Setting up COSMO EPS perturbing lower boundary conditions: sensitivity and case studies

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1 Introduction

The present work aims to pursue the goal started in the a previous study (Bonanno et al., 2014) that is to find the best setting of a soil perturbation technique to be implemented in a high resolution ensemble system based on the Italian version of the limited area model COSMO at a resolution of 2.8 km taking into account soil surface uncertainties.

The need to investigate the role played by the soil in an ensemble system rises from a well known problem: surface atmospheric variables have a little variability as far as ensemble forecast systems are concerned.The reason of this could be find in surface conditions uncertainties not taken into account in ensemble systems (Sutton et al. (2006), Aligo et al. (2007), Quintanar et al. (2008), Klüpfel et al. (2011)).

This work is part of the COTEKINO (COSMO Towards Ensembles at the Km-scale IN Our countries) priority project aimed to develop a convection-permitting ensembles in our country. 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 can not be generalized to a completely different modeling system. To do that we completed the sensitivity started before using two different perturbation techniques applied to several case studies. This work confirms the output of Klüpfel et al. (2011) for the West Africa leading us to a final setting of soil perturbation to be used by the ensemble system. The performances of this setting have been validated studying different case studies and comparing them with the performances of the operational COSMO-LEPS system.

2 Dataset and methodology

In the previous sensitivity study (Bonanno et al. 2014) has been demonstrated that a high resolution, convection permitting ensemble system is sensitive to the initial state of the soil, as far as soil water content is concerned. This sensitivity test was based on the perturbation technique suggested by Lavaysse et al. (2013) hereafter SHP. It consists in 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 has been described in Bonanno et al (2014).

Figure 1 shows two example of initial spatial correlated random field. Both are obtained with a perturbation intensity of $0.06m^3/m^3$, but the first one corresponds to a value of $L = 80$ (namely, to an horizontal wavelength $\lambda_L \approx 2\pi R_{earth}/L \approx 500km\lambda$), whereas the second one is obtained with $L = 160$ ($\lambda \approx 250km$).

In this work we tested another perturbation technique. Soil water content was perturbed using the a second technique based on the work done by Tsyrulnikov et al. in the framework of KENDA Priority project. It consists of a Stochastic Pattern Generator based on solution of a partial stochastic differential equation in spectral space on a 3-dimensional torus. Variance, spatial and temporal scales are tunable.

This technique construct a generic field f as the solution of a stochastic differential equation of the form:

$$\left(\frac{\partial f}{\partial t} + \mu\left(1 - \lambda^2\Delta\right)^q\right)^p f = \sigma\alpha$$

Where p and q are external parameter σ, λ and μ are parameter related to the desired variance, spatial and temporal correlation scale. α is the spatio-temporal white noise. A Fourier decomposition of f is performed and an integration of the equation in the spectral space is done. This procedure simplify the analysis because allows the decoupling of the stochastic partial differential equation into a series of ordinary stochastic differential equations that can be computed by parallel processors. After the integration, a 3D Fast Fourier Transform is applied to obtain the desired random field in physical space.

This second technique has the advantage for being less expensive from the computational point of view. A preliminary test was performed to understand the main differences in terms of spread induced by the two different perturbation techniques (SHP and SPG) with five different configuration obtained modifying the perturbation intensity and the wavelength.

Table 1: Setting of sensitivity experiments to evaluate the performances of the two perturbation techniques (SHP and SPG)

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Test	$Fmaxsurfm^3/m^3$	$Fmaxrootm^3/m^3$	L	$\lambda^2 km$
1	0.06	0.04	400	50
2	0.06	0.04	160	125
3	0.06	0.04	80	250
4	0.06	0.04	50	400
5	0.08	0.06	80	250

The values of λ have been chose according to Lavaysse et al. (2013) while maximum values of the perturbation intensity at the surface and in the root zone have been set according to Lavaysse et al. (2013) and Mc Laughlin et al. (2006) and are comparable or smaller than the errors of the ECMWF operational soil moisture (Albergel et al. (2012), ECMWF newsletter (2012)).

