*Lott and Miller*, 1997). The COU experiment shows how the near-surface temperature is affected by changes to one of the parameters describing the coupling between the surface and the atmosphere, i.e. the skin layer conductivity. This parameter represents the degree of coupling between the radiation intercepting surface and the underlying snow or soil layer. The skin layer conductivity is given a constant value for each surface type, although there is little direct theoretical or observational support for these values.

4 Impacts of Reduced Diffusion on the Atmospheric State

4.1 Near the Surface

First, we examine how the boundary layer structure is affected when using less diffusion close to the surface in stable conditions. Less turbulent mixing leads to shallower STBLs, which means that the radiative loss at the surface is felt in a more confined layer and therefore the near-surface temperature drops more than in deeper boundary layers. Although this effect is obvious for both ST and LT30 experiments, the near-surface cooling during nighttime is the most pronounced in the ST experiments, as illustrated by the mean changes in the minimum of the diurnal cycle of 2 m temperature in Fig. 4. Not surprisingly, the magnitude of this nighttime cooling is higher in winter in regions where STBLs are frequently encountered, i.e. continental areas in the NH and more particularly snow covered regions at high latitudes. The impacts of these changes in the near-surface temperature obtained in the ST and LT30 runs on the model performance are mixed. In winter, the cooling induced during nighttime over land, is mostly enhancing the existing errors (top left panel in Fig. 4), except for parts of East Asia. In summer, when the model has a warm bias over large parts of North America and Eurasia (top right panel in Fig. 4), a slight cooling is beneficial.

The changes made to the turbulence closure in stable conditions in the ST and LT30 experiments affect not only the near-surface quantities but the entire structure of the boundary layer. This can be seen from the mean changes in the nighttime profiles of temperature and wind speed obtained at an individual land site where tower observations are available (Cabauw, Fig. 5). As expected, the radiative loss at the surface is felt in a shallower layer, so the air is colder near the surface and warmer higher up relative to the CTL experiments (Fig. 5). Interestingly, in January the changes to the temperature profile induced by reducing the degree of diffusion in stable conditions are small compared to the 1 K bias seen in the CTL run with respect to observations (Fig. 5). This suggests that the choice of the turbulence closure for stable conditions is in this case of minor importance compared to other factors that may cause the cold bias, such as an overestimation of the radiative loss at the surface caused by an underestimation of the total vapor path.

When reducing the diffusivities, momentum is less efficiently transported downward, so that the wind speed decreases slightly near the surface and increases above. Consequently, the nocturnal low level jet is enhanced, and becomes better represented with respect to observations (Fig. 5). The wind speed bias at 200 m is diminished by more than half in January, while in July it practically vanishes in both the ST and LT30 experiments. Moreover, the reduced diffusivities for momentum lead, as expected (Section 2), to an increase in the wind turning within the boundary layer. In the ST runs, this increase amounts 3.35 degrees on average over Europe during winter, and 1.45 degrees during summer (at the time of the minimum of the diurnal cycle in 2m temperature). In the LT30 runs, the increase is of 1.65 degrees in winter and of 0.75 degrees in summer. Although, this is not enough to neutralize the systematic underestimation of the wind turning in nocturnal boundary layers over Europe (Fig. 2), it does suggest that this longstanding bias is in part caused by the enhanced turbulent diffusion in stable conditions.

The same conclusion is valid for the oceanic regions where stable boundary layers prevail, i.e. where warm air is advected over cold sea surface temperatures resulting in negative sensible heat fluxes at the surface (Fig. 6). This is inferred by the comparison of the first-guess departures (observations - model)

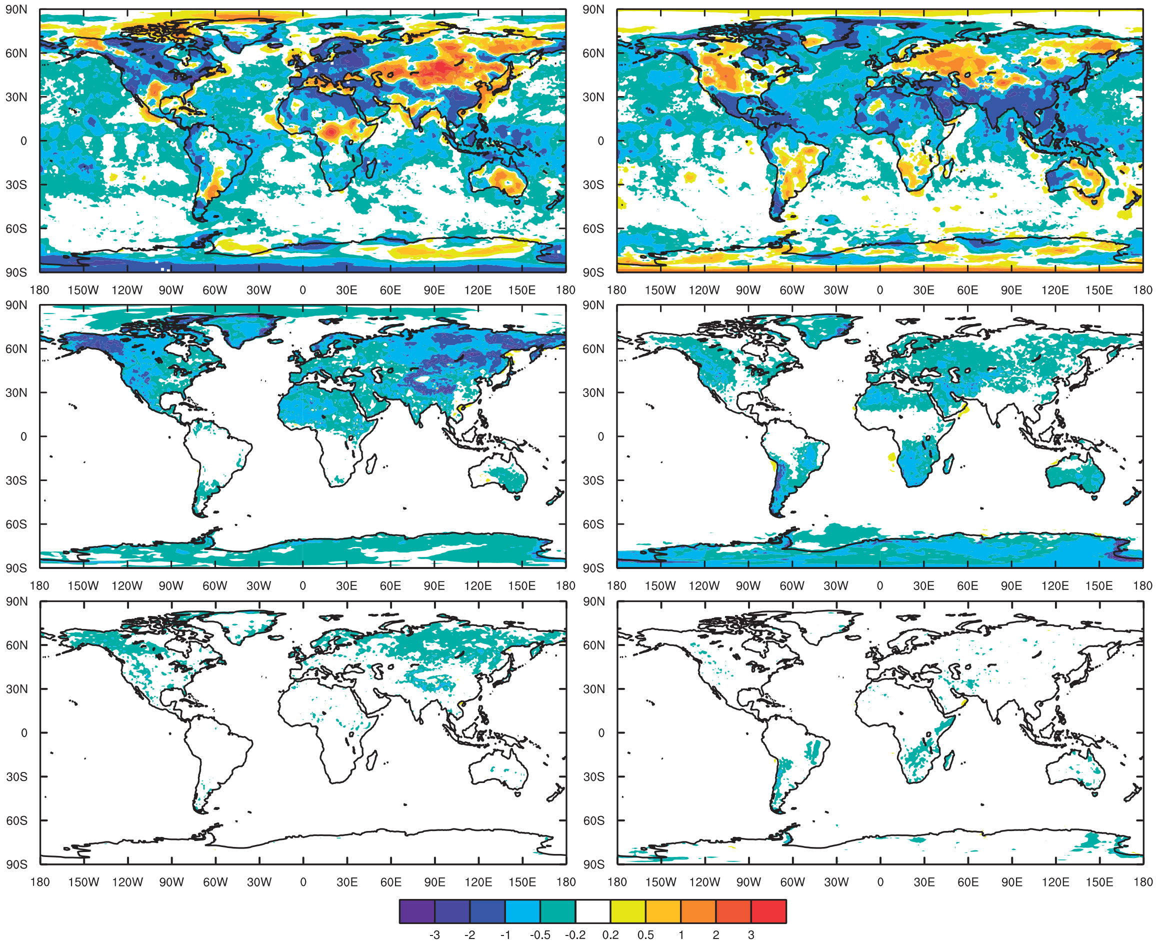

Figure 4: Top: Mean 2m temperature error (K) for the CTL daily forecasts performed for January 2011 (left) and July 2010 (right), with respect to the analyses from which the forecasts were initialized. Middle: Mean change in 2m temperature in the experiments ST with respect to the CTL experiments for January 2011 (left) and July 2010 (right). Bottom: Same as for middle but for experiments LT30. All quantities are plotted at the time of the minimum of the diurnal cycle in 2m temperature derived from the lead times 24 to 42 h of the daily 00UTC forecasts.

