Diagnosis of Turbulence Schema in Stable Atmospheric Conditions and Sensitivity Tests

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1 Introduction

The sensitivity of NWP models to the representation of the stable boundary layer (SBL) is widely recognised, but unfortunately its simulation is still an open issue. This is partly due to the multiplicity of physical processes at work (turbulent mixing, radiative cooling, interaction with land surface and its heterogeneities, gravity waves, katabatic flow, fog and dew formation) and partly due to the insufficient understanding of them (*Steenveld, 2011*). In the last 15 years, many operational weather forecast models shows a significant benefit in the prediction of synoptic low pressure systems with the introduction of an enhanced mixing in SBL, which compensated in some way the lack from physics (*Holtslag et al., 2013*). The resulted SBL is too deep, with too strong surface drag and eroded low level jet, underestimated wind rotation with height in the lower levels, weak thermal inversion and too warm temperature in the lower part of the PBL (*Cuxart et al., 2006*). COSMO model is not exonerated and hints of the overmixing in the SBL were detected in the too fast dissolving of low level stratus during night (verified at the German Weather Service DWD, 2012), in the overestimation of temperature at 2m (T2m), verified by all COSMO members during nights with particularly stable stratification (clear sky and weak wind) with an extent ranging between 0.5 and 3°C (*COSMO Common Plot 2012-13*) and in the weak structure of thermal inversion and low level jet (observed operationally over Po Valley, Italy).

This study aims to analyse COSMO performance in stable stratified and weak wind (very stable) atmosphere. Due to the particular orography structure, Po Valley provides a large statistics of this conditions. Then a case study has been selected in winter 2012 without any fog and cloud. At first, a diagnosis of the operational simulation is given, underlining the impact of the most active limits and the presence of a time oscillation (section 2). Then, two modified model versions with a decreased mixing are considered. The effect on PBL mixing and temperature is reported, mentioning also the consequences on the observed oscillations. In sections 3 and 4, the focus is on flat area (San Pietro Capofiume (SPC) station is considered as reference) and then it is extended to heterogeneous terrain (sec. 5). Finally the more promising version has been run for three months in a parallel way to the operational COSMO and the results are here summarized (sec. 6). The operational configuration of COSMO-I7 has been used and the output at every timestep is considered.

2 COSMO turbulence scheme in stable conditions

In the operational COSMO setting, the turbulence scheme uses a 1-D closure with a prognostic equation for Turbulent Kinetic Energy (TKE), which corresponds to level 2.5 in Mellor- Yamada notation (*Mellor et al., 1982*). The time trend of TKE , expressed in term of q ($q = \sqrt{2\,TKE}$) prescribes the balance between different forcings (first three terms r.h.s), the dissipation and its vertical diffusion (4th and 5th terms):

$$\frac{dq}{dt} = -\frac{1}{q}\overline{u'w'}\frac{\partial \overline{u}}{\partial z} + \frac{1}{q}\frac{g}{\theta_v}\overline{w'\theta'_v} + f_C - \frac{\epsilon}{q} - \frac{1}{\overline{\rho} q}\frac{\partial}{\partial z}\left[\frac{1}{2}\overline{\rho}\overline{q^2 w'}\right] \tag{1}$$

Besides the forcings due to the wind shear and the buoyancy (the first and second terms r.h.s., later called f_m and f_h), some additional contribute to TKE is given by the interaction with the circulations (f_C), i.e. the energy transfer from subgrid scale (SGS) coherent eddies to turbulent scale (Separated Turbulence Interacting with Circulation, STIC approach, *Raschendorfer, 2007-2011*).

Currently in the operational settings, f_C includes only the circulation due to SGS thermal inhomogeneities of the surface [1]. Practically, this term is parameterized as the vertical variation of the product between a length scale (representative of the SGS surface thermal pattern) and the buoyancy forcing: $f_C \propto \frac{\partial}{\partial z}[L_{therm}\,(-f_h)]$.

[1] In COSMO operationally used at DWD also the effect of circulation forced by SGS orography is enabled

The 'thermal' lenght scale is estimated from grid size dynamic variables, external settings (horizontal resolution and one of the namelist parameter) and the SGS clouds coverage. If SGS clouds are not present, L_{therm} does not include any dependency on SGS features [2].

In stable stratification with weak wind shear, the additional energy coming from circulations is relevant with respect to the small amount of TKE forcings and vertical transport. As example see in fig. (1) the TKE budget terms at the lowest main level in increasing atmospheric stability in the case study considered. When buoyancy forcing is negative and wind shear is weak to maintain mixing, the transfer of energy from the circulation scale should support turbulence, avoiding the zero-going of mixing and fluxes.