As soon as the best perturbation technique with the best setting was chosen, a secondary test consisted in understanding the sensitivity of the ensemble to the initial soil moisture field. In this respect we performed a test perturbing the soil moisture fields produced by the COSMO-EU soil moisture analysis, instead of that coming from ECMWF. A third sensitivity test was conducted to understand how the ensemble is sensitive to external soil related parameters such as LAI (Leaf Area Index), roughness length and vegetation cover (Lavaysse et al. 2013).

In this case a slightly different approach was used to generate the perturbations. In fact, as suggested by Lavaysse et al. (2013) the associated perturbed fields, we used a multiplicative perturbation approach, based on the assumption that the errors are proportional to the values of the considered parameter (Lavaysse et al., 2013).

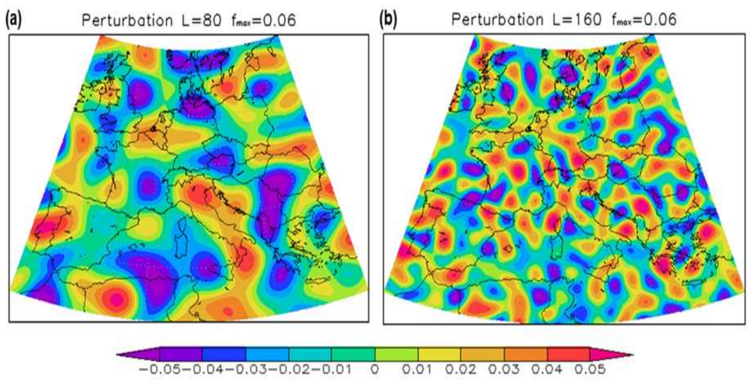

Figure 1: Examples of spatial correlated random fields obtained using two different wavelength in the SHP $L = 80$ ($\lambda_L \approx 500km$, Figure 1a) and $L = 160$ ($\lambda_L \approx 250km$, Figure 1b)

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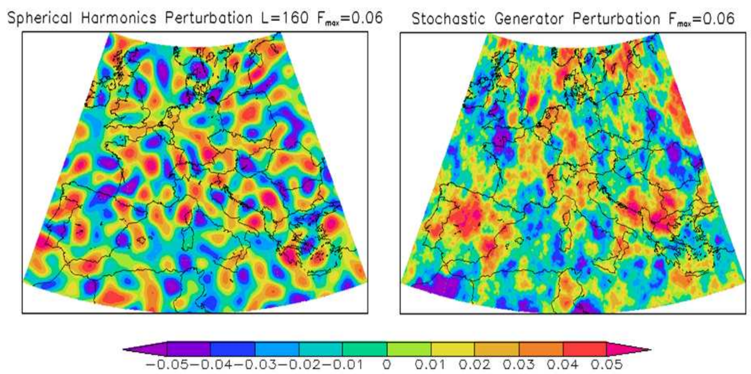

Figure 2: Comparison of a soil water content field perturbation computed by the SHP (Fig. 2a) and SGP (Fig. 2b)

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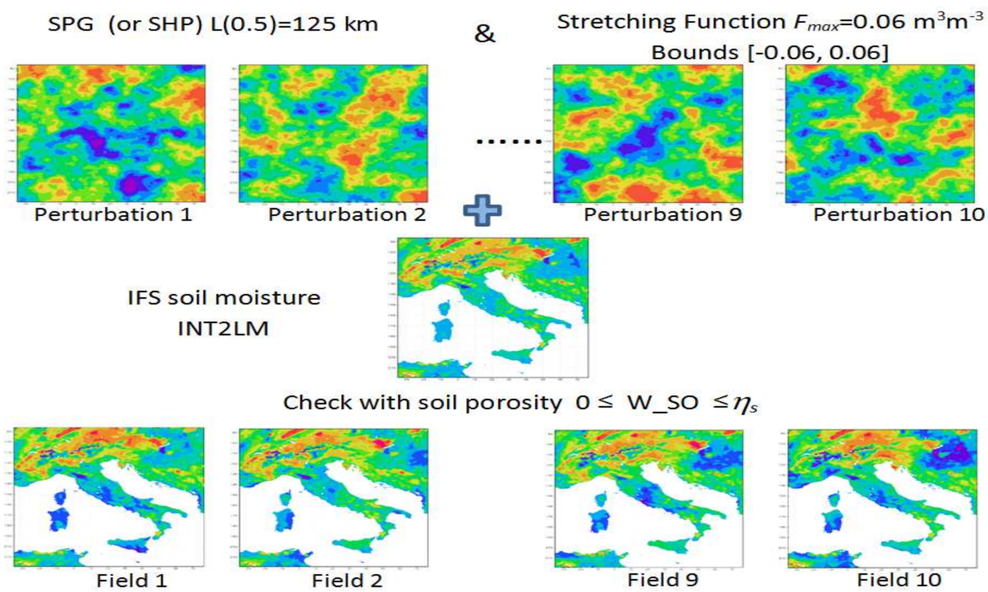