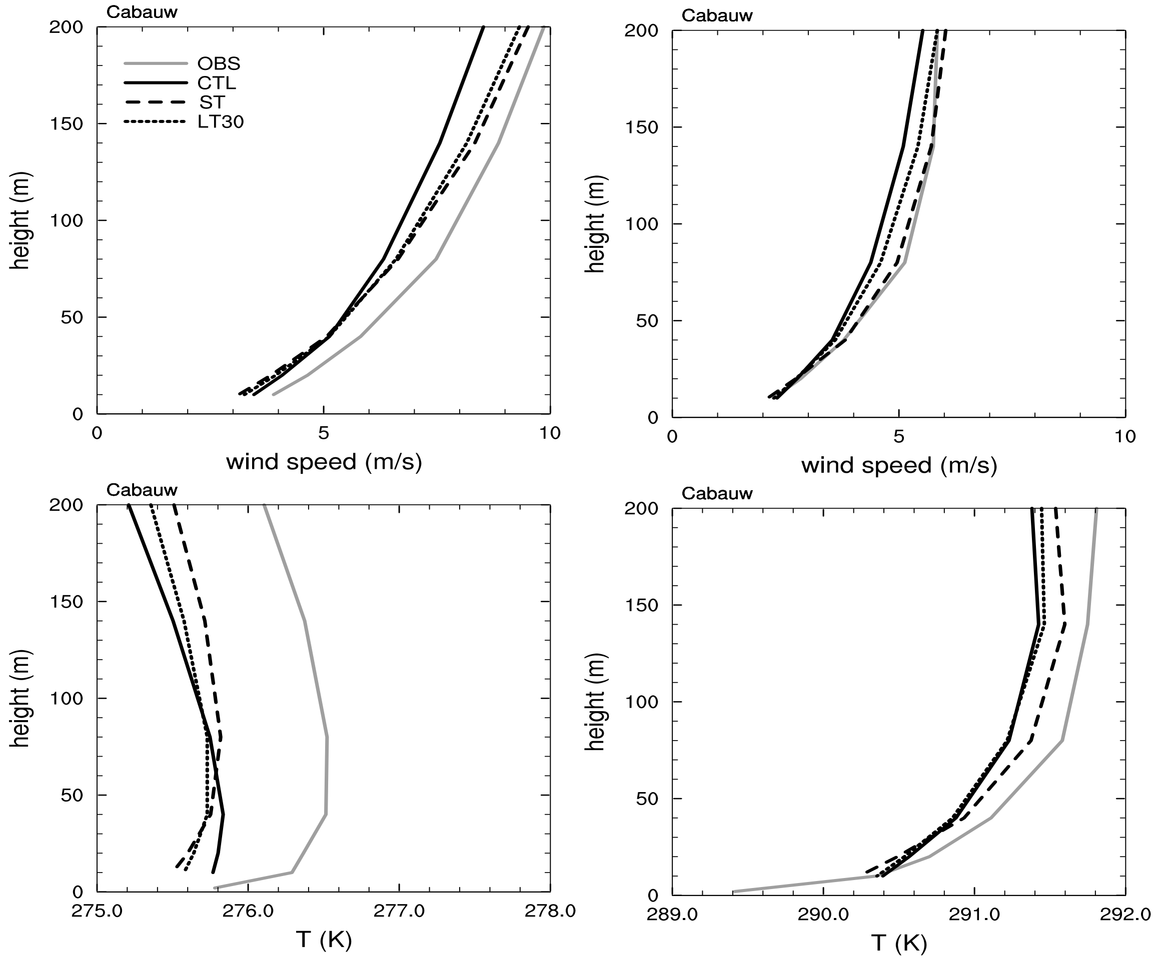

Figure 5: Mean wind speed (top) and temperature (bottom) obtained from the ST (dashed), LT30 (dotted) and CTL (full) experiments performed for January 2011 (left) and July 2010 (right) and from the observations realized at the Cabauw tower (grey). The modelled profiles correspond to lead time 24 h of the daily 00UTC forecasts (verifying at 00UTC).

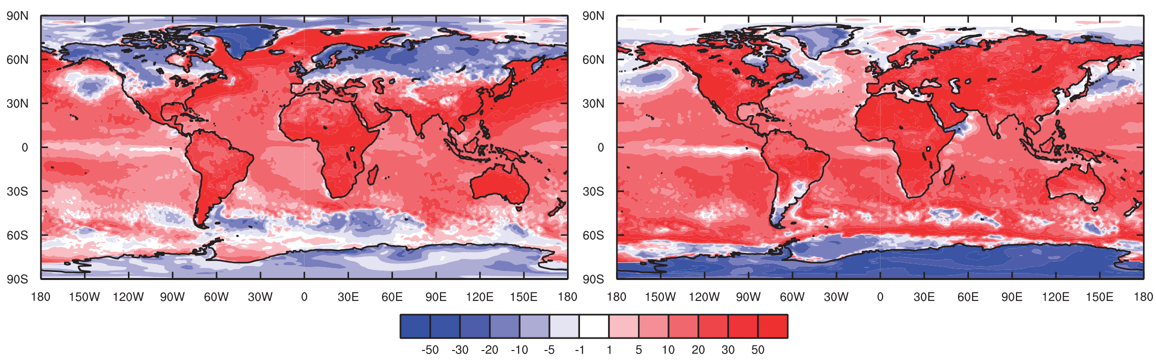

Figure 6: Mean sensible heat flux for the CTL experiments performed for January 2011(left) and July2010(right), derived from the average over the first 24 hours of the daily 00UTC forecasts.

of the wind direction at the surface with respect to ASCAT observations obtained from two analysis experiments performed with the CTL and LT30 formulations of the turbulence closure for January 2011. (In an analysis experiment all available observations are assimilated with the data assimilation suite of IFS). In the CTL analysis run, these first-guess departures are negative (positive) in the NH (SH), indicative of a veering of the wind direction with respect to observations in the NH, in agreement with the errors seen over land (Fig. 2) and a backing of the wind direction for the SH (Fig. 7). In the LT30 analysis run the first-guess departures of the wind direction at the surface are reduced in both Hemispheres with respect to the CTL run (Fig. 7) over the regions where the boundary layer is stably stratified.

