A sensitivity test to assess the impact of different soil moisture initializations on short range ensemble variability in COSMO model

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1 Introduction

A well-known problem with mesoscale ensemble forecasts is their lack of variability between members near the surface.

Surface condition uncertainties are generally not taken into account in ensemble systems, and ensemble forecasts often use the same surface conditions for all members.

However, the sensitivity of moist atmospheric processes to soil conditions has been demonstrated in numerous studies.

Sutton et al. (2006) used two soil moisture analyses originating from two different land surface models (LSM) forced with exactly the same meteorological data. The results showed significant differences in near-surface temperature and precipitation and suggested that the variability induced by soil moisture differences can, in fact, increase the spread of ensemble members and improve on the short-range weather forecasting.

Aligo et al. (2007) used a similar approach showing that perturbations applied only to soil moisture might not be enough to produce sufficient variability to precipitation forecast and a better ensemble set can be constructed from perturbing also other aspects such as atmospheric initial conditions.

Quintanar et al. (2008) used a similar approach to that used by Sutton et al. (2006) and Aligo et al. (2007) providing additional insight for soil moisture impacts on ensemble spread. They evaluated, in addition to precipitation and temperature, also ensemble spread in terms of relative humidity, horizontal and vertical wind and showed that soil moisture perturbations can produce sufficient spread for vertical velocity (thus, precipitation) but not for RH, T and horizontal winds. They also suggested that additional experiments need to be undertaken where soil moisture and atmospheric initial conditions perturbations and model physics would be considered simultaneously.

Klüpfel et al. (2011) investigated the impact of soil moisture on precipitation amount and distribution in model simulations for West Africa with the COSMO model at 0.025^o resolution. They used three analysis fields, satellite measurements, and model output from a Land Surface Model to initialize five convection-permitting model runs of COSMO, forced by reanalyses from the European Centre for Medium-Range Weather Forecasts. The spread between the five precipitation forecasts suggests that a high-resolution limited area ensemble built by applying atmospheric variations as well as variations of the initial land surface conditions lead to an improvement of the prediction of mesoscale convective systems and convective precipitation for West Africa.

Considering all these studies, it is clear that it would be very important to integrate surface perturbations into an ensemble system to account for uncertainties in surface conditions and to effectively increase the ensemble spread near the surface.

In this regard, some techniques have been proposed in the recent years. Sutton and Hamill (2004) implemented an empirical orthogonal function (EOF) method that was used to generate random perturbations with the same spatial structure as the daily deviations of soil moisture from a running-mean climatology.

A non-cycling surface breeding method was proposed by Wang et al. (2010), where short-range surface forecasts driven by perturbed atmospheric forcing are used for generating the perturbation to surface ICs. A simple method proposed by Hacker (2010), consists in the construction of perturbations of the soil moisture field that represent random, spatial correlated errors, to quantify the response to soil moisture perturbations. He recognized that this method is not suited for reproducing the characteristics of the actual soil moisture uncertainty, which varies locally with the properties of the soil, vegetation and background moisture itself (Hacker, 2010).

Lavassey et al. (2013) used a similar approach to assess the impact of uncertainties in surface parameter and initial conditions on numerical prediction with the Canadian Regional Ensemble Prediction System (REPS). In this work, perturbations at the initial time of one or several surface parameters or prognostic variables (soil moisture and temperature) are generated using a two-dimensional random function on the sphere correlated in space, with a probability density function symmetric around the mean. This preliminary study of the impact on the ensemble forecast showed that the inclusion of the surface perturbations tends to increase the ensemble spread for all screen-level variables especially for 2-m temperature and 10-m wind speed and significantly increase the 2-m temperature and 10-m wind speed skill.

Cloke et al (2012) proposed a simple method, perturbation of 2 soil scheme parameters, in the ECMWF seasonal forecasting system.

In the COSMO Priority Project CONSENS a methodology for soil moisture perturbation based on Sutton and Hamill (2004) was developed by the Hellenic National Meteorological Service (COSMO Technical Report No. 22). The method was never tested in ensemble mode but it could be revived and tested on the new ensembles under development.

At DWD a simple method was developed to derive initial condition soil moisture perturbations from differences between COSMO-EU und COSMO-DE soil moisture. This approach is now implemented in COSMO-DE-EPS.

The goal of this study is to perform a sensitivity test to assess the response of the COSMO model to different lower boundary initial conditions in the framework of the COTEKINO (COsmo Towards Ensembles at the Km-scale IN Our countries) Priority Project, aimed at developing convection-permitting ensembles in the COSMO countries. In fact, even if the sensitivity of the atmospheric moist processes to different soil condition initializations has been demonstrated in several studies previously mentioned, it cannot be generalized to a completely different modeling system. Hence, it would be wise to verify a sensitivity in COSMO model before implementing soil moisture perturbations, and to have a quantification of the model reaction. The study of Klüpfel et al. (2011) for the West Africa lead us to imagine positive results also for our test.

2 Dataset and methodology

Different models with different spatial resolution have been chosen to ensure a good variability among the soil moisture fields used to initialize COSMO model for the sensitivity test.

