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Verification of high resolution real-time forecast over the alpine region during the MAP/SOP

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SUMMARY

An analysis is presented of MM5 high-resolution operational weather forecasts performed during the Special Observing Period (SOP) of the Mesoscale Alpine Programme (MAP). The domain-averaged model bias of both surface pressure and 2m-level temperature suggest MM5 shortcomings related to the surface temperature cycle. The Root Mean Square Error for temperature, wind and relative humidity at two different levels and for several time forecasts supports the previous finding. The model results show difficulties in forecasting the 2m temperature during periods of fair weather; furthermore a few difficulties are found in forecasting the minimum of the temperature for region surrounded by the sea as Baleari station. The Equitable Threat Score (ETS), for a few selected IOPs (Intensive Observation Periods) having precipitation over the Po Valley, is used to evaluate MM5 at high resolution over the Alpine region together with the areal distribution of the Root Mean Square Error. The results show reasonable skill in this region, when the model is used with high resolution mode. The ETS using only the stations over the mountains or the plains, suggests a better skill by the model in the mountain areas than in the valley; whereas RMSE shows a MM5 tendency to produce larger error in the eastern side of the Po Valley than on the western one.
Finally, the analysis of the precipitation time series for IOP2b, at a few selected stations, confirms the model tendency to underestimate the rainfall at the stations located along the Po Valley and to shorten the period of the precipitation.

KEYWORDS: Mesoscale Alpine Programme High resolution operational forecast Root Mean Square Error

1. INTRODUCTION

During the fall of 1999, the Special Observing Period (SOP) of the Mesoscale Alpine Programme (MAP) took place. One of the goals of the experiment was to improve the forecast of heavy precipitation, which is one of the most difficult tasks over regions having complex topography (Bougeault *et al.*, 2000). In the recent past, several heavy precipitation events have occurred in the Alpine region (Piedmont Brig, Vaisone-LaRomane, etc) and there have been a few studies which have analyzed these events (Massacand *et al.*, 1998, Buzzi *et al.*, 1998, Richard *et al.*, 1998, Ferretti *et al.*, 2000, Rotunno and Ferretti 2001) with the aim of improving the understanding of the mechanisms of heavy precipitation in this region. During the MAP SOP, results from a few mesoscale models were used to produce daily weather forecasts; among them was the MM5V2 from Penn State/National Center for Atmospheric Research (PSU/NCAR) mesoscale model, which was run as a high resolution (3km) operational weather prediction model over the Alpine region, using three domains two way nested. The aim of this effort was to have the possibility of verifing MM5 over complex topography and to add another piece of information to the discussion about the necessity of high resolution weather forecast on complex topography. Recently an MM5 verification study showed an overwhole skill improvement using high mesoscale model over

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complex topography, over USA (Mass *et al.*, 2002). White *et al.*, (1999) compared several operational models over USA at different resolutions: Rmse for gridded objective analyses showed largest error for highly resolved models, among them MM5. Oncley and Dudhia (1995) found a strong link between temperature bias and soil moisture avalibility by comparing the MM5 results with the surface fluxes of momentum, sensible and latent heat obtained by a tower and an aircraft. Also Manning and Davis (1997) found MM5 shortcomings in forecasting the lower level temperature. They suggested that the wrong temperature diurnal cycle could be produced by a not well represented diurnal cycle at the surface. Another study on the evaluation of the MM5 precipitation forecast over complex topography in the USA, showed an excessive rain shadowing effect of mountain areas and a model tendency to generate too much precipitation along the steep windward slopes (Colle *et al.*, 1999), but an improvement in bias, equitable score, and root-mean-square error scores occurred as the resolution was increased. The study was performed using two domains with grid resolution of 36km and 12km, respectively. Another study by Colle and Mass (2000) was performed to evaluate the MM5 skill in forecasting a flood event at high resolution. Sensitivity to the model resolution allowed the authors to assess a significant improvement in the precipitation skill at resolutions of 4km and 1.33km, respectively.

One of the main problems of high-resolution weather forecasts is model validation since routine high-resolution observations are lacking. During the MAP/SOP Intense Observation Periods (IOPs), a large amount of data was recorded which allows for a detailed description of the weather events over the Alpine region and a verification of the model results. The exceptional high rain gauge density will allow one to test the ability of the model to forecast rainfall in complex topography. The problems that the authors want to address are:

1. a different model response in the precipitation forecast over mountain or plain areas;
2. a strong barrier effect by the Alps that produce a delay of the frontal systems crossing the Po Valley from west to east;
3. difficulties in handling the diurnal cycle.

Therefore, an analysis of the model results along the Po Valley and on the lee and/or the windward slopes should allow to identify model difficulties over complex topography regions, during the MAP campaign. The analysis is accomplished by comparing the MM5 surface pressure and 2m temperature with the observations for the whole period of the MAP campaign at a few locations on both sides of the Alps. Furthermore, bias of pressure and temperature are analyzed, for the whole period over domain 1 (Fig.1), with the aim of highlight eventually MM5 shortcomings.

The Root Mean Square Error (RMSE) for wind, temperature and humidity at different pressure levels is analyzed in space and time to identify model failures related to complex topography. This analysis is performed using model output on domain 2 and the ECMWF data analyses. It is known that using gridded data large error is found at high resolution, as was shown by White *et al.*, (1999), but the gridded data can be better analyzed at different vertical levels over a wide area. Furthermore, the areal distribution of RMSE for the 24h accumulated precipitation during the IOPs is analized over domain 2 to identify model errors related to the complex topography. In this case the observed and forecast rainfall at the stations location are used for Rmse. The Equitable Threat Score (ETS) and Frequency Bias (BIAS) for the precipitation are analyzed over higher resolution

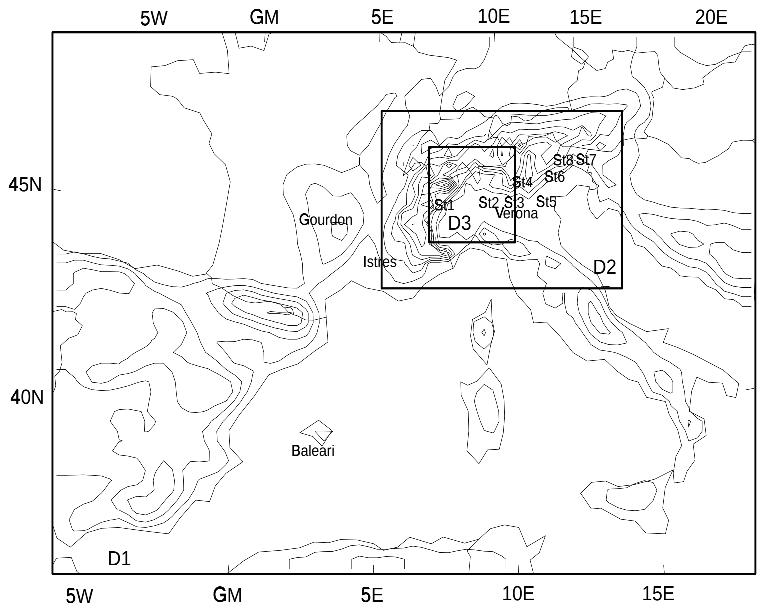

Figure 1. Model domains: the MAP Italian Target Area is on D3. The surface pressure stations are indicate, St2 is Milano station. The precipitation stations are also indicated (St1 to St8 see the text).

domains (domain 2 and domain 3).
Section 2 presents the model configuration and the verification technique used. A brief overview of the meteorological characteristics of the events used for this study is presented in section 3 and the analysis of the surface pressure and 2m temperature bias and time series are presented in section 4. Rmse and mean error for wind, temperature and relative humidity are discussed in section 5. The verification of the high resolution precipitation forecast is presented in section 6. The conclusions are given in section 7.