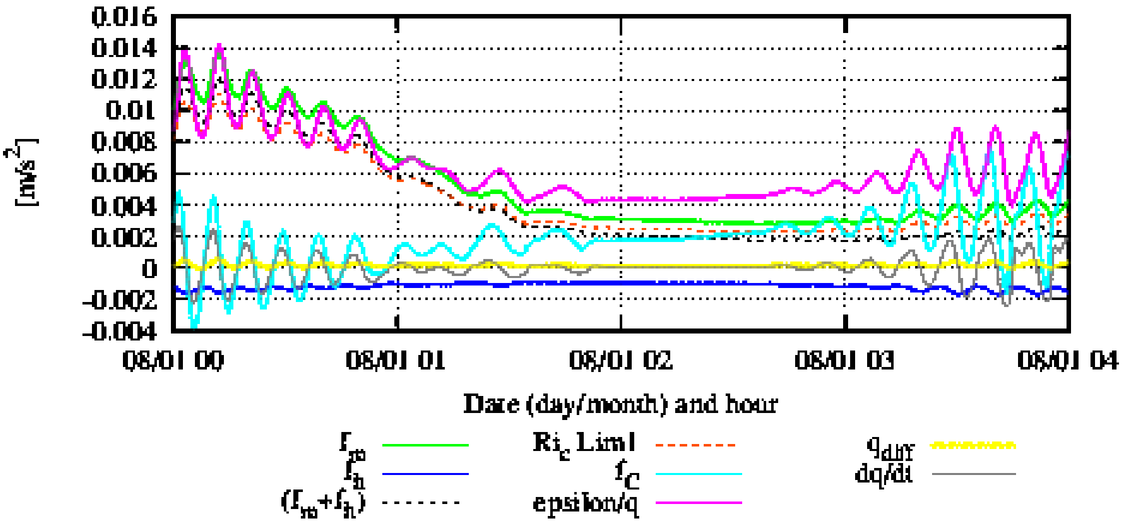

Figure 1: Terms of TKE equation in a stable case in the proximity of $Ri_f = Ri_c$. Ri_c is exceeded at around 01:00 when "Ri_c Lim" line is above the "$f_m + f_h$" line

Nevertheless, some security limitations are active in order to prevent turbulence to decay. The most documented ones are the minimum limits for the vertical diffusion coefficients of momentum and scalars (namelist parameters *tkmmin* and *tkhmin* see *Cosmo User's Guide, 2013*). In principle, they force the system to continue mixing also when the diffusion coefficients would drop below the prescribed minimum values. In the shear driven SBL case study simulated with COSMO Single-Column by Buzzi, the detrimental effect of this measure on the simulation of the SBL structures has been already underlined (*Buzzi et al., 2011*). In the same case study, it appears that the largest minimum limit of the diffusion coefficients not altering the SBL representation is K_{min}=0.01 m^2/s, while in current operational setting it is K_{min}=1 m^2/s (or 0.4 m^2/s as recently suggested by DWD in order to avoid the detrimental effect on boundary layer clouds previously mentioned).

In weak wind SBL, one can expect an even worse effect on the simulation, given that a stronger stratification should be established. In the case study considered here, the limitation to K_{min}=1 m^2/s is frequently occurring (fig. 2). In the next sections, some tests with a reduced K_{min} are described.

Another constraint acts on the sum of buoyancy and wind shear forcings in the TKE equation when the Richardson flux number ($Ri_f = -\frac{f_h}{f_m}$) exceeds the critical value Ri_c (equal to 0.19 in operational setting), i.e. in very stable stratification. Essentially in this case the buoyancy term is excluded from the TKE calculation, so that the forcing sum depends only on mechanical forcing (positive definite), then the sum is prevented to become negative. Therefore, states of the system beyond Ri_c are not described by the TKE equation and are brought back to less stable conditions. In fig. 1 an example of the activation of this limitation is plotted (called "Ri_c *Lim*"). Neglecting this limitation produces a crash of the model run as soon as the forcing sum ($f_m + f_h$) becomes negative (its square root is required in the TKE calculation). A modulation of this limitation is at the moment tested (Raschendorfer and Cerenzia) and possibly will be included in the next COSMO version 5.1.

According to our experience, these limits strongly affect the simulation of the very SBL.

