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Screen-level non-GTS data assimilation in a limited-area mesoscale model

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Abstract. The forecast in areas of very complex topography, as for instance the Alpine region, is still a challenge even for the new generation of numerical weather prediction models which aim at reaching the km-scale. The problem is enhanced by a general lack of standard observations, which is even more evident over the southern side of the Alps. For this reason, it would be useful to increase the performance of the mathematical models by locally assimilating non-conventional data. Since in ARPA Piemonte there is the availability of a great number of non-GTS stations, it has been decided to assimilate the 2 m temperature, coming from this dataset, in the very-high resolution version of the COSMO model, which has a horizontal resolution of about 3 km, more similar to the average resolution of the thermometers. Four different weather situations have been considered, ranging from spring to winter, from cloudy to clear sky. The aim of the work is to investigate the effects of the assimilation of non-GTS data in order to create an operational very high-resolution analysis, but also to test the option of running in the future a very short-range forecast starting from these analyses (RUC or Rapid Update Cycle). The results, in terms of Root Mean Square Error, Mean Error and diurnal cycle of some surface variables such as 2 m temperature, 2 m relative humidity and 10 m wind intensity show a positive impact during the assimilation cycle which tends to dissipate a few hours after the end of it. Moreover, the 2 m temperature assimilation has a slightly positive or neutral impact on the vertical profiles of temperature, eventhough some calibration is needed for the precipitation field which is too much perturbed during the assimilation cycle, while it is unaffected in the forecast period. So the stability of the planetary boundary layer, on the one hand, has not been particularly improved by the new-data assimilation, but, on the other hand, it has not been destroyed. It has to be pointed out that a correct description of the planetary boundary layer, even only the lowest part of it, could be helpful to the forecasters and, in general, to the users, in order to deal with meteorological hazards such as snow (in particular snow/rain limit definition), or fog (description of temperature inversions).

1 Introduction

Data assimilation is a powerful method to feed meteorological models by introducing information about the real state of the atmosphere. Different techniques have been used since the beginning of Numerical Weather Prediction (NWP), from the nudging or Newtonian relaxation (Stauffer and Seaman, 1994) to Ensemble Kalman Filtering (EnKF) (Eversen, 2009), through the variational approaches such as 3DVAR and 4DVAR (see for instance Kalnay, 2002 for a detailed and comprehensive overview on the subject). In this way, we are able to increase the accuracy and the predictability of the numerical models, but still we need a dense network of observations providing high-temporal resolution data. In regions where synoptic observations are scarce in space and in time, it is important to supply asynoptic data if available. For this reason it is crucial to collect the data from various networks which are outside the standard circuit, although these are mainly surface data. In particular, the data assimilated in COSMO are large scale GTS data which are (at least over the Italian territory) sparse and irregular in space and time and, to the author's opinion, are not sufficient to describe the structures of the local-scale circulations. On the other hand, the ARPA Piemonte network of non-GTS ground stations includes more than 500 surface stations measuring the main meteorological variables such

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as 10 m wind intensity (W10m), surface level pressure (Slp), 2 m temperature (T2m), 2 m relative humidity (Rh2m) and precipitation and a full use of them would permit an accurate description of the local forcing. A number of studies have been already published on the assimilation of surface or near surface data in addition to upper air data. For instance, Ruggiero et al. (1996) and Ruggiero et al. (2000) explored the frequent intermittent assimilation of surface data using an objective analysis, which has been found to give superior mesoscale analyses and forecasts compared to the assimilation of synoptic data only, provided the smoothing of these data into the third dimension. However the intermittent assimilation may lead to dynamic imbalances, which is not acceptable. Stauffer and Seaman (1990) and Stauffer et al. (1991) studied the impact of surface data assimilation for few case studies. They found that the continuous Four-Dimensional Data Assimilation (FDDA) of surface wind and moisture gave an improvement in the precipitation field only in case of weak synoptic forcing, while in case of strong synoptic forcing, the assimilation of surface data had to be joined to the assimilation of soundings in order to produce a real improvement. In fact, the assimilation of surface data can sometimes lead to unrealistical fluxes into the planetary boundary layer (PBL) if the relaxation is not properly defined. In these cases, the observations were first analyzed on the model's grid and then assimilated. The same results were obtained by Alapaty et al. (2001) using an idealized 1-D model of PBL. Stauffer and Seaman (1994) compared the use of large-scale analysis-nudging and fine-scale observation-nudging techniques alone or in combination, during two case studies. It has to be pointed out that the latter technique is more useful when the data are more widely separated in time and space. Again they found that in case of large scale forcing, the nudging weights should be large to have an impact, otherwise the assimilation is not effective. They found also that whenever there is a local forcing, the analysis-nudging alone, without the observation-nudging, may be harmful because it could limit the model's natural ability to produce finer-scale features. Something different has been found by Vinodkumar et al. (2008) and Vinodkumar et al. (2009) who studied the Indian monsoon region. They reported a general improvement of the meteorological parameters with surface and satellite data assimilation even in these strongly large-scale-induced conditions. It has to be noted that they modified the surface fluxes using a so-called Flux-Adjusting Surface Data Assimilation System (FASDAS) developed by Alapaty et al. (2008) which is probably able to act as a more effective perturbation in the model dynamics. Also Schraff (1997) showed that it is possible to improve the forecast of low stratus over the Alps using both surface and upper-air data with an observation-nudging method. This work points out that the improvement is more evident if the distribution of surface stations is relatively uniform in the vertical and, anyhow, the benefit ends before +12 h forecast. Finally, it is straightforward that the surface data assimilation may give a strong impulse to the simulation of urban meteorological conditions, as reported by Liu et al. (2006) who found that FDDA reduced the bias in the forecast of surface wind speed when using soil moisture and T2m to initialize the model. Other groups concentrated more on the assimilation of precipitation through the latent heat nudging approach which makes use of radar data to modify the temperature profiles of the models (see for instance Leuenberger and Rossa, 2007).

Concerning the operational COSMO model, it makes use of surface parameters such as wind, pressure and humidity, retrieved from Synop, Ships and Buoy stations. Surface variables such as Rh2m and T2m, despite lots of studies with a demonstrated positive impact of it, are not assimilated since at the beginning of the model's history, in some pre-operational test, their inclusion has been showed to degrade the low-tropospheric thermal structure of the model (Schraff and Hess, 2003), especially in cases of non-uniform distribution of the dataset. The T2m is at the moment only used in the soil moisture analysis, where it has the potential to modify the surface fluxes and to improve the prediction of T2m during the forecast time. Nevertheless, there is an option in the model for the inclusion of T2m in the assimilation cycle. So, on the basis of the work done by the other groups here cited, we believe that it would be useful to test this possibility using the most recent release of the model which is now well developed and assessed. In fact in the last ten years the model has been improved (as well as the nudging algorithm in it) and the horizontal resolution has been upgraded. Furthermore, the density of the ARPA Piemonte network is uniform enough to prevent too localised perturbations in the model.

The main objective of this work is to combine the full-physics COSMO-I2 model (2.8 km horizontal resolution) with some of the available non-standard observations to produce the best-possible real-time local-scale analyses and, in a second step, to provide very-short range forecast starting from these analyses. At the moment, COSMO-I2 has no assimilation cycle in it, therefore the only information concerning the observations comes from the father model COSMO-I7 (7.5 km horizontal resolution) which gives the initial and boundary conditions. As a first step, we focus on the assimilation of T2m coming from the ARPA Piemonte high-resolution network. This paper is structured in the following way: in Sect. 2 we describe the dataset and the test cases (Sect. 2.1), we introduce a general description of the COSMO model with its main features (Sect. 2.2) and then we describe the model setup (Sect. 2.3); in Sect. 3 the main results are shown and commented, comparing the model output and the observed data for surface variables (Sect. 3.1), vertical profiles (Sect. 3.2) and precipitation (Sect. 3.3); eventually some conclusions and short-term perspectives are drawn in Sect. 4.

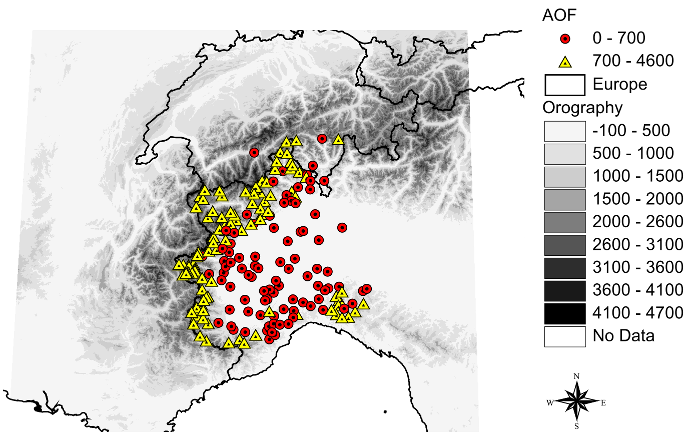

Fig. 1. Piemonte high resolution distribution for temperature sensors assimilated into the model. The red dotes indicate stations below 700 m, the yellow triangles above.

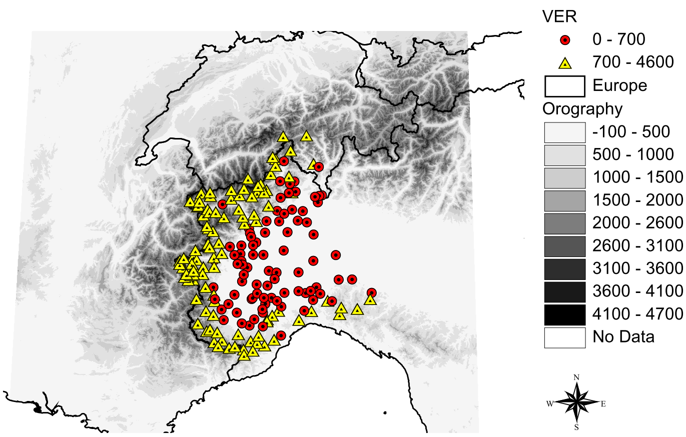

Fig. 2. Piemonte high resolution distribution for temperature sensors used for verification. The red dotes indicate stations below 700 m, the yellow triangles above.

2 Working method

2.1 Data set and test cases

The ARPA Piemonte network of non-GTS ground stations includes more than 500 surface stations measuring the main meteorological variables such as W10m, Slp, T2m and Rh2m. The quality of the data is ensured by a two-step procedure: first an automatic check is applied, then a manual check is performed. In this work we point our attention on the T2m assimilation. In order to have an independent validation of the results, the data have been subdivided into two homogeneously distributed groups (see Figs. 1 and 2): the first one is included into the assimilation cycle, the other one is used for verification. In Table 1 we show the number of stations used according to the purpose (whether they are used in the assimilation cycle or for verification only) and to the parameter. It has to be highlighted the great number of thermometers which is about three times the number of anemometers and twice the number of hygrometers. The stations with thermometers are quite equally distributed in height, that is there are ≈50% of stations below 700 m and ≈50% above.