2. MODEL CONFIGURATION AND SCORE METHODS

The MM5 from PSU/NCAR is a fully compressible non-hydrostatic model that solves the primitive equations (Grell *et al.*, 1994, Dudhia 1993); during the campaign the model configuration was basically the one used operationally at the Scientific and Technology Park of Abruzzo/University of L'Aquila (PSTd'A/UNIAQ) (Paolucci *et al.*, 1999): 24 unequally spaced sigma levels; Kain-Fritsch (Kain and Fritsch, 1990) cumulus convection parameterization associated with an explicit moisture scheme (Hsie *et al.*, 1984, Reisner *et al.*, 1998) for domains 1 and 2, whereas only the last one for domain 3; the Troen and Marth (1986), and Hong and Pan (1996) parameterization for the boundary layer (MRF), are used. An upper-radiative boundary condition (Klemp and Durran, 1983) was applied to prevent reflection of gravity waves at the top of the model. Three domains two-way nested (Fig.1) were used; the coarse domain having a grid size of 27 km, 9 km for the inner domain and 3 km for the innermost domain, over the Italian Target Area (ITA). The model was initialized using European Center for Medium-Range Weather Forecast (ECMWF) data analyses and the boundary conditions were upgraded every 6h using ECMWF forecasts. All the forecasts start at 1200UTC every day and last for 48h. During the MAP SOP several cases of precipitation were recorded, therefore the following events will be analyzed (they cover almost all the precipitation events on the south side of the Alps, during the MAP experiment): IOP2 (17-21 Sept), IOP3 (24-27 Sept), IOP5 (2-5 Oct), IOP8 (19-22 Oct), IOP10-11 (24-27 Oct), and IOP15 (5-10 Nov).

High resolution precipitation verification is a difficult task, because the rain-gauge measurements have errors; for example there are wind effects near the sensor (Groisman and Legates, 1994). A brief review of the errors related to the precipitation measurements can be found in Colle *et al.*, (1999). Moreover, if a comparison between the rain gauge data and the model forecast is performed one has to be aware of the different quantities: rain gauge are point measurements, whereas a precipitation forecast represents an areal mean. Furthermore, the observations of the precipitation, because their localized character may miss features nearby. Indeed, a line of thunderstorms developed during IOP2b in the late afternoon of 20 Sept. 1999; it was completely missed by the rain gauge but it was both observed by Radar (http://www.map.ethz.ch), and simulated by MM5V2 (Rotunno and Ferretti, this issue, hereafter RF02). Therefore, with these problems in mind and also being aware that no correction is applied for undercatchment, a verification of the high-resolution precipitation forecast is performed using the Equitable Threat Score (ETS), the Frequency Bias (BIAS), and the Root Mean Square Error (RMSE). To account for model spinup, the first 18 hours for all the simulations are neglected. The precipitation forecast is interpolated at each recording site using an inverse-distance method (Cressman, 1959) for the four model grid points surrounding the station:

$$PF = \frac{\Sigma_{n=1,4} W_n \cdot PF_n}{\Sigma_{n=1,4} W_n} \quad (1)$$

where PF_n is the precipitation forecast; W_n is the weight given by

$$W_n = \frac{R^2 - D_n^2}{R^2 + D_n^2} \quad (2)$$

where R is the distance between the model grid points, and D is the distance from the model grid point to the station.
A contingency table (Wilks, 1995) is build up to compute both ETS and BIAS. Based on the table (not shown), BIAS is given by:

$$BIAS = \frac{NPF}{NOC} \quad (3)$$

where NPF is the number of precipitation forecasts at the station equal to or exceeding a given threshold, it is given by the sum of A (which represents both the observations and the forecasts exceeding a given threshold) and B (which represents the observations not exceeding and the forecasts exceeding a given threshold); NOC is the number of occurrences in which the observation is equal to or exceed the threshold, and it is given by the sum of A and C (which represents the observations exceeding a given threshold and the forecasts not exceeding a given threshold). BIAS allows one to evaluate the model tendency to systematically overestimate (BIAS>1) or underestimate (BIAS<1) the precipitation. ETS is given by:

$$ETS = \frac{G - P}{NPF + NOC - G - P} \tag{4}$$

where G is the number of the forecasts in agreement ('Good') with the observations, that is: both the model results and the observations equal or exceed a given threshold. P represents the good forecast by chance and is given by:

$$P = \frac{NPF \cdot NOC}{TOTOBS} \tag{5}$$

where TOTOBS are the total number of observations used for the score (Wilks, 1995). ETS allows for evaluating non-probabilistic grided precipitation forecasts, but for cases of large overestimation ETS may be inflated, therefore also the Root Mean Square Error (RMSE) is used to evaluate the MM5 skill. RMSE is given by:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{NOBS}(P_n - X_n)^2}{NOBS}} \tag{6}$$

where P_n is a predicted quantity at the station location, X_n are the observations if RMSE is computed for the precipitation; otherwise P_n is the predicted quantity at the grid point, and X_n is the analysis at the same grid point. RMSE measures the magnitude of the difference between the forecast and the observation, it is affected by large forecast error.