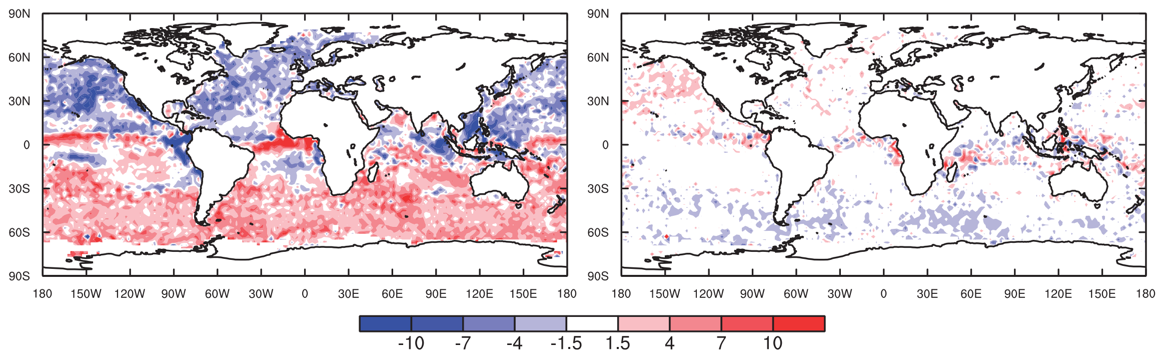

Figure 7: Mean first-guess departure (observations - model) of wind direction at the surface (degrees) with respect to ASCAT observations in a CTL analysis run performed for January 2011 (left) and the mean change in these first-guess departures when the LT30 formulation for turbulent diffusion in stable conditions is used instead of the CTL formulation (right). These quantities represent the average over the 00 and 12 UTC analyses.

4.2 Further Away from the Surface

Changing the turbulent closure in stable conditions may also affect the representation of the stratocumulus layers, through the modification of the inversions capping the boundary layers where these clouds form (*Koehler et al.*, 2011). In the free-shear layers, the changes imposed in the ST and LT30 experiments lead, as mentioned in Section 3, to smaller diffusion coefficients for momentum, but to either larger or smaller diffusion coefficients for heat depending on the stability of the layer. The cloud cover decreases on average by 5 up to 10 % in the ST runs, and by maximum 5 % in the LT30 runs (not shown) in the five oceanic regions where stratocumulus prevail off the west coast of continents. This suggests that the increase of the diffusion coefficients for heat at small and moderate stabilities dominates over other effects. The changes to the turbulence closure in both experiments thus lead to an overall enhanced entrainment of warmer and drier air from the free-troposphere in the boundary layer, which favors a reduction of the cloud cover. This hypothesis is supported by a slight warming and drying of the upper part of the boundary layer obtained in these regions in the ST and LT30 experiments.

The degree of mixing prescribed for the stable parts of the atmosphere also affects the representation of the jets in the free-troposphere. For example, the smaller diffusion coefficients for momentum used in stable layers in the LT30 experiments lead to an increase in both the mean and the variability of the wind speed compared to the CTL case, particularly in the jet regions (third and bottom rows in Fig. 8). These changes have mixed impacts on the model performance, defined with respect to analyses from