Four different test cases have been run for 36 h (12 h of assimilation and 24 h of forecast) over a domain centered on the Piemonte region (Fig. 3) ranging from spring to winter, from cloudy to clear sky. More in detail, the date, the initial time of the simulation and the weather characteristics are here described:

– 17 August 2006 starting at 00UTC: summer situation with stormy weather; super cell in the northern part of the region; intense large-scale (south-western winds) and orographic (local) forcing;

– 1 May 2007 starting at 12:00 UTC: mixed advective/convective situation with diffused precipitation and localized thunderstorms not correctly described by the operational COSMO-I7; initially there is a weak large-scale forcing, which is enhanced only during the second day of forecast with the passage of the low (cold front associated with strong high-level currents);

Table 1. Number of stations distributed over the territory, according to the parameter.

	assimilation	verification	total
T2m	193	193	386
W10m	–	112	112
Rh2m	–	178	178

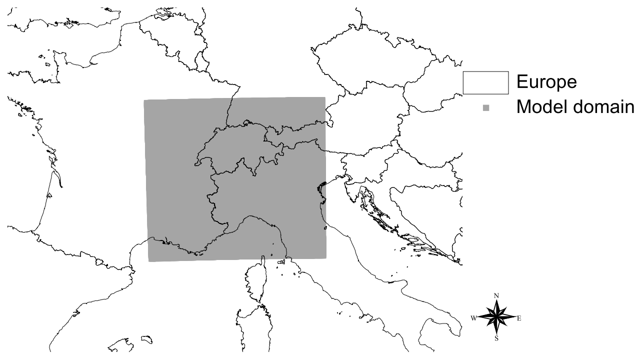

Fig. 3. Domain of the simulations.

– 17 February 2008 starting at 00:00 UTC: stratiform low-level clouds underestimated by the operational COSMO-I7 model; strong inversion; large-scale forcing due to easterly winds;

– 23 July 2008 starting at 00:00 UTC: clear sky summer situation; very weak large-scale forcing.

These test cases are characterized by different features. In August 2006 the event was mainly convective in nature and characterized by the occurrence of intense deep moist convection leading to relevant rainfall depths, enhanced by the orography structure (ARPA Piemonte, 2006); the analysis of the atmospheric scenario at the synoptic scale highlighted the presence of an intense cyclonic circulation during the event. An upper air trough (500 hPa) was localized near the Biscaglia gulf and during the afternoon the trough moved gradually towards the Atlantic French coastline. Meanwhile, an anticyclonic ridge continued its expansion over Eastern Europe; this structure triggered an intensification of the pressure gradient between Western and Eastern areas of Europe and consequently an increase of large-scale advection of moist and unstable air over Northern Italy and in particular in the area of North-Western Alps. The flux of moist air continued for the whole day and during the evening of the first day of simulation the upper-level cold front crossed Piemonte region intensifying deep moist convection in complex orography areas. This test case has been also studied in the framework of a COSMO Priority Project (see Milelli et al., 2008 and Dierer, 2008 for more details about the study and the project, respectively) because the operational COSMO Model forecast had some discrepancy regarding the correct localisation and intensity of the main precipitation structure.

In May 2007 a deep North-Atlantic low moved from Southern France towards Northern Italy where a strong South-Western flow brought a significant amount of humidity at all levels. The cold front, associated to the low, affected Piemonte region starting from the night between 1 and 2 May until the next morning determining a significant temperature decrease and great instability over the whole region. Diffused advective/convective precipitation phenomena were recorded over the whole region (ARPA Piemonte, 2007). The forecast given 24 h before the event (starting on 1 May 00:00 UTC) by three different versions of the COSMO model was affected by an error in the localization of the main precipitation pattern. The same displacement was recorded also in the 12:00 UTC forecast runs and in the corresponding ECMWF (European Centre for Medium-Range Weather Forecasts) model.

In the third case, the synoptic situation was determined by a high pressure system over Central Europe; Northern Italy was in the downward branch of this system, receiving a flux of easterly currents which brought moisture from the upper Adriatic Sea. This is a typical winter situation for Piemonte, with a strong inversion at about 1000 m and accumulation of low stratus towards the barrier of the Alps. Again the COSMO Model had some problem in forecasting the amount of humidity persisting along the whole day.

The last case, in July 2008, was a clear-sky day, with a stable high pressure system over the western Mediterranean Sea; in this case horizontal gradients were weak and turbulent mixing processes were the dominant mechanism responsible for the PBL growth.

The initial time of the simulations has been chosen in order to have the relative phenomena of interest in the time window +12 h/+24 h from the beginning of the simulation, that is around the end of the assimilation cycle.

2.2 The COSMO-Model

COSMO stands for *CO*nsortium for *S*mall-scale *MO*delling. The general goal of COSMO is to develop, improve and maintain a non-hydrostatic limited-area atmospheric model, the COSMO-Model, which is used both for operational and for research applications by the members of the consortium that at the moment are the National Meteorological Services of: Germany, Switzerland, Italy, Greece, Poland, and Romania. Additionally, there are a few regional and military services within the member states which are also participating.

The COSMO-Model is a non-hydrostatic limited-area atmospheric model developed within the COSMO community for applications on the meso-β and meso-γ scale (Steppeler et al., 2003). The model is based on non-hydrostatic, fully compressible hydro-thermodynamical equations in advection form. Generalized terrain-following height coordinates with rotated geographical coordinates are used. The model equations are solved on an ARAKAWA C-grid with user-defined vertical grid staggering. They are spatially discretised with 2nd-order finite differences. Time integration uses a 2nd-order leapfrog (horizontally explicit, vertically implicit) time-split integration scheme including extensions proposed by Skamarock and Klemp (1992). A 4th order linear horizontal diffusion is calculated. 3-D divergence damping and off-centering are applied in split time steps. Damping at the top of the model domain is done by Rayleigh damping (see for instance Doms and Schättler, 2002) in the upper layers. Data at the lateral boundaries are prescribed using a Davies-type one-way nesting (see Davies, 1976 or Davies, 1983). Subgrid-scale turbulence is parameterized by a prognostic turbulent kinetic energy closure at level 2.5 including effects from subgrid-scale condensation and from thermal circulations (Mellor and Yamada, 1974). The surface layer parameterisation is based on turbulent kinetic energy and includes a laminar-turbulent roughness layer. The formation of precipitation is described by a bulk microphysics parameterisation including water vapour, cloud water and ice, rain and snow with a fully prognostic treatment of precipitation, i.e. 3-D transport of rain, and snow is calculated. Condensation and evaporation are parameterized by saturation adjustment while depositional growth/sublimation of cloud ice is calculated using an explicit non-equilibrium growth equation. Subgrid-scale cloudiness used for radiation calculations is parameterized by an empirical function depending on relative humidity, ice content and height. Moist convection is parameterized using a mass-flux scheme with an equilibrium closure based on moisture convergence following Tiedtke (1989). Radiation is calculated using a two-stream scheme for short- and long-wave fluxes (eight spectral intervals) including a full cloud-radiation feedback. A two-layer or a multi-layer version of the soil model solving the heat conduction equation can be applied.

As far as the data assimilation is concerned, a nudging or Newtonian relaxation scheme is implemented. It consists of relaxing the model's prognostic variables towards prescribed values within a given time window. In the present scheme, nudging is performed using observations which is more appropriate for high-resolution applications than nudging towards 3-dimensional analyses (Stauffer and Seaman, 1994). A relaxation term is introduced into the model equations, and the tendency for a prognostic variable $\psi(\mathbf{x},t)$ is given by

$$\frac{\partial\psi(\mathbf{x},t)}{\partial t} = F(\psi,\mathbf{x},t) + G_{\psi}\cdot\sum_{k} W_k\cdot[\psi_k - \psi(\mathbf{x}_k,t)] \qquad (1)$$

where F denotes the model dynamics and physical parameterizations, ψ_k the value of the k-th observation affecting the grid point $\mathbf{x}$ at time t, $\mathbf{x}_k$ the observation point, G_{ψ} the constant called nudging coefficient and W_k an observation-dependent weight which varies between 0 and 1. In practical applications, the nudging term (second term to the right hand side of Eq. 1) usually remains smaller than the largest term of the dynamics (first term to the right hand side of Eq. 1) so that the dynamic balance of the model is not strongly disturbed. Moreover, a hydrostatic upper-air pressure correction is applied in order to balance hydrostatically the total analysis increments and to avoid spurious sources of vertical wind.

Table 2. Main differences between the 7 km and the 2.8 km versions.

	COSMO-I7	COSMO-I2
horizontal resolution (°)	0.0625	0.025
vertical levels	40	45
time step (s)	40	25
time integration scheme	Leapfrog	Runge-Kutta
deep convection scheme	Tiedtke	–
assimilation cycle (h)	12	–
ICs and BCs	ECMWF	COSMO-I7

The factors W_k give the relative weights assigned to the different observations at a single grid point. These factors include four different aspects: the quality of the observations ϵ_k, the horizontal w_{xy}, vertical w_{z} and temporal w_{t} distance between the observation and the assigned point, resulting in

$$W_k = \frac{w_k}{\sum_j w_j}\cdot w_k \qquad (2)$$

with

$$w_k = w_{\mathrm{t}}\cdot w_{\mathrm{xy}}\cdot w_{\mathrm{z}}\cdot\epsilon_k \qquad (3)$$

From the operational point of view, there are a few differences between the 7 km and the 2.8 km versions that can be summarized in Table 2.

2.3 Model setup

Two simulations have been run for each test case: a control (Ctrl) run with no assimilation and a Temp run with the assimilation of T2m. For each run, we have performed simulations of 36 h in which the assimilation takes place in the first 12 h. The domain is shown in Fig. 3, it is centered over the Piemonte region but includes part of the Mediterranean Sea (Genua Gulf) and the whole Po valley. We started from the ECMWF initial and boundary conditions to produce the 7 km simulations which are then used as initial and boundary conditions for the 2.8 km simulations. In the 7 km simulations we used the operational settings, including the assimilation of GTS data in the first 12 h (see Table 2). The version 4.3 of the COSMO Model has been used.

In the 2.8 km runs the T2m observed in the high-resolution network of ARPA Piemonte is assimilated every hour via the nudging technique. With respect to the 7 km version of the

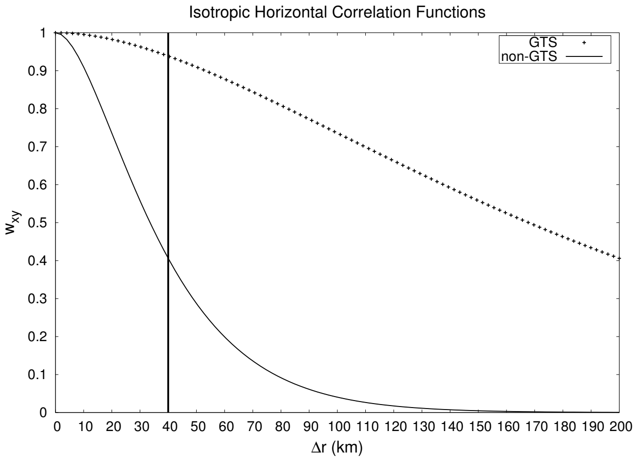

Fig. 4. Isotropic horizontal correlation functions in case of non-GTS data (continuous line) and GTS data (dotted line). The former is truncated at 40 km and the latter at 200 km.

model, a different horizontal correlation coefficient has been used, because of the increased density of the observations. The isotropic horizontal correlation function w_{xy} in Eq. (3) is defined as

$$w_{\mathrm{xy}} = (1+\Delta r/s)\cdot \exp(-\Delta r/s) \quad (4)$$

where Δr is the distance between the observation location and the target grid point and s is the correlation scale (in km) which is defined as the product of a constant part and a time-dependent part, that is $s{=}s_{\mathrm{c}}{\cdot}s_{\mathrm{t}}$ (at the observation time, $s_{\mathrm{t}}{=}1$). It has to be pointed out that there is a cut-off radius which determines the horizontal distance of direct influence of an observation and this is simply defined as $2s$. The operational value of s_{c} for surface synop temperature (although not used) would be 100 km, but we decreased it to 20 km, looking at the average distance of our set of non-GTS data. The two correlation functions are plotted in Fig. 4. Moreover, the maximum difference between the model orography and the station height that permits the assimilation of the station has been reduced to 100 m (160 m in the operational version, although not used). This has been done considering the better accuracy of the 2.8 km topography.

