The effects of T2m assimilation on surface fluxes in COSMO-I2

Marco Galli[1], Massimo Milelli[2], Claudio Cassardo[1], Matteo Giorcelli[2,3]

1: University of Torino, Torino, Italy
2: ARPA Piemonte, Torino, Italy
3: ARIANET S.r.l, Milano, Italy

1. Introduction

Recent developments of the numerical weather prediction models make it possible to use very high resolution models in the daily operational routine. The COSMO-I2 operational configuration reflects this trend. The model setup makes it possible to produce operational weather forecasts all the Italian country at a resolution of 2.8 km.

Such a high resolution grid requires an adequate analysis procedure, so that the initial model fields can represent properly the characteristics of the atmospheric state typical of those scales. In particular, in this paper the attention is focused on the use of a high density weather stations network and on the assimilation of surface data, in particular the T2m (2 metres air temperature). ARPA Piemonte owns such a network, with a much higher number of stations in Piemonte region rather than the only 8 SYNOPs in the same area (see figure 1 for their geographical location).

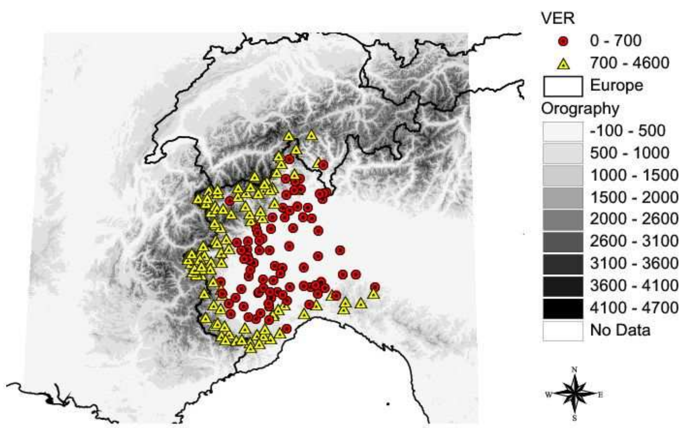

Figure 1: the ARPA Piemonte network of weather stations. The yellow triangles are the mountain stations (over 700 metres ASL), the red circles are the plain stations.

The goal of the work presented in this paper is to take advantage of such a network for enhancing the quality of the COSMO-I2 analysis production. In previous studies (Milelli et al., 2008; 2010), it has been shown how the assimilation of T2m has a major importance in making the forecast simulation differ significantly if it is included in the surface data assimilation or not. The step to this main goal presented in this paper deals with the study of the effect of the assimilation of the T2m on the surface fluxes, hence on how it influences the coupling between the soil state and the atmospheric state. It has been studied how the temperature data assimilation introduces perturbations in the model simulations.

2. Organization of the study

In order to get to this goal, it has been decided to carry out an experiment aimed at comparing the performance of COSMO-I2 with and without the T2m assimilation (from now on, these different model setups will be identified as TEMP - with T2m assimilation - and CTRL - without T2m assimilation). The experiment has been carried out in an operational-like framework.

This means that forecast simulations were performed initialising the model at 00 UTC and at 12 UTC, and carrying on, for each initialisation, a 24 hours simulation, with the first 12 hours of T2m assimilation and then 12 hours of free forecast for the TEMP, to be compared with the correspondent CTRL simulation. To have a better statistics for the results of the experiments, the simulations have been carried out not just for one day, but for a period of consecutive days. The first period goes from the 19th to the 25th of May 2009, and the second period from the 3rd to the 17th of January 2009. These periods have been chosen because the first one represents typical anticyclonic and sunny stable weather conditions in Piemonte (see figure 2), and the last one was characterised by a snow covered land and a strong surface temperature inversion (see figures 3 and 4).

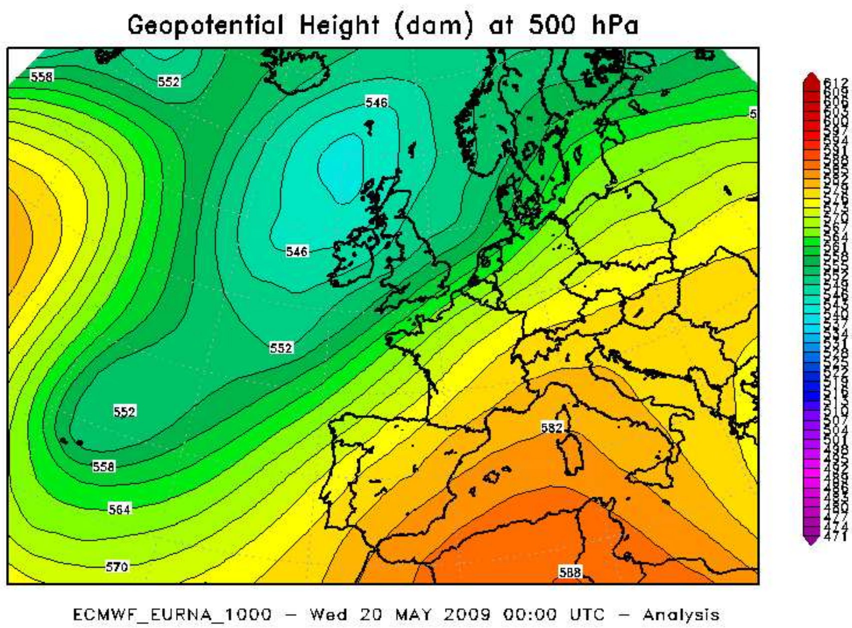

Figure 2: the anticyclonic conditions of the May period shown by the 500 hPa geopotential height by the ECMWF analysis.

It has to be mentioned that the operational setup of COSMO-I2 gets the boundary conditions from the COSMO-I7, which gets its own from the ECMWF IFS.

The area considered for this study is reported in figure 5.

The goodness of the TEMP with respect to the CTRL runs has been evaluated by comparing the mean error (ME) and the root mean square error (RMSE) of such simulations. These statistical indices have been calculated with respect to the ARPA ground stations network observations for the standard variables (T2m, RH2m, W10m[1]); for the land surface energy

[1] From here on, RH2m will stand for 2 metres relative humidity and W10m will stand for 10 metres wind

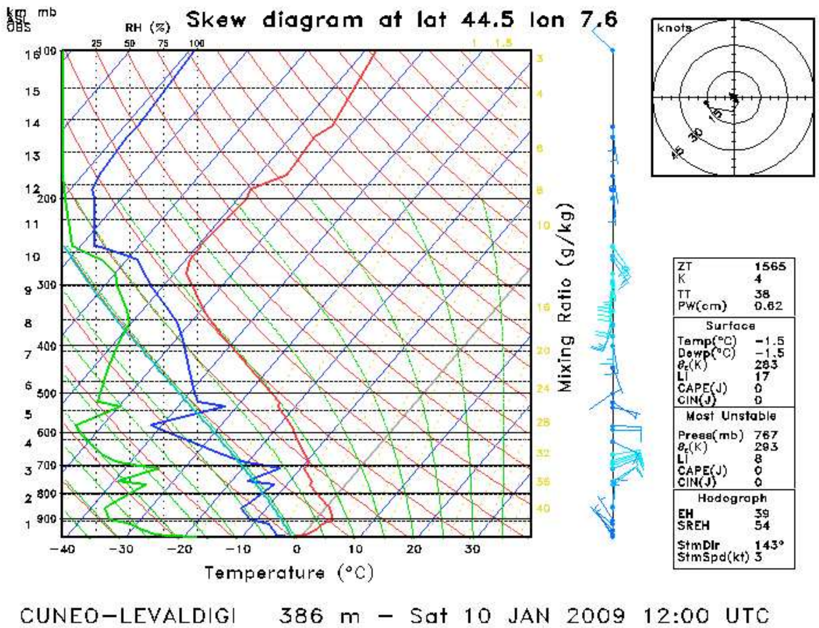

Figure 3: a radiosounding diagram from Cuneo Levaldigi to show the strong surface temperature inversion conditions characterising the January period.