Figure 3: The procedure to create ten soil moisture initial conditions starting from ECMWF soil moisture analysis and applying SPG or SHP as additive Gaussian patterns

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We report in Figure 4 a scheme of the above mentioned approach as far as Leaf Area Index is concerned.

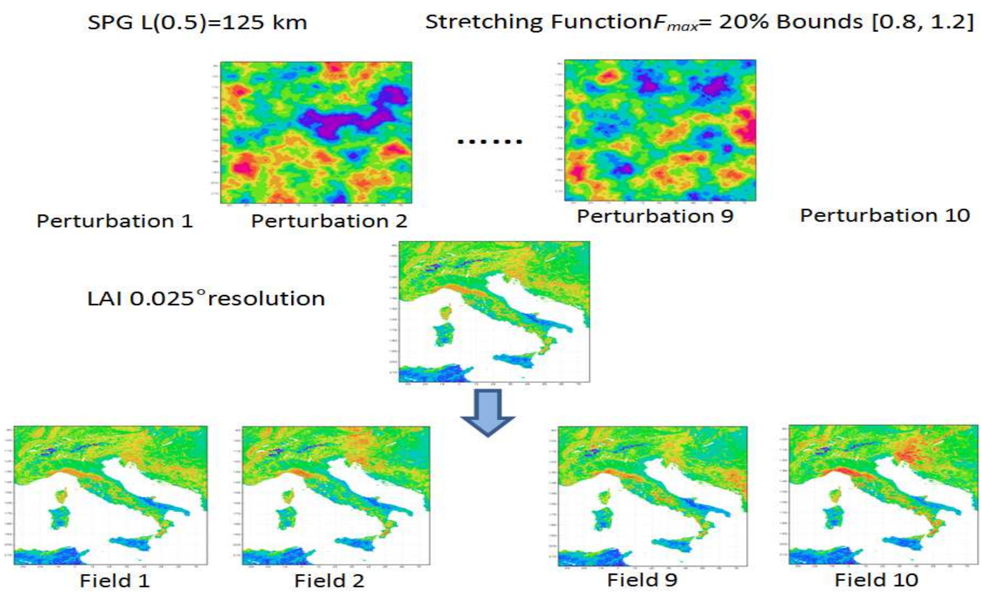

Figure 4: The procedure to create ten LAI initial conditions starting from ECMWF field and applying SPG as multiplicative perturbation

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As result of the three tests we chose the best setting for the soil perturbation and evaluated the spread on the upper atmospheric levels in the two case studies selected as representative of two different meteorological regimes (Bonanno et al. 2014). Finally, the performances of the selected perturbation technique were compared with those coming from the operative COSMO-LEPS.

3 Simulations and results

-Selection of the best perturbation technique.

Following are the output from the first sensitivity test chosen to understand the most performing perturbation techniques and its best setting. As mentioned before we applied SHP and SPG to create the perturbed soil moisture initial conditions starting from the ECMWF soil moisture analysis of two case studies. The first one (CS1) is a case of convection induced by a strong synoptic forcing (June 29th 2011) the second one (CS2) is characterized by strong wind over the whole domain (November 10th 2013).

