The parameterization of the interaction between the subgrid-scale orography scheme and the turbulence closure in COSMO model

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Abstract

The COSMO model considers a direct impact on the employed prognostic equation of Turbulent Kinetic Energy (TKE) by accounting for the effect of the Subgrid Scale Orography (SSO) scheme on the momentum budget. The treatment of that interaction is already implemented in the COSMO code and can be optionally activated by the namelist parameter *ltkesso*. The impact on the simulated TKE and dynamical variables is investigated by the use of two case studies over North Italy area. Results indicates that the related increase of turbulent mixing at grid points above a pronounced SSO at different altitudes produces main changes in the temperature and wind fields in the same points and downflow to them. Further, within the Stably stratified Boundary Layer (SBL), some (small) impact is also visible above less pronounced SSO. Moreover, near surface variables are verified against observations, distinguishing between stations located at model grid points with a high or low amount of SSO. Scores are improved at high-SSO points and they do not change at the other ones, with the exception of temperature at 2m level, which worsens for SBL cases.

1. Introduction

In the present study, we are dealing with the effect of an extra source for TKE, which has been expressed as a function of the momentum sink term generated by the SSO scheme. This additional TKE source term is already present in M. Raschendorfer's scheme and can be activated by the namelist switch *ltkesso*. The feature is running operationally at DWD (COSMO-EU) since 2011 and has also been activated at Meteo-Swiss (COSMO-7), following the results of a verification performed at DWD in 2011 over a 2 months parallel run with COSMO-EU (*Raschendorfer, 2011*). In that, the main differences over the COSMO-EU domain were on biases of near surface temperature, wind speed and pressure respectively (for the latter the bias was always reduced). The root mean square errors (rmse) of the three variables remained almost unchanged or they improved slightly.

As a supplement, we now present an analysis of the impact on the structure of the whole troposphere. For that purpose we have interpreted the differences in the wind and temperature fields with and without this additional term in different meteorological conditions represented by some cases. The first case is a 3 days period in January 2012, characterized by stable anticyclonic conditions. The second case is a 2 days period in May 2012, characterized by unstable conditions with a cold frontal passage and associated precipitation. The case studies have been performed for the COSMO-I7 domain using the COSMO5.0 version with a namelist configuration similar to that of COSMO-EU [1]. COSMO's initialization and boundary conditions came from

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[1] Differently from COSMO-EU, the sea ice and lake formulations were not activated.

ECMWF analysis and no data assimilation was activated. For each case study, we obtained a COSMO run with the *ltkesso* option set off and on. We focus on the differences between the 2 runs over Northern Italy, which contains regions with high and low SSO (e.g. the Alps and the Po Valley respectively).

The direct impacts of *ltkesso* on turbulence and the indirect effect on the dynamical fields are described in sections 3 and 4. Further on, we verified the experimental and control runs against the stations network of Northern Italy for both the cases, distinguishing between stations with high and low SSO (sect. 5). Finally, the results are summarized in sect. 6. In the next section there is a short description of the idea behind the additional TKE source term.

2. Background and parameterization description

The presence of the Subgrid-Scale Orography (SSO) induces additional pressure forces (form drag) to the mean flow, which are firstly related to a direct sink term in the budgets of the mean horizontal momentum components (blocking effect). Further, a small part of the Mean Kinetic Energy (MKE) of the flow is converted into vertically propagating gravity waves. As soon as they break, they cause a disturbance of the mean flow, associated with an additional sink term in the mean momentum budgets. In the COSMO model, these sink terms are parameterized following Lott and Miller's approach (*Lott and Miller, 1997; Schulz, 2009*), providing the related sink terms of horizontal momentum in the following form:

$$\left.\frac{\partial \overline{\rho} u_i}{\partial t}\right|_{SSO} = \left.\frac{\partial \tau_i}{\partial z}\right|_{SSO}, i = x, y \tag{1}$$

In eq. (1), $\tau_i|_{SSO}$ is a virtual vertical flux density of horizontal momentum (stress), which includes both the stress by gravity-waves and blocking. The scheme further provides a local dissipation heating term to be considered in the temperature equation.
The new development of M. Raschendorfer considers that all sink terms in the budget of the mean momentum vector are always associated to sink terms in the budget of the Mean Kinetic Energy (MKE), which in turn correspond to source terms in the budget of subgrid-scale Kinetic Energy (SKE) according to the following fomula (see e.g. *Raschendorfer, 2011*):

$$\partial_t MKE|_{SSO} = \overline{u_i} \cdot \partial_z \tau_i^{SSO} = -\partial_t SKE|_{SSO} \tag{2}$$

