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High resolution forecast of heavy precipitation with Lokal Modell: analysis of two case studies in the Alpine area

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Abstract. Northern Italy is frequently affected by severe precipitation conditions often inducing flood events with associated loss of properties, damages and casualties. The capability of correctly forecast these events, strongly required for an efficient support to civil protection actions, is still nowadays a challenge. This difficulty is also related with the complex structure of the precipitation field in the Alpine area and, more generally, over the Italian territory. Recently a new generation of non–hydrostatic meteorological models, suitable to be used at very high spatial resolution, has been developed.

In this paper the performance of the non–hydrostatic Lokal Modell developed by the COSMO Consortium, is analysed with regard to a couple of intense precipitation events occurred in the Piemonte region in Northern Italy. These events were selected among the reference cases of the Hydroptimet/INTERREG IIIB project.

LM run at the operational resolution of 7 km provides a good forecast of the general rain structure, with an unsatisfactory representation of the precipitation distribution across the mountain ranges. It is shown that the inclusion of the new prognostic equations for cloud ice, rain and snow produces a remarkable improvement, reducing the precipitation in the upwind side and extending the intense rainfall area to the downwind side. The unrealistic maxima are decreased towards observed values. The use of very high horizontal resolution (2.8 km) improves the general shape of the precipitation field in the flat area of the Piemonte region but, keeping active the moist convection scheme, sparse and more intense rainfall peaks are produced. When convective precipitation is not parametrised but explicitly represented by the model, this negative effect is removed.

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1 Introduction

The aim of this paper is the numerical investigation of two meteorological cases which can be considered representative of the intense precipitation events frequently affecting Northern Italy during the autumn season. The synoptic description of these case studies is presented in the paper by Milelli et al. (2005)[1].

The new generation of non-hydrostatic high resolution models permits a better description of mesoscale processes and associated precipitation events. In presence of complex topography, as in the Alpine area, these models should also improve the representation of the interaction between meteorological structures and orography. Orographic forcing plays in fact a major role in the localisation and intensification of precipitation in this region, where moist Mediterranean flows undergo to sudden uplift.

The capability of numerical models to forecast correctly local and intense precipitation is still nowadays limited. This is true even at short time-range, up to 48 h, due to the loss of atmospheric predictability going down to small spatial and temporal scales. With regard to high-resolution modelling (1 to 10 km), it is not completely satisfactory just to reproduce precipitating structures, but a correct localisation in space and time is required together with realistic peak values. This is even more crucial when hydrological models need to be coupled in a full hydro-meteorological chain.

A representative review of the state-of-the-art in the field of high resolution modelling of intense precipitation in the Alpine area can be found in the Special Issue of the Quarterly Journal of the Royal Meteorological Society devoted to the MAP (Mesoscale Alpine Programme) results (Bougeault et al., 2003).

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[1] Milelli, M., Llasat, C., and Ducrouq, V.: The cases of June 2000, November 2002 and September 2002 as examples of Mediterranean floods., Nat. Hazards Earth Syst. Sci., submitted, 2005.

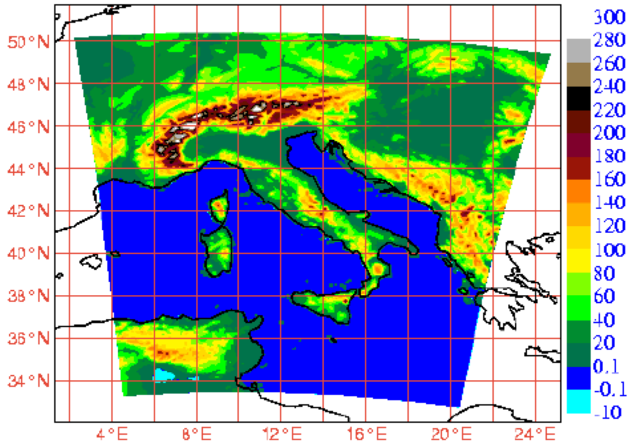

Fig. 1. Integration domain and orography field (in decameters) of LM used operationally by ARPA–SIM (LAMI).

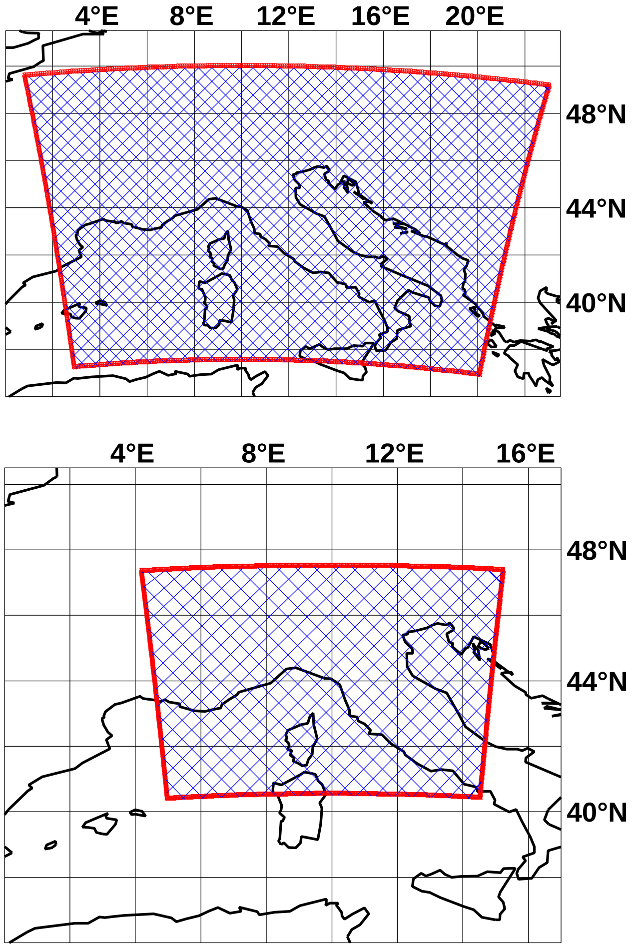

Fig. 2. Integration domain used for the simulations at 7 km of horizontal resolution (top panel) and at 2.8 km of horizontal resolution (bottom panel).