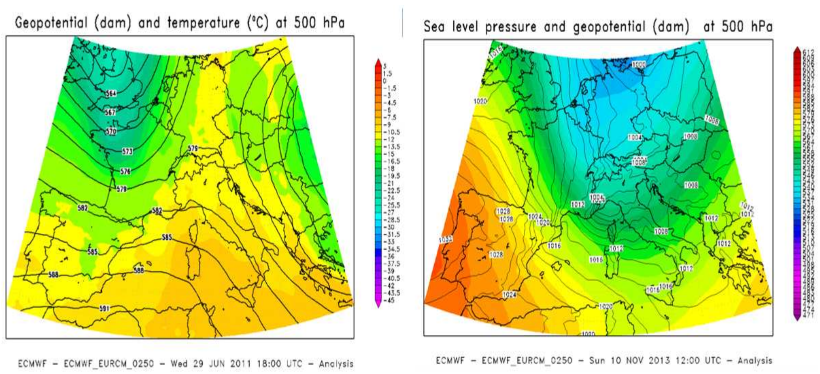

Figure 5: Case studies: convection induced by a strong synoptic forcing (left) strong wind over the whole domain.

A total amount of hundred simulation were performed (10 perturbations x 5 different settings (Tab. 1) x 2 perturbation techniques (SHP, SPG)) for each one of the two case studies.

Figure 6 shows the comparison of the spread induced by SHP (left) and SPG (right) as far as 2 meters temperature is concerned. Both the techniques produce significant spread increasing with the lead time and showing a pronounced diurnal cycle.

The differences among the 5 different settings are not appreciable whenever the perturbation intensity is kept constant. The best setting for both SHP and SPG is the one corresponding to the fifth case in Table 1, that is with the highest intensity of the perturbation considering a medium wavelength. The differences between SHP and SPG are almost negligible.

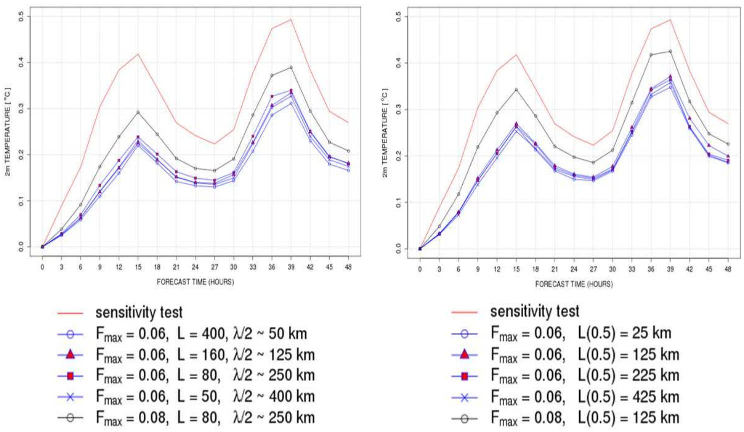

Figure 6: Comparison of the spread induced by SHP (left) and SPG (right) on 2 meters temperature for case study CS1. Solid red lines is spread obtained with the sensitivity done in Bonanno et al. (2014) using different soil moisture analysis from different GCM, LAM and LSM models.

Other variables such as 2 meters dew point, 10 meters wind speed, cloudiness, vertical velocity, precipitation soil temperature and moisture, show a similar behavior except for vertical velocity and precipitation where negligible differences are produced by all the different settings and soil moisture for which the spread, after an initial small decrease in the first hours of the run, remains almost constant throughout the entire ensemble cycle. For the sake of brevity figures are not shown.

This first step in understanding the sensitivity of the model to the initial soil moisture field led us to choose the fifth setting of Table 5 and SPG as the best setting for the soil moisture perturbation technique.

- Sensitivity to the initial soil moisture field.

A second test consisted in understanding the sensitivity of the ensemble system to the initial soil moisture field. In this respect we performed a test perturbing COSMO-EU soil moisture fields instead of that coming from ECMWF.

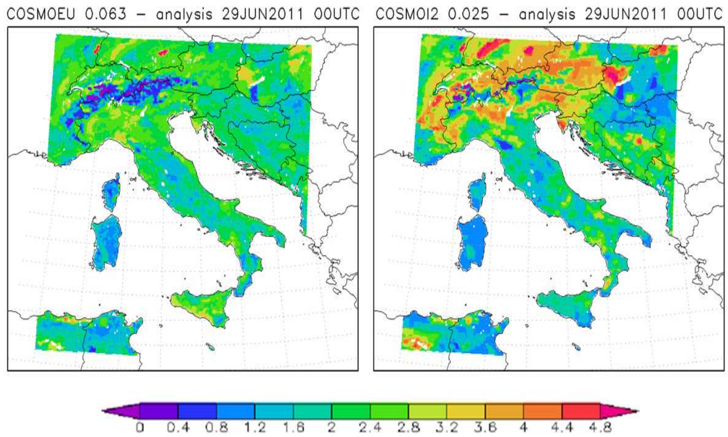

Figure 7: The initial soil moisture field interpolated on the COSMO-I2 domain from COSMO-EU (left) and ECMWF (right) for case study CS1.