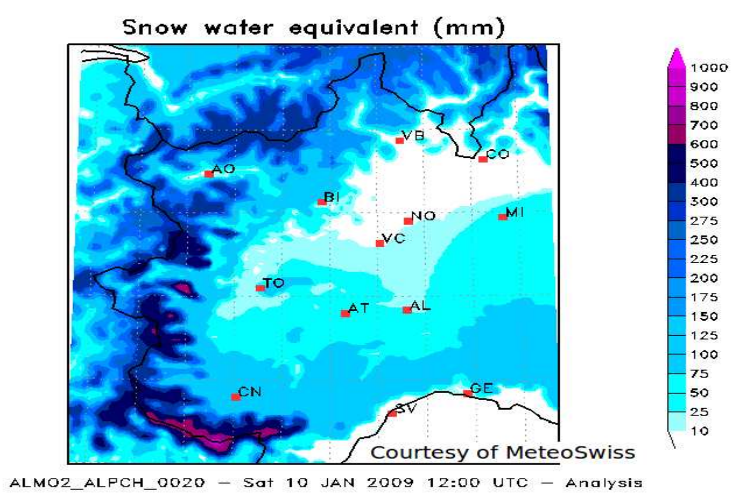

Figure 4: the snow coverage as represented by the snow cover analysis in the January period. Courtesy of MeteoSwiss.

fluxes, the COSMO ones have been compared with the output of a land surface dedicated model, UTOPIA (University of TOrino land Process Interaction with Atmosphere), considered as proxy data of reality. UTOPIA model is already operational in ARPA Piemonte for hydrological and agrometeorological monitoring purposes.

speed.

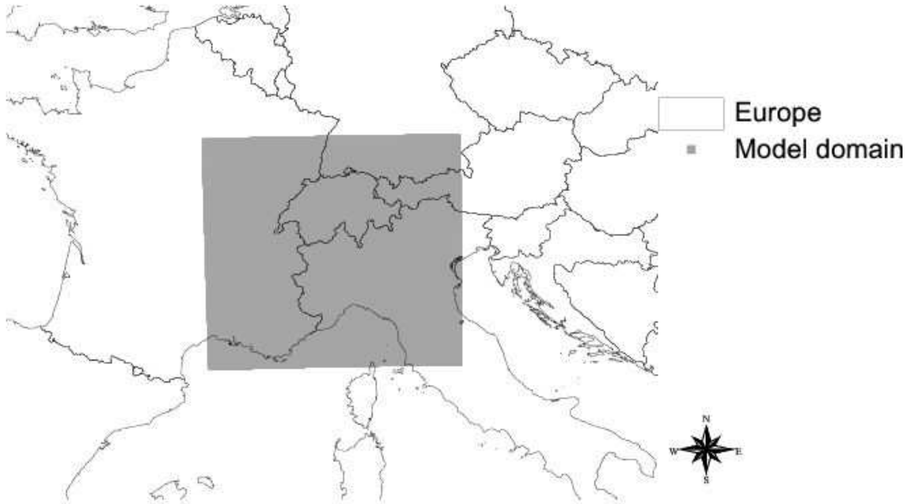

Figure 5: simulations domain. In grey the area integrated with the COSMO-I2 setup, in white the area involved in the COSMO-I7 runs.

3. The current COSMO performance

Effects on standard variables As a first step, the difference of the RMSE scores between the TEMP and the CTRL runs has been calculated, and its statistical significance has been assessed using the bootstrap technique. All the graphics in this section represent the differences of the RMSE calculated for the TEMP and the CTRL runs, for each forecast time (reported along the x-axis) and for each day of the test case (reported along the y-axis). White areas in the graphics represent a non significant difference in the statistical scores, green areas mean that the TEMP simulation shows a better RMSE than the CTRL and red areas mean that the TEMP simulation behaves worse than the CTRL.

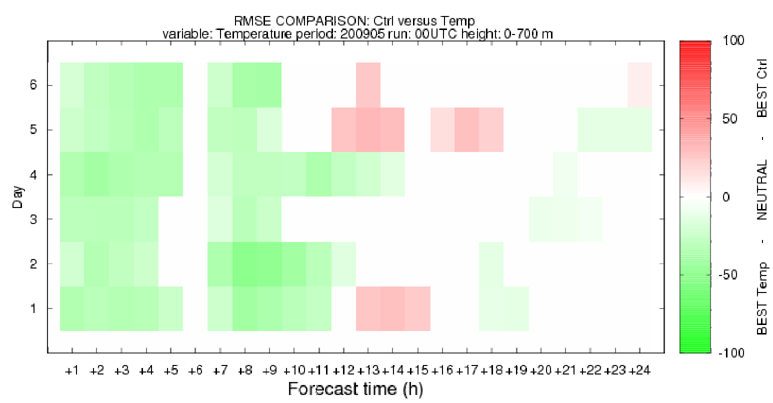

Figure 6: summary of the significance of the difference of the RMSE scores for T2m between the TEMP and the CTRL runs, May period, 00 UTC initialised runs.

Figures 6 and 7 are about the scores calculated for the temperature for the May case. For the 00 UTC initialised runs, the effect of the T2m assimilation on the COSMO description is positive just during the data assimilation process, then, at the start of the free forecast, the effects become negligible or slightly negative. By the end of the forecast runs, the effects

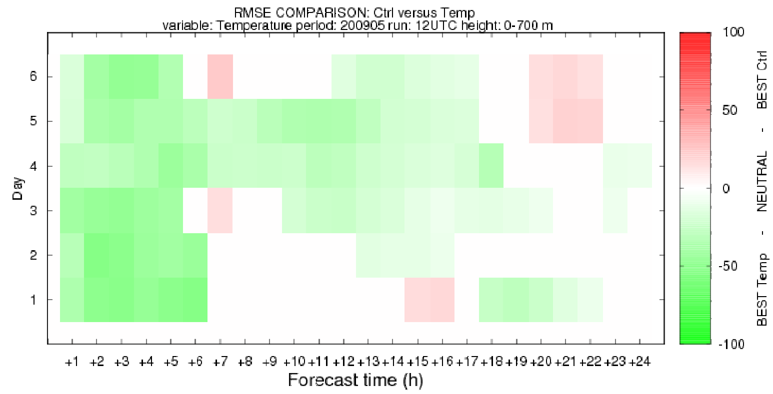

Figure 7: summary of the significance of the difference of the RMSE scores for T2m between the TEMP and the CTRL runs, May period, 12 UTC initialised runs.

turn out to be negligible or slightly good. For the 12 UTC runs the positive effects of the T2m assimilation last for some hours after the end of the nudging, and in only very few cases the result of the experiment is bad.

Temperature is the physical variable which is best affected by the assimilation of T2m. The variable with a worse response to the T2m assimilation is the RH2m. Figures 8 and 9 summarise the RMSE comparison between TEMP and CTRL.

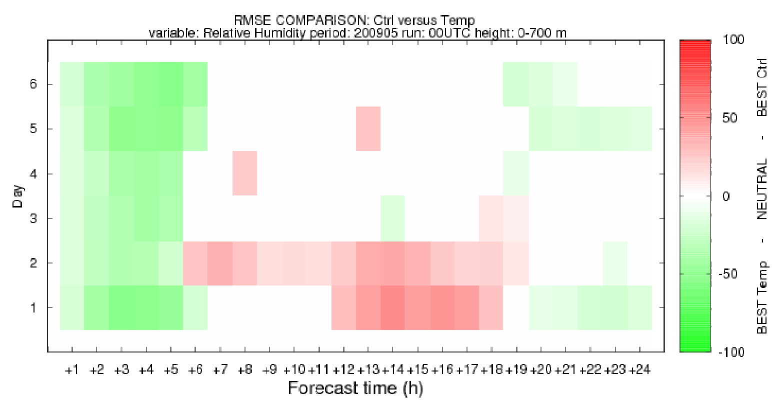

Figure 8: summary of the significance of the difference of the RMSE scores for RH2m between the TEMP and the CTRL runs, May period, 00 UTC initialised runs.