Formally, $\partial_t SKE^{SSO}$ (2) contains also the energy production of the gravity waves, which takes place below the SSO effective height together with the blocking and which is then transformed in drag where the waves break. Neglecting the remote character of this part of SKE release, $\partial_t SKE|_{SSO}$ thus describes the direct conversion of MKE into SKE, as wake production. As those motions typically are not in accordance with the closure assumptions of a turbulence scheme, they cannot be treated as a part of the latter. Based on a formal scale separation, M. Raschendorfer developed the concept of Separated Turbulence Interacting with (non-turbulent and still unresolved) Circulations (STIC), which is also part of the COSMO Science Plan for the current year. In the framework of this approach, which is so far only described in an internal paper, the Sub-Grid Scale (SGS) motions induced by SSO themselves produce kinectic energy of scales that can be described by the turbulence scheme(*Raschendorfer, 2011*).

Thus in a first approximation, $\partial_t SKE|_{SSO}$ can be treated as an additional production term of TKE, which intensifies the vertical turbulent mixing for all prognostic variables whenever the SSO scheme is active. Hence by this extension, the kinetic energy extracted from the mean flow by the action of SSO is not immediately dissipated into inner energy. Rather it is transported through all SGS motions until it is finally dissipated.

3. Effects on turbulence

The additional source term in the TKE equation appears with the largest increment at model grid points at pronounced SSO (often corresponding with high altitude of resolved orography), mainly within the following three ranges of altitude: at the lowest model levels, at the top of the troposphere (around $10km$ height) and at the highest model levels (Fig. 1). Obviously the effect at the lowest model levels refers mainly to the direct blocking component, while the middle and highest levels are affected by the breaking gravity waves.

In these regions, a large increase of TKE and diffusion coefficients due to the SSO effect is simulated by the model (Fig. 1; diffusion coefficients not shown). This significant effect demonstrates the potential of this measure to simulate strong signals of Clear Air Turbulence (CAT) above structured orography, which also has valuably improved the turbulence forecast for aviation (*M. Raschendorfer and A. Barleben, 2014*).

At model grid points above low SSO, the additional source term in the TKE equation and the consequent impact on values of TKE and diffusion coefficients is very small (not visible in Fig. 1). However, in the stable stratified atmosphere a non-negligible feedback in terms of destabilization may appear.

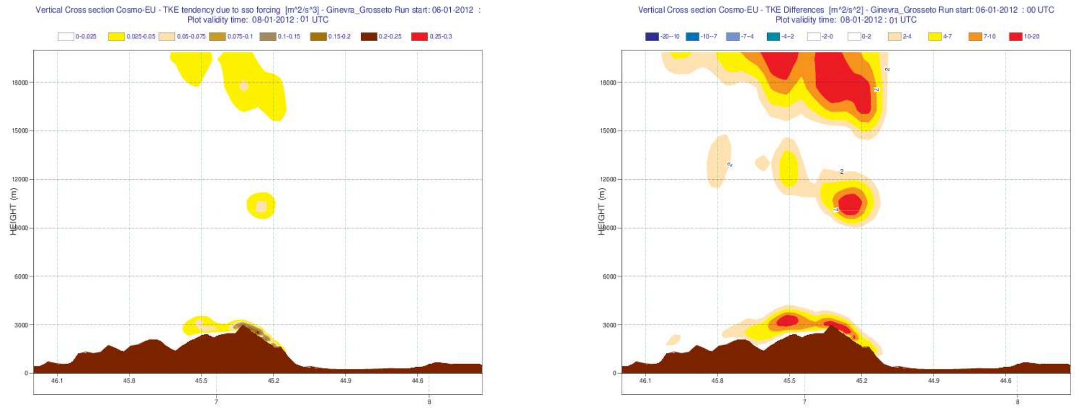

Figure 1: Cross vertical sections of the additional term into TKE equation (left) and the difference in TKE between the case with *ltkesso* enabled and without (right). The plots refer to the January case study (08/01/2012-01:00). The cross sections are parallel to the main component of the geostrophic flow (from North-NorthWest), in the plot coming from the left side.