In fact, as can be noticed from Figure 7, the initial soil moisture field on the COSMO-I2 domain is very different from COSMO-EU to ECMWF with the first one much drier respect to the second one.

This fact lead us to assess if this strong difference could lead to a production of different values of spread when the soil moisture is perturbed.

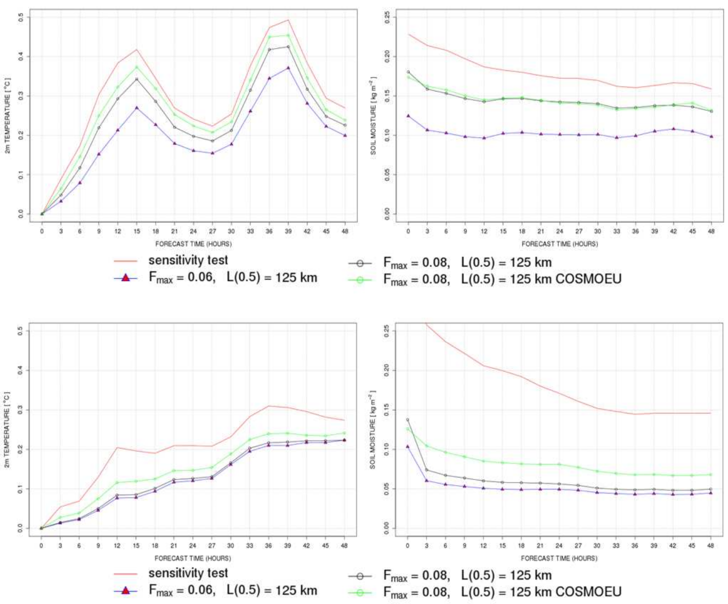

Figure 8: Case study CS1 (top panel) CS2 (bottom panel): spread produced by the ensemble system for 2 meters temperature (left) and soil moisture (right). Different lines represent different soil moisture analysis/ different SPG setting.

From Figure 8, which represents the results relative to CS1 and CS2, one can notice how a drier soil moisture analysis lead to an higher spread on 2 meters temperature due to higher fluxes at the soil-atmosphere interface.

There is not an appreciable difference as far as soil moisture spread is concerned in CS1.

Looking at other variables (not shown for the sake of brevity) such as 2 meters dew point, 10 meters wind speed, cloudiness, vertical velocity, precipitation soil temperature and moisture, similar conclusions can be inferred.

- Sensitivity to external soil related parameters.

A third and last test was performed to evaluate how sensitive the ensemble system is to the perturbation of soil related external parameters such as LAI (Leaf Area Index), roughness length and vegetation cover. Following are the comparison of the results obtained with different combinations of the perturbations.

From Figure 9 and 10 one can notice as the perturbations of the external soil related parameters do not have a great impact in the generation of spread for 2 meters temperature as well as soil moisture.

Same results have been obtained for other variables such as 2 meters dew point, 10 meters wind speed, precipitation, vertical velocity and soil temperature. Moreover, a complete perturbation accounting for uncertainties of soil moisture and soil related parameters all together, do not have an impact in generating spread on surface variables.

- Best perturbation setting choice.

The three sensitivity tests described above led us to conclude that the best setting for a soil perturbation technique is the following: Stochastic Pattern Generator was selected as the best perturbation technique.