3. METEOROLOGICAL OVERVIEW OF THE EVENTS

A frontal system crossed Northern Italy during IOP2b: an upper level trough associated with a strong surface pressure gradient, reached ITA by 0600UTC 20 September (Fig.2a), at 850hPa a low level westerly flow, produced by the Alpine barrier, was observed (RF02). A frontal cloud system, associated with the trough, produced heavy rainfall over ITA. IOP3 was characterized by southwesterly flow ahead of a frontal system and an upper level trough was extending from Spain to North Africa (Fig.2b). Heavy rainfall was recorded during the two days of this IOP, near the Lago Maggiore area. In this case the trough and the surface depression were weaker than for IOP2b. Another front crossed northern Italy during IOP5; southwesterly flow over the Maritime Alps and the Ligurian Appennine produced downslope wind associated with clear sky in the early stage of this event, the front reached the Po Valley by the early 3 October (Fig.2c). A deep upper-level trough entered ITA during IOP8, by 0600UTC Oct 21, this was associated with a low-level depression (Fig.3a). The system moved slowly eastward, producing persistent stratiform precipitation, but weaker than the one recorded during IOP2b; these two events (IOP2b and IOP8) were very similar, as discussed by RF02. IOP10 was characterized by a large-scale structure similar to the one observed during IOP3 and IOP5: an upper-level southwesterly flow was associated with stratiform precipitation ahead of a front slowly moving eastward (Fig.3b). Finally, IOP15 was characterized by a deep upper-level trough

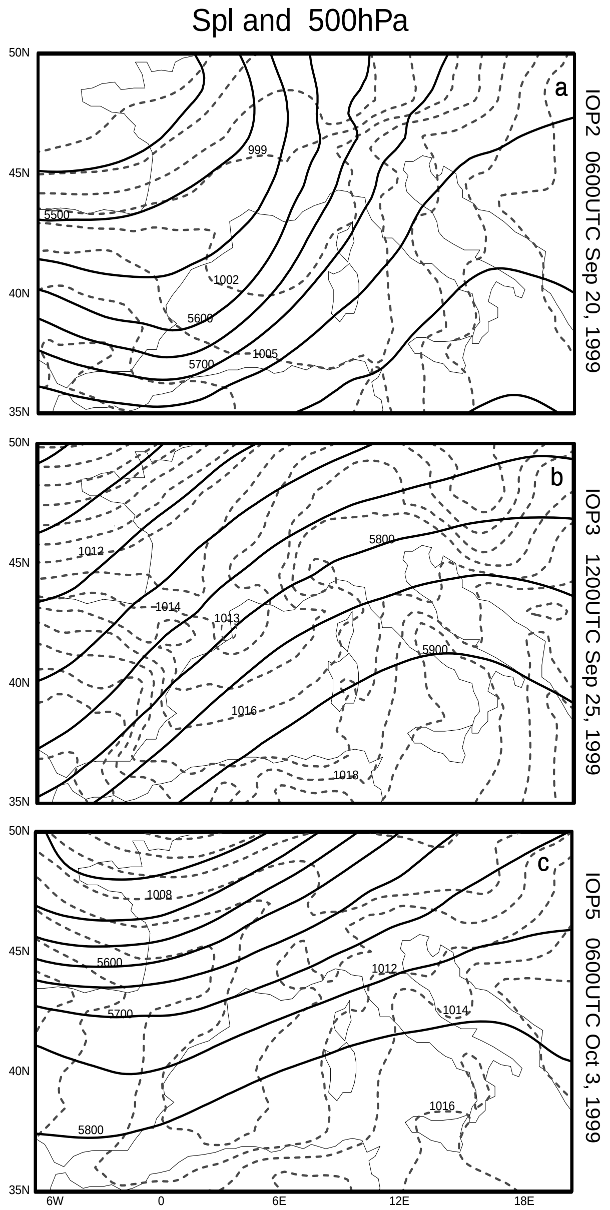

Figure 2. ECMWF analyses of Surface pressure (dashed, grey) and 500hPa (solid line c.i.= 50m) for: a) IOP2 at 0600UTC 20Sep, 1999 (c.i.= 3hPa for Spl); b) IOP3 at 1200UTC 25Sep, 1999 (c.i.= 1hPa for Slp); c) IOP5 at 0600UTC 3Oct, 1999 (c.i.= 2hPa for Spl).

producing a cut-off low over the Mediterranean area; a low level surface pressure was well in phase with the cut-off low (Fig.3c). The passage of the cold front was characterized by strong northwesterly wind over the western Italian region. Local floods were recorded along with the passage of the front crossing northern Italy; when it crossed the Tyrrhenian sea, convective precipitation associated with the

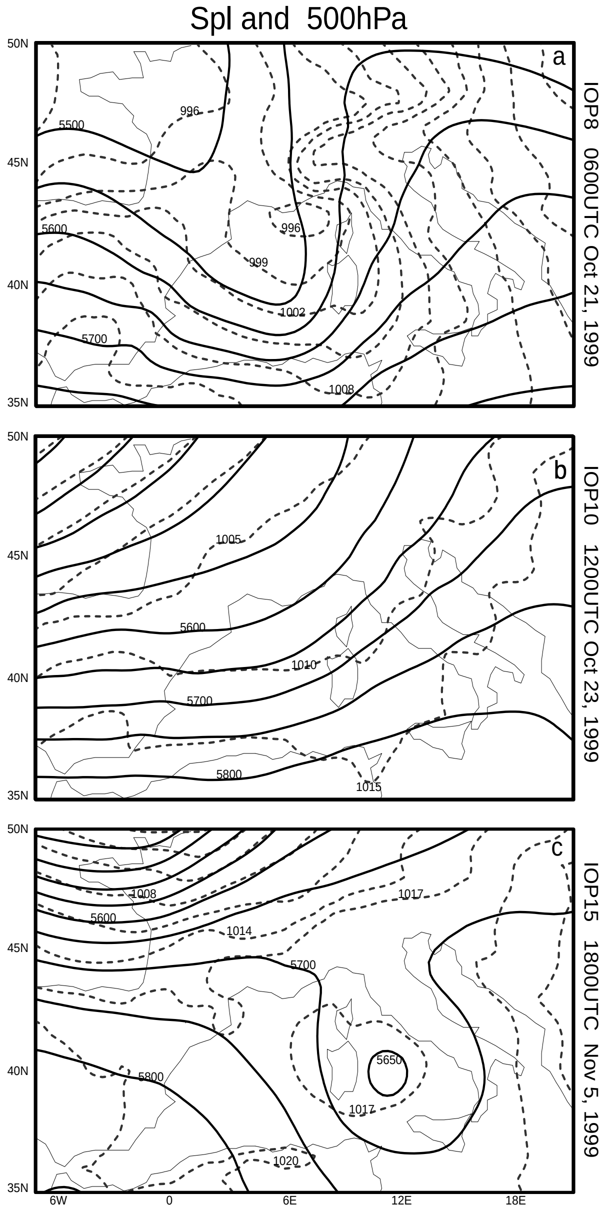

Figure 3. As for fig. 2 but for: a) IOP8 at 0600UTC 21 Oct, 1999 (c.i.= 3hPa for Slp); b) IOP1 0 at 1200UTC 23Oct, 1999 (c.i.= 5hPa for Slp); c) IOP15 1800UTC 5Nov, 1999 (c.i.= 3hPa for Slp).

cyclone was observed (see the satellite imagery on http://www.map.ethz.ch).

4. VERIFICATION OF TEMPERATURE AND PRESSURE

The bias of surface pressure and 2m temperature are computed on domain 1, using all the stations available during the IOPs: both synoptic and IOPs

stations, are used (a map of the areal distribution of the stations is available on: http://www.map.ethz.ch). The bias for both these parameters is given by the difference between the observation at each station and the closest model grid point to the station itself; zero means no bias. For this analysis domain 1 only is used, because a larger amount of stations is available than on the other domains. However, this does not imply a low resolution analysis as information from the higher-resolution sub-domains (domain 2, 9km; domain 3, 3km) is feed back to domain 1.
In addition, the time series of temperature and pressure at a few selected stations are compared with the model results at the resolution of the region were the station is located. The stations are chosen to track the meteorological systems crossing the Alps and moving eastward (stations location in Fig.1), to evaluate the influence of the mountain ridge on the pressure and temperature forecast.