Furthermore, the operational scheme appears to be not fully stable in stratified atmosphere. In fact, especially when Richardson flux number is close or above the critical value, some high frequency oscillations (about 15 timesteps in the used configuration) are excited (fig. 1, 2). All turbulence related variables (diff. coefficients,

[2]For a detailed description refer to *Raschendorfer, 2007* and *Cerenzia et al., 2013*

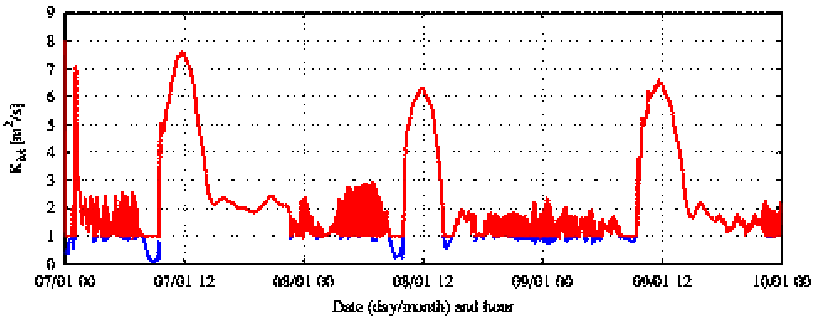

Figure 2: Time series of momentum diffusion coefficient at the lowest model level. Blue segments are the coefficient below the limit $K_M = 1m^2/s$

TKE, wind, temperature, humidity, surface values..) near the surface (three to four levels up to the bottom one) are involved. Some tests performed to check the numerical origin underlined as the oscillations are sensitive to changes of numerical scheme or integration timestep but their behaviour is not directly pointing to a numerical issue (*Cerenzia et al., 2013*).

3 Reduction of minimum limit of vertical diffusion coefficients - Test 1

For this test, the minimum limits of vertical diffusion coefficients are lowered to the value $K_{min} = 10^{-2}m^2/s$. Since values of $K_{M,H}$ below these thresholds are quite uncommon also in very SBL (e.g. *Yague et al., 2006*), then these limits would not reasonably influence the PBL modelling.

At first the flat terrain case is analysed. The closer grid point to SPC station site (2 km away) is considered and the horizontal homogeneity assumption is done in order to compare model results with observations.

In the stable case examined, the diffusion coefficients drop below the default threshold along all the vertical profile (see fig. 3, scalar coefficient not shown but similar to the momentum one). However at 900 hPa a spurious peak is present (described later). Temperature profile indicates a strengthening of stratification in the modified run with lower temperature at the surface and higher at the inversion. Wind speed profile does not show relevant changes, with the exception of the layer at around 900 hPa.

Looking at the time series at the bottom level (fig. 4), the diffusion coefficients slightly reduce in stable cases (on the average also during oscillations despite high mixing is locally produced). This is beneficial for T2m, that shows a lower overpredition of observations each time the diffusion coefficients drop below $K_{min} = 1m^2/s$. Unfortunately a decrease of T2m is present also during day, likely due to an indirect effect since the mixing is not significantly modified. The oscillations visible in stable cases are sensitive to the reduction of the diffusivity limit: their amplitude is strongly enlarged, their period is approximately doubled and they are less wavy and periodic (fig. 4).

4 Elimination of thermal circulation term (f_C) - Test 2

The thermal circulation term resulted as the most active source in increasing the TKE at low levels in stable conditions, especially when the Ri_f exceeds the critical value (fig. 1). Furthermore, it seems to have some special correlation with the oscillations since it anticipates the wave of one-two timesteps with respect to other terms (fig. 1). Therefore, a second case study has been performed switching off the thermal circulation term in TKE budget (setting namelist parameter *patlen*=0) and keeping $K_{min} = 0.01m^2/s$.

The first result is a complete elimination of time oscillations at all levels and in each field. However, preliminary tests (not showed) indicate that the triggering cause of oscillations is not due to an instability in the parameterization of f_C term. Other possible sources of the oscillations (interaction between f_C and the stability functions or with the limitation for Ri_c number, ..) will be further investigated.