Model	COSMO EU analysis	ECMWF analysis	GFS analysis	GLDAS-NOAH LSM reanalysis	UTOPIA LSM reanalysis
Resolution (^{o})	0.063	0.125	0.500	0.250	0.250
Soil levels depth (cm)	1, 2, 6, 18, 54, 162, 486, 1458	7, 28, 100, 289	10, 40, 100, 200	10, 40, 100, 200	1, 2, 6, 18, 54, 162, 486, 1458

Table 1: List of the analyses and reanalyses used to initialize COSMO model with the correspondent spatial resolution and soil level depths in cm.

As regards the reanalysis of land surface state coming from NOAH LSM, this is driven by a Global Land Assimilation System (GLDAS). GLDAS is a system that integrates satellite and ground-based data within multiple offline LSMs to produce fields of land surface states and fluxes at several spatial resolution (See Rodell et al., (2004) for further details).

The UTOPIA (University of TOrino land Process Interaction in Atmosphere, Cassardo et al. (2006)) model is a diagnostic one-dimensional land surface model (similar to TERRA LSM) developed at the University of Torino since 1989, and can be categorized in the class of the SVAT schemes. UTOPIA can be used both as a stand-alone model or coupled with an (global or mesoscale) atmospheric circulation model, behaving as its lower boundary condition.

A first step towards the creation of a soil moisture field ready to initialize COSMO model, is to take into account the soil texture distribution of the original soil model. To this end, we computed the degree of saturation S:

$$S = \frac{\eta_w}{\eta_S} \tag{1}$$

where η_w is the volumetric soil water content and η_S is the soil porosity of the original model depending on the spatial distribution of the soil texture used in the original model. For this computation, the soil texture map for each model considered was necessary, together with the raw initial soil moisture fields.

Afterward, the vertical interpolation of S over TERRA-LM soil levels was performed and then also the rotation and the spatial interpolation over the finer COSMO 0.025^o grid. As regards the vertical interpolation over TERRA LM soil levels, we noticed that for most of the models the depth of the bottom soil level is lower than the one in TERRA LM (289 cm for ECMWF, 200 cm for NOAH and GFS vs. 1458 cm for TERRA LM). Hence for these models, being the vertical interpolation not possible for the two deepest levels of TERRA LM (486 and 1458 cm), we extrapolated the values at these two depths using the soil moisture values of the bottom soil level of the original model (289 cm for ECMWF, 200 cm for NOAH and GFS). Finally, the final value of the volumetric soil water content $\eta_{w\,final}$ ready to initialize the model is computed by multiplying the degree of saturation S by the soil porosity of COSMO model at 0.025^o resolution $\eta_{S\,COSMO}$:

$$\eta_{w\,final} = S\,\eta_{S\,COSMO} \tag{2}$$

The only exception to this preprocessing procedure was for the COSMO EU fields for which only rotation and spatial interpolation over the COSMO 0.025^o resolution grid was performed.

The procedure adopted here is different from the one used operational version of INT2LM. Setting in the namelist l_smi=TRUE, the soil moisture index SMI is used instead of the degree of saturation S:

$$SMI = \frac{\eta_w - \eta_{wp}}{\eta_{fc} - \eta_{wp}} \tag{3}$$

where η_{wp} and η_{fc} are the wilting point and field capacity of the original model.

Further considerations have to be done for the reanalysis coming from UTOPIA LSM. The model needs the following boundary atmospheric condition to run: 2m air temperature, relative humidity RH, X and Y components of the wind speed, total cloudiness, low cloudiness, and precipitation. The first 6 variables are taken from ECMWF analyses, whereas for the last one (precipitation) the TRMM gridded precipitation dataset has been used. TRMM (Tropical Rainfall Measuring Mission) is a gridded precipitation product at 0.25^o resolution coming Multisatellite Precipitation Analysis (see Huffman et al., 2007 for further details). Despite the higher resolution of ECMWF analyses (0.125^o), all the initial boundary conditions for UTOPIA LSM coming from the IFS are upscaled at 0.25^o resolution to ensure the homogeneity of resolution with the gridded precipitation product. Another possibility was to use ERA-Interim reanalysis to obtain the gridded precipitation data that we needed, but for this product the horizontal resolution was too small for our purposes ($\approx$ 80 km of ERA-Interim 0.5 vs. $\approx$ 25 km of TRMM 0.25 precipitation data).

Since the soil moisture and temperature in UTOPIA LSM were initialized arbitrarily at the beginning of the simulation, a spin up period was necessary to let the two fields approach real values. To this end, two months simulation before the desired date were performed for each case study considered here.

Snow depth initialization was also taken into account at the beginning of each simulation using the ECMWF analyses, because of the important role of the snowpack on the soil water budget, especially over the alpine region and in the winter case studies.

3 Case studies

For this sensitivity test several few case studies taking into account summer and winter conditions were selected to evaluate the (potential) differences in sensitivity of the COSMO model in the different seasons.

As regards the summer case studies, we have chosen a case with strong synoptic forcing (a cold front approaching Northern Italy, 29-06-2011), and a second case with a weaker forcing (an upper level trough moving westward from eastern Europe, 25-05-2012). The aim was to assess if differences in the synoptic condition could lead to changes in the sensitivity of the model.