For the verification procedure, we compare directly both Direct Model Outputs (DMOs) to observations in terms of root mean square error (RMSE), mean error (ME) and diurnal cycle. The verification is carried out in an objective manner by using (for the temperature) a set of data (still homogeneous in space and time) different from the one that has been assimilated.

In order to evaluate if the performances of the two model versions are statistically different, we adopted an approach based on hypothesis testing (see for instance Hamill, 1999 or Wilks, 1995) in which we construct a confidence interval for the performance differences directly (as suggested in Jolliffe, 2007). The null hypothesis is that (for a given variable) there is no difference in quality between the modified run (Temp) and the Ctrl run, and the alternative hypothesis is that one of the runs is better than the other. Then we form a resampled distribution consistent with the null hypothesis, randomly choosing either one or the other run on each station and calculating the scores. This permutation procedure is similar to the hypothesis tests proposed by Hamill (1999). The hypothesis test is finally carried out by determining the position of the real score difference in the resampled distribution. To better illustrate the basic idea of the permutation test, we consider now the forecast errors for a fixed forecast time on each station of the two runs (Temp and Ctrl). We define the vector RMSE1 (for Temp) and RMSE2 (for Ctrl) on which each element is the RMSE on a station. We want to test, at 5% significance level, whether they come from the same distribution, i.e. there is no improving on the assimilation of T2m. The test proceeds as follows:

1. for each station the RMSE (both for Temp and for Ctrl) is calculated to form the two vectors RMSE1 and RMSE2 (from these vectors we also calculated the average RMSE of the two models, used then at point 7);
2. the elements of the two vectors relative to Temp and Ctrl are pooled;
3. these pooled values are randomly divided into two groups to obtain the two vector RMSE1* and RMSE2*;
4. the mean difference in RMSEs*, is calculated and recorded;
5. the steps among 2 and 4 are repeated 1000 times;
6. these calculated differences are the distribution of possible differences under the null hypothesis that model label does not matter;
7. finally, the hypothesis test is carried out by determining the position of the real score difference in the resampled distribution. A level of significance of 5% is used, so we plot the 95% confidence interval for the difference itself added to the metric (RMSE or ME) for the Ctrl run: when the metric of the Temp run is outside the interval, the differences may be considered statistically significant at 95%.

The permutation test assumes that the data are independent. In this case, in which the two runs are performed to generate each piece of data, this is certainly true, while, for example, it could be not true in case of consecutive forecasts.

3 Results

The results are shown in terms of average RMSE, ME (with a significance interval given by the permutation method, see Sect. 2.3) and diurnal cycle of surface variables like

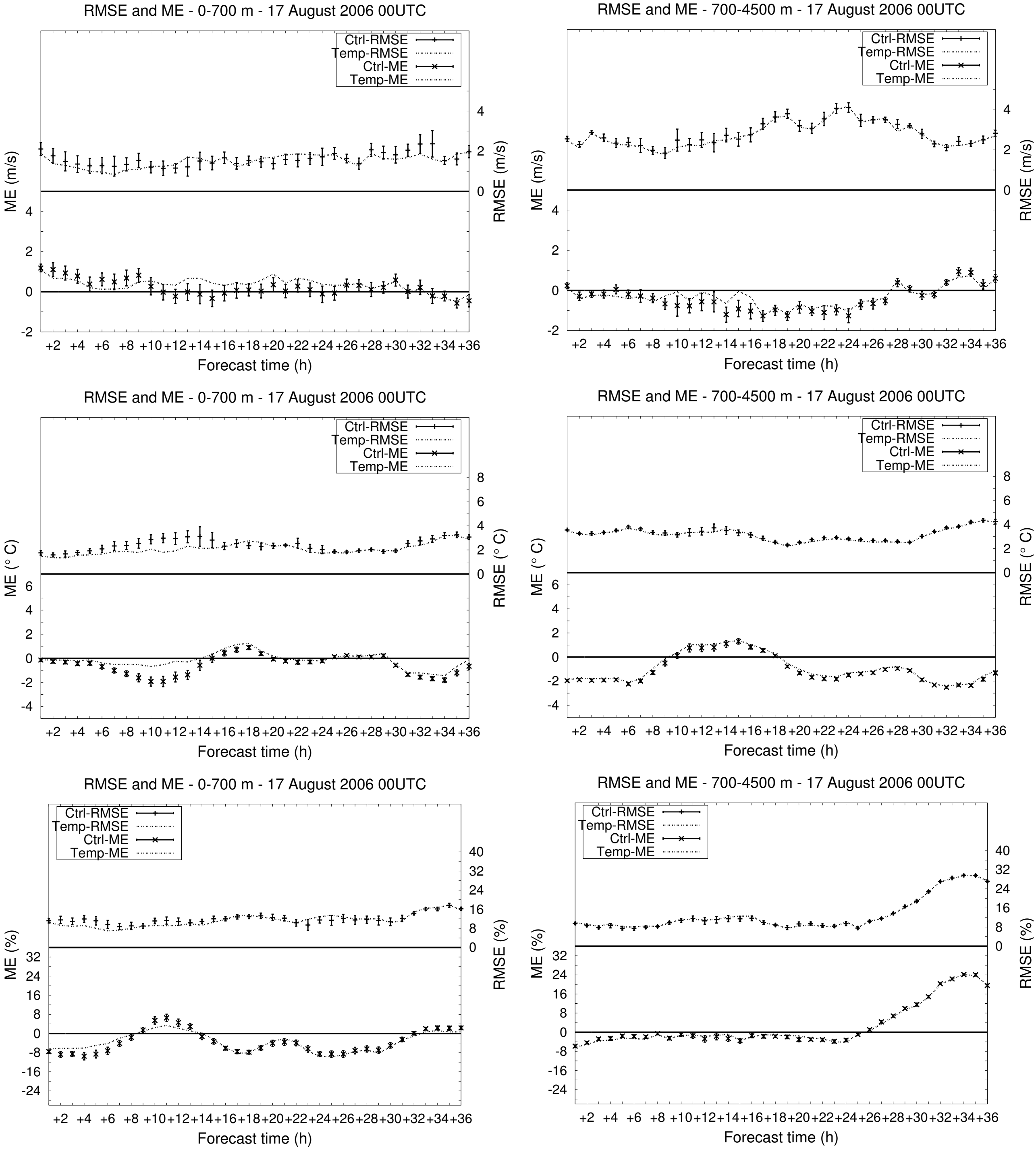

Fig. 5. RMSE and ME for the August 2006 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run with the significance bar and the dotted line represents the Temp run.

T2m, RH2m and W10m. Since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. This means the RMSE is mostly useful when large errors are particularly undesirable (Wilks, 1995). Therefore we have chosen the RMSE instead of the Mean Absolute Error (MAE) which weights in the average all the individual differences equally. The plots are differentiated according to the elevation h of the measurement station, that is we observe the temporal evolution over the plains ($0<h\leq 700$) and above ($h>700$). The values are calculated

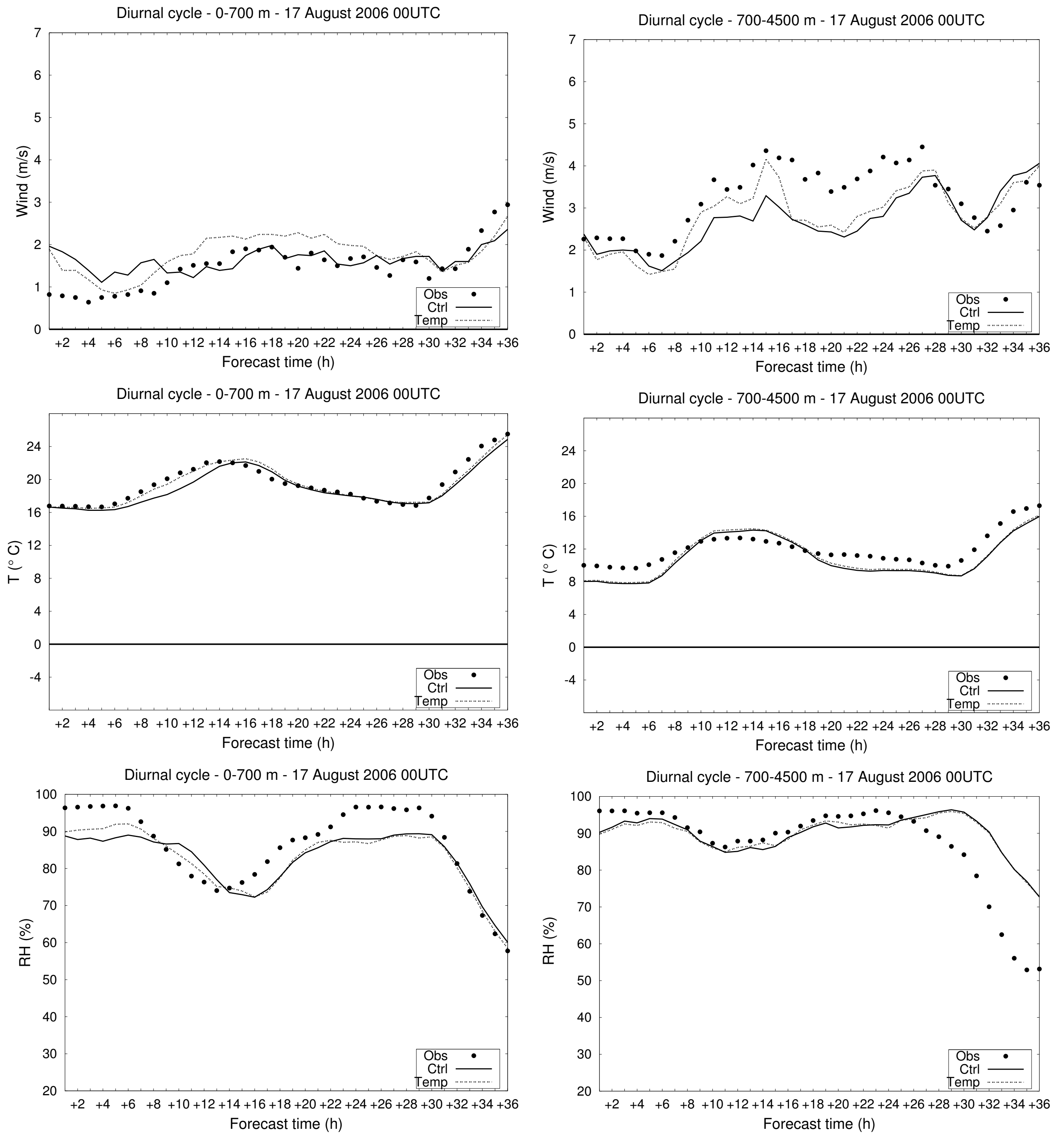

Fig. 6. Diurnal cycle for the August 2006 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run and the dotted line represents the Temp run.

as a mean (for each forecast time) of the values in that range of altitude. The stations considered are those belonging to the verification dataset and the model values are calculated on those points by an interpolation of the nearest grid points which do not have a strong difference in height. Moreover, we show the behavior of some vertical temperature profile in Cuneo and Milano, where and when the radiosonde data are available. In the plots, the dotted line represents the Temp run and the dots the Ctrl run, with the significance bar.