(*a*) *Pressure bias and Time series*

The surface pressure bias for MM5 is presented in Fig.4. During the whole period the model shows a small oscillation of the pressure bias around zero probably produced by the diurnal cycle. The oscillation of the surface pressure bias is out of phase with the one of the 2m temperature; this feature is found for the whole period. The oscillation is consistently reduced during IOP2 (17–21 Sept. 1999, Fig.4a), and a small underestimation of the surface pressure is found, as the pressure time series also show (Fig.5, this point will be discussed later). During October and November the period of oscillation of the surface pressure bias changes. Moreover, the bias is reduced and it seems that it is not driven any more by the diurnal cycle. By the end of September (21 Sep) a few MM5 parameters (moisture availability, thermal capacity etc.,) change the reference values on the lookup table accordingly to the season, from Summer to Fall. As a consequence, the impact of the radiative forcing changes in the model. The bias reduction during October and November, and during cloudy days, as for IOP2b and a few other IOPs, supports the hypothesis that the bias oscillation observed during September is driven by a too strong impact of the radiative forcing, which obviously decrease during both cloudy days and the fall season. A large reduction of the bias oscillation is found during IOP8 (19-22 Oct, 1999) and IOP10-11 (24-27 Oct., 1999)(Fig.4c); the bias shows almost no oscillation during IOP15 (5-10 Nov, 1999) (Fig.4d). A large increase of the bias is found by the end of IOP15. It is necessary to point out that a reduced number of observations (OBS) was available during November, the fewer observations may explain the different behaviour of the bias during this period.
A comparison between the forecast and the observed surface pressure is shown (Fig.5) for a few selected stations (from west to east): one in the western Mediterranean Sea (Baleari), two to the west of the France Alps (Gourdon and Istres), and two southeast of the Italian Alps (Milano and Verona). The position of these stations is shown in Figure 1; they are chosen to allow for tracking the weather events crossing the Alpine region. During the whole MAP SOP a good agreement between the observed surface pressure time series and the model forecast is found. The strong events associated with IOP2, IOP8, and IOP15 are well-predicted by the model with respect to both timing and pressure magnitude. Noteworthy is the consistency of the model signal on both sides of the Alps (Istres and Milano) and at the Baleari station; this consistency would suggest that there are no model shortcomings in handling complex topography. Altough,

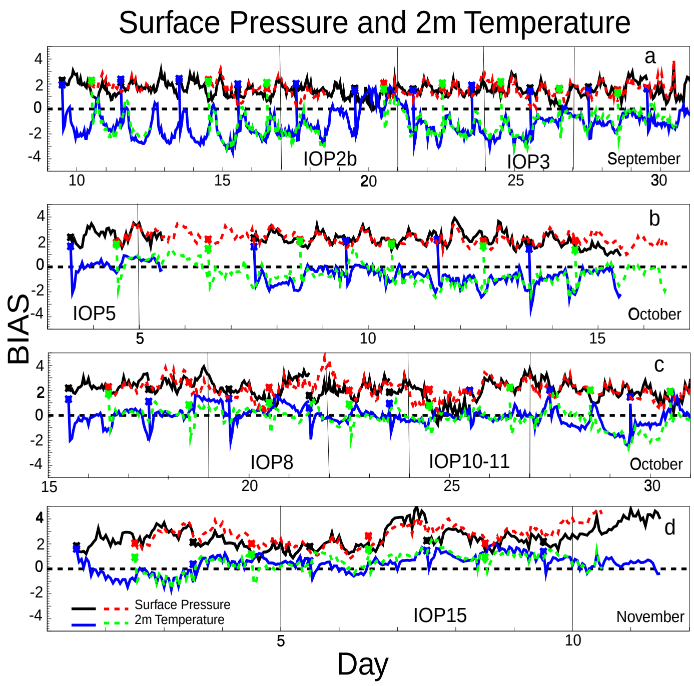

Figure 4. The surface pressure and 2m temperature bias on domain 1 for the whole MAP/SOP period. The black and red lines represent the pressure forecasts starting with 24h of time delay; similarly the blue and green for the 2m temperature. The vertical black bars indicate the duration of each IOPs.

a few small model errors are found: during IOP2 the model slightly lagged the observed surface-pressure at the stations close to the Alps, particularly at Istres and Milano (Fig.5a); a time shift occurred for IOP8 (Fig.5b) also, but the model surface pressure anticipated the observed one, in this case. A model tendency in deepening the surface pressure minimum is found at Istres, Verona and Milan, the last one showing a larger discrepancy than the others, for this case. This would suggest a disturbance in the signal caused by the interaction of the large scale flow with the steep topography (these three stations are the ones closest to the Alpine barrier) or by just the storm developing differently in this region because of initial conditions and physics uncertainties. Because of the reduction of the observations the comparison between the model forecast and OBS is more difficult during November. During the first half part of this month (Fig.5c) the model is in good agreement with OBS at most of the stations. During IOP15 the surface minimum is well-reproduced by the model at Gourdon, Istres and Verona, whereas for Baleari and Milano an overestimation of the surface pressure is found; the same tendency is found after IOP15 at most of the stations except for Istres and Gourdon.

In summary, the surface pressure bias and time series show model difficulties in reproducing the signal during September, but during October and November an improvement is found. Furthermore, a fair model response is found during events driven by strong forcing as for IOP2, IOP8 and IOP15, this would suggest a better model performance during cloudy sky periods than in clear sky ones.