The meteorological model employed for the numerical simulations presented in this work is Lokal Modell (LM), operationally managed by ARPA–SIM (the regional HydroMeteorological Service of Emilia-Romagna) since 2001. LM is developed by the COSMO Consortium (COnsortium for Small-scale MOdelling), which coordinates the cooperation of Germany, Italy, Switzerland, Greece and Poland (http://cosmo-model.cscs.ch/).

LM is a fully-compressible (non-hydrostatic) primitive equation model without any scale approximation. Due to the unfiltered set of equations, the vertical momentum equation is not approximate, allowing a better description of non-hydrostatic phenomena such as moist convection, breeze circulations and some kind of mountain-induced waves.

The Italian implementation of LM (LAMI), managed by ARPA–SIM in the framework of an agreement among UGM (Ufficio Generale di Meteorologia), ARPA–SIM and ARPA–Piemonte, consists of two runs a day (at 00:00 and 12:00 UTC) for 72 h with a spatial horizontal resolution of 7 km and 35 levels in the vertical on the domain represented in Fig. 1. Hourly boundary conditions are provided by the DWD (Deutscher Wetterdienst) global model GME ("one-way nesting"). Initial conditions are obtained through a mesoscale data assimilation system based on the nudging technique (Schraff and Hess, 2003). LM contains a full set of physical parametrisations, described in Cosmo Newsletter number 4 (2004).

One of the major problems of Limited-Area Models, in forecasting intense precipitation in presence of a mountain range, is the tendency to overestimate the rainfall in the upwind areas, with a related drying effect in the downwind regions. This error heavily reduced the usefulness of Quantitative Precipitation Forecast (QPF) as input to hydrological forecasting models.

In order to improve the forecast distribution of the precipitation, some recent improvements of LM have been tested. The operational set-up of the model at the time of the experiments included only two micro-physical species: water vapour and liquid water. The addition of a prognostic treatment of rain and snow (Gassmann, 2002; Baldauf and Schulz, 2004) has been tested, together with the recently developed cloud ice scheme (Doms, 2002).

To test the impact on precipitation forecast of higher horizontal resolution, simulations of these case studies have been performed also at 2.8 km. The boundary conditions for these runs have been provided every hour by the 7-km model runs through a one-way nesting procedure.

The paper is organised as follows: in Sect. 2 a short description of the case studies is given, together with the model configuration used. In Sect. 3 the results of the simulations are presented, comparing the precipitation forecasts obtained with different model set-up. Conclusions are drawn in Sect. 4.

2 Case studies and model configuration

The case studies presented in this paper have been selected within the Hydroptimet Project (an EU/INTERREG IIIB, area MEDOCC project), whose aim was to improve the short

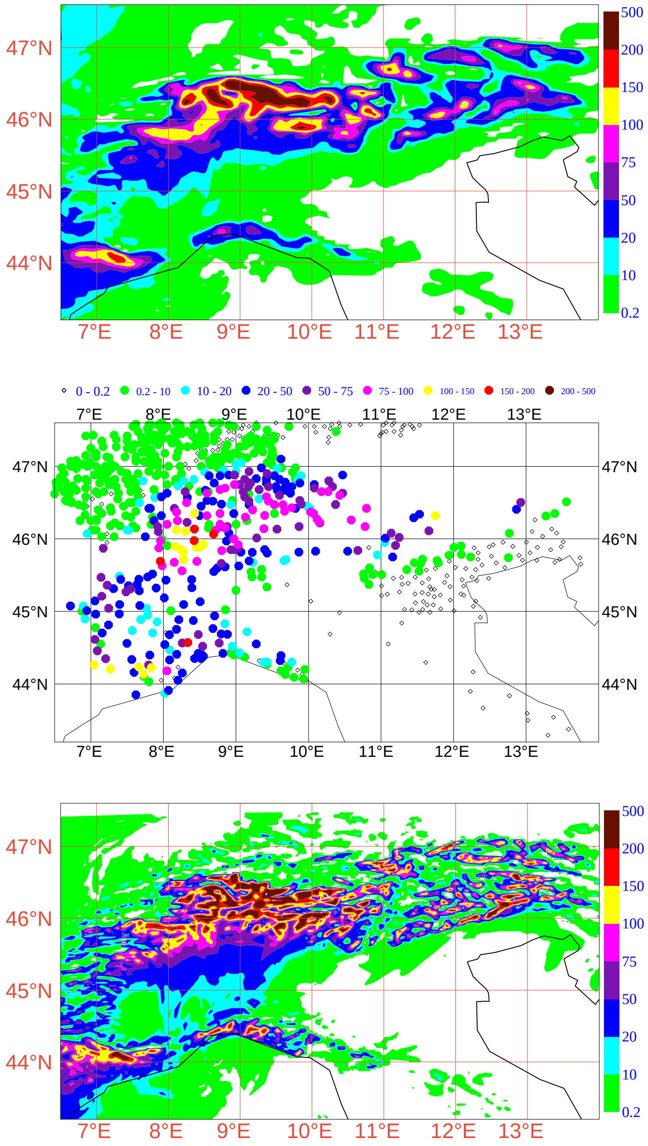

Fig. 3. Cumulated rain field (mm) between 06:00 UTC of 15 Nov. 2002 and 06:00 UTC of 16 Nov. 2002 (first event) for the simulations OPE_7KM (top panel) and OPE_2p8KM (bottom panel). Observational data are shown in the medium panel, the colour scale is the same of the other two figures; the empty diamonds represent stations where no precipitation is observed.

range forecast of the hydro-meteorological events leading to natural hazards, in order to provide guidance during Civil Protection alert conditions.