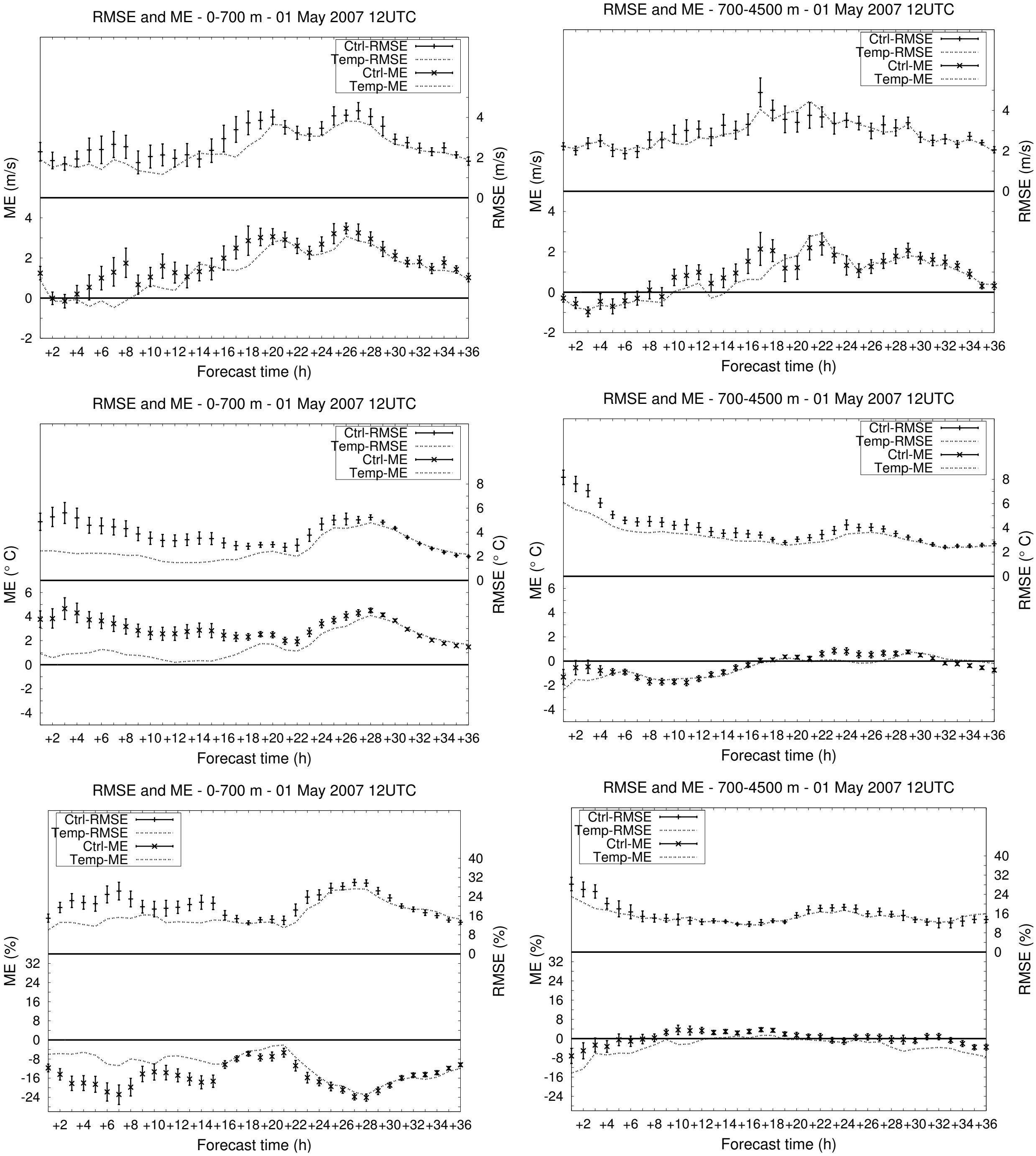

Fig. 7. RMSE and ME for the May 2007 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run with the significance bar and the dotted line represents the Temp run.

3.1 Surface variables

The main indications concerning RMSE and ME, looking at Figs. 5, 7, 9 and 11 are the following:

– the wind intensity (upper panels) does not show significant differences between the two runs, both over the plains and over the mountains. The RMSE is always between 1 and 4 m/s and the ME between –1 and 1 m/s showing a slight overestimation with the exception of the 2007 case when the errors are larger for both runs;

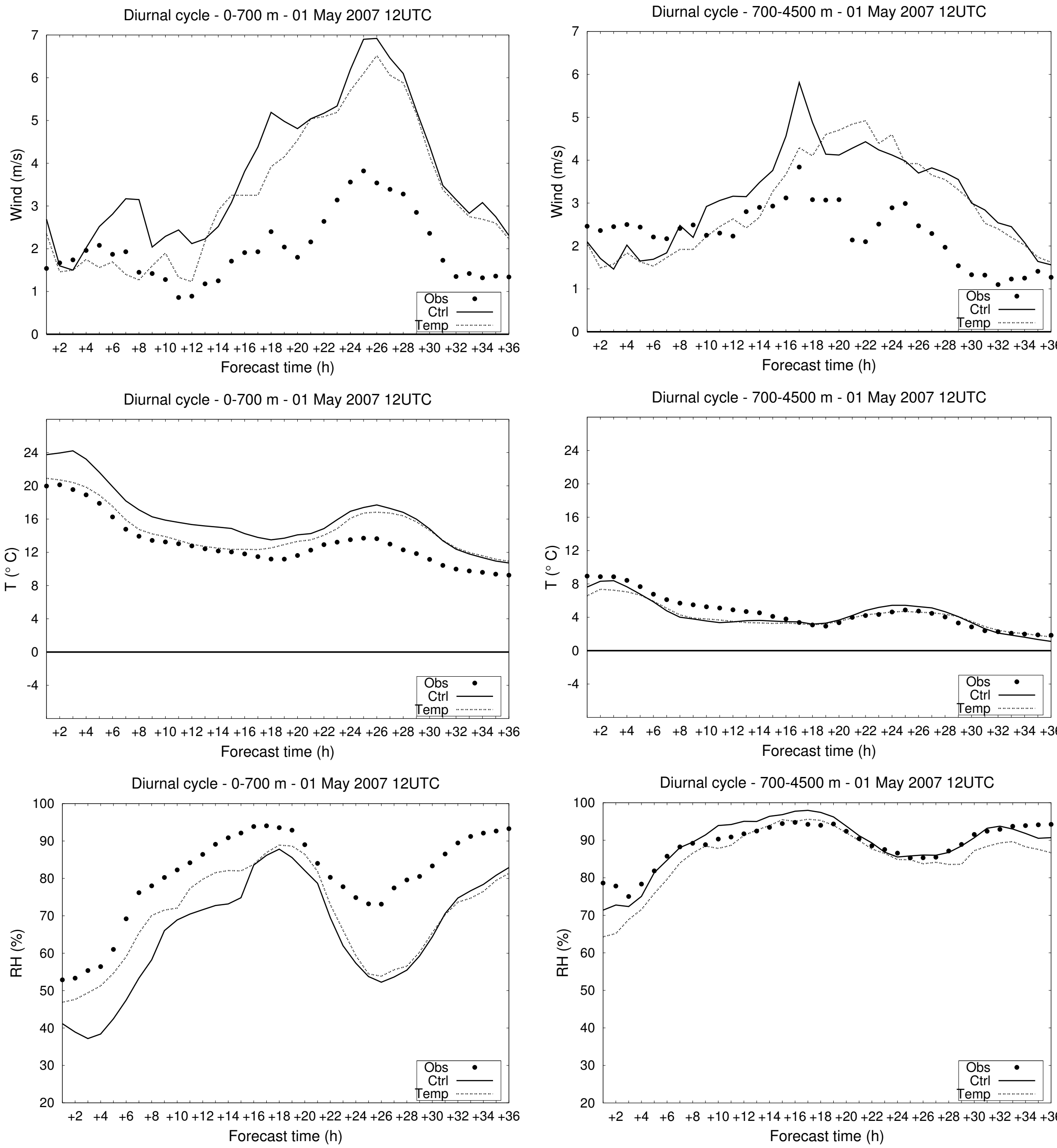

Fig. 8. Diurnal cycle for the May 2007 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run and the dotted line represents the Temp run.

– the temperature profiles (central panels) show indeed the largest benefit from the assimilation technique. The RMSE and the ME of the Temp runs are always statistically better than the Ctrl runs in the assimilation cycle (first 12 h) and then the runs tend to overlap: the effect of the nudging vanishes after 16 h–20 h, that is 4 h to 8 h after the end of the assimilation. Only the 2007 case shows and unexpected long-lasting improvement up to +30 h and the RMSE and ME are reduced by 2–3 °C in the first hours of simulations (over the plains). It has to be noted that in this case the simulations start at 12:00 UTC, when the PBL is already fully developed, therefore it is premature to draw conclusions upon this fact; we also point out that the amplitude of the oscillations in the ME of the Temp run are smaller than for the Ctrl;

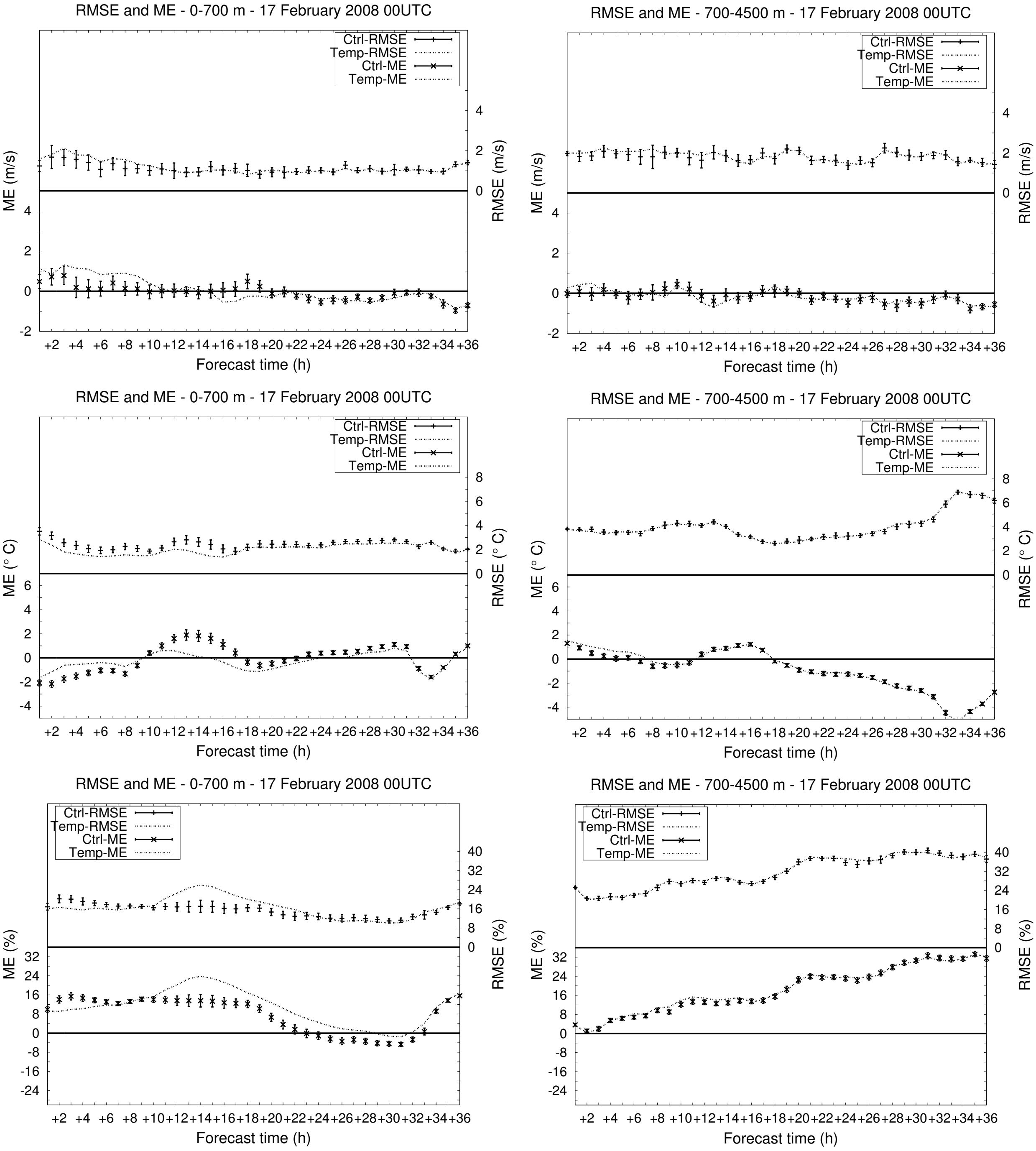

Fig. 9. RMSE and ME for the February 2008 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run with the significance bar and the dotted line represents the Temp run.