It has the best numerical performances in terms of computational demands to compute the perturbed fields. Moreover the SPG code is already compatible with the internal code of COSMO model;

Soil Moisture is the only field to be perturbed. Perturbation of other soil related external parameters and/or a combination of them do not produce enough spread compared to the one produced by soil moisture initial condition perturbation;

Initial soil moisture field from the COSMO-EU is the initial soil moisture analysis to be perturbed. In, fact

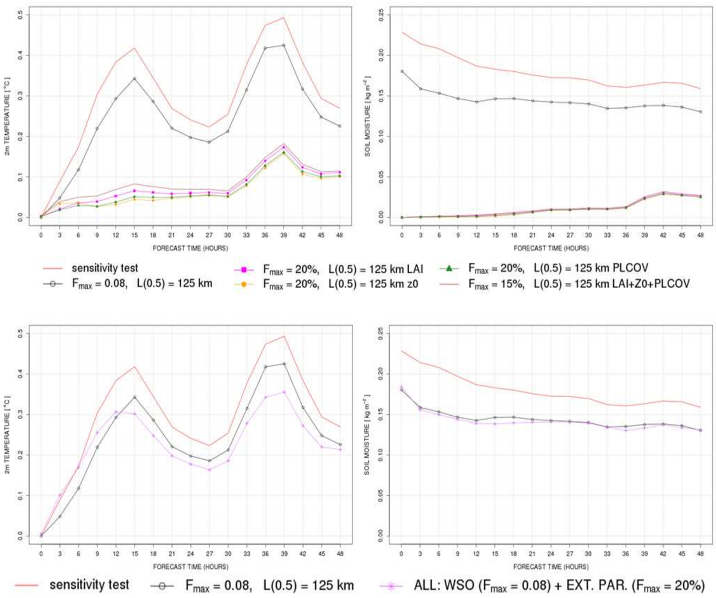

Figure 9: Comparison of different combinations of perturbations for the case study CS1.

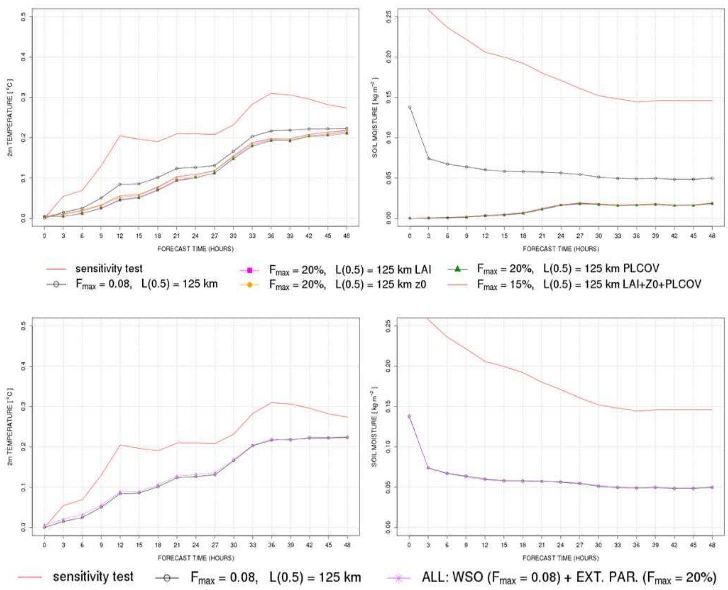

Figure 10: Comparison of different combinations of perturbations for case study CS2.

using ECMWF soil moisture analysis have a negative impact in terms of spread generation. This is partly due to the fact that ECMWF systematically overestimate the soil moisture content respect to COSMO-EU, reducing the fluxes at the soil-atmosphere interface.

- Impact of surface perturbation on upper levels of atmosphere.

The effects of an initial soil surface perturbation on surface prognostic variables have been analyzed. But does this soil initial perturbation have an effect on the upper atmospheric levels? To answer this question we plotted the cross section of main atmospheric variables over the whole domain at coordinate 11° East, 45° North (Figure 11) for the two case studies CS1 and CS2.

For sake of brevity we quote for CS1 in Figure 12. Both cross section demonstrates how the soil moisture initial condition perturbation with SPG and the selected setting is able to propagate spread from the bottom layer to middle troposphere.

-Comparison with an ensemble system with IC e BC perturbations: COSMO LEPS.

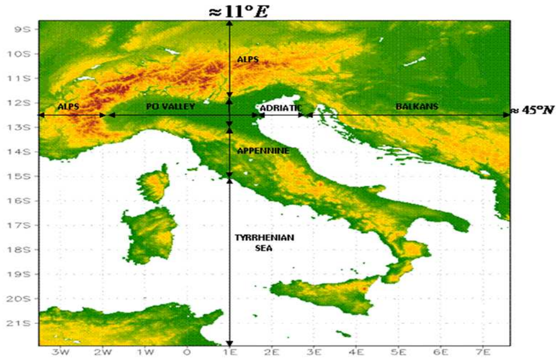

Figure 11: The COSMO-I2 integration domain with the selected latitude and longitude.