The effects on the RH2m description vary according to the day-night cycle rather than according to the time distance to the end of the data assimilation. In fact, from both figures it is possible to notice that the TEMP description is generally improved at night time, and worsens or shows no significant difference during day time.

For the January case, the scores of T2m and W10m are reported, because in these conditions it's wind speed more negatively affected by the T2m assimilation.

The effects on T2m are good for a longer time compared to the May case. The 00 UTC runs (figure 10) are positively affected by the T2m assimilation. In some days, the positive effect lasts for all the 24 simulated hours, for other it ceases during the data assimilation time,

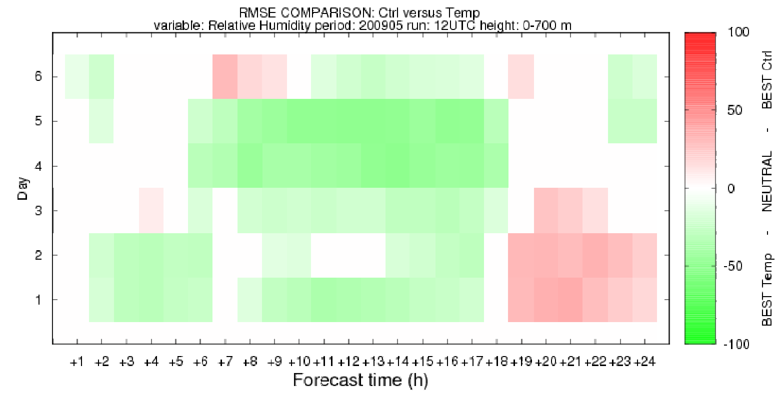

Figure 9: summary of the significance of the difference of the RMSE scores for RH2m between the TEMP and the CTRL runs, May period, 12 UTC initialised runs.

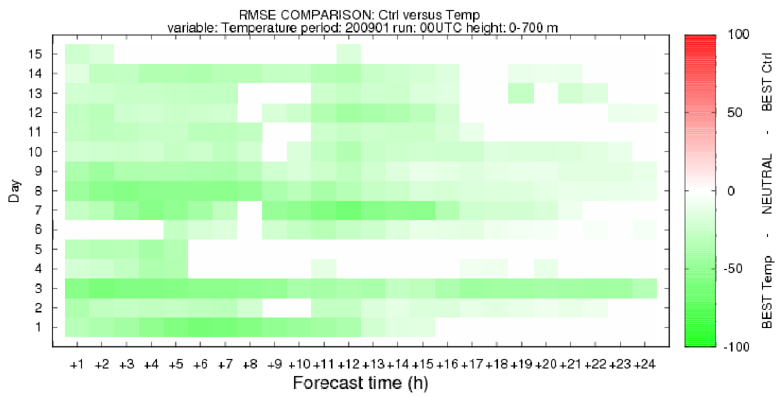

Figure 10: summary of the significance of the difference of the RMSE scores for T2m between the TEMP and the CTRL runs, January period, 00 UTC initialised runs.

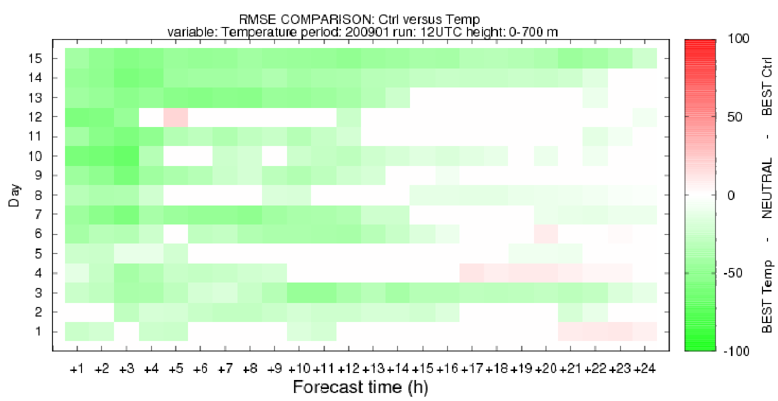

Figure 11: summary of the significance of the difference of the RMSE scores for T2m between the TEMP and the CTRL runs, January period, 12 UTC initialised runs.

and there are no worsening in the TEMP runs compared to CTRL ones. The 12 UTC runs (figure 11) show good results as well, even if there are some isolated forecast times and days in which the T2m description worsens.

The reason of this general great improvement has to be found in the presence of the strong temperature inversion: an improvement in the analysis “is trapped” in the lower atmospheric layers, and is not influenced by the development of convection.

On the other hand, if for T2m the results are very good, for W10m are not. Figures 12 and

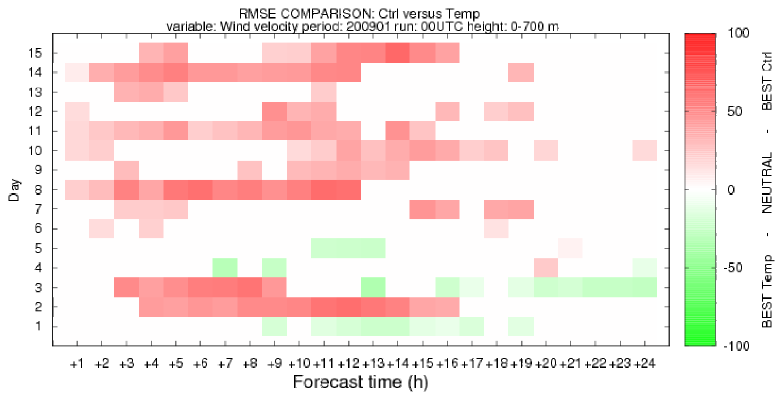

Figure 12: summary of the significance of the difference of the RMSE scores for W10m between the TEMP and the CTRL runs, January period, 00 UTC initialised runs.

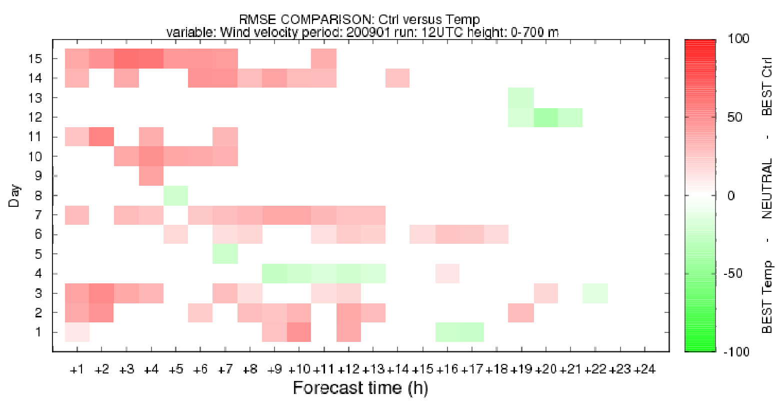

Figure 13: summary of the significance of the difference of the RMSE scores for W10m between the TEMP and the CTRL runs, January period, 12 UTC initialised runs.

13 show, in fact, how the RMSE generally worsens or, at least, is not significantly changed in the TEMP runs. In general, worsening is heavier for 00 UTC runs rather than 12 UTC ones, and during the data assimilation time window rather than in the free forecast time.

Effects on soil-atmosphere fluxes As previously mentioned in section 2, the comparisons of the statistical scores of TEMP and CTRL simulations has been carried out also for the soil-atmosphere fluxes, i.e. sensible heat flux and latent heat flux. The graphics in this section represent a comparison of the RMSE (top) and the ME (bottom) of the TEMP simulations (dotted line) and the CTRL simulations (marker with the confidence bar), at the different forecast times. The markers show a 90% confidence bar, obtained by using the bootstrap technique. The statistical scores have been calculated globally over all the experiment days, for each experiment (the May and the January one).

The data presented in this section are averaged along the different days for both experiments.