4. Effects on dynamical variables

The case study of January is used to analyze the situation (Fig. 2). The geostrophic flow comes from North-North-East and crosses the Alps (from the left side in Fig. 2). Gravity waves are developed and break at the tropopause producing a slowing down of wind. In the lee of the mountain, the flow weakly interacts with the SBL located at the mountain feet, being dragged only slightly.

The main impact of *ltkesso* appear at model grid points above considerable SSO (which mainly is the case, if gridscale orography is pronounced as well) and at points downflow to the latter where flat SSO is prevailing. One grid point for each of these regions has been selected (see black dashed line in Fig. 2). For these two points, vertical profiles of potential temperature θ, horizontal wind speed $\overline{u}$ and TKE between the surface and 14km are shown in Fig. 3. Above that level, the impact of *ltkesso* on those profiles is negligible.

At point above high SSO, the vertical gradients of θ and $\overline{u}$ are reduced in correspondence with the turbulent mixing increases (surface-4 km and 8-14 km).

Conditions of a stably stratified atmosphere (generally scarcely diffusive) are the ones being most sensitive to the increase of turbulent mixing. In those cases, the reduction of the vertical θ gradient causes a warming in the lower part and a cooling above, as it is visible between the lowest model level and 4km in Fig.2. Similarly, the positive vertical gradient of wind speed at the lowest levels reduces, leading to stronger wind close the surface and weaker above. Moreover, the combination of intensified wind speed and higher diffusivity produces a higher surface momentum flux, which subtracts kinetic energy to the mean flow, causing a further reduction of it in the upper layers. At the level of breaking-waves, the increased mixing planes out the perturbation of the wind and θ profiles generated by the SSO scheme.

At point above low SSO downflow to the high-SSO region, it is supposedly the advection that leads a layer of colder air with weaker horizontal wind speed and higher TKE between 2 and 4km in the run with *ltkesso* activated (Fig. 3). Similarly above 4km, the increase of $\overline{u}$ refers to the smoothing of the gravity-wave-breaking perturbation.

The downward flow along the mountain slope has a non-sufficient MKE to significantly interact with the SBL underneath. Thus, in the mountain lee a more intense thermal inversion develops (Fig. 3). However, notice that this is a local effect, since at a proper distance from the mountain slope it is the the slight increase of mixing at the lowest model levels that dominates the modification on the vertical boundary layer profiles, as a direct effect of *ltkesso* (visible also in TKE profile in Fig. 3). As in the previous case, the impact is mostly visible in the SBL, where the thermal stratification slightly reduces, leading to a near surface warming and a cooling above. In the case study of May, the geostrophic flow comes from South and the main deviations in θ and $\overline{u}$ appear over the Alps and in their downflow on the Swiss side (graphs not shown). As the additional source of TKE equation is smaller compared to the one of January, this holds also for the magnitude of its feedbacks on the other prognostic model variables. Nevertheless, the same tendencies have been observed.

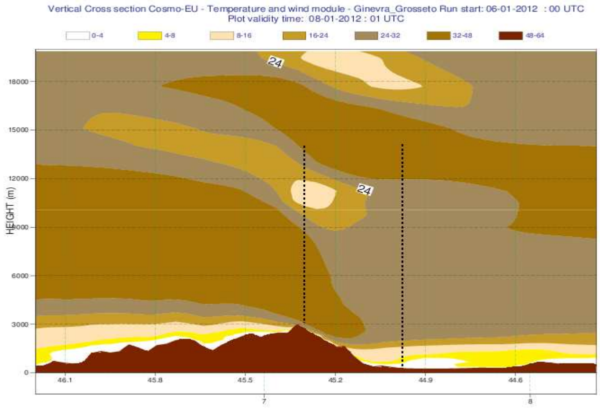

Figure 2: Vertical cross section of the horizontal wind speed [m/s] in the run without *ltkesso* enabled in the January case study. The section is parallel to the geostrophic flow (from North-NorthWest), in the plot coming from the left side. Time: 08/01 01:00. The two dottet lines correspond to the profiles plotted in Fig.3