– the relative humidity (bottom panels) has also an improvement in the Temp runs up to +18 h, at least over the plains, except for the winter 2008 case, when there is actually a worsening around 12:00–15:00 UTC below 700 m (Fig. 9 bottom left), that is at the beginning of the free forecast period.

In general we can state that the impact of the T2m assimilation is positive or neutral, more evidently over the plains. Concerning the results above 700 m, in the August 2006 and February 2008 cases the effect of the assimilation is basically negligible (Figs. 5, 6, 9, 10, right panels), which is in agreement with the results found by Stauffer and Seaman (1994),

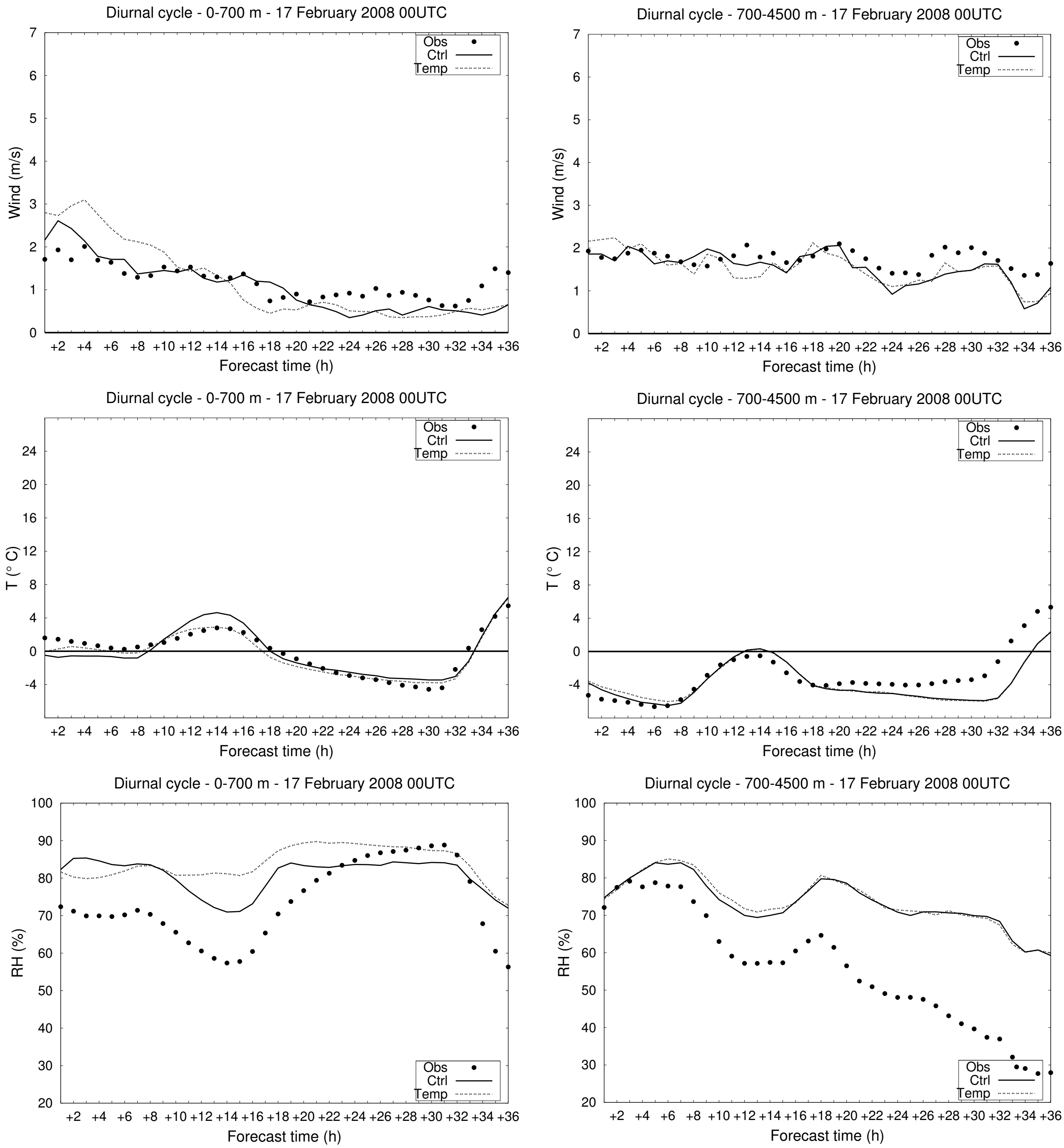

Fig. 10. Diurnal cycle for the February 2008 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run and the dotted line represents the Temp run.

Stauffer and Seaman (1990) and Stauffer et al. (1991). In fact the synoptic situation is dominated by large structures which interact with the Alps and in those circumstances the large-scale forcing overwhelms the effect of the assimilation of surface variables especially at higher elevations. In May 2007, the first 12 h of the simulations still coincide with a period of weak forcing and the effects above 700 m are more interesting, at least for T2m and at least in the first part of the runs (Figs. 7 and 8, right panels). Later on, the synoptic evolution (through the boundary conditions) acquires importance. Eventually, in the July 2008 case, with only local forcing acting, there is a very small positive impact on T2m, neutral on the other variables (Figs. 11 and 12, right panels). It has to be highlighted that the results over the plains are

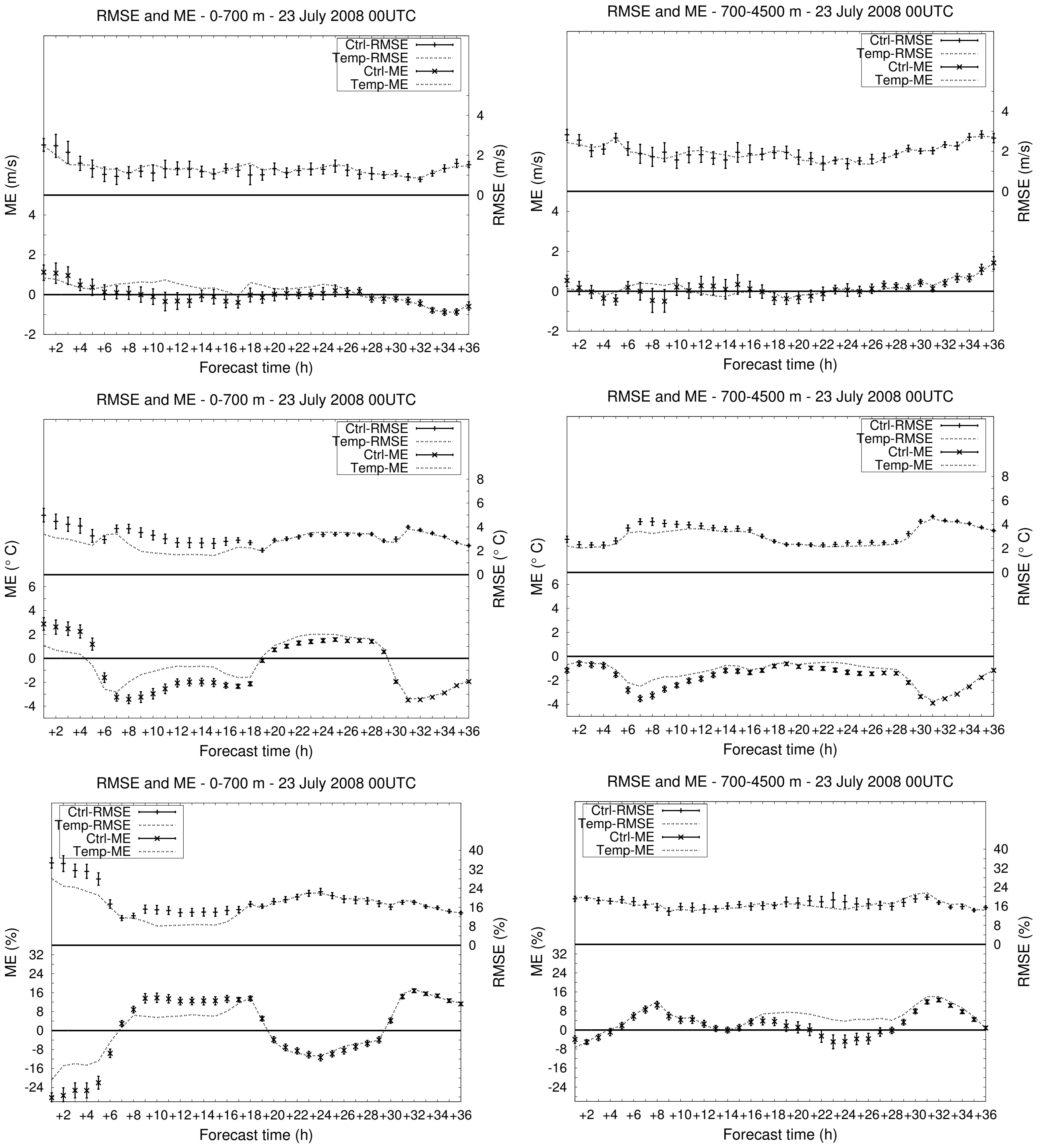

Fig. 11. RMSE and ME for the July 2008 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run with the significance bar and the dotted line represents the Temp run.

not negligible even in cases of large-scale forcing because the number of surface data assimilated is larger. In fact, due to an internal check of the assimilation routine which rejects the stations for which the model orography differs too much with respect to the real one (Δ=100 m), the data actually assimilated below 700 m are about 30% more than those above 700 m, therefore their influence on the model is stronger.