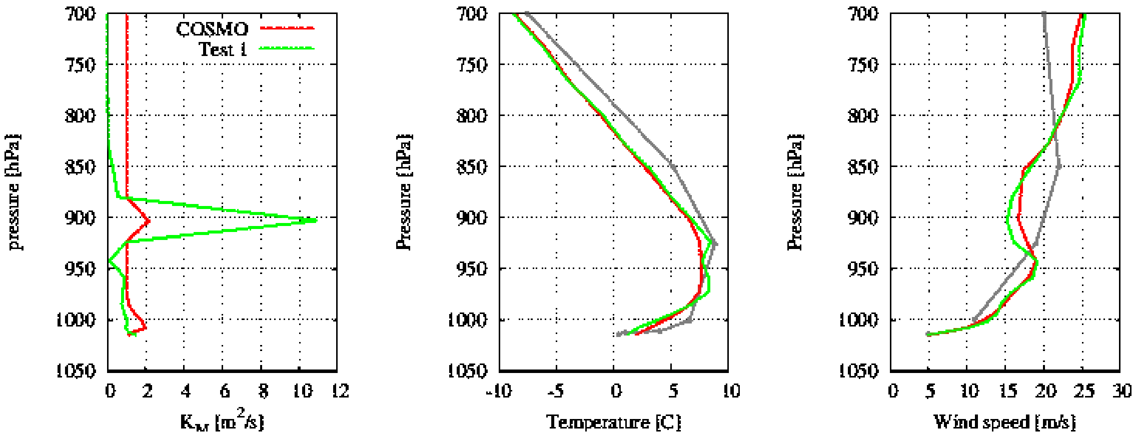

Figure 3: Vertical profiles of Momentum diffusion coefficient(left), Temperature(centre), and Wind speed (right) at SPC site, on the 08/01/2012 at 00:00. Grey line represents the radiosounding observations, if present, red and green lines are COSMO default and Test 1 respectively

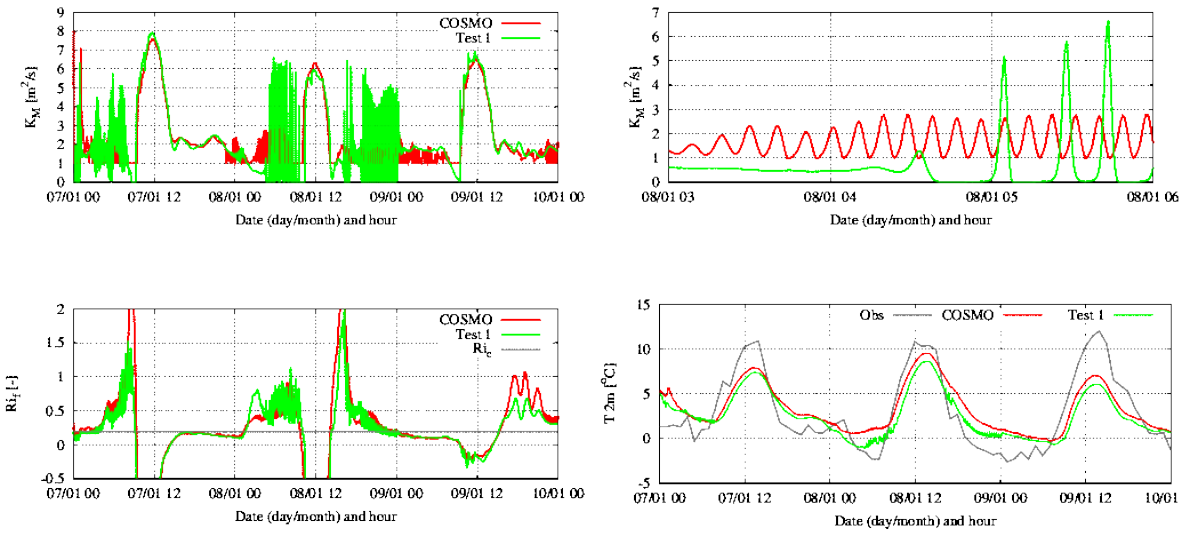

Figure 4: Time trend at the lowest main level of momentum diffusion coefficient (top left) with a zoom during oscillations (top right), Ri_f number (bottom left) and 2 metre temperature (bottom right). Red line represents COSMO default while green line is Test 1. Grey line are observations, if available

In this second case study, the mixing during stable conditions strongly decreases with respect to Test 1, partially because of the disappearance of the oscillations and partially for the lack of the additional TKE production. Consequently, temperature at low levels and at the surface drops (fig. 5, centre), leading to a lower T2m in close agreement with observations (fig. 6). Daily maxima are unchanged compared to Test 1. With respect to the observations, the modified run shows a delay of the surface warming up after sunrise.

The shortcomings rise looking at the vertical profiles of temperature, wind and K_M where some unrealistic "jumps" come now to light (fig 5). The peak of K_M at 900hPa already observed in Test 1 may be attributed to these fluctuations. Another inconsistency is for instance the exceptional positive mixing on the night of 9 January (fig. 6), due to an unstable layer at the bottom level (in fact, Ri_f is negative, not shown).