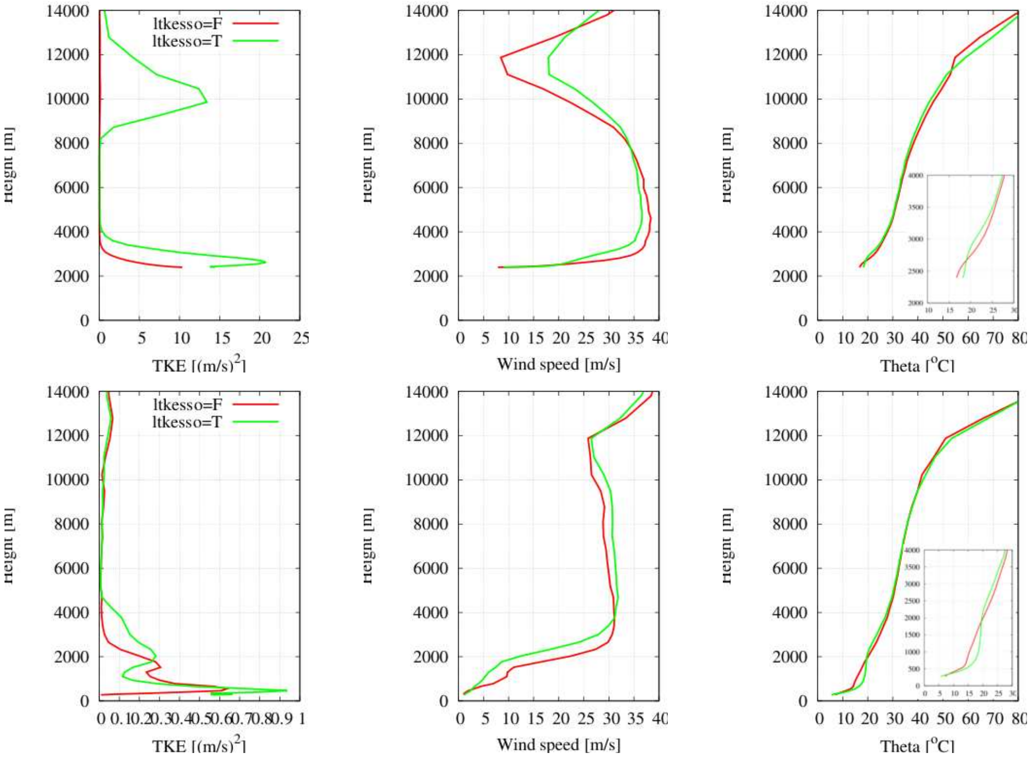

Figure 3: Simulated vertical profiles of TKE (left), horizontal wind speed (middle) and potential temperature (right) in a model grid point with high SSO (lat=45.3, lon=7.2; top line) and in a point downflow (lat=45.0, lon=7.5; bottom line) simulated with and without *ltkesso*. Time: 08/01 01:00

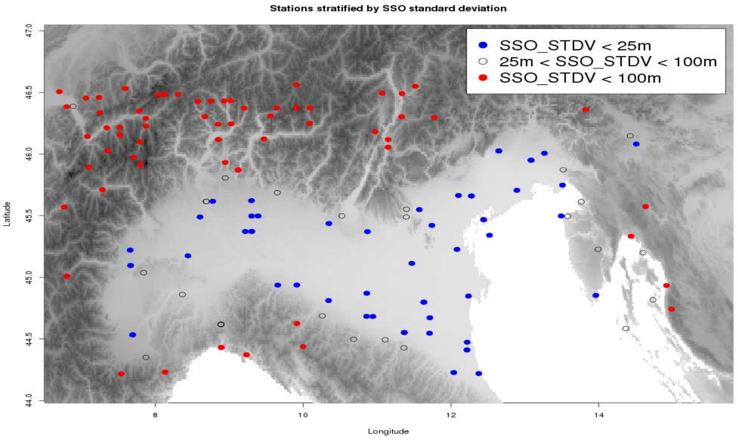

Figure 4: Stations used in the verification aggregated on the base of the sso_stdv value of the closer model gridpoint

5. Verification

The verification is performed by aggregating model grid points with similar SSO standard deviation (sso_stdv), as an indication of the presence of SSO [2]. Two categories are considered: stations which nearest model grid point has sso_stdv-values below 25m in the first category, and above 100m in the second one (Fig. 4). The geographical pattern of sso_stdv broadly corresponds to that of the grid-scale orography, however this is not always true (e.g. the highlands have high altitude but small sso_stdv). The verification of 2m temperature (Fig 5) at high sso_stdv points outlines how the negative bias is mitigated, mainly by the effects of the increased mixing at the lowest model levels (see sect. 4). In the January case, the bias and rmse decrease is about $1 - 1.5K$, while in the May case the improvement is smaller ($\leq 0.5K$), due to the lower impact of *ltkesso*.