As regards the other case studies, we considered two typical autumn/winter conditions. The first one is characterized by a strong katabatic wind (foehn) over the Po valley (10-11-2013) with the subsequent formation of a low pressure system over the Tyrrhenian sea; the second one (26-01-2013) consists in a stable atmosphere with an inversion over the Po valley causing dense fog over most part of the plain. In this last case, we opted to start the run the 25-01-2013 at 12 UTC. In fact, because the fog in winter season appears in the late afternoon after the sunset, we thought it would be more appropriate to start the run before the beginning of the event (at 12 UTC) instead of in the middle (at 00 UTC of 26-01-2013). In figure 1, the synoptic description of the case studies considered in our experiment is reported, whereas in figure 2 an example of soil moisture fields used to initialize the COSMO run for the 29-06-2011 case study is shown.

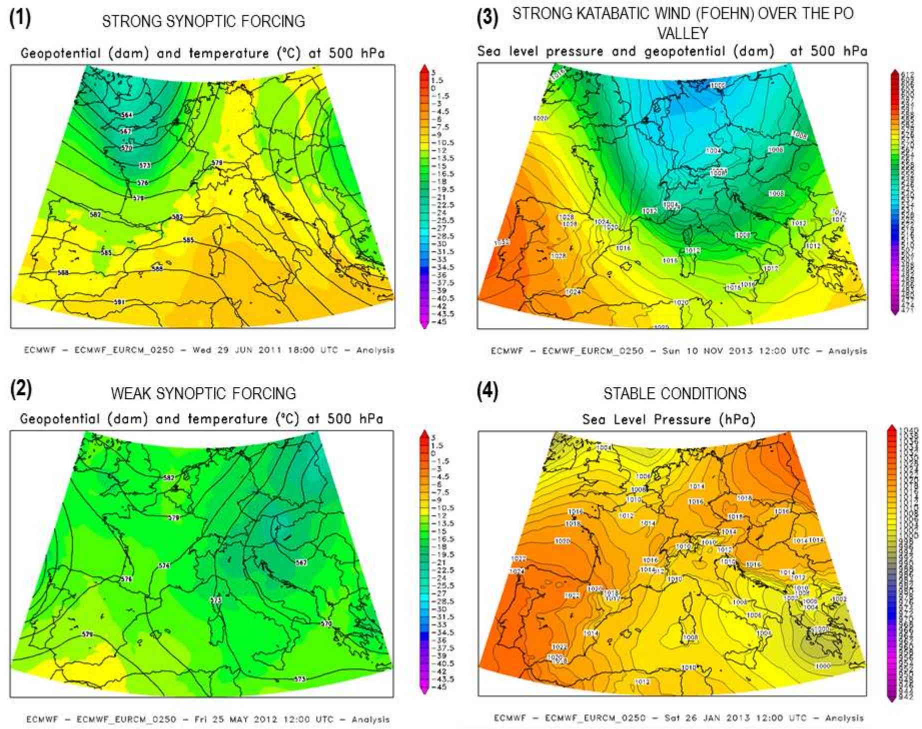

FIGURE 1: Synoptic maps of the case studies considered in the sensitivity test. The top left figure (1) represents the case of strong forcing with a cold frond approaching the Alps (29-06-2011), the bottom left figure (2) represents the weaker synoptic forcing with the upper level trough moving from the east Europe toward the north Italy (25-05-2012), the top right figure (3) represents the foehn condition generated by the strong pressure gradient across the Alps (10-11-2013), the bottom right figure (4) represents the fog condition with the north Italy crossed by a corridor of high pressure connecting the Azores anticyclone with the Siberian one.

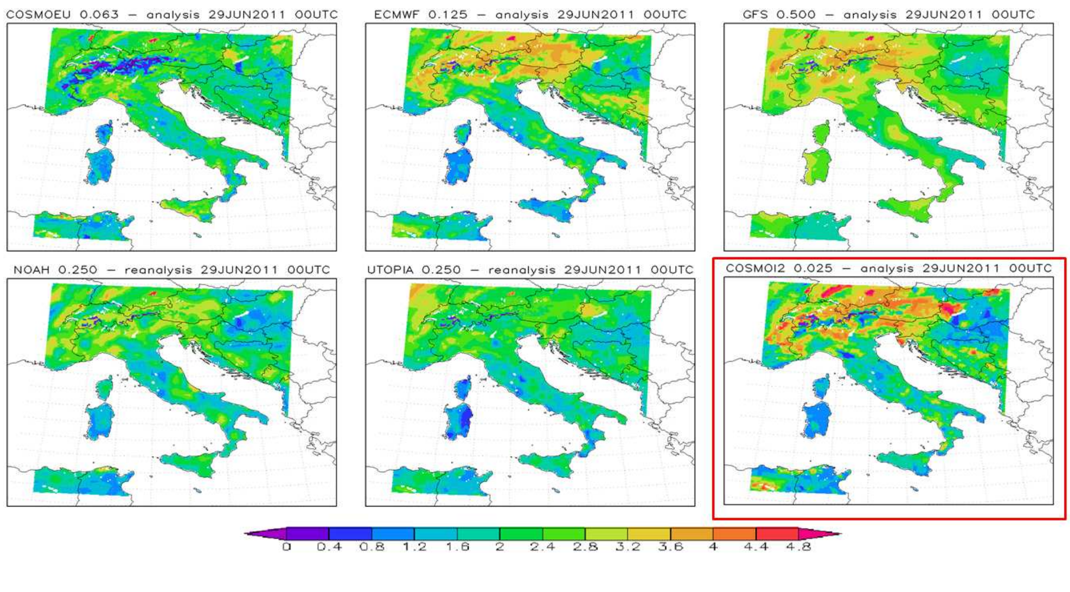

FIGURE 2: Soil moisture fields ($kg\,m^{-2}$) used to initialize the COSMO run for the case study 29-06-2011 at 00UTC. The fields are relative to the first soil layer (1 cm depth). The red box shows the control run.