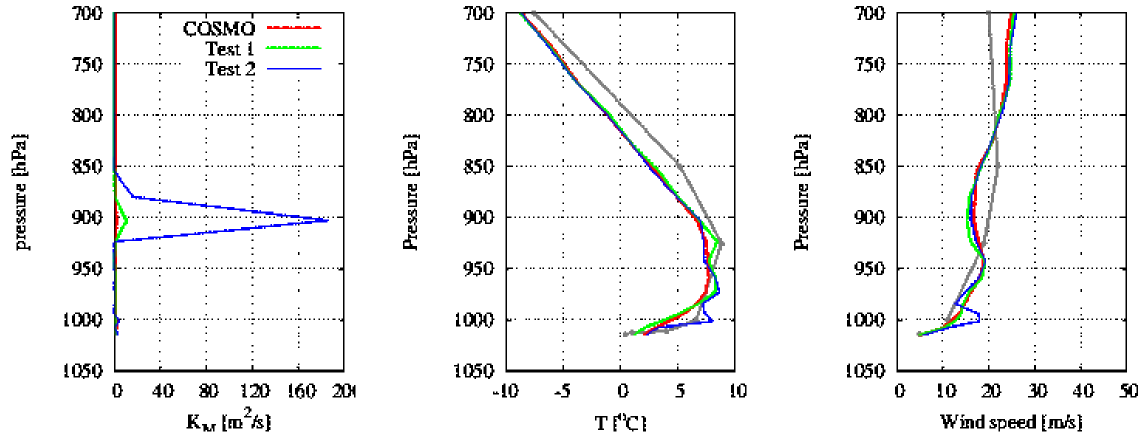

Figure 5: Vertical profiles of momentum diffusion coefficient(left), temperature (centre), and wind speed (right) at SPC site, on the 08/01/2012 at 00:00. Grey line represents the radiosounding observations, if present. Red line is COSMO default, green line is COSMO with $K_{M,H} = 0.01m^2/s$ (Test 1) and blue line is COSMO with $K_{M,H} = 0.01m^2/s$ and $patlen = 0$ (Test 2)

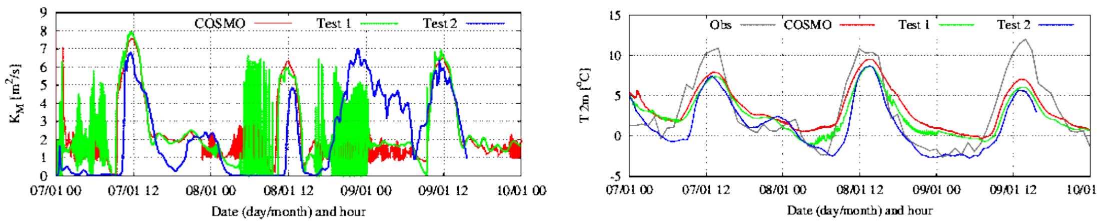

Figure 6: Time trend at the lowest main level of momentum diffusion coefficient and 2 metre temperature. Red line represents COSMO default, green line is Test 1 and blue is Test 2. Grey line are observations, if available

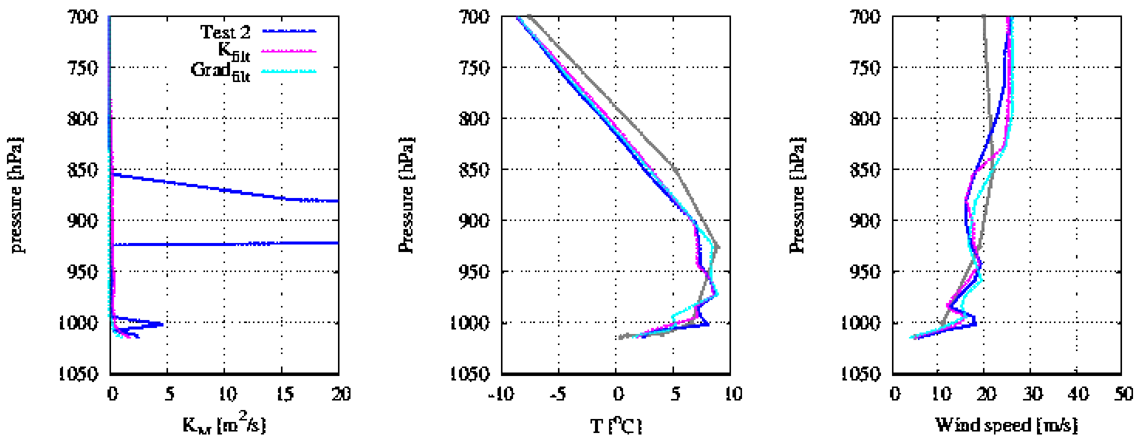

Figure 7: Vertical profiles of momentum diffusion coefficient(left), temperature (centre), and wind speed (right) at SPC site, on the 08/01/2012 at 00:00. Grey line represents the radiosounding observations, if present. Blue line is Test 2, dotted magenta and ceylon lines are the runs with the filter applied respectively on $K_{M,H}$ and on the vertical gradients before evaluating the stability functions