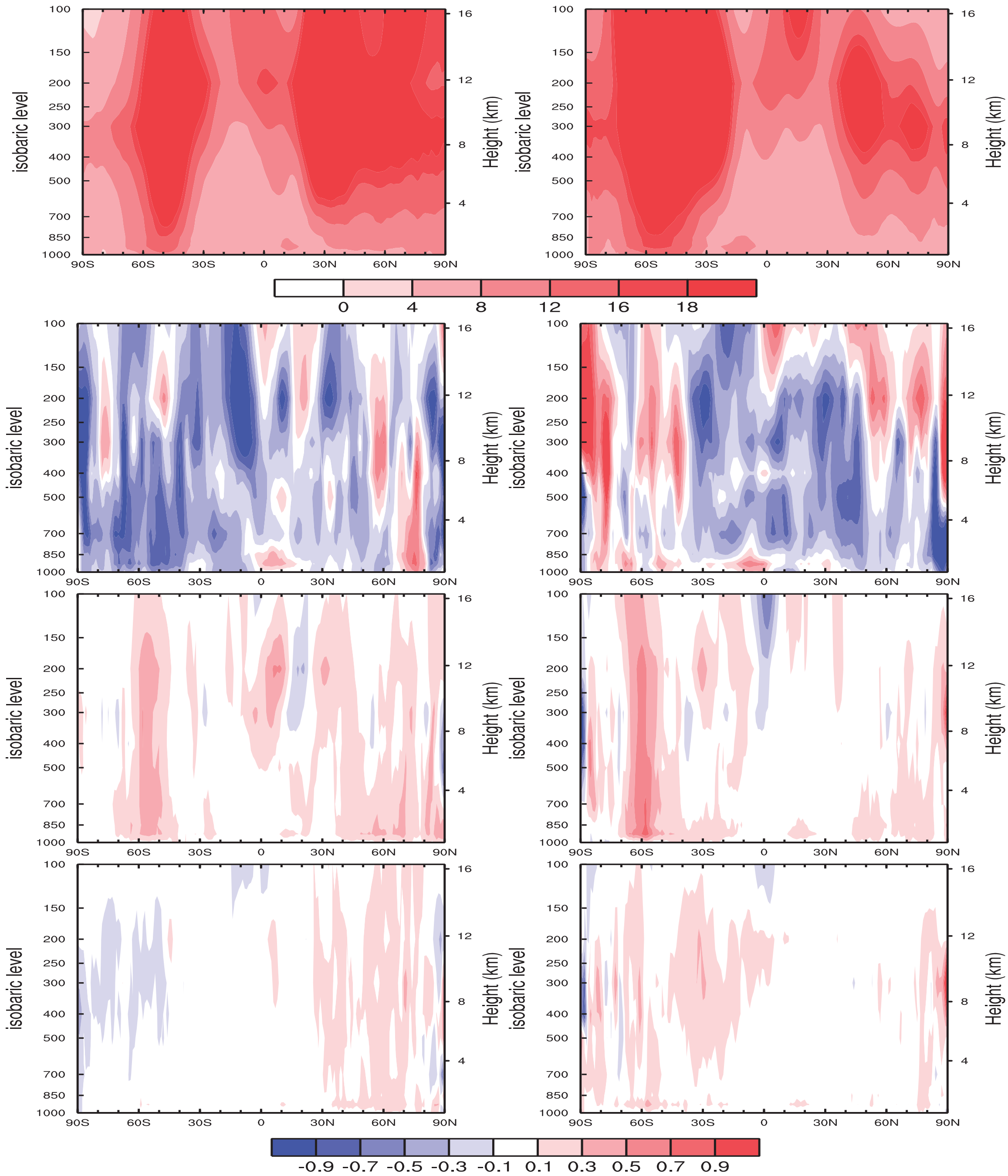

Figure 8: Top to bottom: Zonal mean wind speed in the CTL run; zonal mean wind speed bias in the CTL run with respect to the analyses from which the forecasts were initialized; changes in the zonal mean wind speed in the LT30 compared to the CTL run; changes in the wind speed RMSE in the LT30 compared to the CTL run, with respect with the analyses from which the forecasts were initialized (all in m/s). All the plots correspond to lead time 120 h (day 5) of the 00UTC forecasts performed for January 2011 (left) and July 2010 (right).

which the forecasts were initialized. The mean bias in wind speed decreases in some regions where the winds were too weak in the CTL experiment (e.g. storm track region in the SH, tropics, sub-tropics in the NH during January), but increases in others (storm tracks in the NH/SH during January/July) (Fig.8). Moreover, an increase in RMSE, which is indicative of a deterioration in the model performance, is visible everywhere except in January in the SH. These results highlight that the choice of the level of mixing in free shear layers is important for the large-scale performance of a NWP model because it can affect the representation of the tropospheric jets. Moreover, the results emphasize the difficulties in correctly representing the flow in different regions when using a constant value for the asymptotic mixing length.

5 Impacts of Reduced Diffusion on the Large-scale Circulation

Beljaars and Viterbo (1998) suggested that enhancing the turbulent diffusion in stable conditions damps the synoptic cyclones by modifying the Ekman pumping, and thereby improves the performance of the ECMWF model, which at the time tended to have a too strong synoptic activity. Some support for this idea was brought by *Beare* (2007), who showed for an idealized case study that an extratropical cyclone decays slower if the diffusion is reduced in stable conditions because the integrated cross-isobaric flow is weakened. However, the relationship between the turbulence closure in stable conditions and the lifetime of the synoptic systems was not, as far as we are aware, investigated in detail using a global NWP model. In this section, we take a closer look at how the reduction in diffusion in stable conditions affects the large-scale circulation and impacts the model performance.

We first examine how the changes to the turbulent closure in stable conditions performed in the ST and LT30 experiments modify the mean and root mean square of the 1000 hPa geopotential height, which is a good proxy for the surface pressure (Figs. 9 and 10). As we are particularly interested in the changes brought to the weather systems, in Figs. 9 and 10 we highlight by dashes the regions of mean low sea-surface pressure (lows) and by full lines the regions of high sea-surface pressure (highs). The lows and highs are defined from the monthly mean analyzed fields of 1000 hPa geopotential height, while the bias and RMSE are defined with respect to the analyses from which the forecasts were initialized.

For January, 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, and the lows are either relatively well represented or not deep enough, i.e. the geopotential is too high, especially in the storm tracks region in the SH (top panels of Fig. 9). For both Hemispheres the model activity is underestimated at both planetary and at synoptic scales compared to the analysis in the short to medium range of the forecasts (Fig. 11).

In both ST and LT30 experiments, the geopotential height at 1000 hPa increases in the high pressure systems and decreases in the low pressure systems from the beginning of the forecasts (Fig. 9). This suggests that the reduction in diffusion strengthens the pressure systems, most likely by diminishing the integrated cross-isobaric flow (*Beare*, 2007; *Svensson and Holtslag*, 2009). This supports previous findings related to the impact of the degree of diffusion in stable conditions on the synoptic cyclones (*Beljaars and Viterbo*, 1998; *Beare*, 2007), while it further demonstrates that the anticyclones are also affected. Moreover, the experiments suggest that these impacts do not only concern individual cyclones and anticyclones at the synoptic scale, but are also persistent in the mean state (Fig. 9). This implies that the stationary waves are affected by the changes in the turbulent diffusion in stable conditions. This idea is further supported by a diagnostic of the model activity at synoptic and planetary scales (Fig. 11), which shows that the activity increases at both scales commensurately in the two experiments compared