The two cases are characterised by severe precipitation events affecting Northern Italy and mainly the Piemonte region:

- the first event occurred between 14 and 16 November 2002; observed precipitation cumulated over 24 h starting from 15 November 2002 06:00 UTC is shown in the middle panel of Fig. 3; precipitation exceeding 100 mm/24 h were recorded over most of the Northern Piemonte, where sparse peaks were also above 150 mm, and along the Southern border of Piemonte.

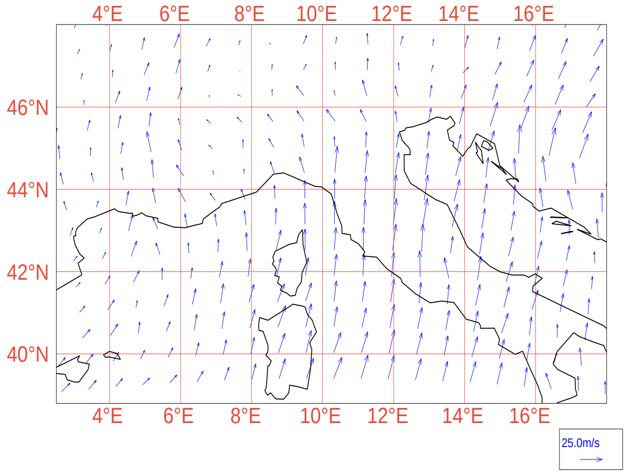

Fig. 4. Wind at 850 hPa forecast at +18 h by the OPE_7KM run starting at 00:00 UTC of the 15 Nov. 2002 (first event).

  On 12 November the synoptic situation showed a weak ridge over the Central Mediterranean Sea and a trough stretching from North-western Europe to the Atlantic coastline of the Iberian Peninsula. During the day, the axis of the trough gradually moved eastward, and the upper level winds became south-westerly over all Northern Italy. This situation permained during the following day, because of the high pressure area present over Eastern Europe, which was blocking the eastward motion of the trough. A minimum of the sea level pressure was moving from Ireland to the Iberian Peninsula and a secondary minimum formed in the afternoon of the 15th over the Balearic Islands, which gradually moved towards the Ligurian Gulf.

- the second event occurred between 24 and 26 November 2002; observed precipitation cumulated over 24 h starting from 25 November 2002 06:00 UTC is shown in the middle panel of Fig. 5; precipitation exceeded 50 mm/24 h over a vast Alpine area, with peaks above 100 mm over Northern Piemonte and also above 150 mm in Liguria region.

  The synoptic situation was characterised by a deep low off the Irish coastline, that, from 23 November, began to expand southward, reaching the North-African coastline and directing moist air towards Northern Italy. Due to the long duration of the southerly flow, the height of the freezing level was constantly increasing and the relative humidity recorded was always very high, close to 100% up to 5000 m.

A more complete meteorological description of these case studies is given in the paper by Milelli et al. (2005)^1.

Both cases are characterised by the presence of a large scale forcing which determines a moist south-westerly flow

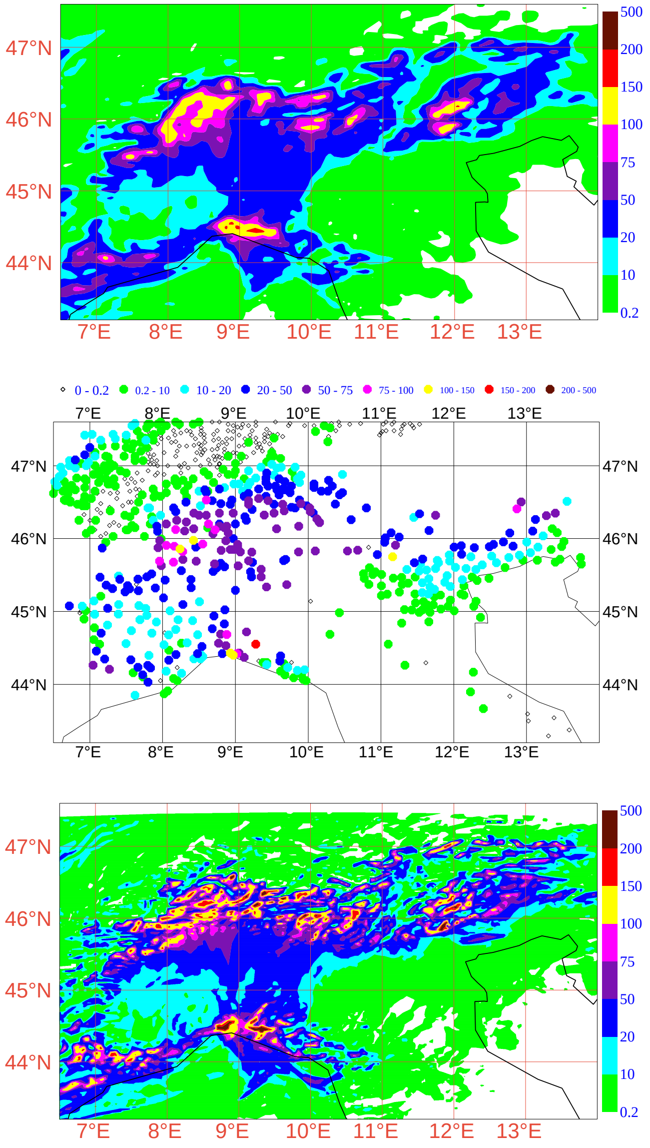

Fig. 5. Cumulated rain field (mm) between 06:00 UTC of 24 Nov. 2002 and 06:00 UTC of 25 Nov. 2002 (second event) for the simulations OPE_7KM (top panel) and OPE_2p8KM (bottom panel). Observational data are shown in the medium panel, the colour scale is the same of the other two figures; the empty diamonds represent stations where no precipitation is observed.

over the Mediterranean Sea directed towards the Western Alps. The heavy precipitation is mostly due to the uplift of the moist air by the steep orography, while a convective enhancement of the precipitation, due to local effects, is embedded in the large scale systems. An improvement of the QPF for these cases can be expected from a more accurate modelling of the physical processes which determine the distribution of the precipitation.