The origin of this vertical fluctuations is still not understood. The thermal circulation term represents in TKE calculation practically the main interaction between different vertical levels in stable conditions, because it includes a second order vertical derivative and it largely exceeds in magnitude the same order term, i.e. vertical TKE diffusion (compare in fig. 1 f_C and q_{diff} terms). Therefore, if it is removed (as in Test 2), the levels are more decorrelated. However, signs of the vertical instability can be seen also in Test 1. Therefore the absence of f_C can not be the only reason of the vertical fluctuations.

Many analogies are present with the instabily detected by Buzzi (2011) in the shear driven idealized case study above mentioned, which is performed with the same configuration (no thermal circulation and reduced $K_{M,H}$ limit). He relates this instability to a physical inconsistency of the stability functions in Mellor-Yamada scheme (*Mellor 2003; Burchards and Deleersnijder 2001*) and he showed that a 5-points vertical filtering of the stability functions and of variables connected to them (diffusion coefficients,wind gradient, dimensionless momentum gradient) is able to completely remove the fluctuation.

In order to test if the origin of the "jumps" seen in the present case study is the same and if the solution is working, the filtering of the diffusion coefficients (named "K_{filt}" in fig. 6) and of both wind and potential temperature gradients before evaluating the stability functions (named "$Grad_{filt}$") are applied to Test 2. In both cases, the spurious peak of K_M at 900hPa is eliminated as a direct effect of the vertical filter. Instead the fluctuations on the profiles of derived variables as temperature and wind are smoothed (with a greater extent in "$Grad_{filt}$") but not removed. This is a hint of the fact that some other source of instability is present in the present case study.

5 Effect of both modifications on Northern Italy area

The results of Test 1 and 2 have been analysed on the Northern Italy scale during the same three days, in order to get a sense of the effects of the two modifications on a non-homogeneous rough terrain. The vertical filtering has not been applied in this study.

If the minimum diffusivity is reduced (Test 1), a decrease of T2m is evident with greater extent on gridpoints sited in flat and hilly area during the more stable periods (fig. 8, left side). There is a minor impact on mountain because in general the stronger wind shear keeps the diffusion coefficients above the value of 1 m^2/s and the atmosphere in a less stable condition. The effect of time oscillations can be retrieved in the onset of some localized peaks at low levels changing location and intensity in time (graph not shown). They are more visible in TKE and diffusion coefficients, coherently with the larger amplitude recognized also at SPC, and they appear only in flat or hilly regions.

Neglecting f_C in the TKE equation together with the diffusivity limit reduced (Test 2) causes a further reduction of mixing in more stable periods accompanying a decrease of T2m (fig. 8). However, the decrease shows different extents on different topography, due to the relative impact of the thermal circulation.

- In flat regions the reduction varies between 1 and 5^oC. In this area, the modified run is overall in agreement with the majority of stations showing anyway a slightly negative mean error (BIAS between $+1^oC$ and -2 ^oC, fig. 9). The overestimation of T2m typical of COSMO operational setting is avoided.
- The lowering is about 5^oC in hilly and low mountain area and the comparison with the observations indicates that it is excessive (fig. 9). In fact, thermal surface inhomogeneities are always present in rough topography (creating a differential cooling and heating) and the additional turbulence production is effectively required.
- Generally, in very high mountain regions there is a small difference between COSMO default and Test 2, again because the atmosphere is less stable due to mechanical forcing and the thermal circulation term has not a leading role in TKE budget.

This suggests some considerations on the correct formulation of f_C, which currently does not include any information on the subgrid scale pattern of temperature or even orography (in absence of SGS clouds, like in this case). Clearly the additional production of TKE due to thermal circulation is not necessary when a SGS heterogeneity is not effectively existing.

As a final consideration on Test 2 performance, the horizontal peak-structures variable in time seen in Test1 disappeared, demonstrating that they are really the manifestation of the time instabilities.