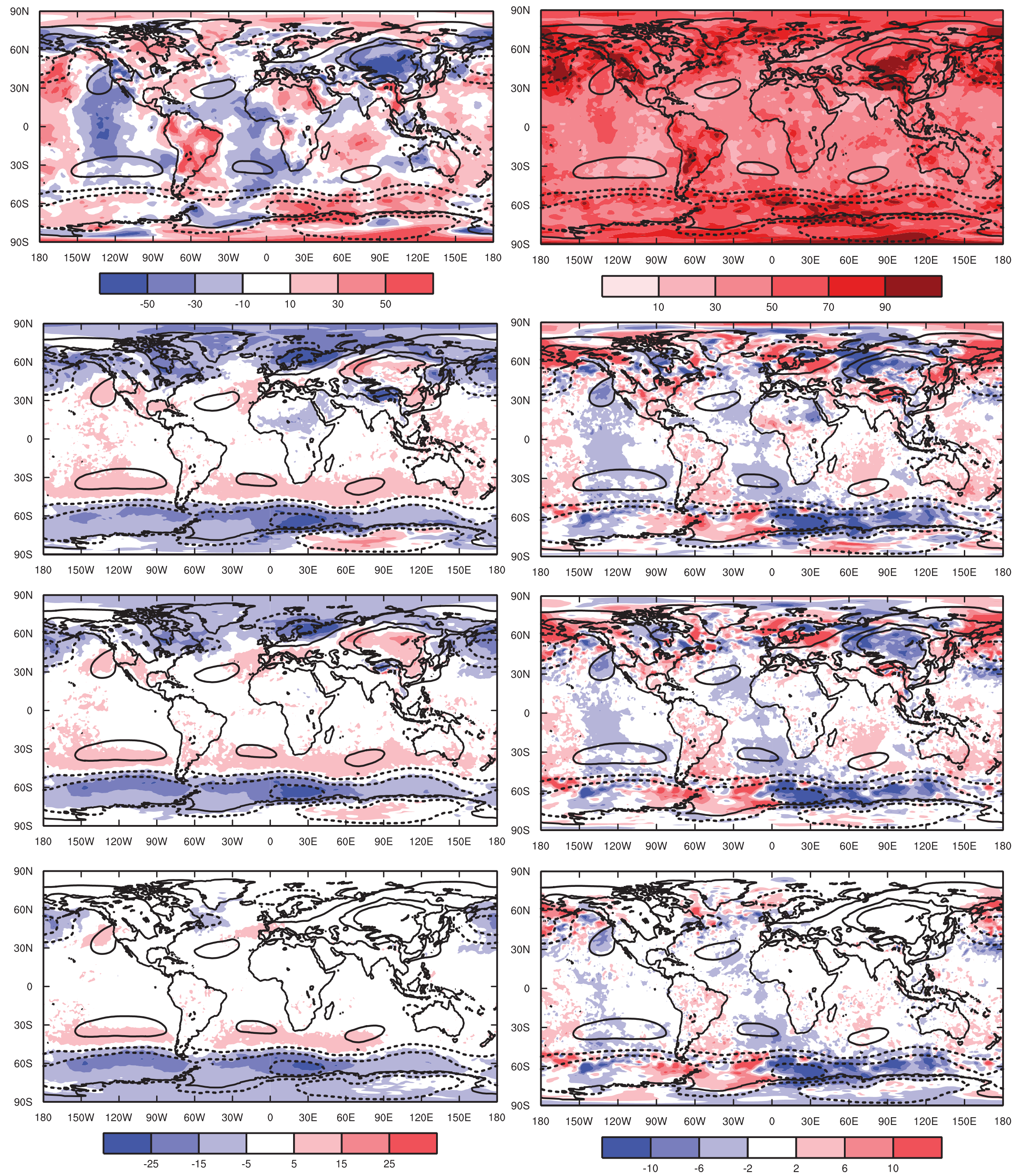

Figure 9: Top: Mean 1000 hPa geopotential height bias (left) and RMSE (right) of the CTL experiment for January 2011, with respect to the analyses from which the forecasts were initialized, at forecast lead time 24 h (verifying at 00UTC). 2nd to 4th row: Change in mean (left) and RMSE (right) of the 1000 hPa geopotential height in the runs ST, LT30, LT30-SEA with respect to the CTL run (all in m). A decrease in bias and RMSE indicate an improvement of the model performance.

to the CTL run.

The changes induced by the modification of the turbulence closure to the pressure systems and ultimately to the stationary waves have mixed effects on the model large-scale performance depending on the season and region. For both ST and LT30 experiments, the impact is on average negative in the NH and positive in the SH. This is visible both in the activity plots (Fig. 11) and in the large-scale scores of geopotential height (Fig. 12). The changes in the forecast anomaly correlation and RMSE show that both the deterioration in the NH and the improvement in the SH in terms of geopotential height are significant and not negligible, not only at the surface (not shown) but also higher up, for e.g. at 500 hPa (Note that the 500hPa geopotential height is an important headline score for NWP models). Moreover, it is interesting that even for the NH, the impact of the changes to the turbulence closure in stable conditions is not negative everywhere. The changes in mean and RMSE of geopotential height at 1000 hPa suggest that the model performance is improved over the continental zones characterizated by persistent high presssure systems at the surface (lower bias and RMSE, Fig. 9), but it is deteriorated in the vicinity of low pressure systems (higher bias and RMSE).

For July, the findings are similar for both ST and LT30 experiments. That is, using a less diffusive closure in stable conditions leads to stronger highs, deeper lows (Fig. 10), and thus to an enhanced activity at both synoptic and planetary scales over the entire forecast range (Fig. 11). The model performance is improved in the high pressure systems (lower bias and RMSE, Fig. 10), but it is somewhat deteriorated in the storm track region in the SH where the lows were already too deep in the CTL experiment. Hence their further deepening in the ST and LT30 experiments translates into larger bias and RMSE for the geopotential height (Fig. 10), and stronger activity at the planetary scales (Fig. 11). Consequently, the forecast anomaly correlation decreases, particularly close to the surface (not shown), and the variability increases at all levels (Fig. 12). For the NH the large-scale scores of geopotential height are not significantly impacted, except in the very short range.

To understand whether these impacts on the large-scale circulation are predominantly due to changing the diffusion in stable conditions over land, we performed the LT30-SEA experiments (Table 1). For the NH, these sensitivity experiments corroborate previous findings that the changes to the weather systems in this Hemisphere are mainly caused by the reduction of the diffusion in the STBLs present over continental regions (Figs. 9 to 12), although the changes in the diffusion in STBLs present over ocean also contribute to some extent to the increase in activity (Fig. 11). In the SH, the deepening of the cyclones in the storm track region is instead associated with a reduction of the diffusion in the STBLs present in these regions. The changes in geopotential height, activity or large-scale scores of geopotential height with respect to the CTL run obtained for the SH in the LT30 and LT30-SEA experiments are indeed very similar (Figs. 9 to 12).

6 Processes Other than Diffusion

The formulation of turbulent diffusion in stable conditions appears thus to have multiple impacts on different aspects of the flow at all scales ranging from the boundary layer to synoptic, and even planetary scales. Our experiments confirmed that using less diffusion in stable conditions close to the surface allows to reduce some of the biases related to the representation of STBLs, e.g. low-level jets and wind turning in the boundary layer. However, they also showed that such a change would still be detrimental for the large-scale performance of the model, and therefore it cannot be implemented as a stand alone change. In this section we explore whether there are modifications to other parameters, or schemes, that could offset the degradation of the forecast system performance caused by using a less diffusive