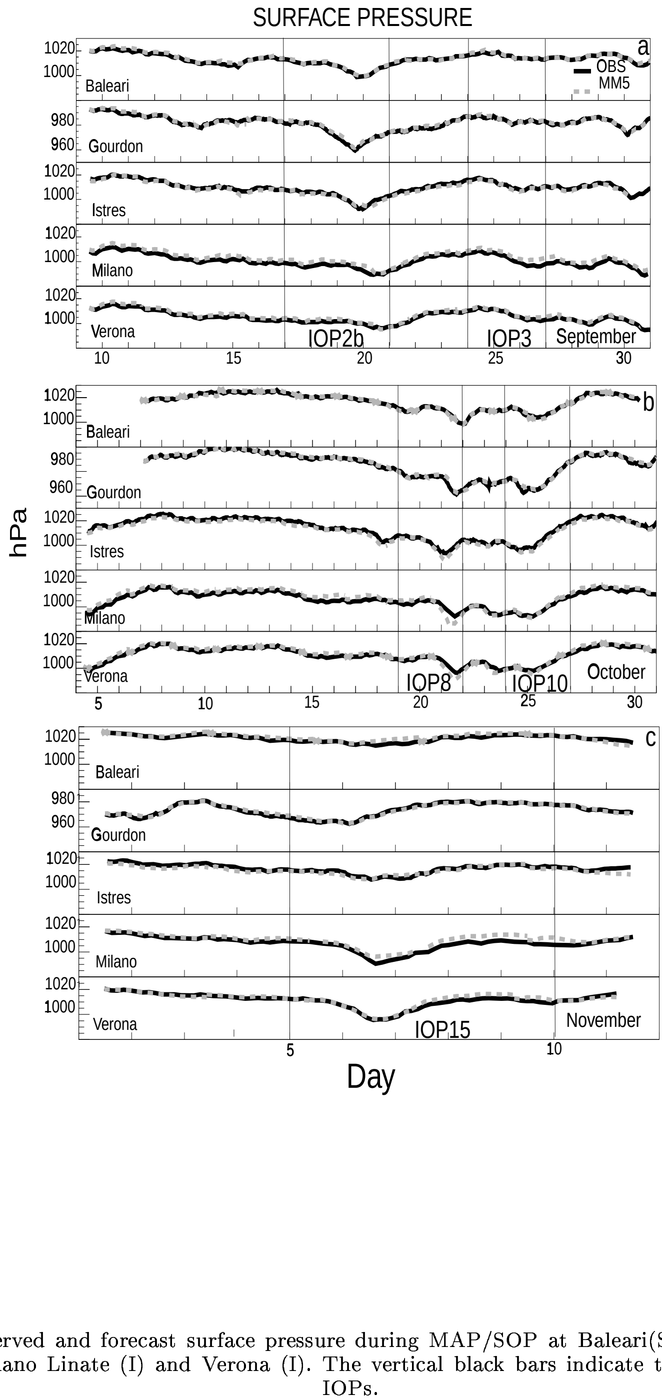

Figure 5. Observed and forecast surface pressure during MAP/SOP at Baleari(SP), Gourdon (FR), Istres (FR), Milano Linate (I) and Verona (I). The vertical black bars indicate the duration of each IOPs.

(b) *2m Temperature bias and time series*

The 2 m temperature bias shows (Fig.4) a clear model tendency to overestimate the temperature, furthermore a large oscillation of the bias associated with the diurnal cycle is found. The diurnal oscillation is strongly reduced during cloudy periods as for the IOPs under consideration: during IOP2b (Fig.4a) the bias is strongly reduced. The 2 m Temperature time series will confirm this tendency (Fig.6) as will be discussed later. By the end of September a reduction of the bias and a change in the frequency of the bias oscillation are found, which clearly continues during the second part of October and November (Fig.4b,c,d). The small increase of the bias during the first part of October is related to high pressure conditions. This behaviour agrees with the change of the impact of the radiative forcing already discussed. The periods of reduction of the bias are associated with cloud covered sky as for the IOP2b, IOP8 etc., this would suggest a model tendency to produce a warm bias during clear sky conditions. This warm bias is a well known MM5 shortcoming as discussed by Oncley and Dudhia (1995), which found a strong correlation between the warm bias and the soil moisture avalability (M). In their study a rapid increase of relative humidity error was produced by M: a large injection of water vapor produced an overestimation of the latent heat flux reducing the surface energy available for the surface heat flux turning in a cold bias. Similarly, Manning and Davis (1999) showed a MM5 shortcoming in correctly reproducing the temperature diurnal cycle at the surface. As already pointed out, in this case the warm bias may be related to a similar phenomenon, an understimation of M would produce a quick drying of the soil which would produce a warm bias. This effect shows clearly during clear sky conditions. October shows a large reduction of the bias, and the oscillation almost disappears (Fig.4b,c), supporting the hypothesis of a correlation between the warm bias and M: as already pointed out, by 21 September the amount of M sligthly increases because of the fall season allowing for a reduction of the surface heat flux that produces a reduction of the warm bias for the following months. The bias reaches zero during IOP8 and IOP10-11, but a significant negative increase during IOP12 (29-31 Oct, 1999) is detected. A similar trend is found for November, generally values of the bias close to zero are found during the first part of IOP15 (Fig.4d). During this event the large scale forcing was strong but the rainfall over the Po Valley was rapidly followed by clear sky and strong northwesterly wind (in the evening of Nov 6). This would suggest a difficulty of MM5 in reproducing correctly the low-level temperature if driven by radiative forcing only, whereas a correct forecast is obtained if a strong dynamic forcing is present, as for IOP2b and IOP15 (Nov 4-5).

The time series of the temperature at the same selected locations (Fig.6) help to understand the feature of the 2 m Temperature bias. All the stations show a warm bias and a small phase lag is also associated with the maximum, both these problems may cause the bias oscillation. On the other hand, the large reduction of the bias and the change in the frequency of the bias oscillation suggest that MM5 was able to reproduce the meteorological changes associated with IOP2b, but a warm bias at Milano and Verona is still found (Fig.6a). The temperature time series show an underestimation of the minimum during IOP8 and IOP10-11 (Fig.6b) at the same stations, correlated to the surface pressure minimum.

A separate discussion is necessary for the Baleari station (Fig.6a,b,c): this station is represented as a few land points surrounded by the sea in the MM5 land use.

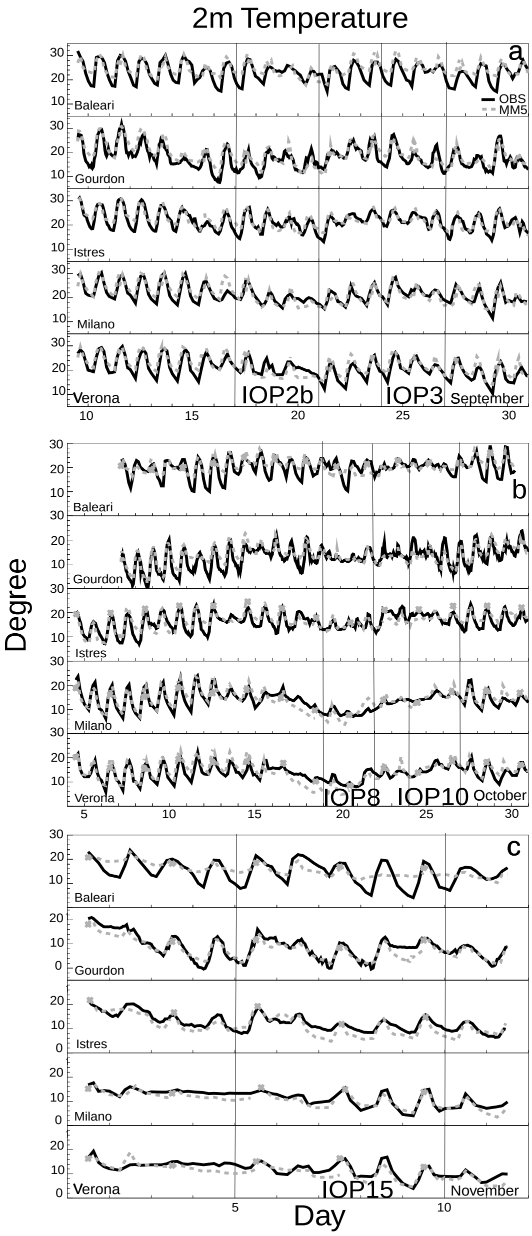

Figure 6. Observed and forecast 2m temperature during MAP/SOP at Baleari(SP), Gourdon (FR), Istres (FR), Milano Linate (I) and Verona (I). The vertical black bars indicate the duration of each IOPs.