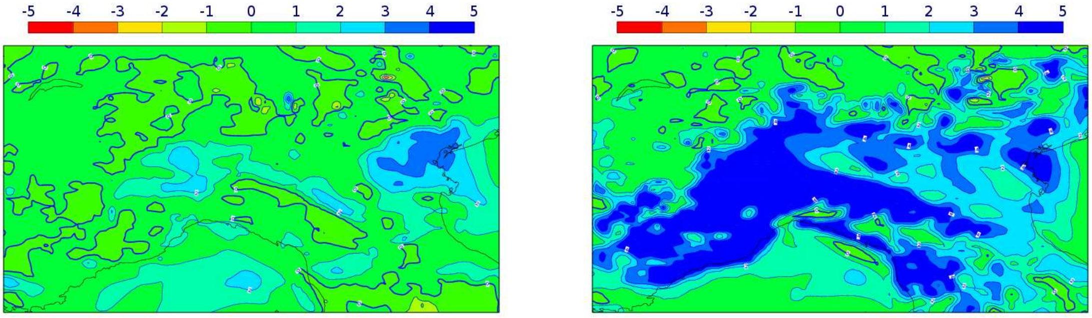

Figure 8: Maps of difference of T2m between COSMO default and Test 1 (left side) and Test 2 (right side). The scale is in $[^oC]$. The maps refer to the output at 08/01/2012-4:00 am

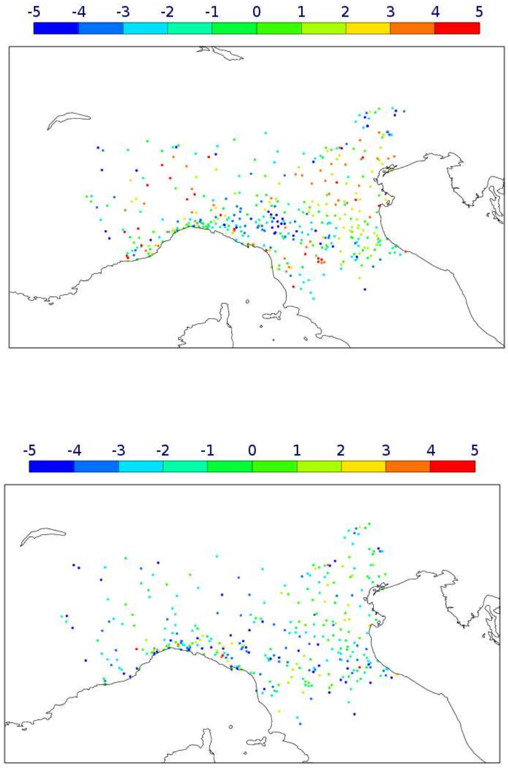

Figure 9: BIAS of T2m in COSMO (top) and in COSMO Test 2 (bottom) against observations. The scale is in $[^oC]$ and red points indicate positive BIAS while blue points negative BIAS. The maps refer to 08/01/2012 at 4:00am

6 Operational verification

A further analysis has been performed running the COSMO version with the reduced limit of diffusivity and without the thermal circulation term (Test 2) on COSMO-I7 domain for three months (no vertical filtering has been applied). The boundary conditions come from GME, while the soil state is obtained from the analysis of the assimilation cycle of Test 2, based on continuous nudging ("independent soil"). The forecasts of T2m are verified and compared to COSMO operational performance (BC taken from IFS, with "independent soil" as well). The deviation on T2m due to the different initializations is negligible compared to the effects of the changes in COSMO version (from a comparison between COSMO-I7 with the BC of IFS and GME, not shown).

The general effects of Test 2 over all meteorological conditions and in all stations in Italy are a modified and smaller daily amplitude of BIAS and an increased RMSE during night with respect to the operational run (fig. 10, left side). The first aspect indicates that the modifications applied in Test 2 strongly impact on T2m forecast. With respect to the observations, T2m appears colder at every hour with a larger extent during night, which means that the nocturnal reduction of mixing is often occurring and is on the average overpowered. The increase of the RMSE during night (when Test 2 modifications are active) is an indication that the changes effect is negative, if applied to all the atmospheric and topographical conditions. This is not surprising, seen that the modifications are led by considerations valid on the very stable atmosphere. Encouraging is the almost unchanged RMSE of T2m during day, suggesting a small influence of the modifications on the error in these hours.