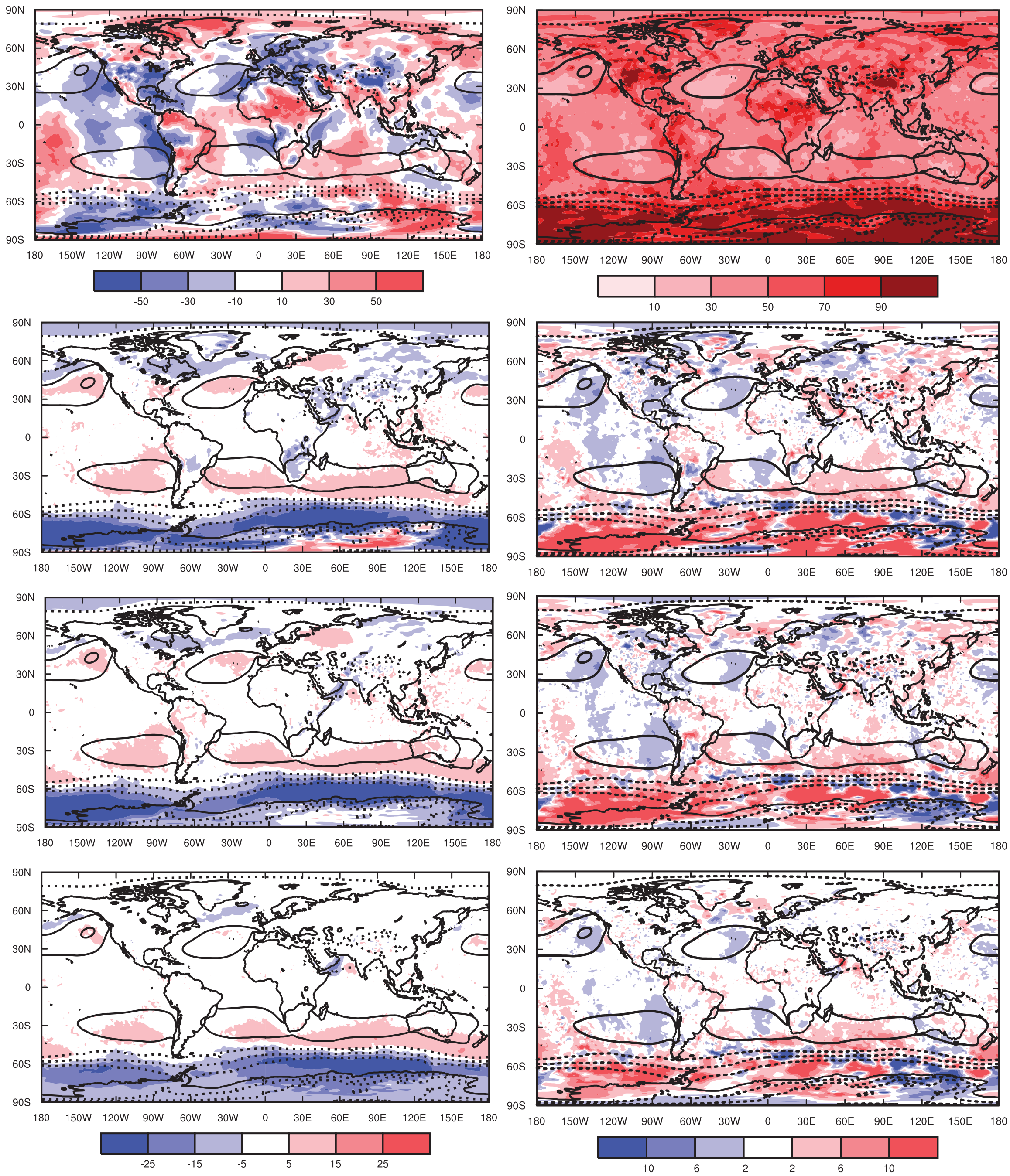

Figure 10: Top: Mean 1000 hPa geopotential height bias (left) and RMSE (right) of the CTL experiment for July 2010, with respect to the analyses from which the forecasts were initialized, at forecast step 24 (verifying at 00UTC). 2nd to 4th row: Change in mean (left) and RMSE (right) of the 1000hPa geopotential height in the runs ST, LT30, LT30-SEA with respect to the CTL run (all in m). A decrease in bias and RMSE indicate an improvement of the model performance.

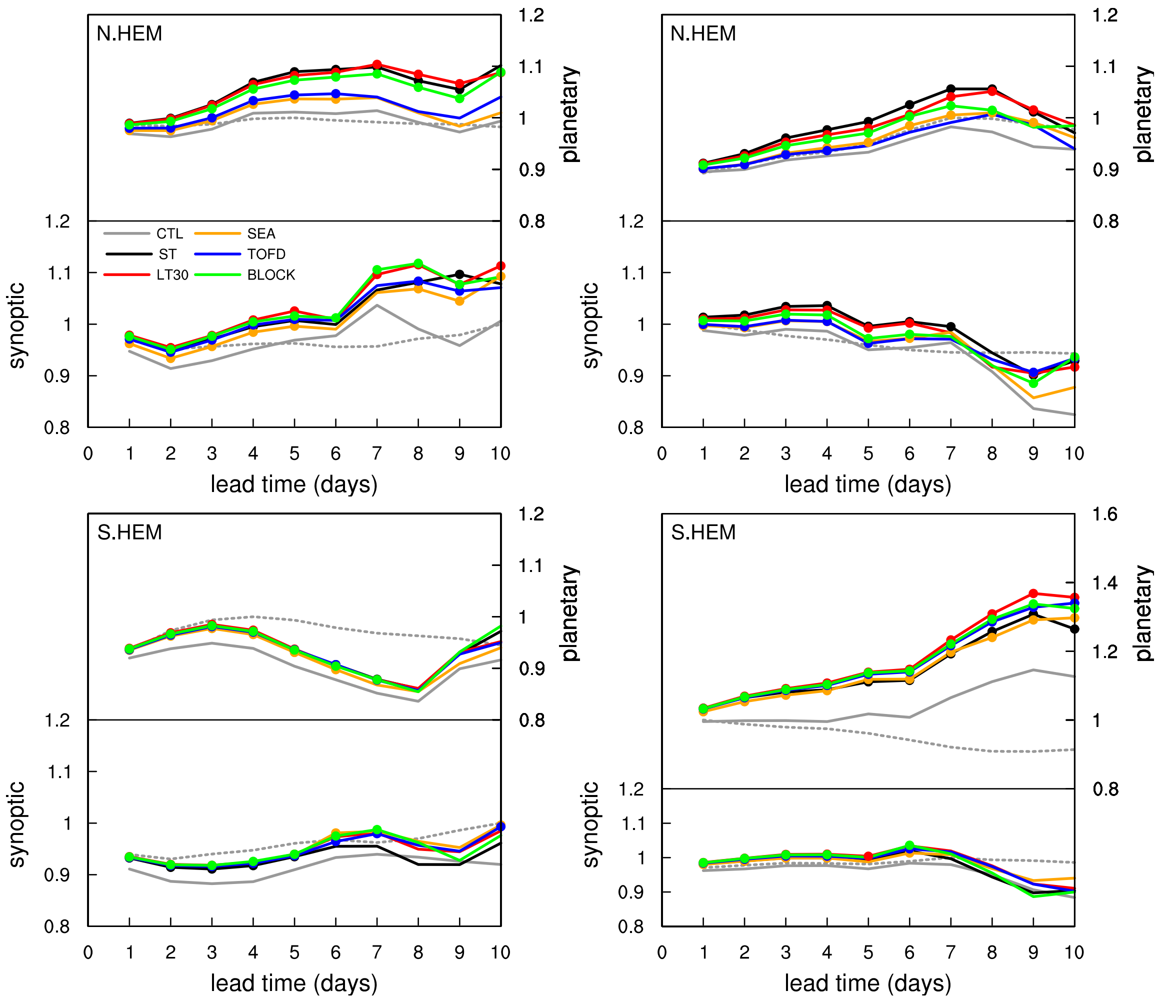

Figure 11: Model activity in terms of geopotential height at 1000hPa at synoptic (lower panels) and planetary scales (upper panels) for the Northern (top) and Southern Hemispheres (bottom) for the various runs performed for January 2011 (left) and July 2010 (right). The dashed grey line indicates in each case the activity in the analyses from which all the forecast are initialized. The activity is computed with respect to a climatology, i.e. $2(a-c)^2$*, or* $2(f-c)^2$*, and in the panels is normalized for all runs by the maximum during the 10 days of the activity in the analyses (at synoptic and planetary scale, respectively). When present the dots indicate that the respective experiment is significantly (95 % confidence interval) better or worse than the CTL, that is the activity in the forecast is closer or further to the one in the analyses than in the CTL run.*