At low sso_stdv points, a light warming up is visible, but only in the January case. During day this mitigates the negative bias, however during night it enlarges the positive bias. This nocturnal positive bias is correlated to the over-diffusive turbulence scheme in the SBL, related to some un-physical limits in turbulence code preventing the TKE to fade out (*Cerenzia et al., 2014*). Hence, the activation of an additional source of TKE (despite its small entity) further promotes the over-mixing. However, this induced destabilization in SBL demonstrates the potential of *ltkesso* to sustain the turbulent diffusion even above points with low SSO. Thus, this measure will be beneficial in order to substitute the still present additional unphysical mixing in the scheme.

The verification scores of the wind speed at 10m (Fig 5) in points at high sso_stdv are improved by the intensification due to the increased mixing at the lowest model levels (see sect. 4). The improvement is about $0.5m/s$ in the January case, and less in the May case, for the same reason mentioned above. The verification in points at low sso_stdv provides a very small signal, which is difficult to interpret. The verification performed against all the stations (Fig 5, 6, top line) shows a general improvement by the application of the *ltkesso*-option in terms of 2m temperature, 10m wind speed and mean sea level pressure (the latter not shown for brevity). The observed intensification of temperature and wind speed, and lowering of pressure (all at the near surface levels) are in agreement with the results obtained over the full COSMO-EU domain in 2011 (*Raschendorfer, 2011*).

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[2] sso_stdv is a constant field employed in COSMO model in the SSO scheme and it can be retrieved from the model output.