Figure 3 shows the boxplot of the distribution of the soil moisture fields related to the first soil layer (1 cm depth) for all the 4 case studies considered, whereas figure 4 illustrates the maps of the standard deviation of the surface soil moisture fields at initial time, representative of the spread.

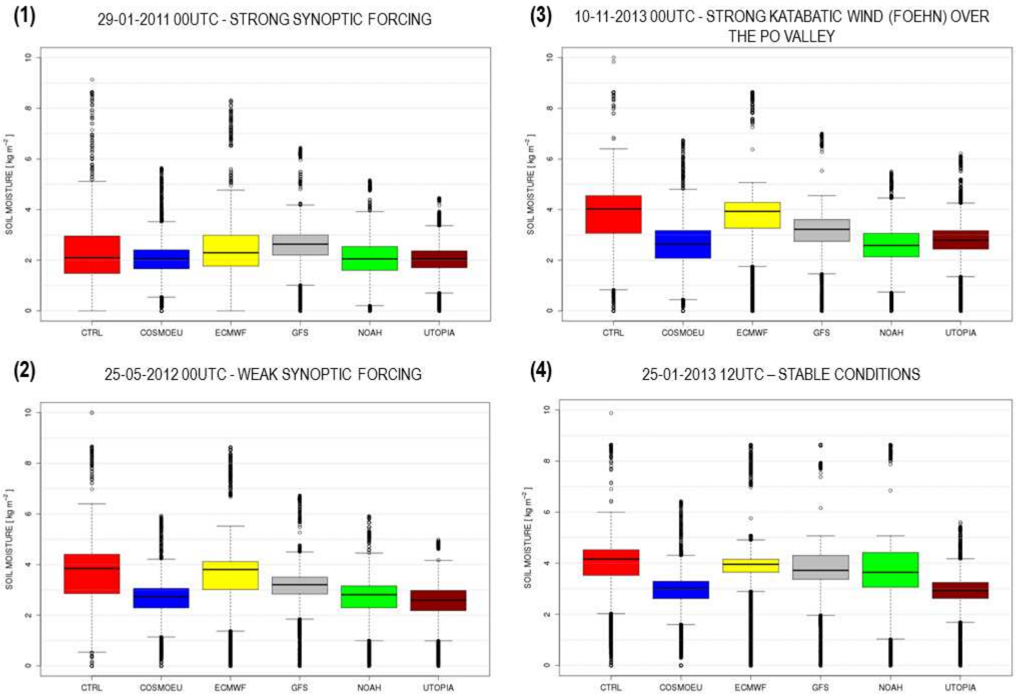

FIGURE 3: Boxplot of the distributions of the soil moisture fields (1 cm depth) for all the 4 case studies.