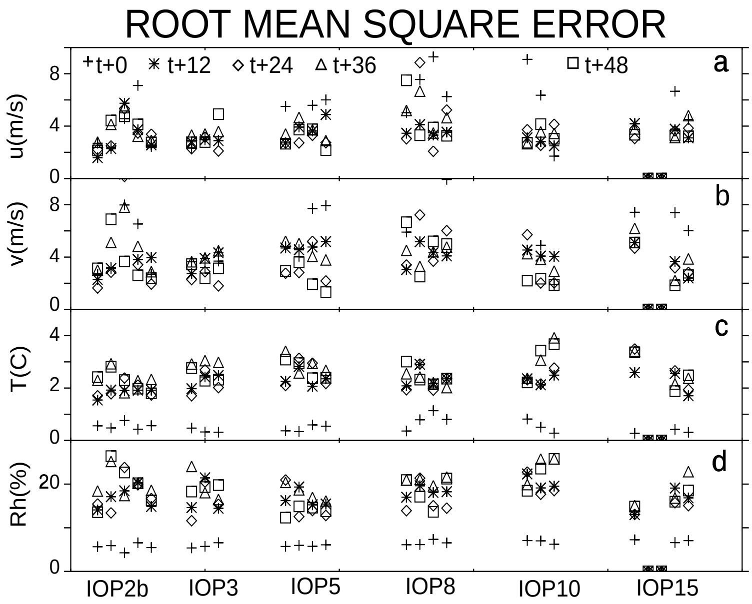

Figure 7. Root Mean Square Error at 925hPa for the forecast of : u-component of the wind; v-component of the wind; temperature; relative humidity. The plus sign indicates the forecast at t+0; the asterisks the forecast at t+12 ; the diamonds the forecast at t+24; the triangles the foreca st at t+36; the squares the forecasts at t+48.

At this station the warm bias of the temperature is not correlated to the large scale forcing, indeed high temperature are found for the whole period associated to a small diurnal oscillation, suggesting an overestimation by the model of the effect of the sea damping: the water thermal capacity was too strongly influencing the temperature forecast.

5. RMSE FOR WIND, TEMPERATURE AND RELATIVE HUMIDITY

The Root Mean Square Error (RMSE) and the Mean Error (ME) for the selected IOPs are computed for a few meteorological parameters in the lower troposphere. Two different levels are chosen for model output on domain 2: the 925hPa and 850hPa. The RMSE time series at 925hPa show a large initial error for the whole period for the horizontal wind components U and V , but the error generally decreases during the forecasts (Fig.7a,b). As already pointed out, large error at high resolution was also found by White *et al.,* (1999). ME shows large negative values for U and V at initial time for IOP2b and IOP8 (Fig.8a,b); but it shows values close to zero or positive at the following time step for most of the IOPs. A tendency for ME to remain negative during IOP8 and IOP2b is found for V larger than for U. On the other hand, IOP15 shows large positive errors for U and V at initial time decreasing with the forecast (Fig.8a,b). RMSE for temperature and relative humidity at the 925hPa show a small initial error, but largely increasing during the forecast especially for Rh (Fig.7c,d). Oncley and Dudhia (1995) found a similar increase of the error for Rh, which was closely related to the warm bias, as in this study. At the 850hPa a similar behaviour is found for wind, temperature, and relative humidity (not shown). ME is close

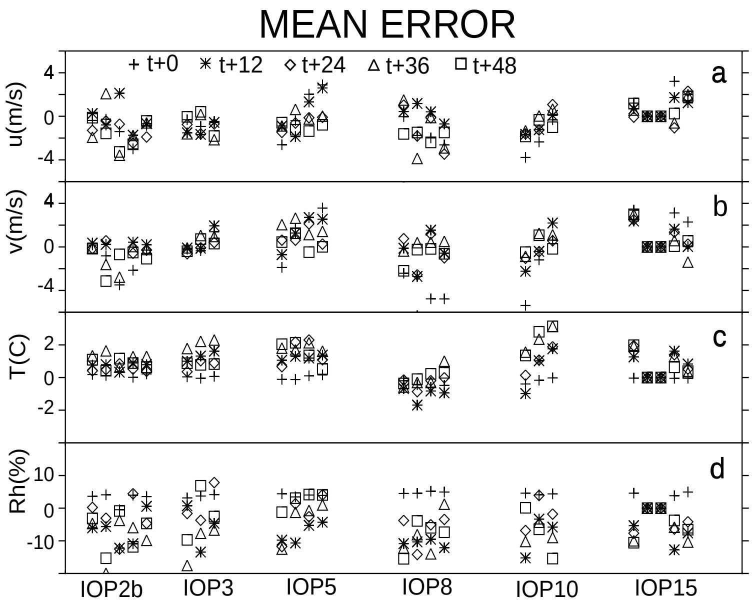

Figure 8. As for fig. 7, but for Mean Error.

to zero for the temperature for all the IOPs (Fig.8c) except for IOP10 and IOP15. A large variability of ME for Rh is found (Fig.8d), a clear tendency to produce negative values is found for all IOPs, suggesting a tendency of MM5 to underestimate relative humidity.

6. VERIFICATION OF HIGH RESOLUTION PRECIPITATION

The Equitable Threat Scores (ETS) and bias for the selected IOPs are computed to verify the model skill over the Alpine region, during the MAP season. Furthermore the areal distribution of RMSE for the whole period and for IOP2b, IOP8 and IOP15 are computed separately to identify model failure over complex topography and under different large scale forcing. A further evaluation of the MM5 is performed by comparing the precipitation time series recorded at a few selected stations along the Po Valley, with the forecasts at the same locations. The reader should keep in mind the difficulties related to the evaluation of high resolution rainfall as already pointed out.