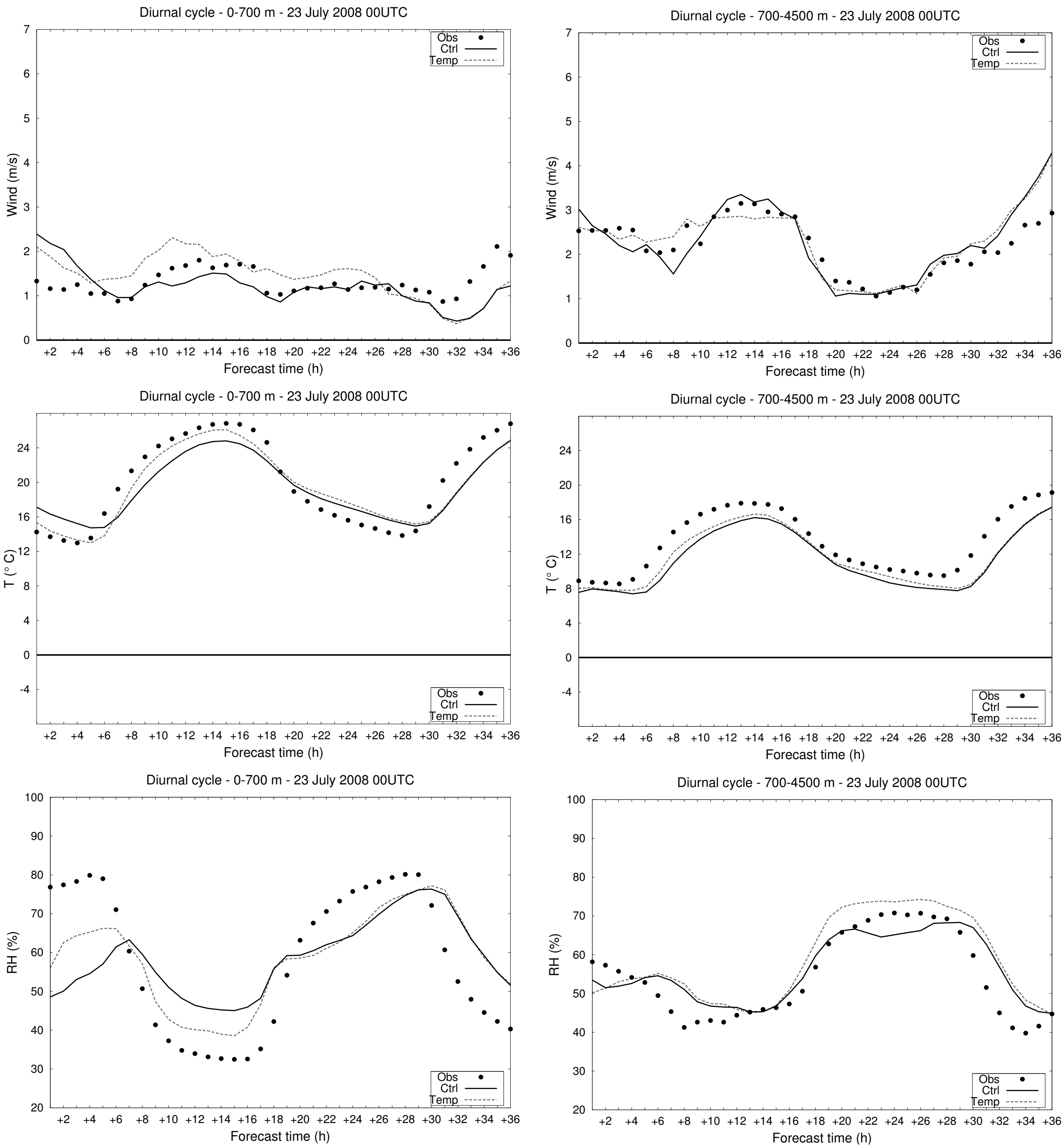

Fig. 12. Diurnal cycle for the July 2008 case, over the plains (left) and over the mountains (right); wind intensity (upper panels), temperature (middle panels) and relative humidity (bottom panels). The dots represent the Ctrl run and the dotted line represents the Temp run.

The same kind of information is given by the diurnal cycles:

– in August 2006 (Fig. 6) the observed diurnal variation is followed very well by the model, apart from the sharp decrease of Rh2m at the end of the simulations above 700 m (Fig. 6 bottom right panel); also the peaks of W10m at +14 h and +28 h are well captured;

– in May 2007 (Fig. 8) we had larger errors in the synoptic (initial and boundary conditions) because during those days the number of available GTS measurements was reduced by 30% with respect to a normal situation. Therefore, on the one hand temperature and humidity profiles are indeed well represented by the Temp run even for a longer time, but on the other hand there are some fluctuations in the wind profiles which follow the

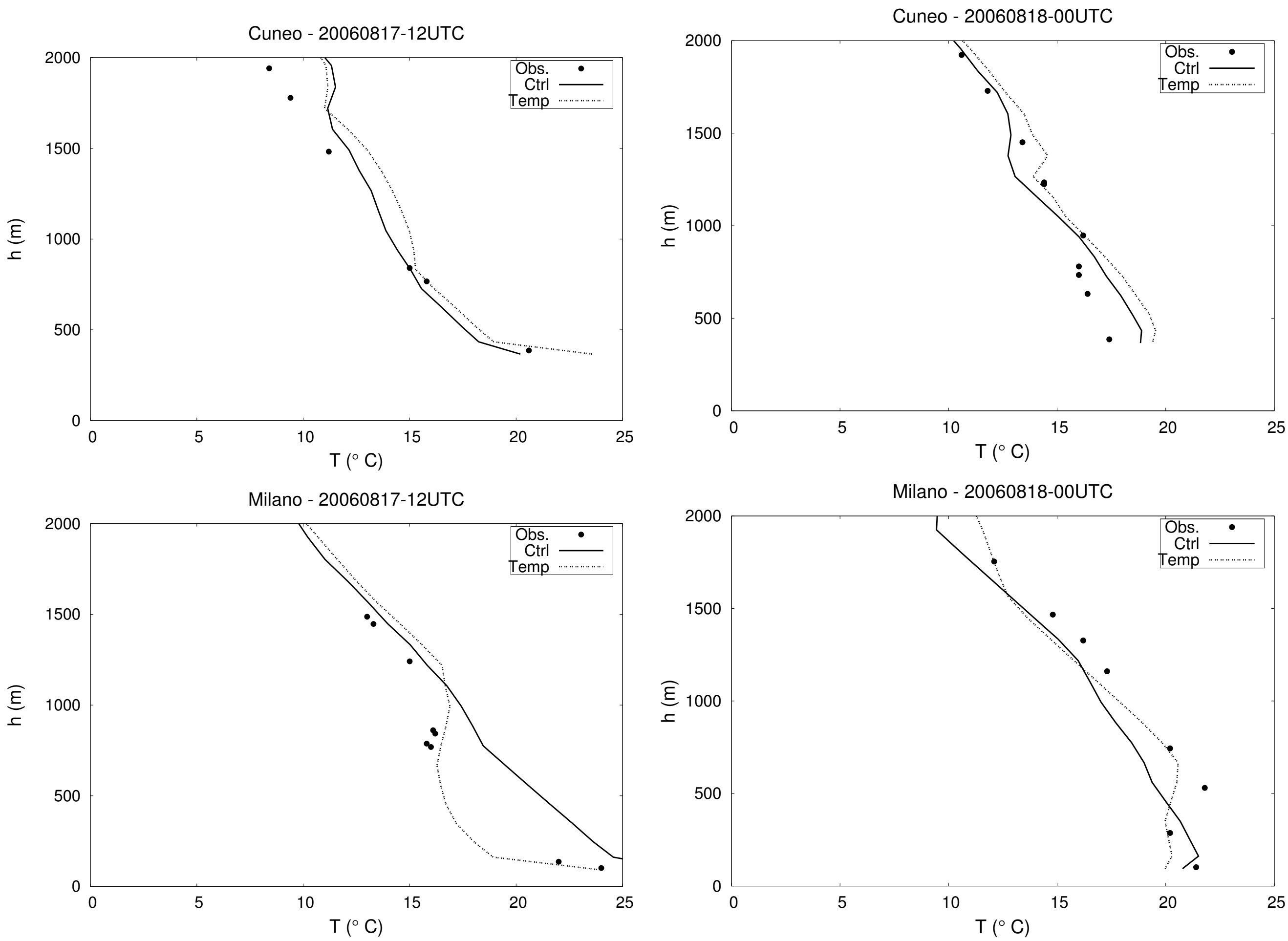

Fig. 13. Vertical temperature profile in Cuneo (above) and Milano (below), at +12 h (left) and +24 h (right) for the August 2006 case. The dots represent the observations, the continuous line represents the Ctrl run and the dotted line represents the Temp run.

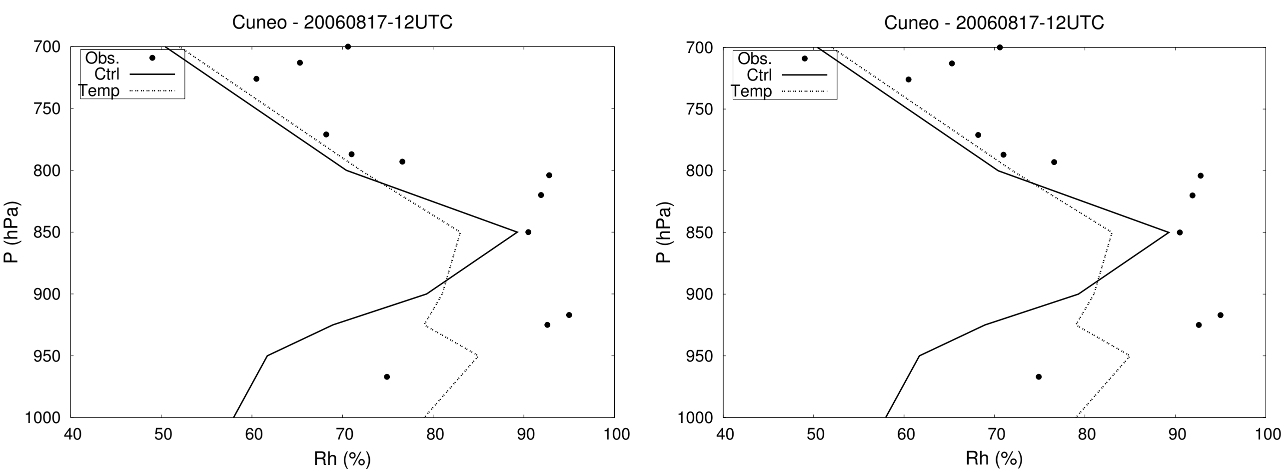

Fig. 14. Vertical relative humidity profile in Cuneo at +12 h (left) and +24 h (right) for the August 2006 case. The dots represent the observations, the continuous line represents the Ctrl run and the dotted line represents the Temp run.