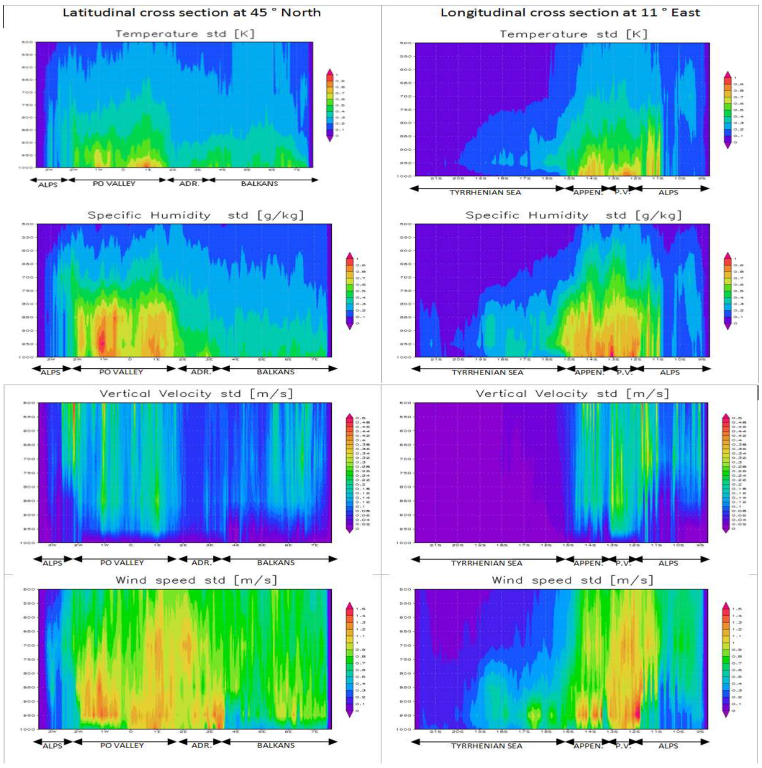

Figure 12: Latitudinal and longitudinal cross section of the time mean spread of different atmospheric variables.

In this final paragraph we compare the spread obtained with the selected soil perturbation technique with the one coming from a an ensemble system with perturbed atmospheric initial and boundary conditions, in this case COSMO-LEPS (Montani et al.,2011).

Figure 13 shows the spread obtained with the two different ensemble systems. One can notice that both systems produce comparable spread as far as inland surface atmospheric variables are concerned. In fact, the main difference between the two ensemble technique is that COSMO-LEPS is able to produce spread also over the sea. Perturbing soil moisture initial condition, in fact, has its great impact on the mainland.