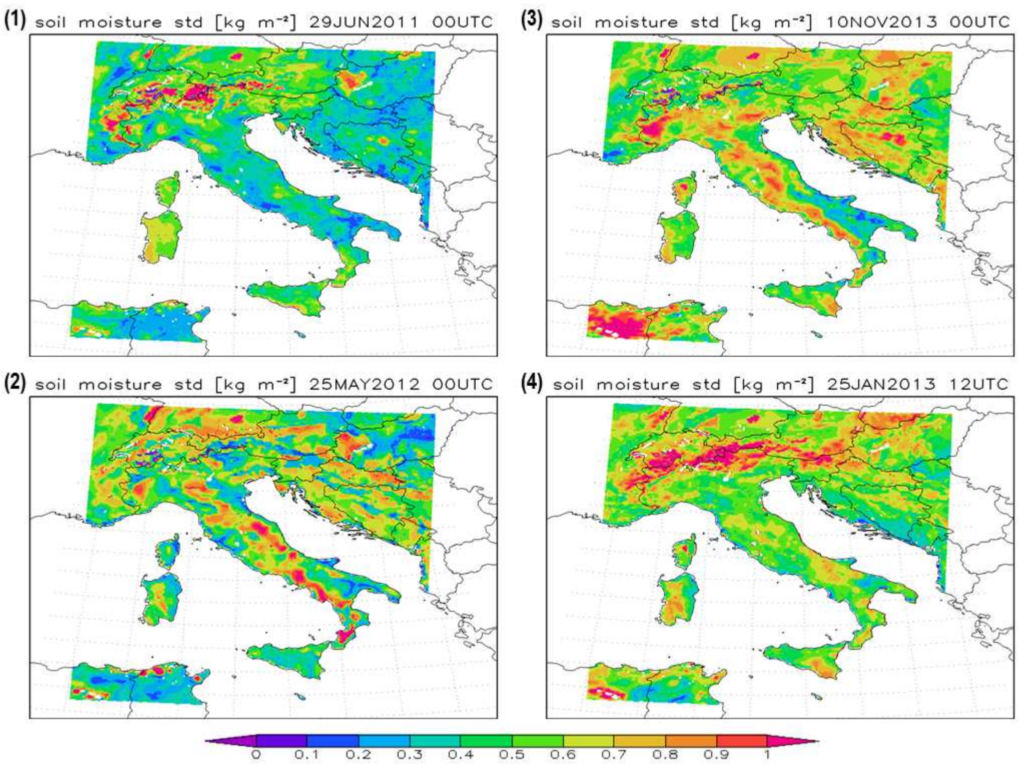

FIGURE 4: Maps of standard deviation (spread) of the initial soil moisture fields (1 cm depth) used to initialize the COSMO runs for all the 4 different case studies.

Examining the boxplot in figure 3, it can be seen that the first case study shows, on average, the lowest soil moisture values and the lowest variability among the distributions compared to other cases. The variability of soil moisture fields can be noticed both in terms of mean values and of width of the distributions.

Considering the spatial distribution (figure 4), the first case study shows, on average, also the lowest spread compared to other cases, according to the considerations coming from the boxplot analysis. Moreover, always in the first but also in the fourth case study, the spread maxima are not homogenously distributed all over the domain but are mostly concentrated over the alpine region.

Considering again the boxplot (figure 3), and in particular the CTRL and the ECMWF boxplot, the effect of the different methodology adopted for the soil moisture interpolation can be inferred. In fact, in both cases, the original model is the same, but the two different interpolation techniques (SMI and S) give different results in term of soil moisture fields values. In particular, the SMI used to interpolate the soil moisture from ECMWF in the operational suite gives a distribution of soil moisture values with a similar average, but wider compared to the one obtained with the technique of the degree of saturation S. As result, the SMI technique gives more "extreme" values of soil moisture as it can be also noticed comparing the ECMWF soil moisture field and the COSMOI2 one (red box) in the example reported in figure 2.

4 Simulations

Once soil fields were available and ready to initialize COSMO model, a number of simulations were carried out to study the response of the model itself to different soil moisture initialization. Being 4 the case studies considered and 5 the different soil moisture analyses (+ 1 of control), we obtained 24 different COSMO runs.

For the model runs, COSMO model version 5.0 was used with an horizontal resolution of 0.025^o (about 2.8 km).

The variables that we opted to analyze for each case study to assess the increase in spread due to different initializations were: 2 meters temperature and dew point, 10 meters wind speed (module), vertical velocity (w) at an altitude of about 1000 m, total precipitation, cloud cover, soil temperature and moisture.

Considering figure 5, showing the spatial average of the spread for all the atmospheric and soil variables considered in this study, a considerable increase in spread can be noticed for the summer, spring and autumn cases, whereas in the winter one the increase is less appreciable. Moreover, the diurnal cycle in some variables is evident (temperatures, wind speed and cloudiness), more pronounced in summer and spring condition (1, 2) and almost absent in winter stable case (4). To be noticed in particular is the fact that the summer case, showing the highest values in spread and the most pronounced diurnal cycle, is also the one with the lowest initial mean spread. These results can be justified by the fact that during spring and summer seasons the fluxes, namely the exchanges of moisture and energy between soil and atmosphere, are stronger compared to autumn or winter conditions, especially during daytime. For this mechanism, variations in soil moisture may deeply affect the boundary layer and influence atmospheric processes leading to a considerable variability among the COSMO runs. This assumption is also confirmed by the behavior of the soil moisture spread of the first soil layer. For the winter stable case study (4) soil moisture spread remains nearly constant, because of small fluxes leading to a limited exchange of moisture between soil and atmosphere. In the other cases where the fluxes are stronger, the initial spread in soil moisture tends to decrease, especially in the first day of the run.

As regard the spread in precipitation, the highest values are reached in the summer case study with strong synoptic forcing (1) when events of heavy rainfall occur. In general for this variable and for all the cases considered, a diurnal cycle is less evident or absent. In fact, for the two convective cases, thunderstorm events may occur also in the late evening and in the nighttime where the cold front (case 1) or the upper level trough (case 2) interests some region of the domain. In the autumn case (3), finally, less convective precipitation due to the deepening of a low pressure system in the Tyrrhenian sea leads to a more uniform increase in spread. For the winter case (4) no spread appears because of stable synoptic conditions.

Also as regards the wind speed and the vertical velocity, the different behavior in spread between spring-summer (1, 2) case studies and the autumn one (3) can be noticed. Whereas for the cases 1 and 2 an evident diurnal cycle appears, for the autumn case a continuous and constant increase in spread can be observed due to the intensification of the winds caused by the deepening of the low pressure system over the Tyrrhenian sea in the second day of the run.

Figure 6 and 7 report maps of spatial distribution of the spread at a chosen time of the run. An example with the 2m temperature and the 48h cumulated precipitation for all 4 case studies considered is shown. It can be seen that locally the value of the spread of these two variables can be really appreciable. Values greater than 3^oC and more than 20 mm as regard the temperature and precipitation respectively can be observed in some part of the domain for the strong synoptic forcing case (1). For the other case studies the values are smaller, but anyway relevant (about 1-2^{o}C for temperature and 10-20 mm for precipitation). To be noted the foehn effect over the Po valley on the 2m temperature in the 3rd case study and the spread nearly absent for the stable winter case (4).