The LM simulations at 7 km of horizontal resolution presented in this paper are carried out in a configuration somehow different from the operational one. The initial condition and the 3-hourly boundary conditions are supplied by the operational ECMWF (European Centre for Medium-range Weather Forecasts) global model. The mesoscale assimilation cycle (nudging) is not applied.

Table 1. Analysed simulations for the first event.

– **7 km resolution**

Initial time and date	Type	Label
00:00 UTC of 15 Nov. 2002	OPE	OPE_7KM
00:00 UTC of 15 Nov. 2002	QI	QI_7KM
00:00 UTC of 15 Nov. 2002	PROGN	PROGN_7KM

– **2.8 km resolution**

Initial time and date	Type	Label
00:00 UTC of 15 Nov. 2002	OPE	OPE_2p8KM
00:00 UTC of 15 Nov. 2002	QI	QI_2p8KM
00:00 UTC of 15 Nov. 2002	PROGN	PROGN_2p8KM
00:00 UTC of 15 Nov. 2002	PRO_EXP	PRO_EXP_2p8KM

Table 2. Analysed simulation for the second event.

– **7 km resolution**

Initial time and date	Type	Label
00:00 UTC of 24 Nov. 2002	OPE	OPE_7KM

– **2.8 km resolution**

Initial time and date	Type	Label
00:00 UTC of 24 Nov. 2002	OPE	OPE_2p8KM

The model version operational in 2004 (3.5), released by COSMO in September 2003, is used. The 7-km runs domain is shown in the top panel of Fig. 2. The 2.8-km simulations, whose domain is shown in the bottom panel of Fig. 2, are nested on the 7-km simulations having the same features.

The features of the simulations are in Table 1 for the first case study and in Table 2 for the second one. The terms used in these tables are explained here:

Initial time and date: represents the starting point of the simulation;

Type:

- OPE: operational setting with prognostic cloud water, no cloud ice, diagnostic rain and snow;
- QI: cloud ice added as prognostic variable, diagnostic rain and snow;

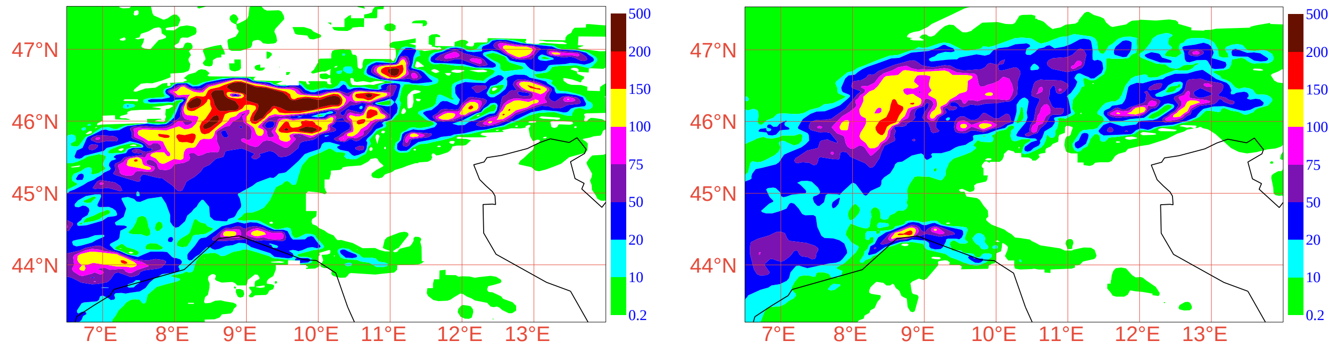

Fig. 6. Cumulated rain field (mm) between 06:00 UTC of 15 Nov. 2002 and 06:00 UTC of 16 Nov. 2002 for the QI_7KM run (left panel) and the PROGN_7KM one (right panel).

– PROGN: cloud ice added as prognostic variable, rain and snow also treated as prognostic variables;

– PRO_EXP: Tiedtke scheme of precipitating convection not used; cloud ice added as prognostic variable, rain and snow also treated as prognostic variables.

Label: name used in the text to refer to the simulation;

The parametrisation of precipitating convection, based on the Tiedtke scheme (Tiedtke, 1989), is actived in all the 7-km simulations presented here. Moving to 2.8-km resolution, where an explicit representation of cumulus convection should be allowed, the Tiedtke scheme has been switched off in one of the first case runs (PRO_EXP_2p8KM run, nested on the PROGN_7KM run).

Every simulation, both at 7 km both at 2.8 km resolution, lasts for 36 h.

3 Results

3.1 Impact of resolution

Referring to the first case, in Fig. 3 the forecast rain field is shown for the OPE_7KM (top panel) and for the OPE_2p8KM (bottom panel) runs; precipitation is cumulated over 24 h, from 06:00 UTC to 06:00 UTC. The observed precipitation for the same period is also shown in the medium panel. This accumulation period allows to compare the forecast against observations over the whole area where heavy precipitations were recorded, since Swiss observations are available only cumulated over this 24-h period.

The 7-km simulation produces a good forecast as regards the structure of the rain field and its localisation, but precipitation is overestimated over the Western Alps, between 9 and 10 degrees East. This is linked to the above mentioned difficulty of models to provide adequate values of the rain field across mountain ridges. Another difference with the observations is the underestimation of the precipitation over the flat part of the Piemonte region in the Western Po Valley.