If only conditions favourable to the presence of highly stable stratification (clear sky, low wind intensity and data observed in stations only coming from flat, low altitude regions) are considered, the reduction of the daily cycle of BIAS is even greater (fig. 10, right side). Furthermore, an improvement is visible in both BIAS and RMSE during the first night. Subsequently, the T2m simulated by Test 2 is colder than COSMO-I7 at every hour and it is approximately 1.5^{o}C colder than the observations. This is a hint of the fact that the reduction of mixing which causes the decrease of 2m temperature is slightly excessive also for highly stable stratification in flat area, in agreement with the considerations done on the Northern Italy domain in the case study. Furthermore, after the first night, the RMSE is greater in Test 2 than in COSMO-I7, which implies a larger variability of the error. This is partially due to the the redundant drop of mixing and partially points out the difficulty of the turbulence scheme to represent the very SBL. Moreover, the vertical fluctuations noted in this case can have some effect in increasing outlying results and finally, also the erroneous representation of the stable boundary layer in hilly and low mountain regions can negative affect the large scale flow (due to its sensitivity to SBL simulation), then leading errors also in flat, low level regions.

7 Conclusions

The simulation of PBL in condition of stable stratification (night with clear sky and weak wind) in unsaturated atmosphere has been studied.

In the operational configuration, it appears that the SGS parameterization of sources of TKE and some unphysical limits aim to increase mixing, often in an artificial way. Moreover, an oscillation in time exists in all turbulence related variables at the lower PBL in very stable conditions or close to. Its influence is negligible for operational necessity (e.g. time oscillations on T2m have an amplitude of approx. 0.1-0.2°C), however it is clear that the current turbulence scheme is so far not fully tested in this condition.

A reduction of the limit on the vertical diffusion coefficients to a value not affecting the physics ($K_{min} = 0.01m^2/s$) generates a stronger stratification and generally improves the simulation of minimum T2m. Unfortunately, this reduction reinforces the previously mentioned time instability. A second test run shows that the time oscillation is related to the term added to the TKE budget considering the turbulent kinetic energy induction by thermal SGS circulations (f_C). In fact, neglecting it, the time oscillation is removed. However, some vertical fluctuations of all fields are now evident. An attempt to solve them through a vertical filter of some variables related to the stability functions (following Buzzi et al., 2011) produces a smoothing of peaks but not the removal of the fluctuations. It is concluded that this second instability has another origin, still to be understood.

A collateral effect of the setting to zero of the thermal SGS circulations term (together with a reduced minimum limit for the diffusion coefficients) is the further reinforcement of the stratification with the drop of T2m, due to the role of strengthening of mixing that f_C assumes in very stable stratification. However, it appears that this drop is excessive on T2m both in flat terrain, where the underestimation is about $1.5^{o}C$ (note that the removal of the operational overestimation of T2m during night implies a damping of the daily cycle of BIAS), and mainly in rougher terrain (hilly and low mountain), where the underestimation can reach 5°C. This indicates the necessity to reformulate the parameterization of circulations due to sub-grid scale surface thermal heterogeneities and their effect on turbulence, for example enabling a dependency on some SGS features like SGS orography.

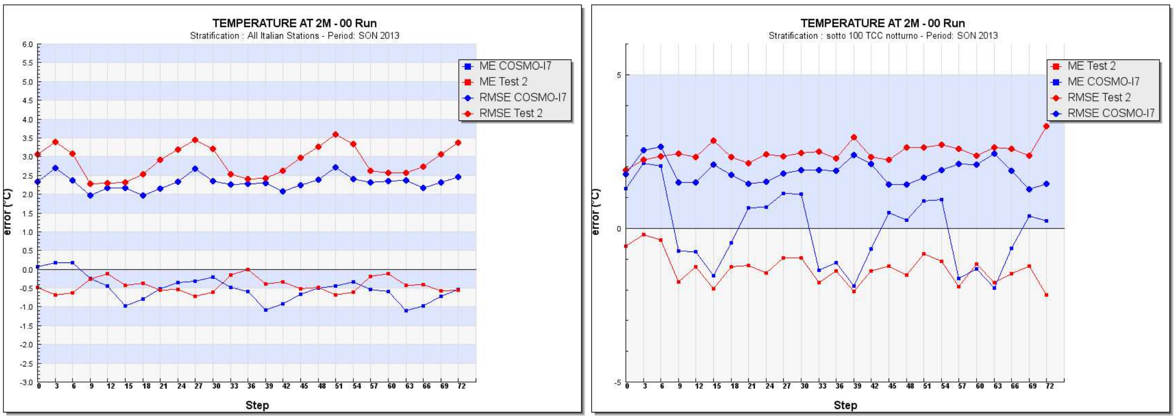

Figure 10: Verification of T2m in COSMO (blue line) and COSMO Test 2 (red line). In the left plot the 3 months data coming from all italian stations are considered while in the right plot only observations in clear sky ($TCC < 25\%$) and low wind ($U_{speed} < 2m/s$) conditions coming from stations sited below 100m of height are verified

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