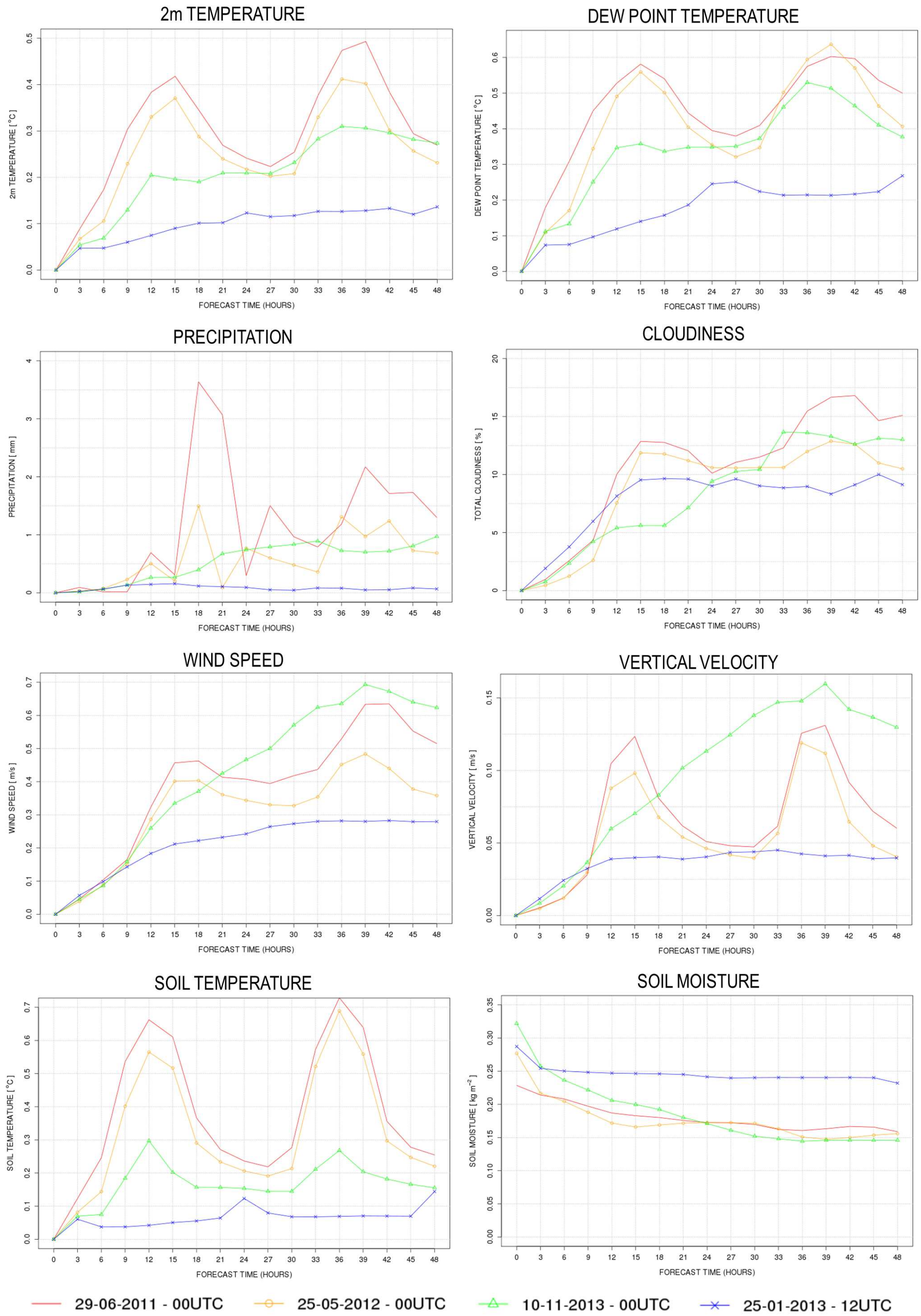

FIGURE 5: spatial average of the spread of different atmospheric and soil variable for the 4 different case studies.