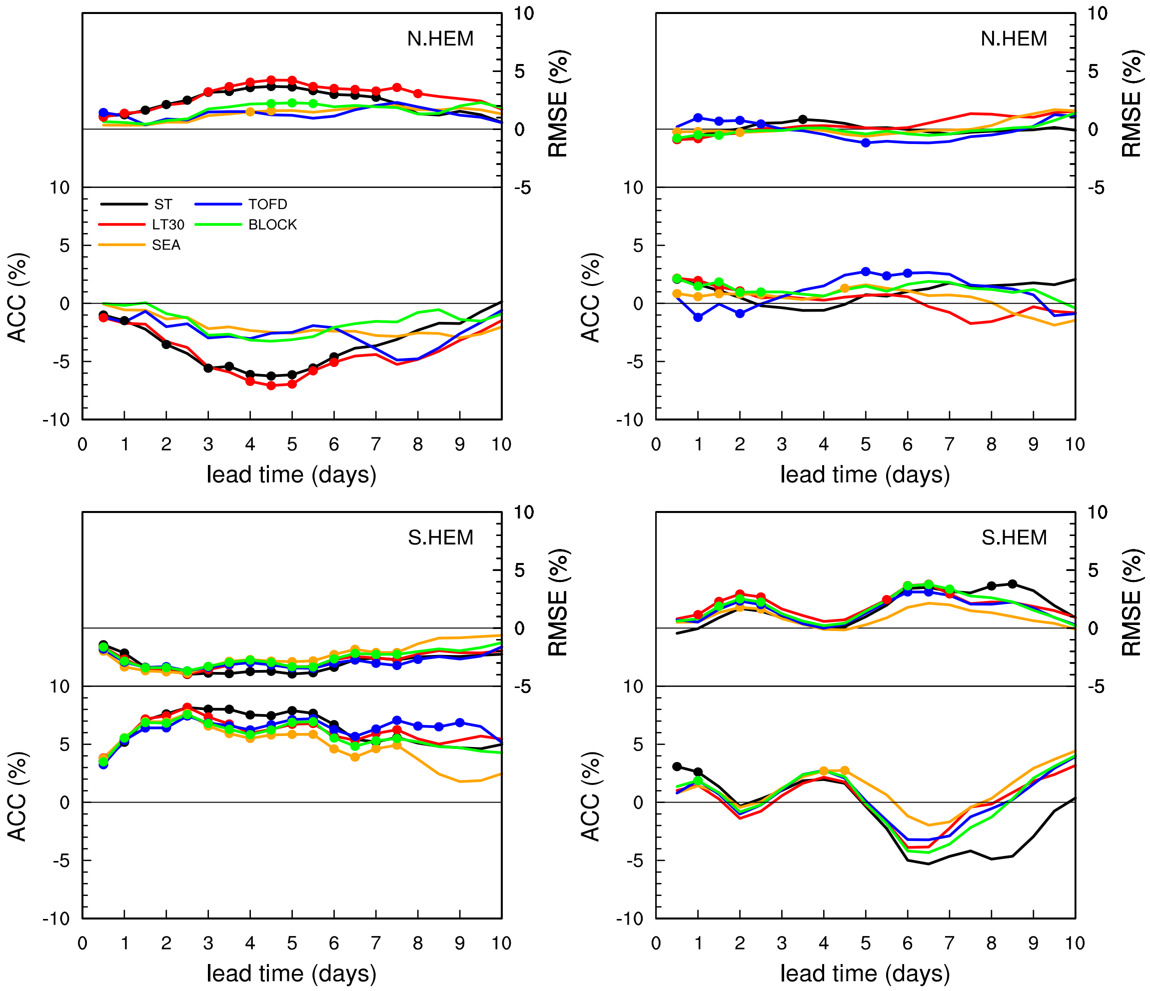

Figure 12: Relative difference of forecast anomaly correlation (ACC) and RMSE of 500hPa geopotential height, between the different experiments and the CTL forecasts performed for January 2011 (left) and July 2010 (right), for the Northern (top) and Southern Hemispheres (bottom). When present the dotts indicate that the respective experiment is significantly better/worse (95 % interval) than the CTL. A negative/positive difference in ACC/RMSE indicates a deterioration of the model performance in the experiment with respect to the CTL.

turbulence closure in stable conditions. For this purpose we have performed a number of sensitivity experiments, but we belabor here only the results of the most relevant ones, i.e. the last three experiments in Table 1.

6.1 Turbulent Orographic Drag and Blocking

The ST and LT30 experiments showed that using less turbulent diffusion close to the surface in stable conditions, which is equivalent to using less surface drag, has an overall negative impact on the representation of the flow in the NH during winter. The LT30-TOFD and LT30-BLOCK experiments (Section 3 and Table 1) investigate whether these detrimental effects can be compensated by an increase in drag in regions with orography.

The changes in the drag in regions with orography appear to affect the activity at planetary scales and but have little impact at the synoptic scales (Fig. 11). An impact on the stationary waves is also suggested by the changes in geopotential height, that appear from the very short range of the forecasts (24 hours). The mean lows indeed become less deep, and the mean highs strengthen even more than in the LT30 runs in both cases, but more so in the LT30-TOFD runs (Fig. 13 versus Fig. 9). The bias and RMSE of geopotential height at 1000hPa are thus comparable to the ones in the CTL run in the lows, hence smaller than in the LT30 runs, and their reduction in the highs is stronger than in the LT30 runs (Figs. 13 and 9). Consequently, the deterioration of the geopotential height scores is less marked in both LT30-TOFD and LT30-BLOCK than in the LT30 runs (Fig. 12). The change in TOFD appears, however, more efficient than the one in BLOCK in improving the model performance during this winter month, not only in terms of bias and RMSE of geopotential height at 1000hPa (Fig. 13), but also in terms of large-scale scores (Fig. 12) and activity (Fig. 11). These results suggest that the deterioration of the model performance in the NH during winter caused by the use of a less diffusive closure near the surface in stable conditions could be at least partially compensated for by an increase in the contributions to drag in regions with orography of the TOFD or BLOCK schemes. This also implies that one of the possible reasons the model needs more diffusion in STBLs encountered during winter over continental surfaces in the NH is to compensate for the poor representation of drag over orography.