Considering that the middle-lower tropospheric flow is mainly from the south (see the horizontal wind at 850 hPa forecast by OPE_7KM simulation at +18 h, Fig. 4), it is evident the overestimation of precipitation is in the upwind side of the Alps (Northern Piemonte and Lombardia regions), while in the downwind side (mainly in Switzerland) there is an underestimation.

When the resolution is increased up to 2.8 km, it is remarkable the breaking-up of the rain field with respect to the correspondent 7-km simulation (comparing the bottom panel with the top one in Fig. 3). At this resolution an appreciable overestimation is also detectable over Liguria. It is natural to link this breaking-up of the precipitation field to the finer resolution representation of the orography, even if the associated improvement of the forecast, if any, is difficult to be evaluated. This difficulty is due to the inadequacy of the observational network. The availability of a good estimate of the precipitation field from meteorological radars will help, in the future, to face this problem. This breaking-up effect can also be partially produced by the convective precipitation scheme, not anymore suitable at this resolution.

With regard to the second case, the results relative to the OPE_7KM run and OPE_2p8KM run are shown in Fig. 5; the precipitation is cumulated over 24 h, from 06:00 UTC to 06:00 UTC. In the top panel the 7-km forecast is shown, while the 2.8-km one is shown in the bottom panel. The observations for the same period are reported in the medium panel.

The areas interested by intense precipitation are correctly forecast by Lokal Modell at 7 km, but precipitation is still overestimated in some regions, particularly over the Western Alps between 8 and 9 degrees East. The same breaking-up of the precipitation structure when going to 2.8 km is observed (Fig. 5, bottom panel).

As for the first case, the use of higher resolution determines an increment of the precipitation values on the highest mountains, where the forecast rainfall maxima exceed in some points 500 mm over 24 h. This feature highlights the well known necessity to further adapt numerical models to make them really suitable to be run at a such high resolutions as those associated to cloud resolving scales.

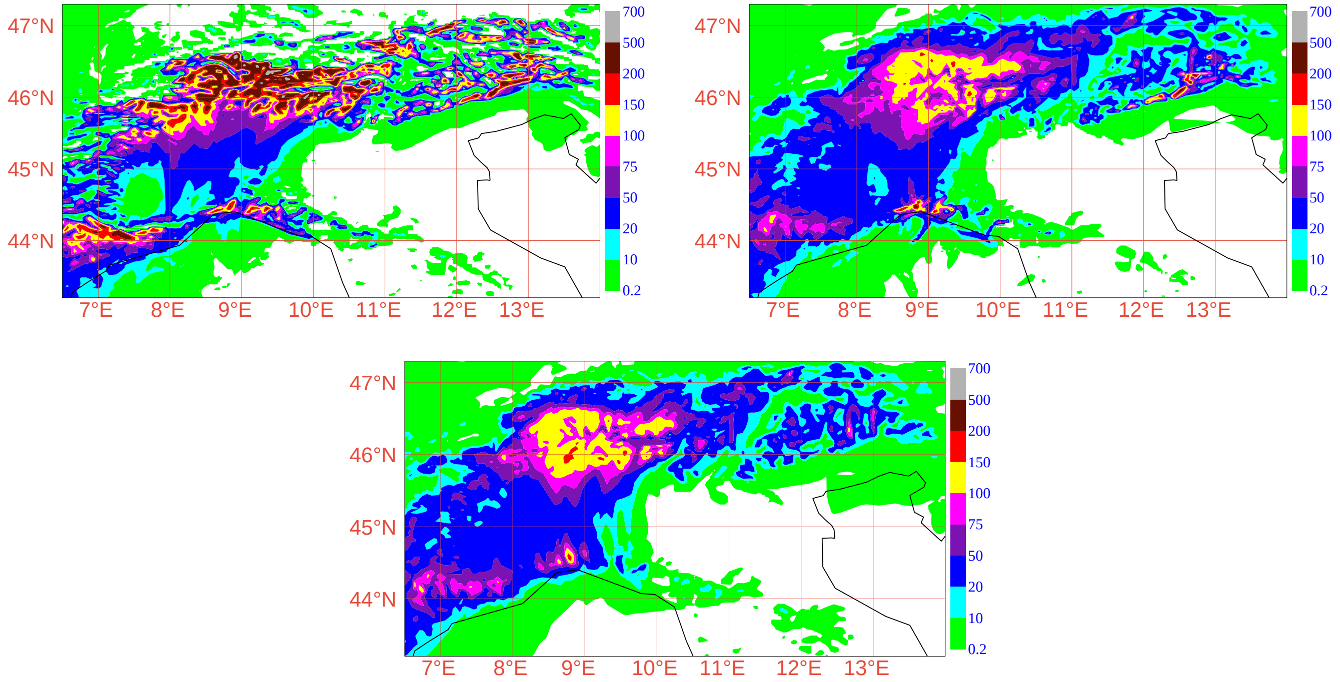

Fig. 7. Cumulated rain field (mm) between 06:00 UTC of 15 Nov. 2002 and 06:00 UTC of 16 Nov. 2002 for QI_2p8KM run (top panel), for the PROGN_2p8KM one (bottom left panel) and for the PRO_EXP_2p8KM one (bottom right panel).

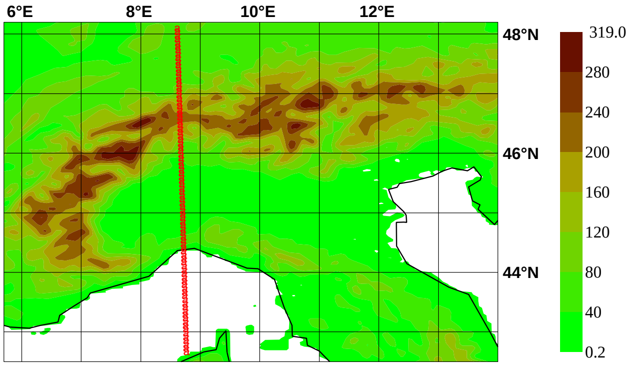

Fig. 8. The red line represents the longitudinal cross-section (the shadowing is the orography field and the colour scale is in decameter).