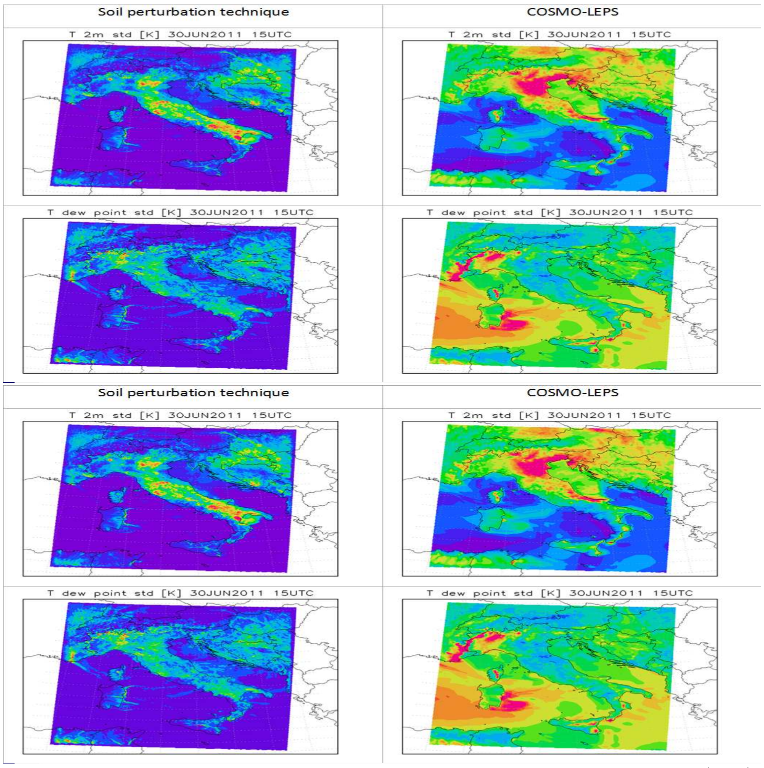

Figure 13: Comparison of the spread obtained with the soil perturbation technique (left) and with COSMO-LEPS (right).

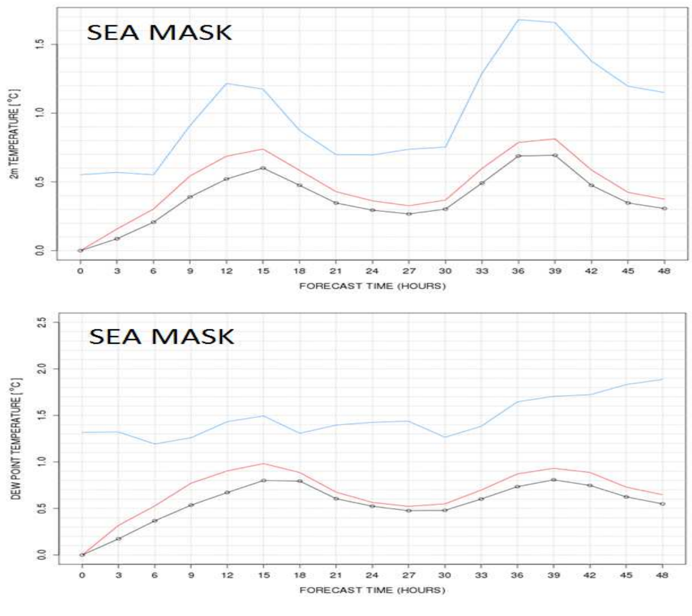

Figure 14: Comparison of the spread obtained by COSMO-LEPS (blue line) and by the soil humidity perturbation technique (black line). 2 meters temperature and dew point are plotted, Solid red lines is spread obtained with the sensitivity done in Bonanno et al. (2014).

If a land-sea mask is considered (Figure 14), the generated spread has the same order of magnitude, demonstrating that the proposed ensemble technique based on the soil moisture initial condition perturbation is able for this case to generate spread comparable with the one coming from an ensemble technique with perturbed atmospheric initial and boundary conditions.

4 Conclusions and Future developments

In this study we continue the work started in a previous study (Bonanno et al. 2013), aimed at finding the best setting of a soil perturbation technique to be implemented in a high resolution ensemble system based on the Italian version of the limited area model COSMO at a resolution of 2.8 km taking into account soil surface uncertainties.

We performed several sensitivity tests based on perturbation of soil moisture initial conditions with two different perturbation techniques and considering different initial field (soil moisture, soil related parameters such as LAI, roughness length, vegetation cover).

The perturbation of the soil using the best perturbation technique found so far produce spread of prognostic surface atmospheric variables comparable, for the case considered, with the one coming from an ensemble with perturbed initial and boundary atmospheric conditions. The proposed technique have an impact to spread of prognostic surface as well as on upper level atmospheric variables.

Future developments

Sensitivity have to be completed accounting for soil temperature perturbations. In this way also the response to initial uncertainties of this variable will be taken into account. The amplitude of soil temperature perturbation will be established according to soil temperature ECMWF bias (Albergel et al., 2014).

This technique will be tested as part of a more complete ensemble set-up, where both atmosphere and soil are perturbed (COSMO-IT-EPS ensemble). To do that, the same case studies, as well as other cases conveniently selected among those producing convection, will be analyzed using a complete perturbation technique accounting for both initial soil and upper level uncertainties. This will be done coupling the best soil perturbation technique with the perturbation of atmospheric boundary and initial conditions coming from ECMWF EPS members.

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