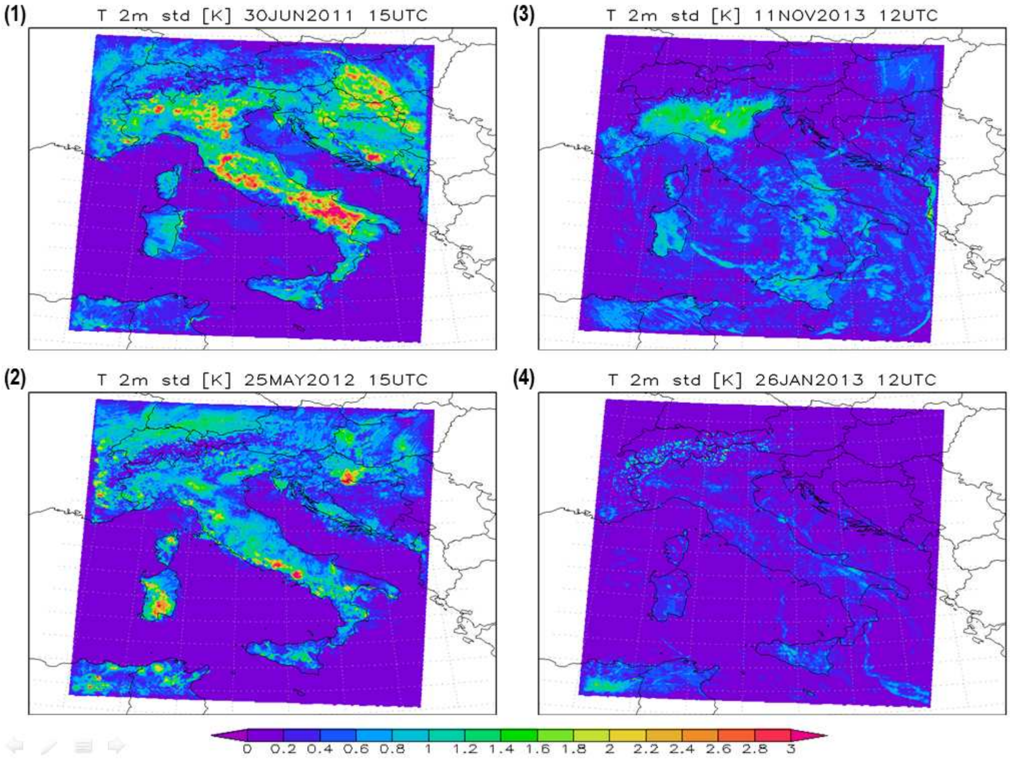

FIGURE 6: 2m temperature spread for the 4 different case studies.

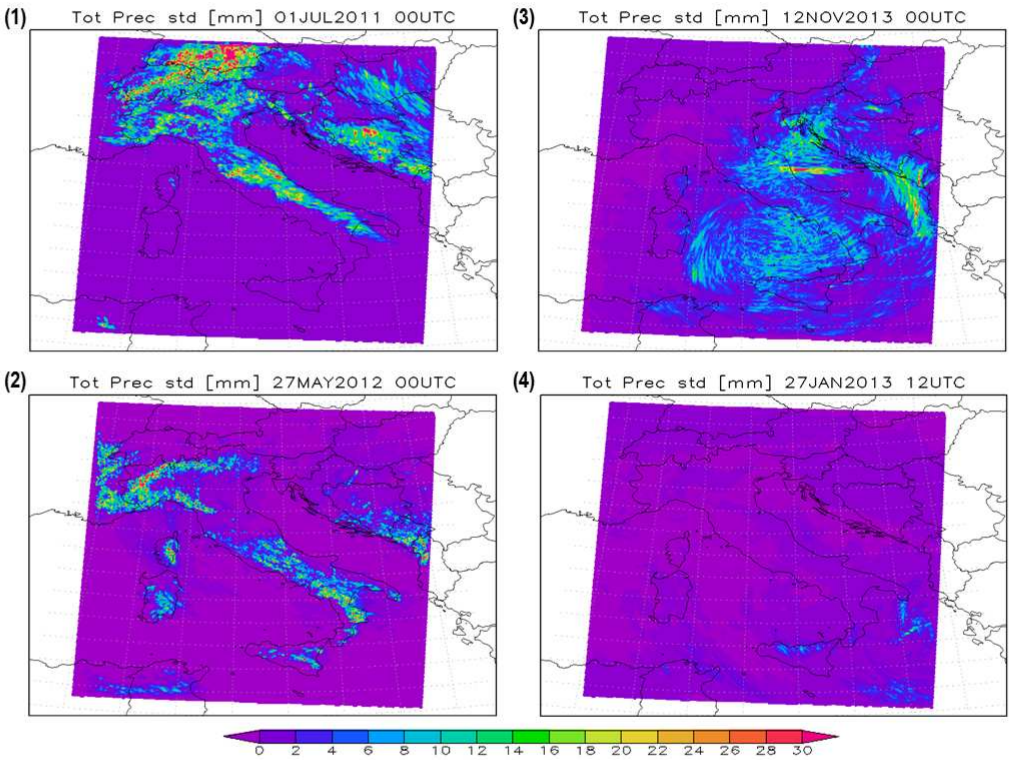

FIGURE 7: 48 h cumulated precipitation spread for the 4 different case studies.

5 Conclusions

In this study we performed a sensitivity test to assess the impact of different soil moisture initializations on short range ensemble variability in COSMO model. For our purpose, five different soil moisture analyses coming from global, regional and land surface models were used.

When examining some variables as 2m temperature and dew point, precipitation, cloudiness, wind speed, vertical velocity, soil moisture and temperature, the results show that the change of the soil moisture initial condition generated some spread, stronger in the spring/summer case studies with convective conditions, weaker in autumn season and nearly absent in stable winter conditions.

To assess if the spread obtained in our test is appreciable with respect to the uncertainty associate to the forecast sufficient it would be wise to compare these values with those coming from an ensemble obtained perturbing the initial atmospheric (and boundary) conditions.

Another point to stress is related to numerical instability. In fact, in our experiments, a simulation of case study similar to the 3^{rd} one presented here failed. Also this case study consisted in a foehn condition in the northwestern Italian Alps with strong winds. This fact remind us how important is to take into account the numerical stability of the model when perturbing soil moisture with a certain technique.