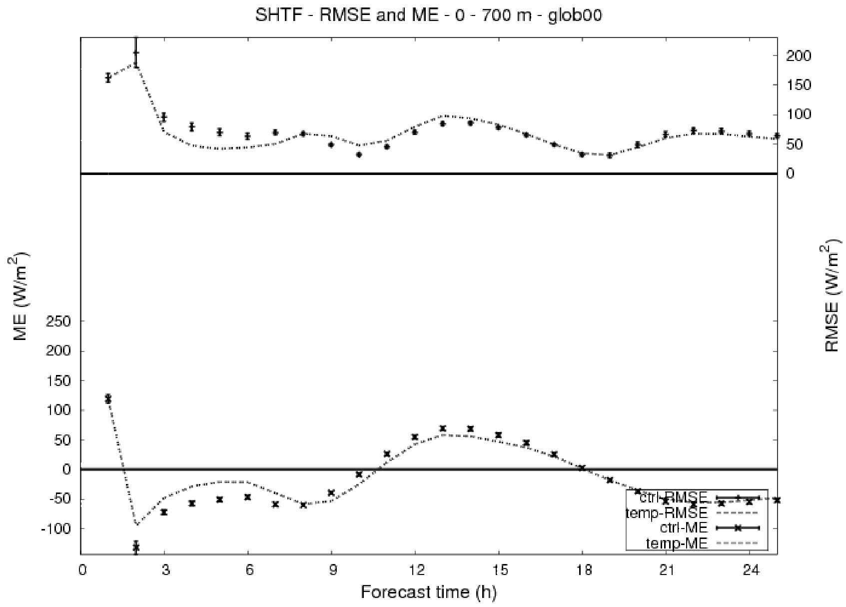

Figure 14: RMSE and ME for the sensible heat flux, May experiment, 00 UTC runs.

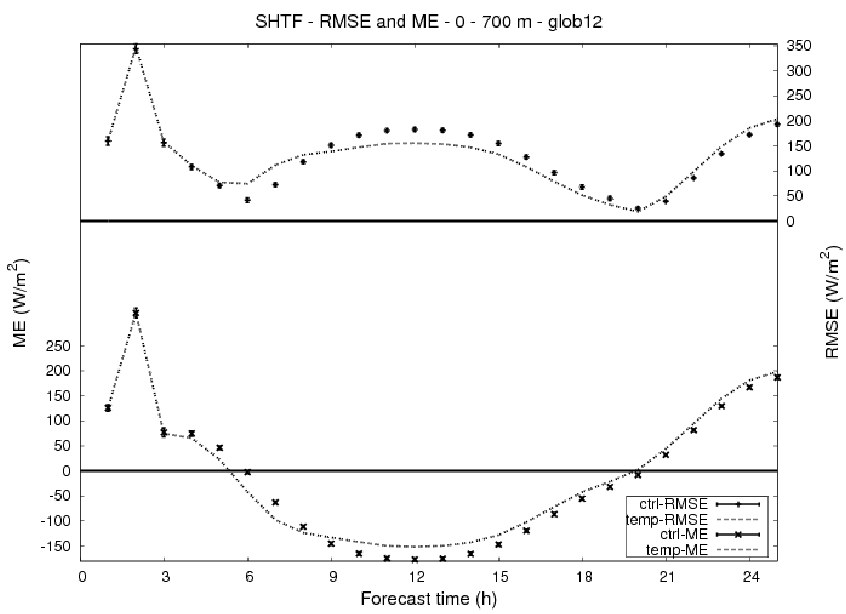

Figure 15: RMSE and ME for the sensible heat flux, May experiment, 12 UTC runs.

Figures 14 and 15 show a comparison of ME and RMSE of sensible heat flux for the May case, in particular for the runs initialised at 00 UTC. In the 00 UTC runs, TEMP simulations show better values of both indexes during the first hours of T2m assimilation; after dawn, but still within the assimilation window, TEMP values worsen.

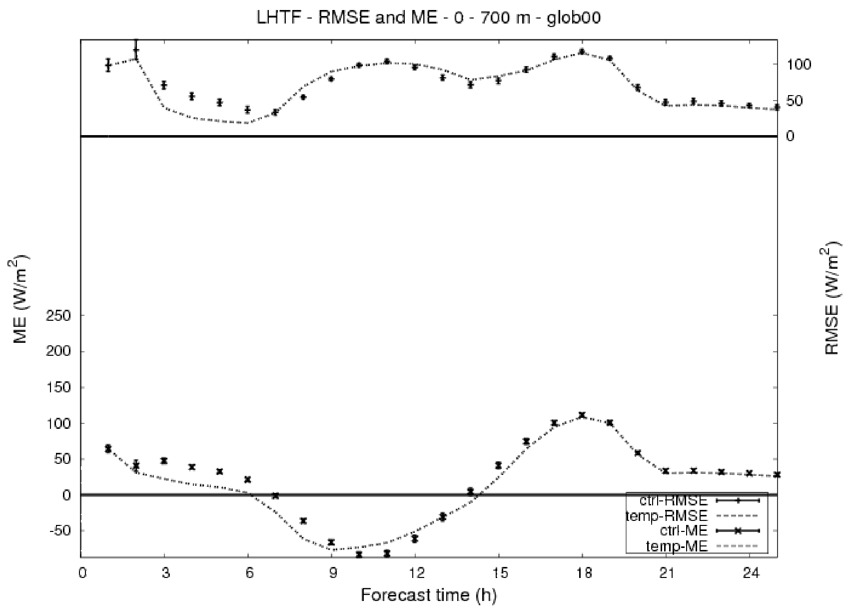

Figure 16: RMSE and ME for the latent heat flux, May experiment, 00 UTC runs.

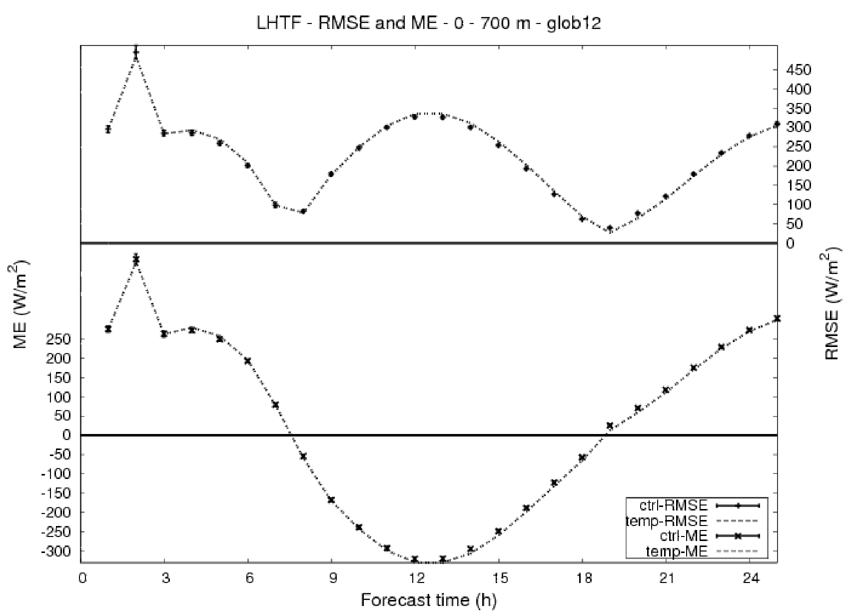

Figure 17: RMSE and ME for the latent heat flux, May experiment, 12 UTC runs.

Figures 16 and 17 show the corresponding values for the latent heat flux. The only important differences can be found in the 00 UTC runs. The TEMP simulations tend to have better values for the latent heat flux in the first hours of T2m assimilation, while they show worse values by the end of the nudging window.

Passing to considering now the January test case, it is possible to notice, from figures 18 and 19, that the sensible heat flux is generally described more poorly by the TEMP simulations than the CTRL ones. This phenomenon is longer in the 00 UTC runs than in the 12 UTC ones.