(*a*) *Equitable Threat Score, Bias and Root Mean Square Error*

The Equitable Threat Score for the precipitation is presented, for the IOPs previously discussed, using different thresholds. ETS shows at high resolution (3km, dashed lines on Fig.9a; Fig.9c,d will be discussed later) similar results to those obtained at lower resolution (9km, full line on Fig.9a). ETS slightly decreases as the threshold increases, reaching approximate 0.3 for large values of rainfall both at high and low resolution. This would suggest that ETS for MM5 is approximately 0.3 beside the number of stations used. ETS at different resolutions does not show large differences because of both the feedback among

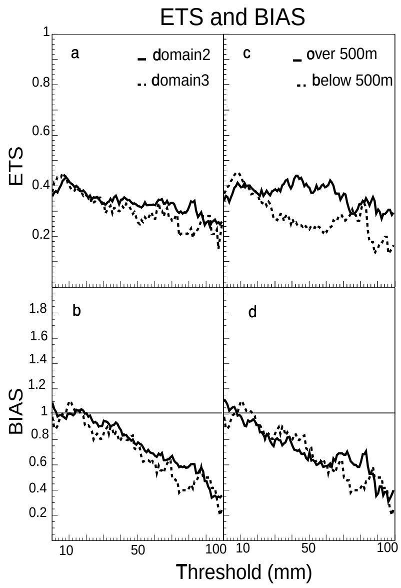

Figure 9. Equitable Threat Score and BIAS of the precipitation as function of the threshold for: a-b) all the IOPs analyzed for domain 2 (solid line) and domain 3 (dashed line); c-d) mountain (solid line) and plain (dashed line) area.

domains, which improves the skill on domain 2, and the reduced number of stations available on domain 3, which, on the other hand, reduce the skill on domain 3.

The BIAS for the whole MAP period (Fig.9b) shows a model tendency to underestimate the rainfall for large thresholds, whereas acceptable values (0.8) holds up to 40mm of rain confirming the finding that the MM5 is dry (Accadia *et al.*, 2002).

ETS, BIAS and RMSE for the whole MAP/SOP for the meteorological parameter and rainfall would support the idea that the model is able to reproduce the rainfall if either a strong dynamic large scale or topography forcing is present. This would imply model difficulties in triggering the precipitation if no uplifting is present; indeed it is well known that deep upper level trough are associated with strong uplifting (Bluestein, 1993).

To better explore this hypothesis an attempt is made to isolate two areas: one containing the stations over mountain regions, that is over 500m, and the other below 500m. ETS clearly shows a better skill by the model over mountain regions (Fig.9c, solid line) than over plain areas (Fig.9c, dashed line) up to high values of the precipitation. BIAS shows for the two regions (Fig.9d) a good model skill on the mountain regions up to 40mm, as the threshold increase an underestimation is found. Similarly over plain areas, but showing a underestimation starting at 20 mm. This analysis is performed for domain 2 only, because the reduced number of stations on domain 3 would not allow for a separation between plain and mountain regions. These results confirm the hypothesis of model difficulties in reproducing the rainfall if no up-lifting produced by either the large scale forcing or the topography is present. Also Colle (*et al.*, 2000) showed similar finding in

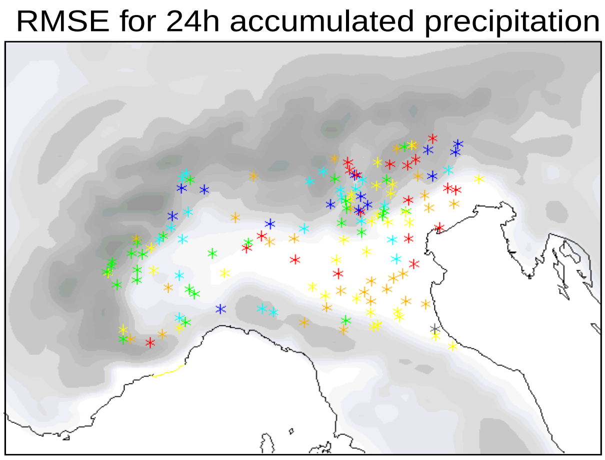

Figure 10. Areal distribution of Root Mean Square Error for the 24h accumulated precipitation for each forecast perfor med for all IOPs. The asterisks indicates rmse at the stations location on domain 2. RMSE is associat ed to bias> 1 or bias< 1 by color code, fo r each range of rmse two colors are given: light grey indicates rmse< 5 for any values of the bias; for 5 <rmse< 15 : a) bias> 1 is yellow, b) bias< 1 is gre en; for 15 <rmse< 25: a) bias> 1 is light brown, b) bias< 1 is cyan; for rmse> 25 : a) bias> 1 is red, b) bias< 1 is blu e.

their study over the Pacific Nothwest. On the other hand, also the rain shadowing may contribute to this effect (Colle *et al.*, 1999), but to verify it a more accurate analysis of the downslope and upslope flow at the stations should be done.

To better explore the ideas of the shadowing effect and of the influence of the topography on the precipitation, the areal distribution of Rmse of the precipitation is presented for the whole IOPs. Rmse is plotted with the additional information of Bias: the color intensity is related to rmse, whereas the warm colors indicate positive bias and the cold ones indicate the negative bias (Fig.10). The computation of rmse is performed neglecting rainfall less than 1mm. The areal distribution of rmse clearly shows small error in the western Po Valley, and large error on the eastern one. Furthermore, on the west side an underestimation of the precipitation is found (negative bias). On the other hand, on the east side of the Po Valley the bias is positive aside from mountain or plain region. It is to be noticed, that the positive bias over plain area in the eastern Po Valley changes to negative if a cut off of 10mm is used for rmse computation (not shown), suggesting that the overestimation is produced by small rainfall. If rmse for a few selected IOPs is computed a different picture is obtained: rmse for IOP2b (Fig.11a) shows a large error associated with overestimation of the precipitation over the mountains, also a few spots of overestimation are found on the valley. Almost no error and bias on the eastern edge of the Po Valley is found. Different results are found for IOP8 (Fig.11b), a clear tendency to produce a large error and overestimation on the east side of the Po Valley over mountain areas is found. On the plains the overestimation and the error are small. Similarly for IOP15 (Fig.11c), also in this case a large error and an overestimation is found mostly on the eastern side of Po Valley. In summary, rmse associated with bias would suggest a model shortcoming in forecasting the precipitation in the eastern Po Valley, both on plain and mountain regions.

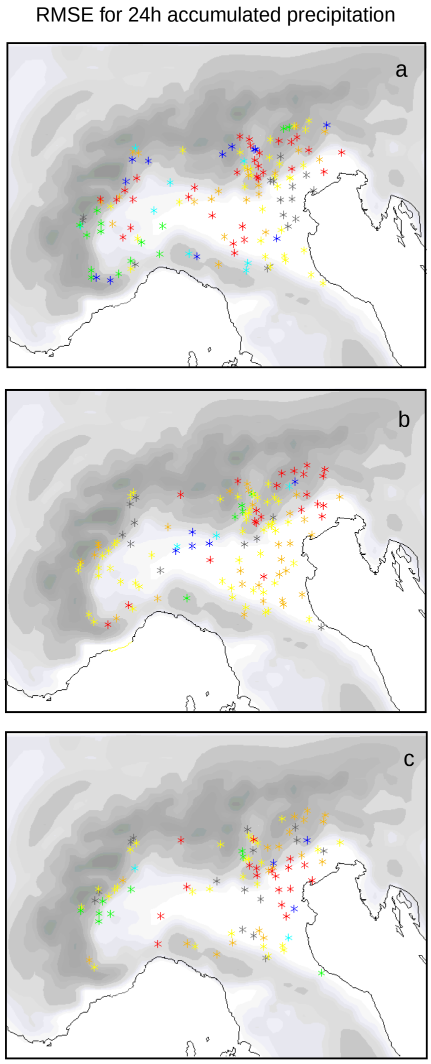

Figure 11. As for fig. 10 but for a few events: a) IOP2b; b) IOP8; c) IOP15. The color code is the same as for Fig.1 0.