6 Proposal for a perturbation technique for soil moisture initial conditions

A simple technique proposed by Lavaysse et al. (2013) consists in perturbing the spectral coefficients of an expansion on spherical harmonics (in the horizontal) and Fourier harmonics (in the vertical). A three-dimensional random function on the sphere $f(\lambda, \phi, \eta, t)$, correlated in space and time, with a probability density function symmetric around the mean, can be defined as:

$$f(\lambda, \phi, \eta, t) = \mu + \sum_{l=1}^{L} \sum_{m=-l}^{l} \sum_{k=-K}^{K} a_{lmk}(t) Y_{lm}(\lambda, \phi) e^{ik\eta} \tag{4}$$

where μ is the global mean of the random function, and the variables λ, ϕ, η and t are longitude, latitude, vertical coordinate, and time, respectively. The Y_{lm} are spherical harmonics, with l being the total horizontal wavenumber, m the zonal wavenumber and k the vertical wavenumber. L and K are the horizontal and vertical truncations of the random function, and their inverse can be interpreted in terms of spatial decorrelation length scales (or horizontal/vertical wavelength). See Lavaysse et al. (2013) and Li et al. (2008) for further details.

As in our case we have a perturbation in the initial condition of a two-dimensional field, the dependence on the vertical coordinate and time is lost and the function $f(\lambda, \phi)$ now is defined as:

$$f(\lambda, \phi) = \mu + \sum_{l=1}^{L} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\lambda, \phi) \tag{5}$$

In this case a_{lm} becomes a simple random coefficient following a normal distribution with zero mean and unit variance. A stretching function is finally used to regulate the intensity of the perturbation and thus to bound the function f between f_{min} and f_{max}:

$$S(f, \mu) = 2 - \frac{1 - exp\left[\beta \left(\frac{f-\mu}{f_{max}-\mu}\right)^2\right]}{1 - exp(\beta)} \tag{6}$$

with $\beta \approx -1.27$. To better explain the meaning of L, in figure 8 two example of initial spatial correlated random field are shown. Both are obtained with a perturbation intensity of 0.06 m^3/m^3, but the first one corresponds to a value of $L = 80$ (namely, to an horizontal wavelength $\lambda_L \approx 2\pi R_{earth}/L \approx 500km$), whereas the second one is obtained with $L = 160$ ($\lambda_L \approx 250km$).

As regards the perturbation intensity, values of 0.06 m^3m^{-3} for the surface layer and 0.04 m^3m^{-3} for root layers are proposed by Lavaysse et al., (2013). These values are comparable of smaller than errors of the operational soil moisture analysis at ECMWF (bias $= -0.081\ m^3\ m^{-3}$, RMSE $= 0.113\ m^3\ m^{-3}$ over the period 2008-2010, Albergel et al. (2012)). Considering instead the horizontal truncation L, some values corresponding to a horizontal wavelength λ_L between 500 and 1000 km are used by the same authors.

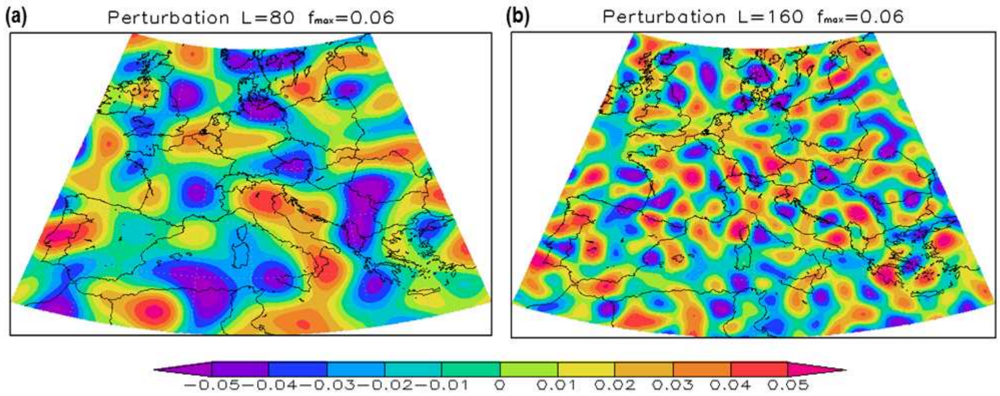

FIGURE 8: Examples of spatial correlated random fields obtained using the function in equation (5) with $L = 80$ ($\lambda_L \approx 500km$, left panel) and $L = 160$ ($\lambda_L \approx 250km$, right panel).

7 Future developments

A test of the perturbation technique proposed here is scheduled with one or more case studies and with different settings of the characteristics of the perturbation fields. In particular, as regards the sensitivity on the spatial scales, values of L corresponding to horizontal wavelength λ_L of about 250, 500, and 750 km may be considered. Also the sensitivity on the intensity of perturbation should be analyzed with a range of values comparable with the typical errors of the soil moisture analysis. Eventually, in case of unsatisfactory results of the test with the technique above mentioned, some more sophisticated approach should be considered, as the one proposed in CONSENS Priority Project or others briefly cited in the introduction.

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