3.2 The use of new prognostic variables

As already mentioned, LM has been recently improved by including new prognostic equations to better describe the evolution of precipitation, either rain or snow. A cloud ice prognostic equation has been also included into the model. These new equations should allow for a more physical description of all the processes related to QPF. The important aspect is that precipitation is allowed to be advected in the surrounding boxes, while previously it was forced to fall out in the same column where it was produced. These model changes are so in the direction to improve the forecast distribution of the precipitation over mountain ranges. This new features have been tested only for the first case study.

In the left panel of Fig. 6 the precipitation forecast by the QI_7KM simulation (where the cloud ice is added as prognostic variable, as defined in Sect. 2) is shown. LM simulation is starting at 00:00 UTC of 15 November 2002 and precipitation is cumulated over 24 h from +6 up to +30 h. A comparison with the correspondent precipitation from the OPE_7KM run (top panel of Fig. 3) shows a general increase of the precipitation, leading to a further increase of unrealistic high values. The same is true also for the correspondent 2.8 km simulations (top panel of Fig. 7). On the other hand, in the PROGN_7KM simulation (where rain and snow are also treated as prognostic variables) a remarkable reduction of the precipitation on the Western Alps and on Southern France (Fig. 6, right panel) is observed. In particular, the overestimation of the precipitation on the upwind side of the Alps is greatly reduced, with a correspondent reduction of the drying effect in the downwind area. Furthermore, the structure of the forecast rain field is smoother, going in the direction of reducing local and unrealistic precipitation maxima (grid point storms). Similar considerations can be extended also to the PROGN_2p8KM run (bottom left panel of Fig. 7), where a significant improvement is also evident as regards the increase of precipitation in the Western Po Valley. In the bottom right panel of Fig. 7 the PROGN_EXP_2p8KM run with explicit precipitating convection (i.e. without the Tiedtke scheme) is shown. The impact of this change is not dramatic. The precipitation field is generally smoother and localised precipitation maxima are reduced or removed.

The differences among the precipitation fields obtained by the above described simulations, are hereafter analysed in greater detail considering a longitudinal cross-section of both

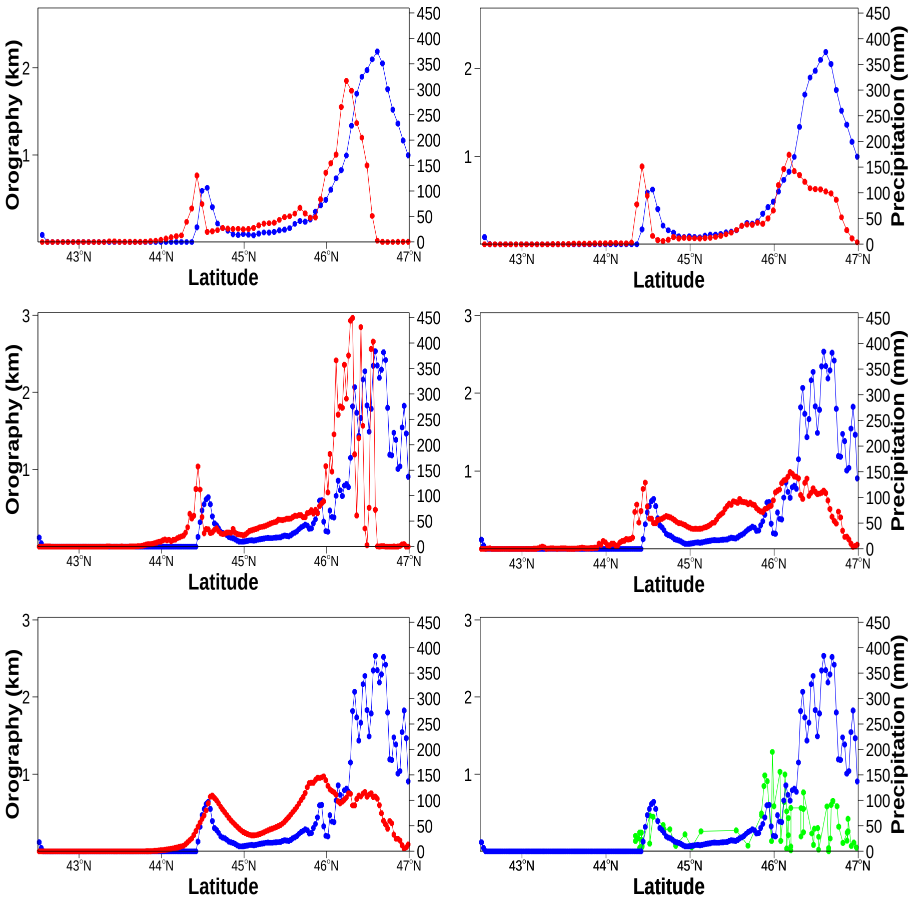

Fig. 9. Longitudinal cross-sections of the orography in km (blue curve) and of the precipitation in mm (red curve), cumulated between 06:00 UTC of 15 Nov. 2002 and 06:00 UTC of 16 Nov. 2002, for the QI_7KM run (top left panel), PROGN_7KM run (top right panel), QI_2p8KM run (medium left panel), PROGN_2p8KM run (medium right panel), PRO_EXP_2p8KM run (bottom panel) and for the observations (green curve) interpolated on the 2.8 km longitudinal cross-section. The latitude is in abscissa.

the model orography and the forecast rainfall along the line shown in Fig. 8. The cross-sections relative to the different simulations are shown in Fig. 9, where orography is plotted in blue and precipitation in red. In the bottom right panel of Fig. 9 the observed precipitations, plotted in green, interpolated over the same cross-section, are shown as a reference. With regard to the QI_7KM simulation (top left panel), it is evident how the highest and unrealistic precipitation values are forecast in the upwind regions south of the two mountain peaks, while almost no precipitation is forecast downwind. Considering the PROGN_7KM simulation (top right panel), the forecast precipitation is more spread out across the mountain range, with a realistic decrease of maxima and a compensating increase of precipitation minima.