(b) *Precipitation time series*

A few precipitation time series are analyzed to highlight the model response along the Po Valley, only IOP2b is used because of the larger amount of rain than for the other IOPs. The stations are chosen with the aim of better understanding the model difficulties over different topography, along the Po Valley from west to east: St1 (close to Turin, 1120m), St2 (Rivolta D'Adda close to Milan), St3 (Cremona), St4 (Garda, 1550m), St5 (Teolo), St6 (Belluno), St7 (Pordenone), and St8 (north-east of Belluno, 1237m), are shown on Figure 1. The time series at the different locations, support ETS and rmse results for plain and mountain regions: St1 shows that the model almost correctly reproduces the rainfall, but a delay in the timing of the maximum of the precipitation is found (Fig.11a). On

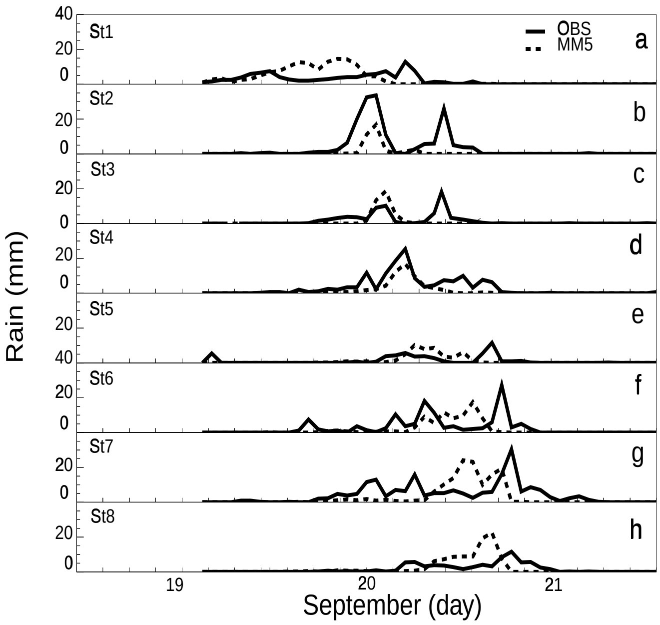

Figure 12. Precipitation time series at Turin (St1), Rivolta d'Adda (Milan) (St2), Cremona (St3), Garda (St4), Teolo (St5), Belluno (St6), Pordenone (St7) and north-east of Belluno (St8). For the stations location see Fig.1.

the other hand, at ST4 (mountain station) the timing is correct, but the rainfall is underestimated (Fig.11d). At St8 an overestimation and a wrong timing of the precipitation is found (Fig.11h), it has to be noticed that also this station is on the mountain. A clear underestimation of the rainfall is found for all the stations located on the plains, except for St3 (Fig.11c). The reader has to remind both the errors of the rain gauge and the different resolution of the observed and forecast rainfall. The time series allow one also to identify a model problem in the timing of the rainfall: the model lags behind at St1, it is well in phase at St2, St3, and St4; again it lags behind for the remain stations. The model lag is larger for the station on the western Po Valley (St1), than for the ones on the eastern side (St8). This would suggest an overestimation of the "holding back" mechanism that is the flow blocking by the Alpine barrier (Steinacker, 1981) and/or an overestimation of the westward flow which would contribute to the retardation of the frontal system (Ferretti *et al.*, 2000 and RF02). The westward deflection of the flow produced by the Alpine barrier is one of the common characteristics for IOP2b and IOP8 (RF02). A larger error for the V-component of the wind than the U-component at 925hPa would support the hypothesis of an overestimation of the "holding back" mechanism by MM5: figure 8b clearly shows a negative ME for V for IOP2b. To evaluate the impact of the topography on the amount and the location of the rainfall a more accurate analysis at higher resolution for all the events is necessary. This will also allow to understand the reasons of the model failure in correctly reproducing the timing and the amount of the rainfall.

7. CONCLUSIONS

The large amount of observations collected during the MAP/SOP made possible to perform a validation of the MM5 high-resolution real-time forecast, and to isolate the model deficiency associated with the most significant events of the MAP/SOP. The bias of the surface pressure and the 2m temperature for the whole period suggests MM5 shortcomings in handling the temperature diurnal cycle during the fair weather days. The comparison between the observed and forecast for both surface pressure and 2 m temperature, for the whole MAP/SOP, shows a good model skill in reproducing events driven by strong large-scale forcing such as frontal systems, upper troughs and low-level cyclones (IOP2b, IOP8, and IOP15). The diurnal surface pressure trend as well as the diurnal temperature oscillation are also reproduced, although a warm bias is found. The model clearly shows some difficulties in reproducing the low-level temperature cycle, as it is clearly shown during clear sky conditions, or for regions strongly influenced by the sea. The 2 m temperature at Baleari station clearly shows an overestimation of the role played by the sea thermal capacity. The comparison between the model results and the observed signal at a few selected stations suggests a good model skill in handling the complex topography of this area. Despite the overall good agreement between the forecast surface pressure and the observed one, a tendency for the model surface minimum both to lag and to overestimate the observations is also found for a few cases. Rmse for wind, temperature and relative humidity at different pressure levels and time steps often shows a large model error at initial time for both wind components, but decreasing with time. Vice versa for temperature and relative humidity: a small initial error largely increases with time. ETS suggests a fair model skill in the precipitation forecast. Furthermore, ETS performed using only the stations located in the mountain or in the plain area clearly shows a model tendency to underestimate the precipitation over plain area. The areal distribution of 24h accumulated rmse shows two different areas: a large error in the eastern Po Valley, and a smaller one in the western. The associated bias shows a tendency to underestimate the rainfall in the western Po Valley and to overestimate in the eastern, but only for light precipitation. On the other hand, if only moderate rainfall is used for the computation of rmse an underestimation all over domain 2 is obtained. The tendency to produce a large error in the eastern Po Valley may be caused by a model difficulty to trigger the precipitation if no uplifting, produced by either the large scale forcing or the topography, is present. An excessive rain shadowing effect may also contribute to underestimate the rainfall over plain region, as already found by Colle *et al.*, (1999). Another competitor mechanism to the overestimation of the precipitation over mountain region may be a too strong holding back mechanism: this effect was produced by MM5 for both IOP2b and IOP8 (RF02), and it may produce an enhanced rainfall in the western Alps and a reduced rainfall in the eastern one. Therefore, a deeper analysis of the role of the topography on the precipitation forecast is necessary to completely understand the model results.

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