During summer, the flow in the NH is affected by the changes in drag over orography, though to less extent than during winter (Figs. 11 and 12). The most notable impact is caused by the increase in the contribution of the TOFD scheme, which seems in this case to slightly deteriorate the performance of the model in the short range, by increasing the errors in geopotential height in mountain regions.

As expected, the changes in drag over orography do not impact the SH to the same extent (Figs. 11 to 13). Here, the changes to the turbulence closure in stable conditions affect the model performance primarily through the effects in the storm tracks.

6.2 Land-Atmosphere Coupling

We also investigated how various parameters used to describe the surface-atmosphere coupling influence the near-surface parameters. One parameter that appeared to play an important role in the representation of the near-surface and soil variables is the skin layer conductivity (Section 3). The COU experiment shows that doubling the values of this parameter for all land surface areas results in a near-surface nighttime warming that ranges on average between 0.2 and 2 degrees. This would partly offset some of the nighttime cold bias (Fig. 4) suggesting that the choice of these coefficients is as important as the one of the turbulence closure for the representation of the near-surface temperature. It also suggests that

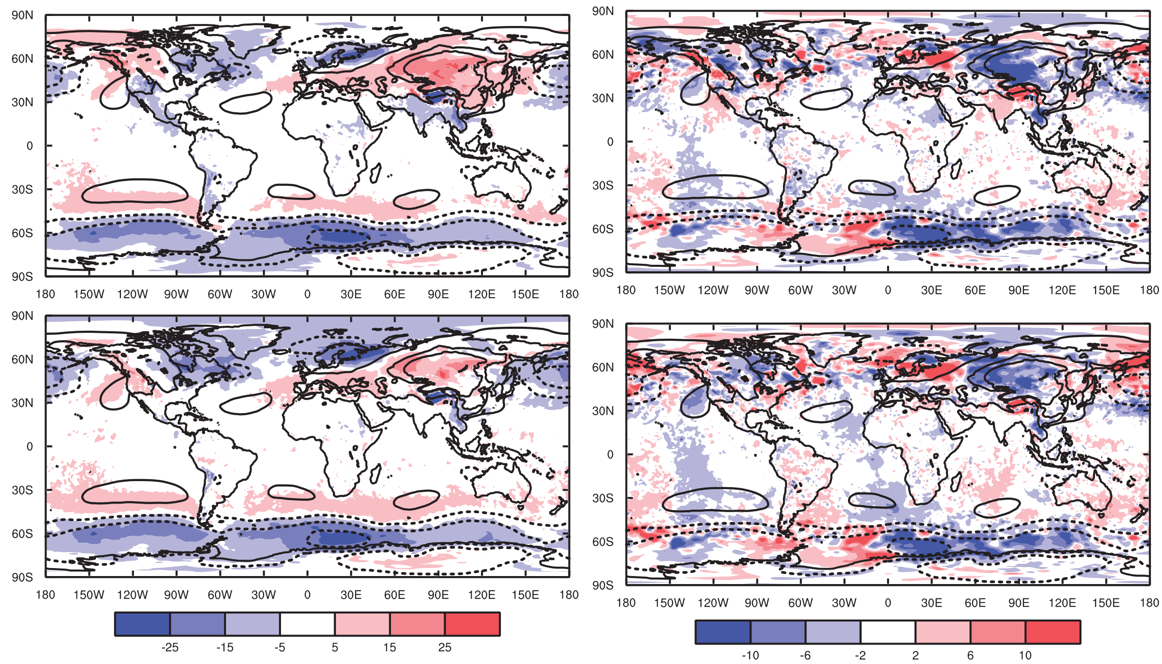

Figure 13: Change in mean (left) and RMSE (right) of the 1000hPa geopotential height at forecast step 24 h (verifying at 00UTC) in the runs LT30-TOFD, LT30-BLOCK compared to the CTL run performed for January 2011 (in m).

increasing the coupling strength could represent a way to compensate for the deterioration of the 2m temperature forecasts that would be caused by a reduction of the turbulent diffusion in STBLs. In order to understand whether such an increase in the coupling would be justified, results from 1 year forecasts relaxed towards the ECMWF reanalysis (ERA-INTERIM) above the boundary layer were compared with observations of soil and near-surface temperature from a couple of hundred stations in Germany. This comparison showed that doubling the current values of the skin layer conductivity would nearly halve the daytime errors for the soil temperature during spring and summer (not shown), while it would not affect the nighttime values. An increase in the coupling would also improve the representation of the nighttime 2 m temperature and of its diurnal cycle (not shown).

7 Summary

The representation of stably stratified turbulence in operational NWP models is a longstanding problem. In a series of forecast experiments we examined the sensitivity of the ECMWF Integrated Forecast System to the formulation of turbulent diffusion and to other parameterizations that may impact the representation of the flow in such conditions.

These experiments showed that using a less diffusive turbulence scheme helps improving the representation of stable boundary layer winds, in terms of low-level jet, wind turning within the boundary layer and diurnal cycle. Moreover, they demonstrated that such a model change impacts the atmospheric flow, by leading to deeper low pressure systems and to stronger high pressure systems. These effects were shown to be 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 situated near the surface has a direct effect on the amplitude of the planetary-scale standing waves. Such effects on the large-scale circulation appear to be related to changes in turbulent diffusion not only above continental surfaces, but also in the STBLs present in oceanic regions, e.g. the storm tracks in the Southern Hemisphere.

This study also demonstrated that using a less diffusive turbulence closure in stable conditions still has detrimental effects on the performance of the ECMWF model, weighing against improvements in boundary layer winds. Although such negative impacts are not obtained for all seasons and regions, they prevent the implementation of a less diffusive turbulence closure as a stand alone change. The most important drawbacks are the deterioration of the geopotential height scores during winter in the NH and an unacceptable increase of the near-surface nighttime cold biases.

It appeared thus that the boundary layer winds, which arguably depend primarily on the turbulence closure, benefit from reduced diffusivity, while other features such as the large-scale flow and the 2 m temperatures are deteriorated by it. This suggests that excessive turbulent diffusion is still needed to compensate for errors in other processes involved in determining the large-scale flow and 2 m temperatures. Therefore we explored possible strategies to mitigate the detrimental impacts of reducing the turbulent diffusion to more realistic levels. We found that (i) ajusting the representation of the orographic drag can help improving the representation of the large-scale flow; (ii) the strength of the land-atmosphere coupling can be used to compensate near-surface cold-biases.

Our investigation suggests that improvements in the representation of stable stratified turbulence in NWP models depend not only on the choice of the turbulence closure for such conditions but also on advances in the representation of other aspects such as the orographic drag or of the land-atmosphere coupling.

Acknowledgments

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