This is even more true for the 2.8-km resolution runs (Fig. 9, medium left panel for the QI_2p8KM run run and medium right panel for the PROGN_2p8KM run). The unrealistic precipitation maxima to the south of the mountain peaks, which reach even higher values due to the increased resolution, are drastically reduced to more realistic values by adding the prognostic precipitation in the model. In the PRO_EXP_2p8KM (bottom left panel of Fig. 9) it is confirmed the smoother distribution of precipitation and it is worth noting the correct distribution of the precipitation across the Apennines ridge (the southern mountain peak in the cross section).

In order to further highlight the positive impact of the prognostic treatment of precipitation and also to allow a comparison with observations, the distribution of the precipitation over two boxes of 1 degree per 1 degree is considered. The boxes are respectively upwind (Fig. 10, the blue one) and downwind (the red one) of the Alpine ridge in the region where the observed precipitation was the most intense.

In Fig. 11 the distributions of the precipitation in the upwind (left panel) and in the downwind (right panel) boxes are shown. The observations (blue histogram) are compared with the forecast values obtained by the QI_7KM run (green histogram) and by the PROGN_7KM run (red histogram).

In the upwind box, the use of the prognostic precipitation removes the presence of forecast values exceeding 200 mm, which are not observed, and tends to reduce the values in the range 100–200 mm. The whole distribution of precipitation forecast by PROGN_7KM run is more similar to the observed one with respect to the QI_7KM one.

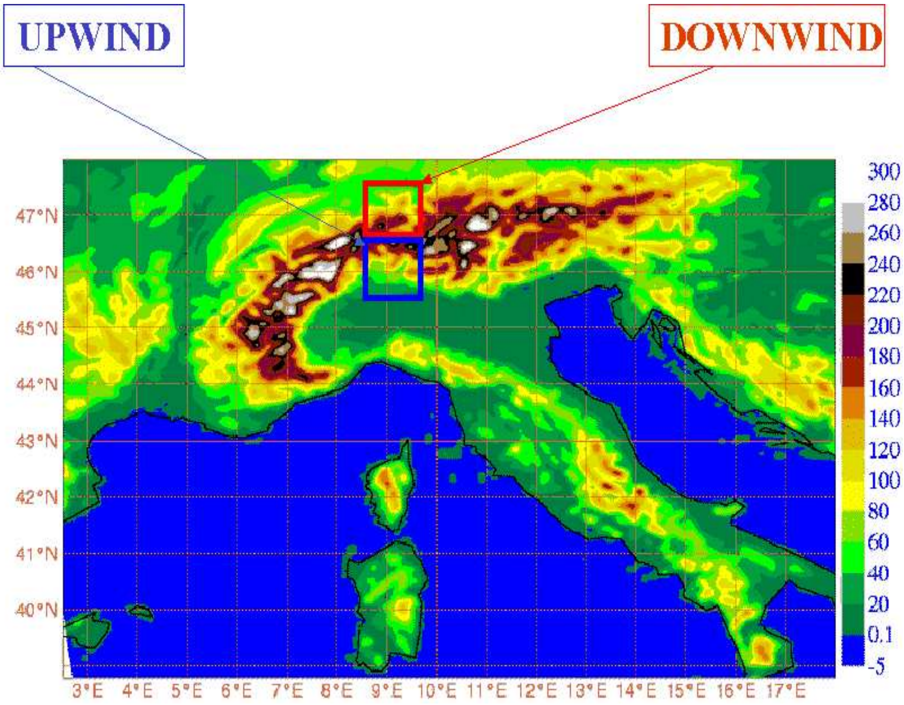

Fig. 10. Location of the two considered boxes of 1 degree × 1 degree, one in the downwind area (red) and the other in the upwind area (blue), over the orography field in decameters.

In the downwind box (Fig. 11, right panel), the PROGN forecast precipitation distribution fits well the observed one. In particular, while the QI_7KM run forecasts precipitation values are mainly concentrated in the first bin (0–20 mm), in the PROGN_7KM run there is a significant number of points where the forecast values are bigger than 20 mm.

Considering the 2.8 km resolution runs (Fig. 12), the occurrence of precipitation belonging to the first two ranges (0–20 and 20–50 mm) in the upwind area (left panel) is underestimated by both PROGN_2p8KM run and QI_2p8KM run. The very high values (over 200 mm) forecast by the QI run and not observed, are completely removed by the PROGN_2p8KM run. Even if the PROGN_2p8KM run still overestimates the precipitation in the 100–200 mm range, there is a general improvement of the whole distribution.

In the downwind box (right panel), the behaviour is very similar to that of the 7-km runs, the distribution of the precipitation forecast by the PROGN_2p8KM run being rather similar to the observed one. Since the explicit convection in the PRO_EXP_2p8KM did not produce a dramatic impact with respect to the PROGN_2p8KM run in the Alpine area, the correspondent histogram is not shown.

4 Conclusions

The performance of the non-hydrostatic limited-area model Lokal Modell in forecasting heavy precipitation over complex terrain has been evaluated on some case studies in the framework of the Hydroptimet/INTERREG IIIB project. Results obtained for the two heavy rainfall events that affected Northern Italy in November 2002 have been presented.

A number of LM runs has been performed on the two cases at two horizontal resolutions, 7 and 2.8 km. Initial and boundary conditions are provided by interpolating the operational ECMWF IFS model. The 7-km simulation with the same setting operational in 2004, but without the mesoscale assimilation cycle, is considered the “reference” run (OPE_7KM). The reference runs for the two cases provide a good forecast of the overall rain structure, but the spatial distribution of the precipitation is badly reproduced across the mountain ranges. Precipitation maxima are increased to unrealistic values and displaced to the upwind side of the Alps, while an artificial drying effect is produced on the lee side.