Figures 20 and 21 show, instead, the behaviour of the statistical indexes for the latent heat

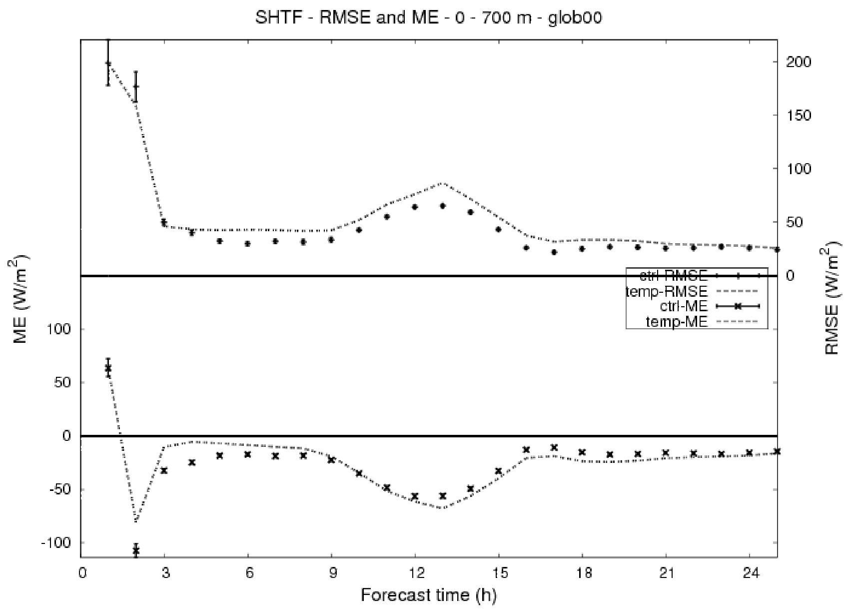

Figure 18: RMSE and ME for the sensible heat flux, January experiment, 00 UTC runs.

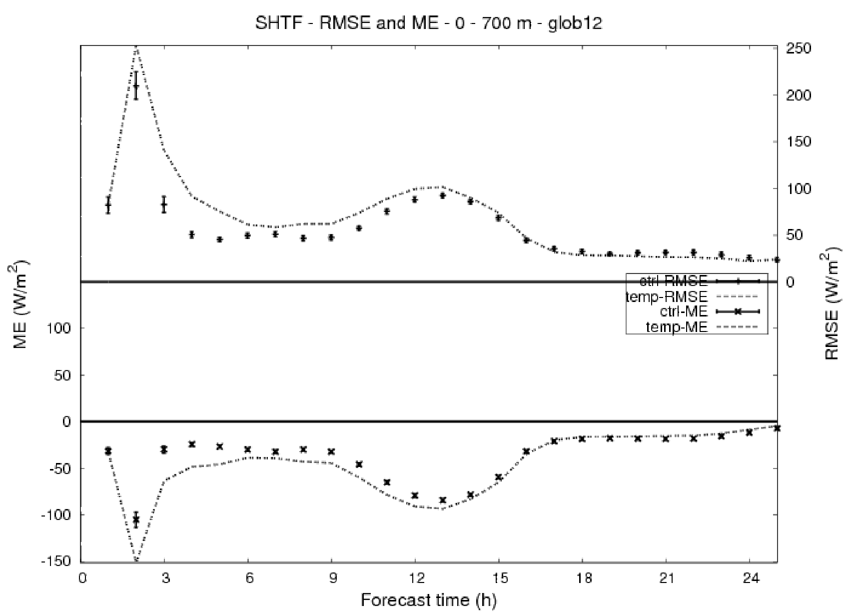

Figure 19: RMSE and ME for the sensible heat flux, January experiment, 12 UTC runs.

flux. Also in this case, the time interested by the T2m assimilation is characterised by worse scores in the TEMP rather than in the CTRL simulations.

In the January case, in general, the description of the soil-atmosphere energy transfer worsens, for both fluxes.

A common feature of all the graphics presented in this section is the initial high value of RMSE and ME. Further investigations are still needed to understand the reason of these spikes, but a first hypothesis to work on are initialisation problems of the first atmospheric layer compared to the soil thermal and hydrological state.

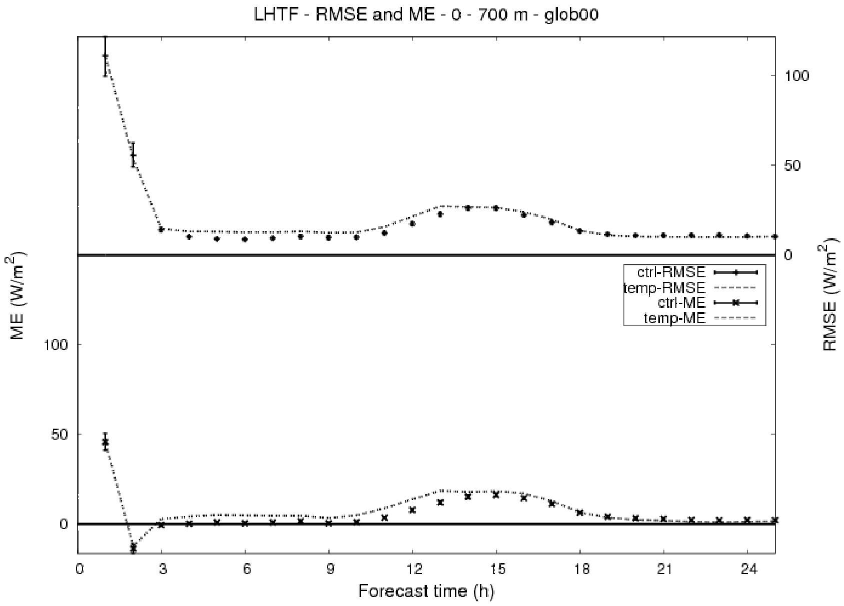

Figure 20: RMSE and ME for the latent heat flux, January experiment, 00 UTC runs.

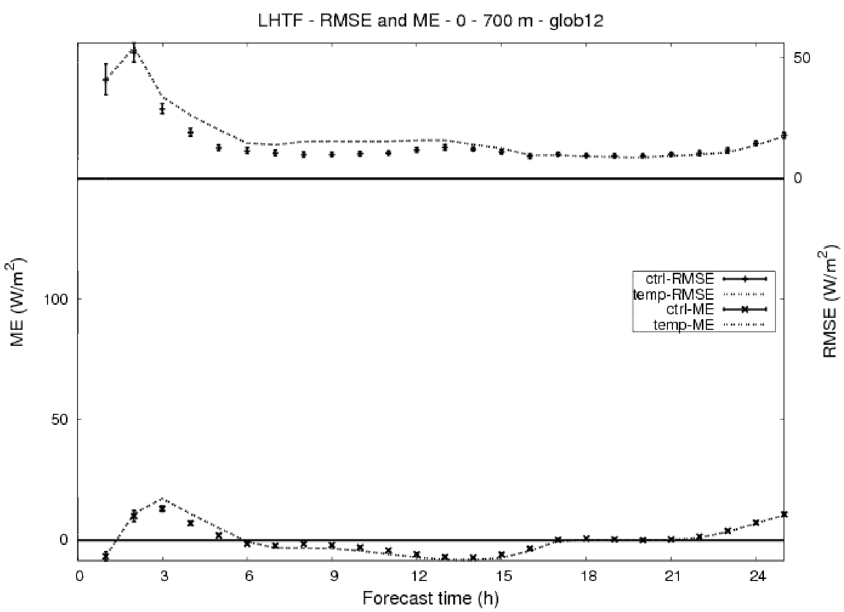

Figure 21: RMSE and ME for the latent heat flux, January experiment, 12 UTC runs.

Effects on the PBL height as an indicator of the stability profile An additional check has been performed on the PBL height, considering it as a way to investigate the atmospheric stability near the land surface. This aims to investigate the effects that the T2m assimilation introduces in the first vertical layers of the model above the surface.

In this part of the study, no comparison against real data has been performed because no enough real or proxy data were available. The only purpose of this part is to assess the statistical difference in the PBL height described by the TEMP and the CTRL simulations.