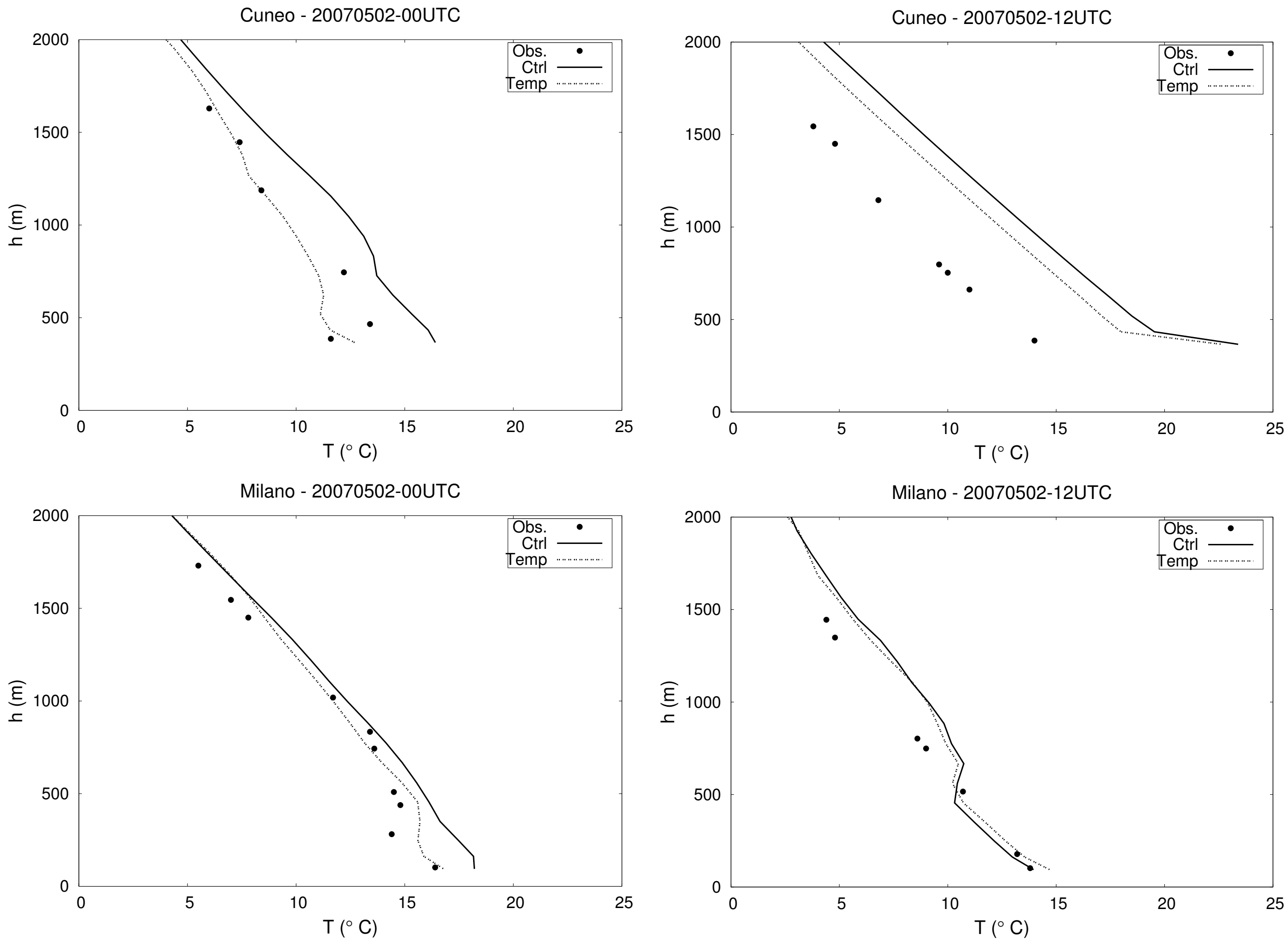

Fig. 15. Vertical temperature profile in Cuneo (above) and Milano (below), at +12 h (left) and +24 h (right) for the May 2007 case. The dots represent the observations, the continuous line represents the Ctrl run and the dotted line represents the Temp run.

observed shape, with an overestimation up to 3 m/s over the plains and slightly less over the mountains. In fact, in the simulations the moist air mass coming from the Mediterranean Sea had a western component stronger than in reality. This produced a general worsening of the wind field in direction and intensity without affecting too much Rh2m and T2m;

– in February 2008 (Fig. 10) the overestimation of Rh2m throughout the simulation for both runs is a negative feature that is probably due to the inefficient mixing in the surface layer; on the contrary we observe the correctness of the T2m diurnal variation describing very well the peak at noon;

– eventually in July 2008 (Fig. 12), with very stable conditions, the model has a real good performance even without assimilation (Ctrl run), but there is indeed an added value in the Rh2m because the peaks of the cycle are better localized in time and also in amplitude.

A final comment could be done for Rh2m, because in all the cases we have an error below 700 m larger than above 700 m, in particular at the beginning of the simulations. This could be due to a better representativeness of the stations above 700 m, but further investigations are required.

3.2 Vertical temperature profiles

The vertical profiles of temperature in Cuneo and Milano have been also examined in Figs. 13, 15, 16, and 17. Above 2000 m the profiles of the two runs are overlapped because, as expected, the influence of the surface nudging is only limited to the first part of the PBL. In fact the vertical correlation function w_z in Eq. (3) which is a Gaussian in height differences, ensures that the effects at the surface do not spread too deeply into the atmosphere. This is the reason why we plot the curves up to 2000 m. The simulated profiles are compared to the radiosonde data in the airports of Milano-Linate and Cuneo-Levaldigi. The data are available at 00:00 UTC and 12:00 UTC and here we use the +12 h and +24 h simulated profiles, at the end of the assimilation cycle and in the

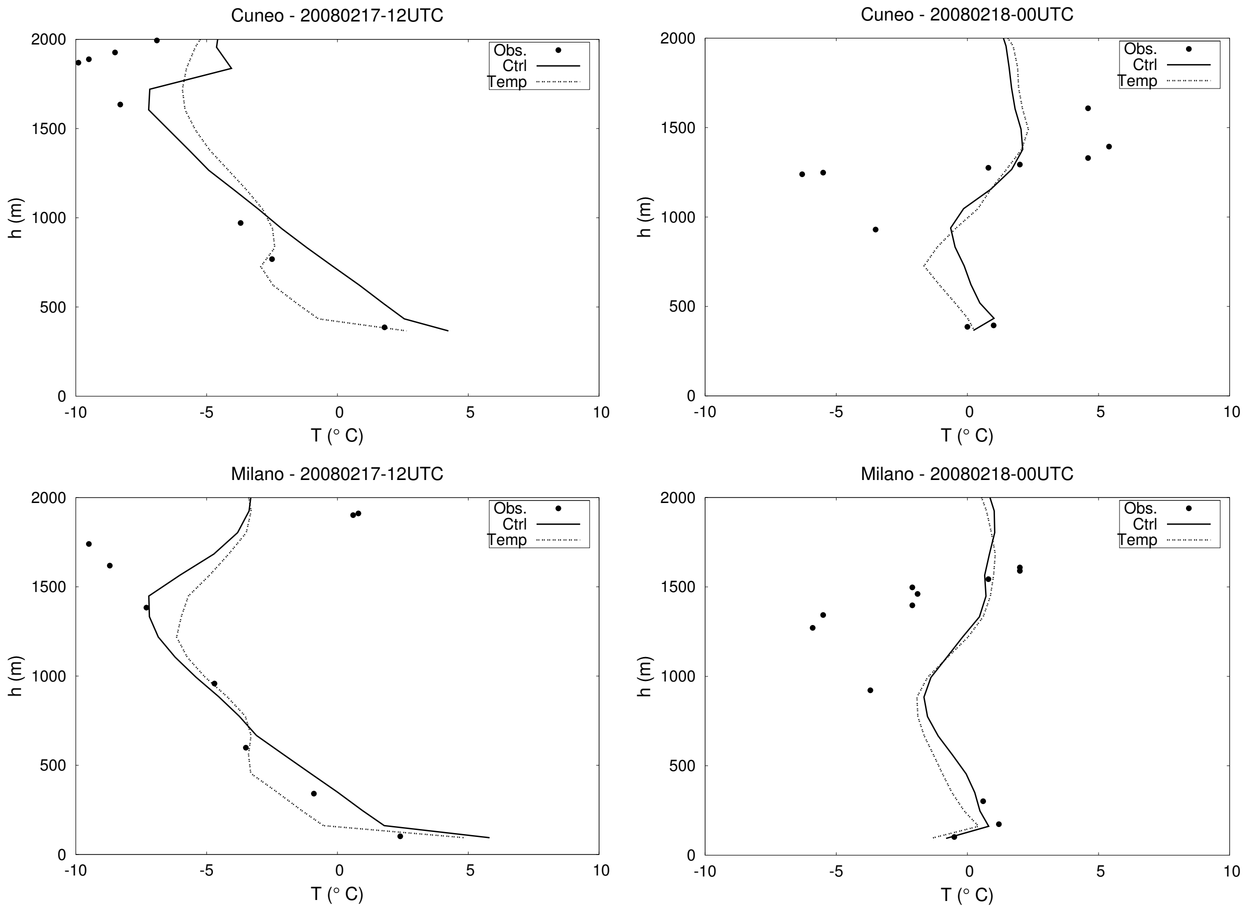

Fig. 16. Vertical temperature profile in Cuneo (above) and Milano (below), at +12 h (left) and +24 h (right) for the February 2008 case. The dots represent the observations, the continuous line represents the Ctrl run and the dotted line represents the Temp run.

free forecast period, respectively. There is a slight improvement, more evident at +12 h, and in general the fine-adjusted surface data assimilation does not perturb too much the vertical profile as it could have happened (Stauffer and Seaman, 1990). In 2006 in Cuneo there is a slight worsening of the +24 h forecast (Fig. 13, upper right corner), so in this case we report here also the relative humidity profile as a function of the pressure (Fig. 14). It could be noted that the +12 h forecast given by the Temp run show an improvement below 900 hPa, while for the +24 h forecast is more difficult to judge. However, Cuneo belongs to an area of extremely complex orography which makes harder the work of the models. In February 2008 the strong inversion responsible for the stationarity of the layer of clouds is not resolved (Fig. 16, right panels). Such a feature would probably require the assimilation of vertical profiles and not simply screen level data. Eventually in July 2008 (Fig. 17), with very stable conditions, both runs are in acceptable agreement with the observations, although in Milano the temperature is constantly underestimated at +24 h (Fig. 17, bottom right panel).

The influence of the T2m assimilation on the model levels is evident from Table 3 where the horizontal mean of 12-hourly sums of analysis increments are shown as a function of the pressure for each test case. The temperature is modified up to ≈900 hPa for any run, and although the sign varies during the phases of the simulations, the mean increments are negative in the 2006 and 2007 cases (with precipitation) and positive in the other two cases (without precipitation). This cooling of the atmosphere in the Temp run in case of precipitation and, conversely, a warming of it in case of no-rain, is actually the main difference found between the two classes of test cases.

3.3 Precipitation

Some remark has to be done for the precipitation field in the 2006 and 2007 cases. We show here (Fig. 18) the results of the average precipitation over the Piemonte warning areas, including Ticino and Valle d'Aosta for the first 12 h of simulation (assimilation cycle) and for the following 24 h (free forecast). In both cases there is a slight worsening of

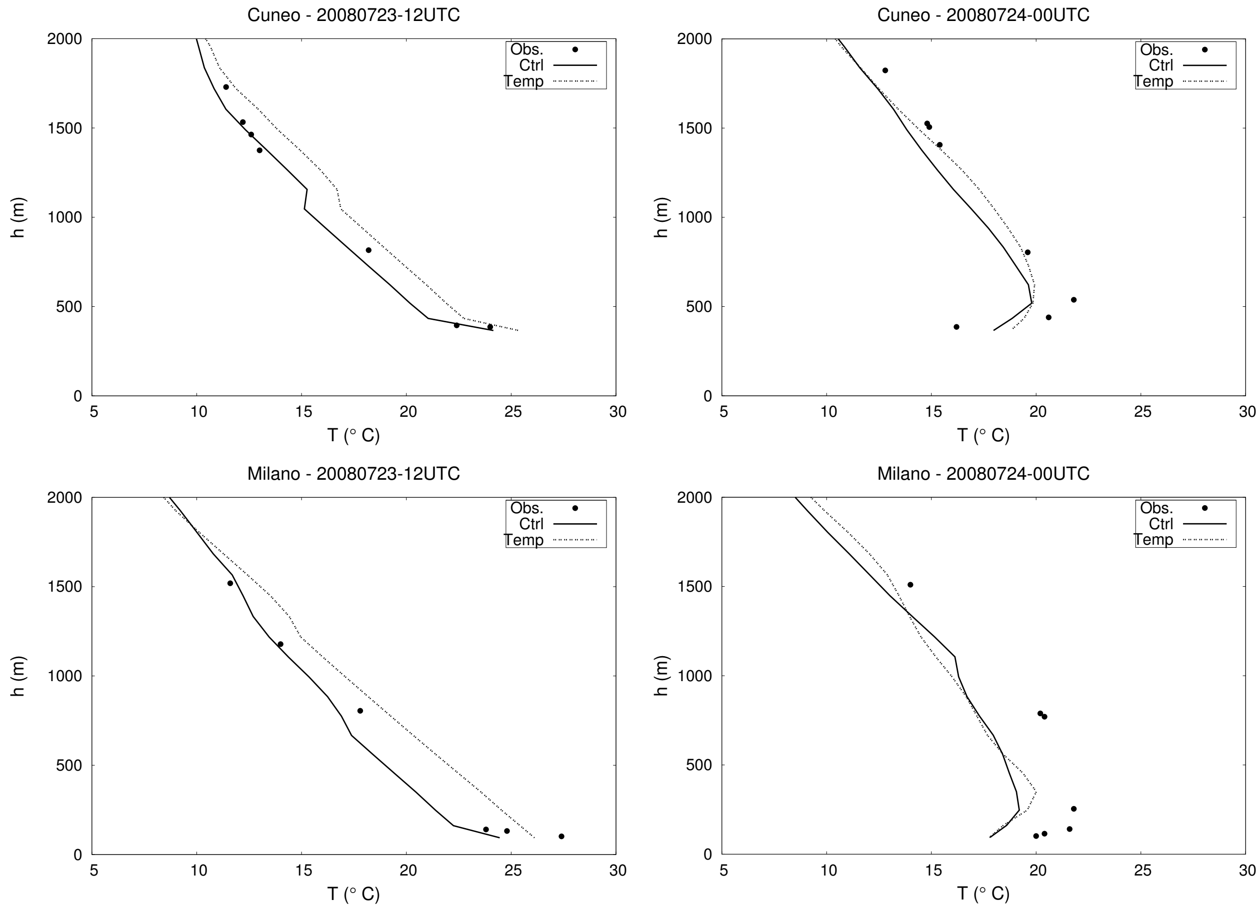

Fig. 17. Vertical temperature profile in Cuneo (above) and Milano (below), at +12 h (left) and +24 h (right) for the July 2008 case. The dots represent the observations, the continuous line represents the Ctrl run and the dotted line represents the Temp run.