The increase of the horizontal resolution up to 2.8 km maintains the general shape of the precipitation fields, but induces a crumbling of the high precipitation regions with associated sparse and more intense peaks. The problems related to the incorrect distribution of precipitation across the mountain ranges are worsened by the higher resolution.

The impact on QPF of the inclusion of the new prognostic equations for cloud ice, rain and snow have been presented only for the first case study. The inclusion of the cloud as prognostic variable (with diagnostic rain and snow) shows a general increase of the precipitation, mostly over the Alpine area, leading to a further increase of unrealistic high values of forecast precipitation. This is true for both the 7 and 2.8 km simulations. When, in addition to the cloud ice, also rain

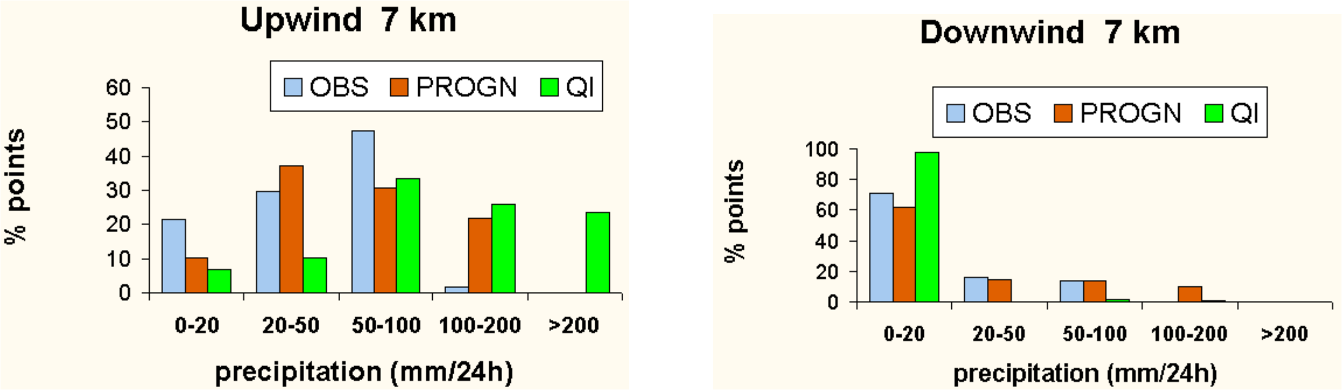

Fig. 11. Percentage distribution of the precipitations in the upwind (left panel) and in downwind (right panel) areas for the QI_7KM run (green histogram), for the PROGN_7KM run (red histogram) and for the observed precipitation (blue histogram).

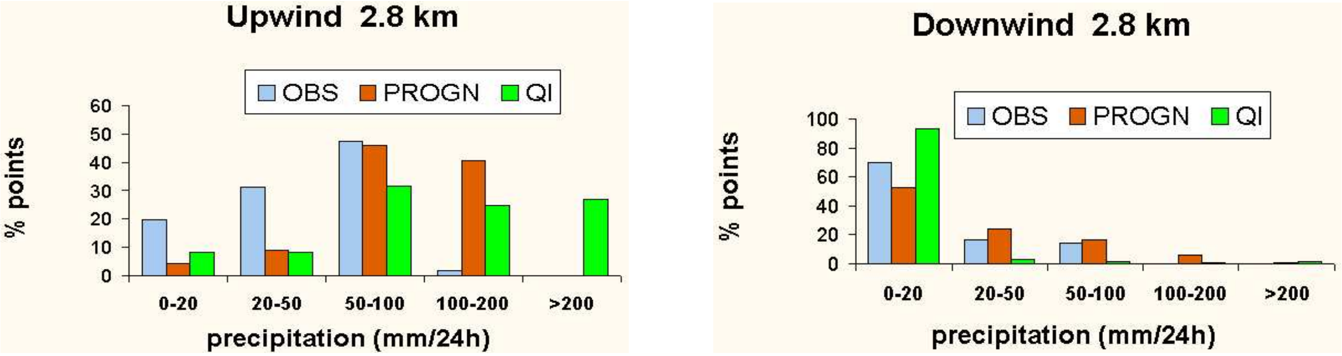

Fig. 12. Percentage distribution of the precipitations in the upwind (left panel) and downwind (right panel) areas for the QI_2p8KM run (green histogram), for the PROGN_2p8KM run (red histogram) and for the observed precipitation (blue histogram).

and snow are treated as prognostic variables, there is a remarkable improvement of QPF, with a reduction of the precipitation in the upwind side of the mountain range and an extention of the intense rainfall area to the downwind side. The unrealistic maxima are decreased towards observed values. This positive effect permains also when the Tiedtke convection scheme is switched off in the 2.8 km run. The explicit representation of the convective processes helps in reducing sparse and localised precipitation maxima, leading to a smoother field.

These positive results are highlighted by considering a longitudinal cross-section of the forecast rainfall crossing the Western Po Valley basin and the surrounding mountain ridges. The positive impact of the prognostic treatment of precipitation is clearly visible in the reduction of the upwind maxima, especially at both 2.8 km resolution.

The new model features, and the explicit representation of precipitating convective processes when moving to 2.8 km resolution, give a substantial help in improving the distribution of the forecast precipitation over the mountain ranges.

These heavy precipitation events are still under investigation to evaluate the impact of other model changes on the QPF produced by LM. The improvement of the precipitation forecast when increasing the horizontal resolution up to cloud resolving scales is still a challenging task. Several options are under testing, focussing on the optimal use of LM as regards intense precipitation events in the Alpine region. The use of QPF as an input to an integrated hydro-meteorological modelling chain is also under evaluation and results will be presented in a forthcoming paper.

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