In the framework of this study, the PBL height has been defined as the point where holds

$$\theta(z = \text{surface}) = \theta_e(z = H_{PBL}),$$

where $\theta(z)$ is the potential temperature profile and $\theta_e(z)$ the potential temperature profile.

The data presented in this section refer to a sample day of the May experiment.

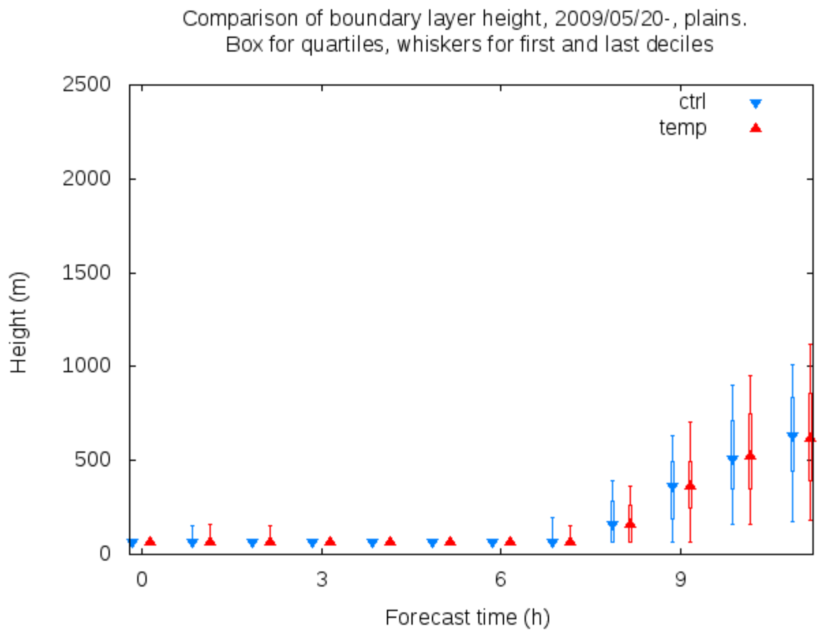

Figure 22: PBL height distributions at different forecast times, during the T2m assimilation time window, 00 UTC initialised run.

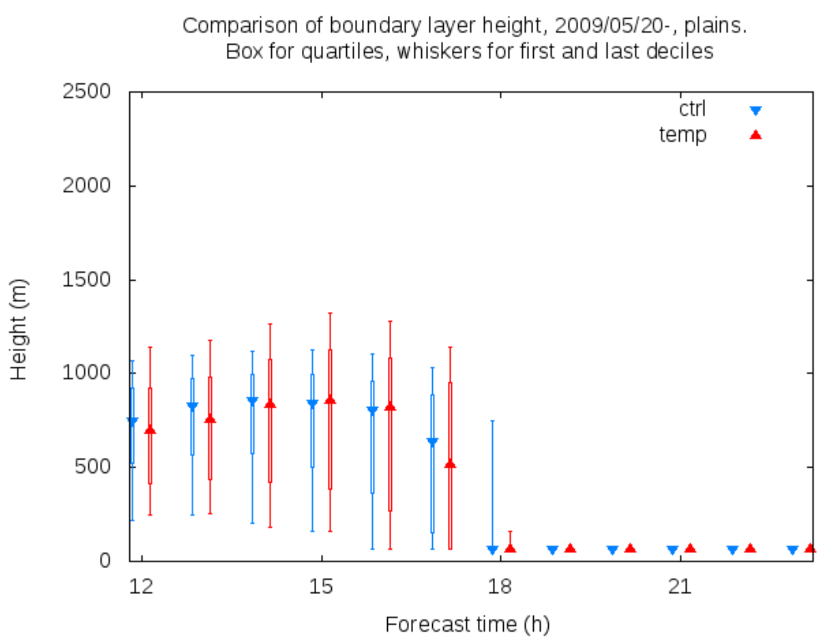

Figure 23: PBL height distributions at different forecast times, after the T2m assimilation time window, 00 UTC initialised run.

Figures 22 and 23 show the time series of the distributions of the PBL heights over the Piemonte domain (14641 points) for a sample day in the May period. The distributions are represented by their mean values (the triangular marker), the quartiles (the boxes) and the first and last deciles (the whiskers). The initialisation of this particular run is 00 UTC.

Due to the high number of data, the runs tests determine with a 99% confidence level that each corresponding distribution of the TEMP and of the CTRL simulations are statistically different, for each forecast time. This is true both for the distributions which refer to forecast times within the T2m assimilation window, and for the ones in the free forecast.

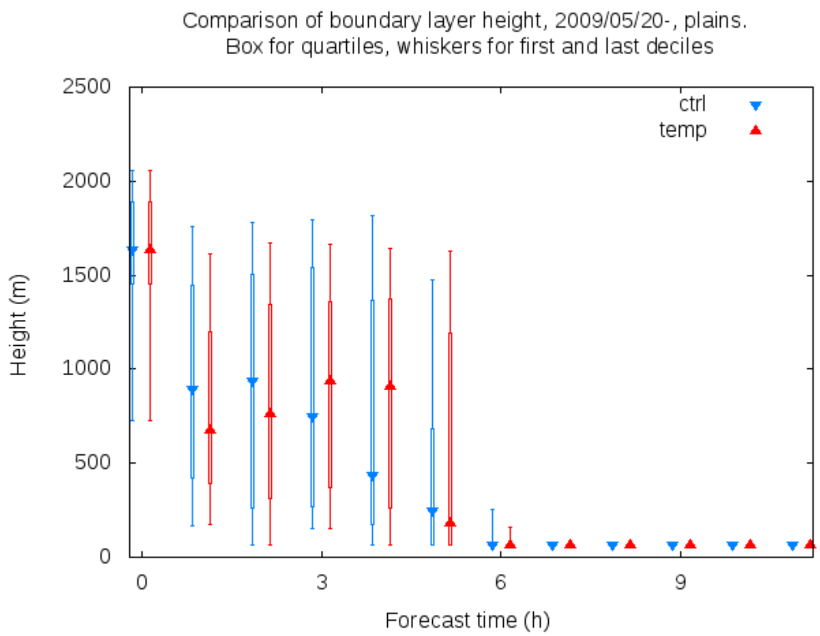

Figure 24: PBL height distributions at different forecast times, during the T2m assimilation time window, 12 UTC initialised run.

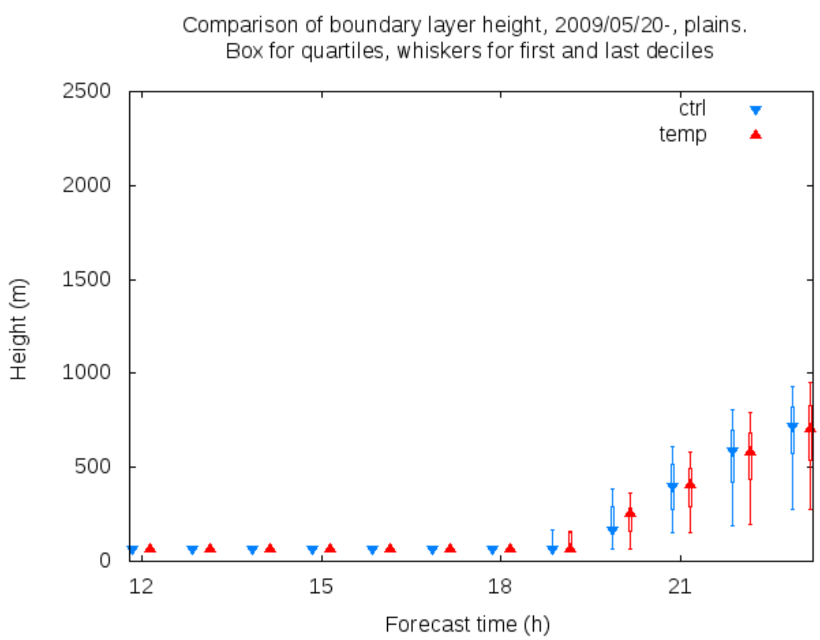

Figure 25: PBL height distributions at different forecast times, after the T2m assimilation time window, 12 UTC initialised run.