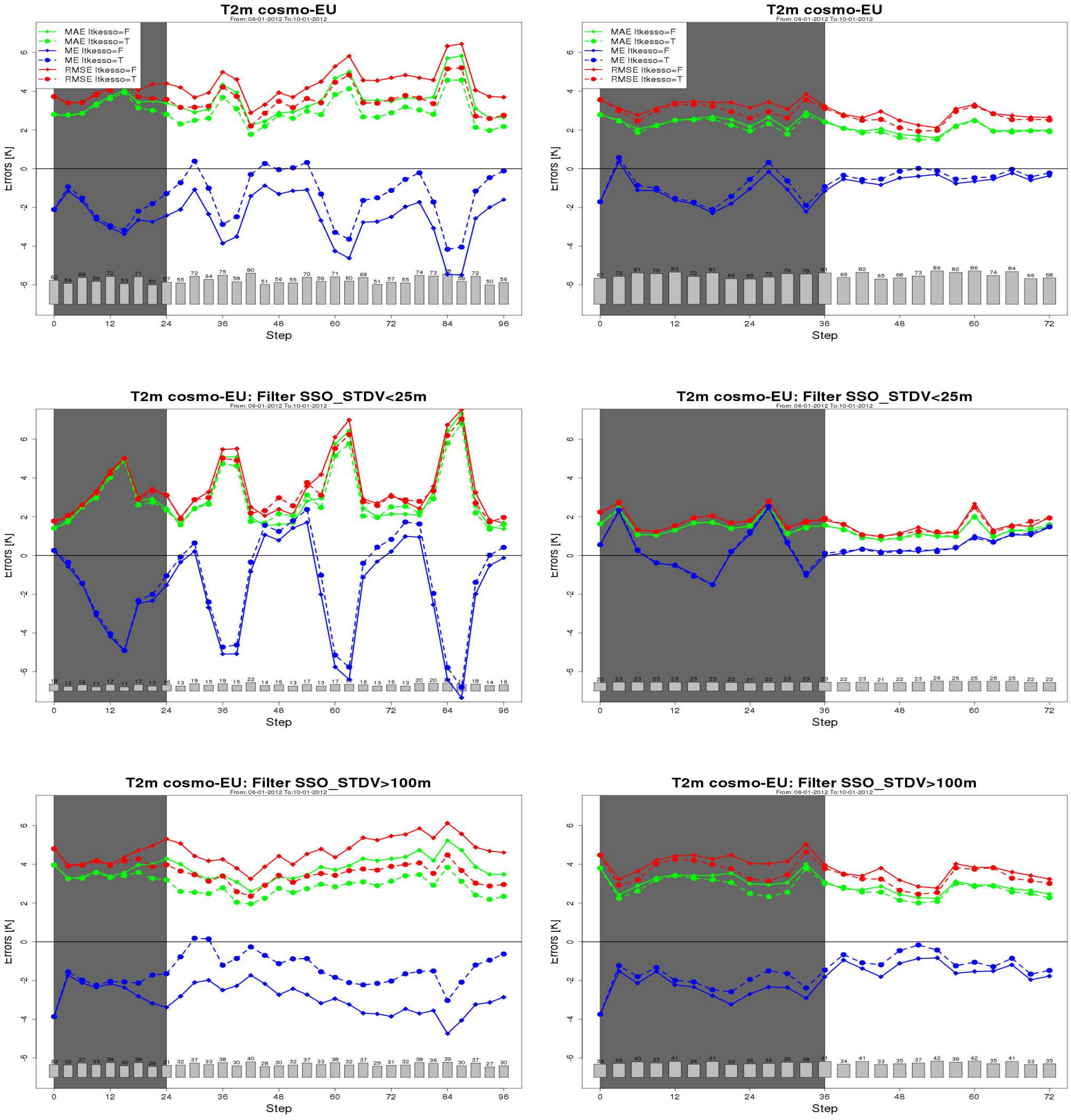

Figure 5: Verification of 2m temperature in the January and May cases (left and right respectively). All North Italian stations (top line), only North Italian stations which nearest model grid point has sso_stdv below 25m (middle line) and only North Italian stations which nearest model grid point has sso_stdv above 100m (bottom line). The histograms represent the sample size for each time range. The grey shaded area is considered as spin-up time and it is not involved in the analysis.