Table 3. Horizontal mean of 12-hourly sums of analysis increments as a function of pressure for the four test cases.

level (hPa)	2006081700 T (K)	2007050112 T (K)	2008021700 T (K)	2008072300 T (K)
892	0.000	0.000	0.000	0.000
904	0.004	0.024	0.031	0.050
916	–0.068	0.010	0.071	0.123
928	–0.166	0.010	0.164	0.282
940	–0.341	–0.002	0.321	0.556
952	–0.604	–0.039	0.535	0.950
964	–0.928	–0.116	0.795	1.406
976	–1.248	–0.253	0.924	1.785
987	–1.462	–0.428	1.079	2.029
996	–1.537	–0.613	1.071	2.071

the results in the Temp run with respect to the Ctrl run in the assimilation cycle (Fig. 18, left panels), while after it, in the free forecast period, the impact becomes almost negligible (Fig. 18, right panels). The reason could be that in the nudging algorithm the pressure is modified in each column of the model because of the hydrostatic upper-air correction (Schraff and Hess, 2003), but this, especially when there is a convective component, may eventually affect the precipitation field. This is done with the hypothesis that the scales analyzed by the nudging are typically larger than 100 km (in the horizontal direction). On those scales, the vertical wind velocities are relatively small and should not be heavily modified by the perturbations arisen by the assimilation, therefore they are suppressed (balanced hydrostatically). In this case this hypothesis is not satisfied because we introduce smaller scales perturbations and perhaps the vertical wind velocities that arise should be kept. This might be the reason for the slight worsening of the precipitation field in the first 12 h, but it is an aspect that has to be investigated in much more detail. However, we can see that in August 2006, both runs do not see the precipitation over the H area (Fig. 18, upper left panel) and in May 2007 the Temp run reduces the precipitation over the North-Western areas (A–D), although the absolute values are in the order of few mm (Fig. 18, lower left panel). A possible improvement could come from

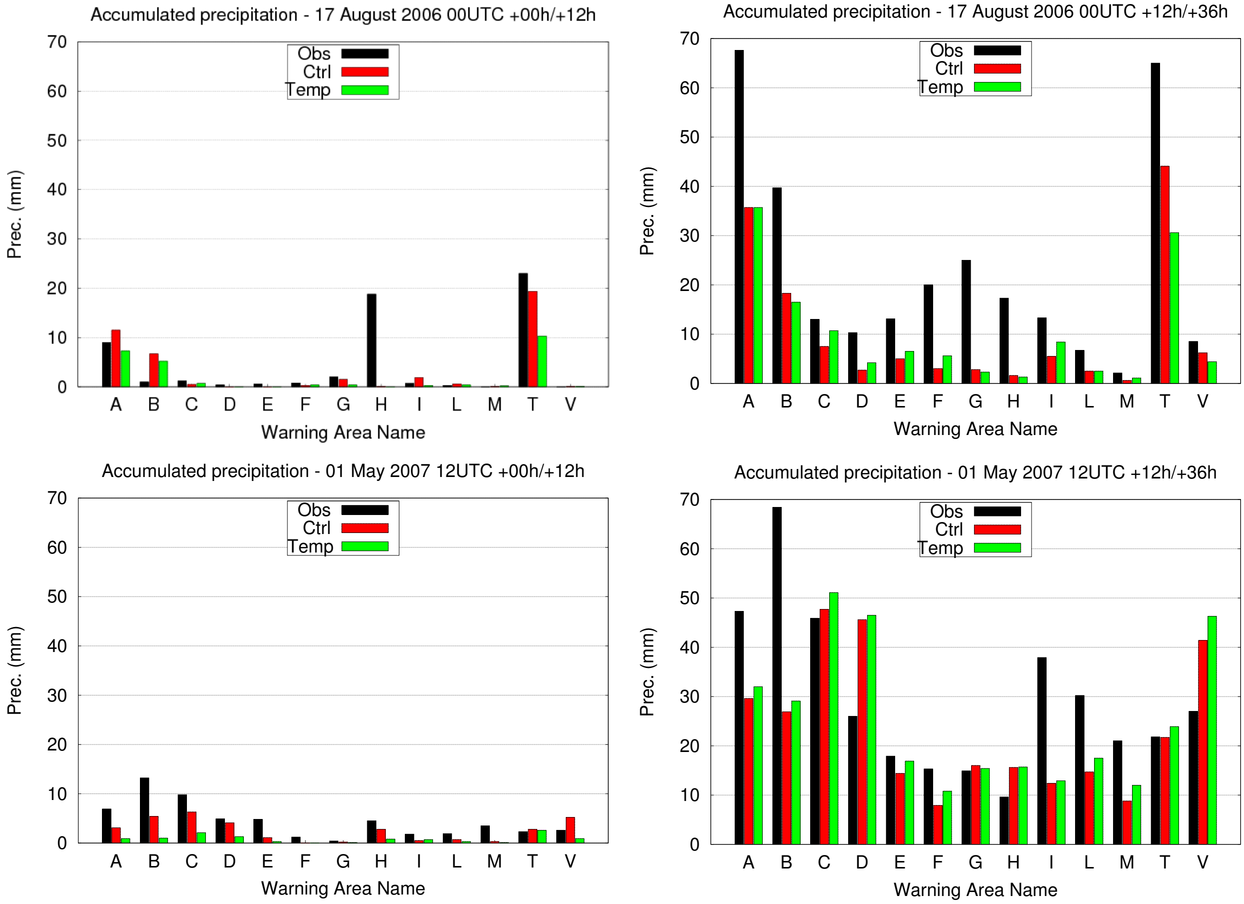

Fig. 18. Average precipitation amount over the Piemonte warning areas (A–M), including Ticino (T) and Valle d'Aosta (V). August 2006 (upper panels) and May 2007 (lower panels). Precipitation accumulated in the first 12 h of the runs (left panels, assimilation period) and in the following 24 h (right panels, free forecast). Comparison between Observations, Ctrl run and Temp run.

the use of 3-D turbulence algorithm which is an option (not operational) in the COSMO model. In fact in such cases, with convection acting over complex orography areas, there could be a benefit. This study was beyond the scope of this work. In fact its original aim was to test the effects of the T2m assimilation and not to test different physical parameterizations. Nevertheless, it is a possibility that it is worth to be tried.

4 Conclusions and future perspectives

We have tested the assimilation of T2m measured by the non-GTS stations of the very-high resolution network of ARPA Piemonte in four different test cases. The T2m has been assimilated for the first 12 h of the simulations and the results have been compared in terms of RMSE, ME and diurnal cycle of surface variables. Moreover, the vertical profiles of temperature have been compared to the data obtained by the radiosonde in Milano and Cuneo airports and the precipitation field (in 2006 and 2007 cases) have been verified against the very dense rain gauges network of ARPA Piemonte. Concerning the surface variables, a permutation technique similar to the hypothesis tests proposed by Hamill (1999) has been applied in order to measure the uncertainty and therefore to be able to judge whether, where and when the modified run (Temp) is better than the Ctrl run. The version of the model was the most recent and only few modifications to the operational settings have been applied, in particular the most relevant is the shortening of the horizontal correlation function in the nudging term, because of the increased number of data over the Piemonte territory. The results show a general positive impact for the T2m during the assimilation cycle, and a neutral impact for W10m and Rh2m, while during the free forecast, the effect of the nudging tends to vanish after 6–8 h. The 2007 case shows the most important improvement in terms of T2m, with a persisting effect up to 24–30 h. This simulation in fact has a large initial error in the boundaries also because in the operational run the number of assimilated GTS data was consistently smaller than usual. Therefore the non-GTS data assimilation brings a more important added value. The vertical profiles of temperature are affected up to ≈1500 m, as revealed also by the analysis of the increments which are non-negligible up to ≈900 hPa. It is important to notice that the stability of the planetary boundary layer has not been altered although the vertical profiles show that some features (strong inversions) are not able to be correctly modelled. Eventually the precipitation seems to be unaffected in the forecast period, but during the assimilation cycle the field is quite perturbed and the results are globally non satisfactory. The problem might be the hydrostatic correction in the atmospheric column which is inherent in the actual version of the nudging scheme. This effect has to be studied more in detail in order to understand whether this correction could be changed or removed.

Despite the fact that we performed only single case studies and the results have to be considered carefully until a larger statistics is available, we have shown that this kind of assimilation has some potentiality for mesoscale models applications, given the quality of the assimilated data, even if more deeper investigation is still needed. Besides, the model does not need to be heavily modified since the T2m assimilation is already implemented as an option. A first example of operational application is the production of hourly very-high resolution analyses starting from the operational COSMO-I7 analyses fields: those are (at the moment) available about 4 h later with respect to the time they are referred to (for instance the 00:00 UTC analysis is available at about 04:00UTC). Our dynamically downscaled analyses at 2.8 km would be ready later, depending on the CPU used, but this would be acceptable at a first stage. Concerning the forecast, it would be preferred to have only short-range simulations (for instance +18 h, considering also that the improvement of the nudging vanishes after a few hours) every 6 h (RUC). This solution actually implies a certain delay for the distribution of the product to the forecasters, therefore it has still to be planned carefully.

Concerning the future work, the next steps can be here presented:

- investigation of a longer period in different weather regimes (summer period and winter period) for a larger statistics, with two runs per day (00:00 UTC and 12:00 UTC) for determining the real differences between the initial conditions;

- enlargement of the domain in order to cover the whole Italian territory. This is possible since there is a large number of non-GTS data not only in Piemonte, but over the entire national territory. Therefore, in principle, it should be possible to extend the data assimilation;

- investigation of the hydrostatic upper-air correction inside the nudging scheme; in presence of small-scale perturbations as we have, is it still necessary?;

- test of other physical parameterizations in conjunction with the assimilation, such as for instance the 3-D turbulence closure, which is an option in the COSMO model and it could be useful in case of convective precipitation;

- as other authors have indicated (Vinodkumar et al., 2008 for example), it is probably worth trying the assimilation of surface variables together with vertical profiles of temperature and relative humidity, or maybe also using the latent heat nudging approach (see for instance the work of Leuenberger and Rossa, 2007) or assimilation of satellite data and fluxes (Alapaty et al., 2008) or GPS data. Those modifications could be helpful to adjust the entire PBL in order to correct the precipitation field.

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