Figures 24 and 25 are conceptually similar to figures 22 and 23. They represent the simulation following by 12 hours the previous one. Also in this case the runs test makes it possible to state that, with a 99% confidence level, each TEMP distribution differs from the corresponding one of CTRL. This is true in general, for every day both of May and January periods (not shown for brevity), and for every initialisation time. Indeed, it is important to see that the PBL heights calculated by the 00 UTC COSMO simulations, for its last 12 hours, which should describe the same physical situation as the first 12 hours of the 12 UTC runs, in practice show very different PBL heights distributions, both in mean values and in spread. Also the model initialisation plays a central role, and not just the COSMO data assimilation.

Effects on the whole temperature profile To conclude the test performed by activating the T2m assimilation in COSMO, also the complete vertical temperature profile have been studied. The description of the temperature profile given by COSMO has been compared to the only radiosounding available on the considered domain, Cuneo Levaldigi. Unfortunately, due to problems in the operational measurements during May, only the January data can be used for this comparison. The statistical scores reported in this paper are, for brevity, only the ones about the ME, because this permits to distinguish between the model overestimations and its underestimations. The graphics presented are averaged over all the days of the January experiment.

It is possible to see in figure 26 that the T2m assimilation introduces a big deviation in the ME profiles. Not only, in the model layers closer to land surface, the magnitude of the errors is rather different, but also the sign in the ME changes. This means that the behaviour of the model changes not just quantitatively, but also qualitatively (the TEMP run underestimates rather than overestimating, at least in this case). Anyway, by the end of the simulation (figure 26) the errors committed by the different simulations become similar.

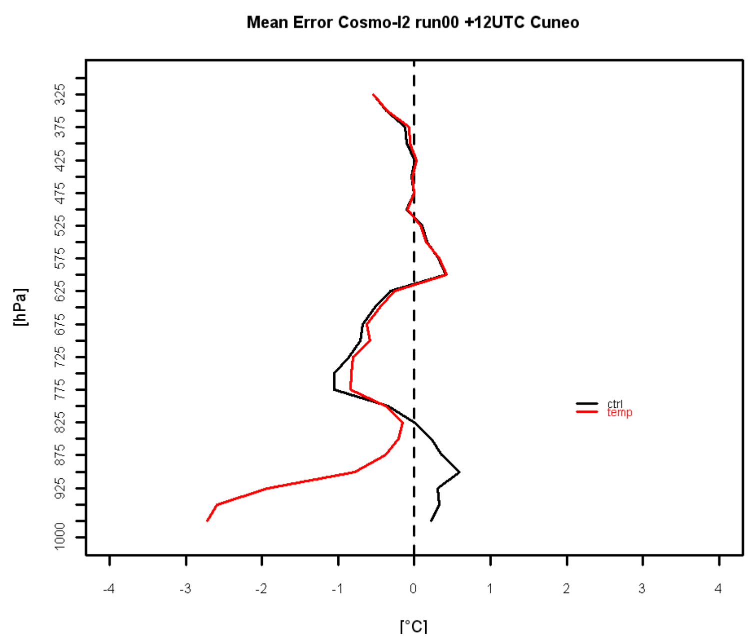

Figure 26: mean error vertical profile for temperature, 12 hours forecast time, 00 UTC initialisation.

Figures 28 and 29 refer to the 12 UTC initialised runs. It is possible to see from these figures how the error, at the end of the T2m assimilation, becomes different in the lower atmosphere, but not at the surface. In this case too, by the end of the simulations the errors of TEMP and CTRL experiments become more similar.

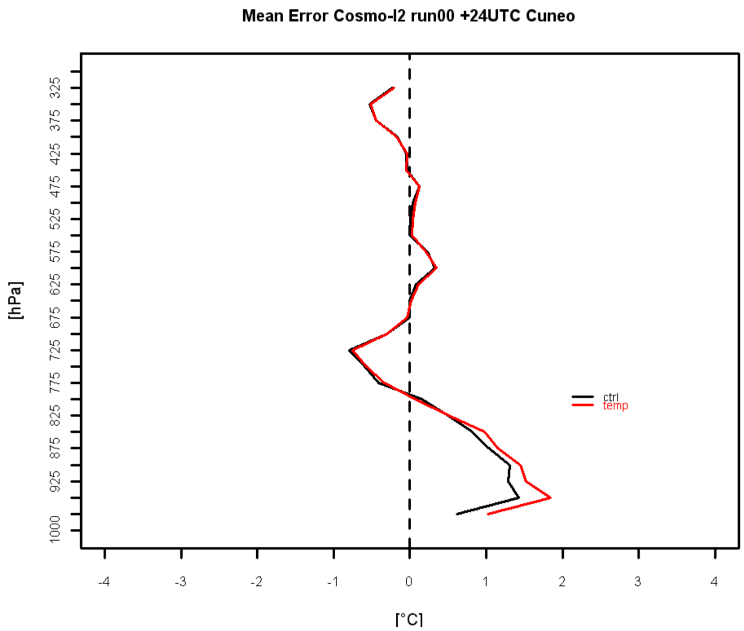

Figure 27: mean error vertical profile for temperature, 24 hours forecast time, 00 UTC initialisation.

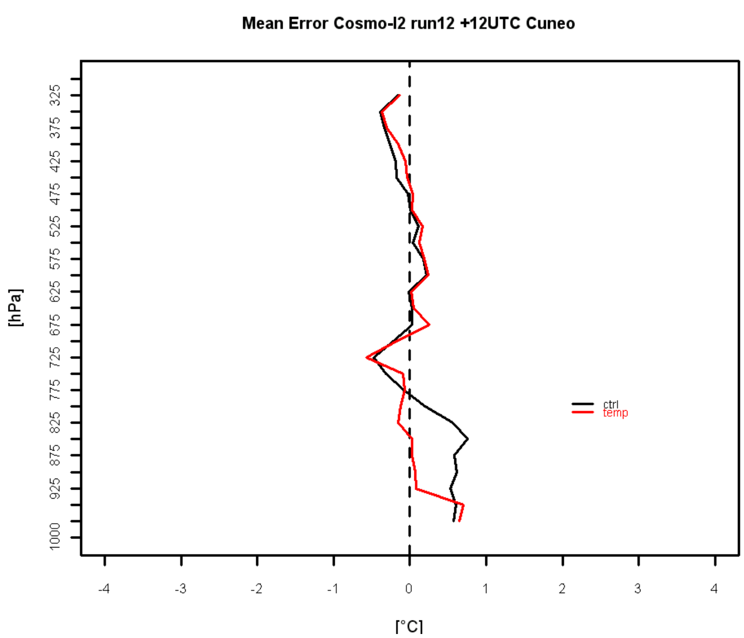

Figure 28: mean error vertical profile for temperature, 12 hours forecast time, 12 UTC initialisation.

All the figures relative to this section suggest, in any case, a revision of the parameters used for the vertical spread of the nudging increments.