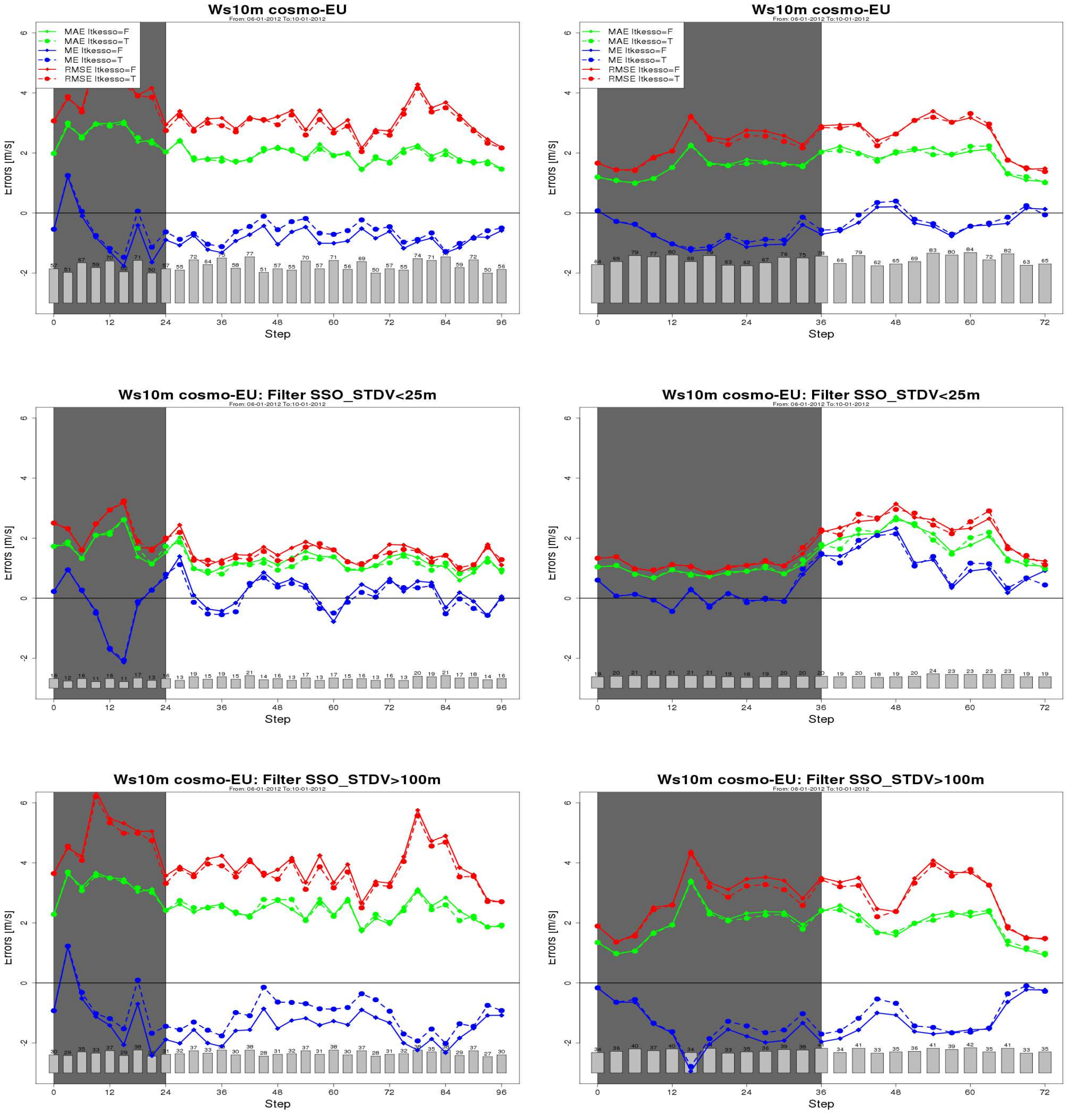

Figure 6: As in Fig.5 but for 10m wind speed.

6. Conclusions

We studied the effect of the additional source for TKE, derived from the sink term of momentum generated by the SSO scheme. It is based on the hypothesis that Sub-Grid Scale (SGS) motions induced by SSO themselves produce kinectic energy, that can be treated by the turbulence scheme. This hypothesis belongs to the framework of the Separated Turbulence Interacting with (non-turbulent and still unresolved) Circulations, developed by M. Raschendorfer.

The analysis of the case studies underlines that a large additional amount of turbulent kinetic energy is generated due to the additional TKE source mainly at three ranges of altitude above areas of pronounced SSO: at the lowest model levels, at the top of the troposphere and at the highest model levels. The first one is associated to the blocking effect on flow by SSO, while the other two to the gravity-wave breaking.

We evidenced that the related increase of turbulent vertical mixing at the lowest levels produces significant feedbacks on the wind profile above those areas. As a primary effect the vertical positive gradient at the lowest levels is reduced, intensifying the near surface wind speed and slowing it above. Since the surface momentum flux intensifies as well, by the increase of the low-level wind speed and diffusivity, effectively more momentum is extracted from the upper layers. In terms of temperature, the impact is significant mainly in cases in which the turbulence activity is weak, e.g. in SBL. In those cases the profile destabilizes, leading to a near surface warming and a cooling above. The effects on the near surface variables are very beneficial by comparing the simulations with the data collected in North Italy stations located in sites at pronounced SSO (sso_stdv higher than 100m). The negative biases of wind and temperature are reduced in both the case studies considered, although the effect is more evident in the case characterized by stable anticyclonic conditions.

Moreover, the significant TKE production at the top of the troposphere is in accordance with the results of Raschendorfer and Barleben (2014) above structured orography and confirms the potential of this measure to reproduce the Clear Air Turbulence occurrences.

A minor impact on the simulation has been observed also at areas above low SSO. It is partially associated to the advection downflow of the modifications generated at points above pronounced SSO, and partially directly induced by an increase of diffusivity at the lowest levels due to the additional TKE-source. Neglecting the local effect of the downflow, only stable boundary layers appear sensitive to this intensified diffusivity, because the increment is comparable with the typical values for stable stratifications. At the moment, the effect is detrimental on the near surface temperature, in comparison with data collected at sites above low SSO (sso_stdv lower than 25m). This may be associated to the fact that the SBL is already over-mixed, due to the use of some un-physical limits in the turbulence code. Nevertheless, the potential of this measure to sustain the turbulent mixing in conditions of weakly diffusive background is an actractive feature. Therefore, we suggest that this kind of physical based additional terms in the TKE equation will help to prevent the use of the current undesired numerical limits in the turbulence scheme.

In order to confirm the results obtained from these two case studies, a verification based on the same thresholds of sso_stdv is currently performed over the COSMO Common Area. The results will be available in the next Common Plots report.

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