Concluding remarks on the current COSMO performance Just to summarise all the different checks results, it is important to state that

T2m description is positively affected by its assimilation;

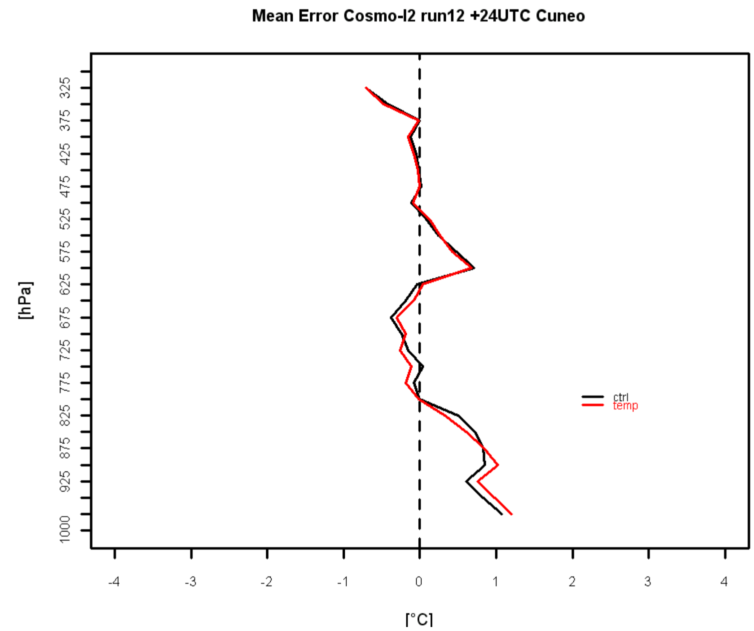

Figure 29: mean error vertical profile for temperature, 24 hours forecast time, 12 UTC initialisation.

RH2m and W10m description is neutrally or negatively affected, depending on the present atmospheric conditions;

surface fluxes description is neutrally affected in the May case, slightly negatively in the January case;

PBL height , hence lower atmospheric stability, differs significantly with or without the T2m assimilation;

temperature profiles are negatively affected by the T2m assimilation for the 00 UTC initialised runs, while positively affected for the 12 UTC runs.

4. The proposed developments: the FASDAS technique

The results of the checks shown in the previous sections suggest to improve the scheme involved in the T2m assimilation, in order to use and take advantage of the great availability of the T2m data in the analysis production. The approach chosen for enhancing the quality of the COSMO analysis production relies on the papers written by Alapaty et al. (2008; 2001), updating, in the surface level data assimilation phase, not just the atmospheric fields, but also the soil state related variables and the soil to atmosphere energy and moisture fluxes. This approach, of course, requires to investigate also the horizontal spreading of the nudging increments.

FASDAS technique (Flux Adjusting Surface Data Assimilation System) is based on the assumption that the T2m and RH2m assimilation should not have heavy consequences on the equilibrium of an atmospheric model.

Recalling the COSMO documentation of the nudging based data assimilation scheme, it is possible to write the time variation of a surface level variable α (let α stand for T2m or

Q2m[2]):

$$\frac{\partial \alpha}{\partial t} = P(\alpha, z, t) + G_\alpha(\hat{\alpha} - \alpha), \tag{1}$$

where P stands for describing all the model dynamics and its physical parametrizations, G_α is the nudging weighting factor, and $\hat{\alpha}$ is an observational value of α.

It is possible to write the two terms of the right hand side of (1) as

$$\begin{aligned} P(\alpha, z, t) &= \frac{\partial \alpha^P}{\partial t} \\ G_\alpha(\hat{\alpha} - \alpha) &= \frac{\partial \alpha^F}{\partial t}. \end{aligned}$$

Recalling that the time variation of a surface variable is proportional to the divergence of the corresponding flux, it is possible to write

$$\frac{\partial \alpha}{\partial t} = -\frac{H_1^\alpha - H_S^\alpha}{\rho C \Delta z}, \tag{2}$$

where H_1^α is the value of the particular flux at the first atmospheric level, H_S^α refers to the surface value, Δz is the thickness of the surface-first atmospheric level layer, and ρC is the product between air density and heat capacity.

Using equation (2), it is possible to calculate the flux associated to the assimilation of α:

$$H^{\alpha,F} = \rho C \left(\frac{\partial \alpha^F}{\partial t} \right) \Delta z. \tag{3}$$

This flux can be considered as the correction to be summed to the values of the fluxes given by the model physics to balance the α assimilation.

It is possible to use the result in equation (3), considering α standing both for T2m and for Q2m, so calculating the sensible heat flux (the energy flux related to T2m) and the latent heat flux (related to Q2m) corrections, and use the results to calculate how much the first soil layer temperature should be varied in order to maintain the equilibrium between all the components of the land-surface system:

$$\Delta T_g^F = \left(\frac{\partial T_g^F}{\partial t} \right) = (H_{\theta,S}^F - H_{q,S}^F)\frac{\Delta t}{C_g}, \tag{4}$$

where $H_{\theta,S}^F$ and $H_{q,S}^F$ are respectively the surface level sensible heat flux and the latent heat flux, Δt is the model time step, and C_g is the soil heat capacity. It must be noted that the minus sign for the latent heat flux is justified because a positive (negative) adjustment of T_g can cause a growth (decrease) of the latent heat flux, because it is a function of the saturation vapour pressure calculated at the temperature T_g.

It is important to observe, however, that the fluxes are adjusted so that T2m and Q2m are shifted towards the observed values. The fluxes are altered to allow the atmospheric structure in a realistic way, regardless of the reason of the errors of the simulated T2m and Q2m.

Before continuing, one must recall the state of art of the 2 metres values analysis. It is common practice (also for the COSMO soil moisture analysis) to attribute the main source of the T2m errors in wrong estimations of just one aspect of the soil state, usually its

[2]Q2m will denote, from this point on, the 2 metres mixing ratio. It will be used to describe atmospheric humidity content in place of RH2m.

```
PROGRAM lmorg
  [...]
timeloop: DO ntstep = nstart , nstop
    [...]
    IF (luseobs) CALL organize_assimilation ('surface',&
                                      izerror, yzerrmsg)
    [...]
    IF(luseobs) CALL organize_assimilation ('FASDAS',&
                                    izerror, yzerrmsg)
    [...]}
    CALL organize_data ('result', ntstep, lartif_data,&
                         1, 1, zgrids_dt,izerror, yzerrmsg)
    [...]
  END DO timeloop
  [...]
END PROGRAM lmorg
```

Figure 30: a schematic overview on how to plug the FASDAS scheme in COSMO.

hydrological state. Sometimes, however, the errors in the T2m values are due to other model errors rather than to be imputed to the data assimilation scheme; in this case, the correction of the soil state (in the COSMO case, the soil moisture) would be the introduction of an additional source of problems.

This kind of problems might be overcome using the FASDAS technique. Before continuing, some definitions are needed:

- q_a: mixing ratio of the surface layer
- Δq: time variation of the surface layer mixing ratio due to mixing
- $\psi_a \equiv q_a/\Delta q_a$: normalization
- $E = E_{\mathrm{dir}} + E_{\mathrm{can}} + \sum_{\mathrm{layers}} E_{\mathrm{trasp}}$: evapotranspiration considered as the sum of the direct evaporation, evaporation from the canopy and transpiration by the canopy from the different soil layers.

These can be used to write the correction to give to the soil water budget components in a balanced way:

$$E_\xi^F = \left(\frac{E_\xi}{E}\right)\psi_a\left(\frac{H_q^F}{\rho_w L}\right), \tag{5}$$

where ξ is a place holder for the components of the land surface system itemised above, ρ_w is the water density and L the evaporation latent heat. Each of these terms calculated in equation (5) should be used to correct the associated water balance equation.

The implementation of FASDAS should not be too invasive on the COSMO code: apart of minor interventions in some of the data assimilation routines, the main interventions should be limited to one routine, in the way shown in figure 30:

5. Conclusions

In the present report it has been analysed the possibility and the issues related to the use of T2m to improve the COSMO analysis production. This is a very important topic due to the great availability of T2m data. Before proposing an integration to the current data assimilation system, the current COSMO performances have been studied.

At the current stage, using T2m data in the assimilation has pros and cons: on the one hand the description of T2m itself is improved, but the other screen level variables might be negatively affected by the perturbations introduced by the T2m assimilation. In particular, the description of the land-surface energy balance is worsened.

The problem might be overcome by integrating the current data assimilation scheme with the FASDAS technique. This technique makes it possible for the observation nudging scheme to update not only the atmospheric fields of the assimilated variables, but also the related ones, such as the land-surface energy balance terms and the soil state.

As shown, the interventions to be performed on the COSMO code are projected to be rather isolated.

This work has been formalised as a WG1 activity, in agreement with USAM, ARPA-SIMC and Cristoph Schraff.

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