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Simulating extreme precipitation with a mesoscale forecast model

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With 13 Figures

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Summary

A statistical analysis of two versions of BOLAM, a numerical model for mesoscale weather forecasting, is performed. The precipitation patterns forecasted by the models are evaluated by means of the standard statistical indexes, using the precipitation values observed in several stations of Liguria and Piedmont Regions (north-west of Italy) during 11 case studies occurred between 1984 and 1994. Results show a remarkable improvement of the performances of the last version of BOLAM, due to the recently implemented features both in the dynamical and the physical schemes of the model.

Based on these results, the case study of 22–25 September 1993 (Brig flood) is simulated using integration domains of different size, in order to verify the possible influence of lateral boundary conditions on the model performance. In particular, results show that the use of larger domains improves the capability of the model in localizing the precipitation patterns correctly.

In addition, the case study is simulated by introducing a delay in the triggering of downdrafts in the Kain-Fritsh convective parameterization scheme (CPS) as proposed by Spencer and Stensrud (1998). Results show improvements in the capability to forecast heavy rain events, in particular in enhancing the precipitation amounts over the Ligurian area.

1. Introduction

Recent advances in the comprehension of atmospheric dynamics have brought, in the last years, to the development of numerical models for weather forecasting which have been operatively used to successfully simulate ‘‘extreme events’’ such as major floods over complex orography areas. It is commonly known that the need and the possibility to enhance resolution of models have been limited by the lack of available computational resources. For this reason in the past two decades many efforts have been directed towards the development of limited area models or mesoscale models, capable to simulate the evolution of the atmospheric state with an increased resolution due to the reduction of the computational effort allowed by a limited integration domain.

However, the choice of increasing the resolution introduces new problems related to the need of redefining the description of physical processes not explicitly described in the model. It is not only a question of increasing the number of grid points and its related computational cost; the point is to get to a better physical description of phenomena such as the interaction of fluxes with complex orography, convection or microphysical cloud processes. Moreover, the need to describe more detailed flow structures introduces the problem of providing the model with the right initial and boundary conditions.

It is therefore clear that the quality of a model and of its new features must be constantly tested and monitored. In the recent years the international community has put many efforts on this issue. In particular, one of the most important projects is the Mesoscale Alpine Programme (Bougeault et al, 2001), which, among its aims, included the development of new techniques to improve high resolution numerical modelling of atmosphere and its verification. Other projects, as for instance the EU project HERA (Volkert, 2000), dedicated effort to this subject.

This work falls within this context. We will consider the performances of a limited area model, named BOLAM, developed at the Institute of Atmospheric and Oceanic Sciences[1] of the National Research Council (ISAO-CNR) in Bologna, Italy, and updated over the last decade with new schemes regarding explicit dynamical processes and physical parameterizations (Buzzi et al, 1994; Buzzi and Malguzzi, 1997; Arena et al, 1998; Buzzi et al, 1998; Buzzi and Foschini, 2000).

In particular, the first part of this work deals with a statistical comparison between the version 3 of BOLAM (BOLAM3) and the less recent version LILAM (LIguria Limited Area Model, operationally used at the Meteo Hydrological Center of the Liguria Region – CMIRL). The comparison of the two models is based on the simulation of 11 case studies, occurred between 1984 and 1994, which have been considered of particular importance for the northwestern part of Italy. Initial and boundary conditions for the two models have been provided by the outputs of DALAM, operationally used at the UCEA (Ufficio Centrale di Ecologia Agraria, Roma, Italy).

Using the indications provided by the first part of this work, a deeper analysis of BOLAM3 is performed in the second part of the paper. Several simulations of the extreme event of 23 of September 1993, known as "the Brig flood" (Benoit, 1996), have been carried out and the produced precipitation fields have been directly compared with the observations. The differences in the simulations concern some modifications to the Kain-Fritsh CPS and to the dimension of the integration domain of the model.

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In the next section, we report a brief description of the BOLAM3 and LILAM models and of the used model chain. The following two sections contain the description of the statistical analysis of the two models. In the final section the modifications to the BOLAM3 model and the results obtained simulating the Brig flood are reported. Final remarks conclude this work.

2. The models

The models used in this work (DALAM, LILAM and BOLAM3) are different versions of BOLAM, a hydrostatic, primitive-equation, gridpoint meteorological model, mainly developed at the ISAC-CNR Institute, Bologna. DALAM has been exclusively considered as the low resolution model used to provide initial and boundary conditions for BOLAM3 and LILAM. Its features are very similar to those of LILAM; therefore we will describe the two models together.

The horizontal discretization of the three models is based on geographical coordinates defined on an Arakawa C grid (Haltiner and Williams, 1980). In the vertical σ-coordinates are used, with vertical discretization of the Lorenz type. Prognostic variables are the horizontal components of velocity u and v, the potential temperature θ, the humidity q and the surface pressure p_s (Buzzi et al, 1994). All the models are characterized by a fourth order horizontal diffusion and a scheme for lateral boundary conditions derived from the Davies-Lehman scheme (Lehmann, 1993).

Physical parameterizations include a PBL scheme, which is based on the mixing length theory, with exchange coefficients depending on the Richardson number (Louis et al, 1981). Surface roughness over land is different for momentum and temperature-humidity, and it is a function of orography aimed at parameterizing the aerodynamic drag. The soil parameterization scheme describes humidity and temperature over three layers. Radiative processes are computed by means of the Geleyn scheme (Geleyn and Hollingsworth, 1979; Ritter and Geleyn, 1992).

BOLAM3 and LILAM are characterized by several differences. LILAM, as well as DALAM, use a leapfrog semi-implicit time integration scheme with an Asselin filter and the Emanuel convective parameterization scheme (Emanuel,

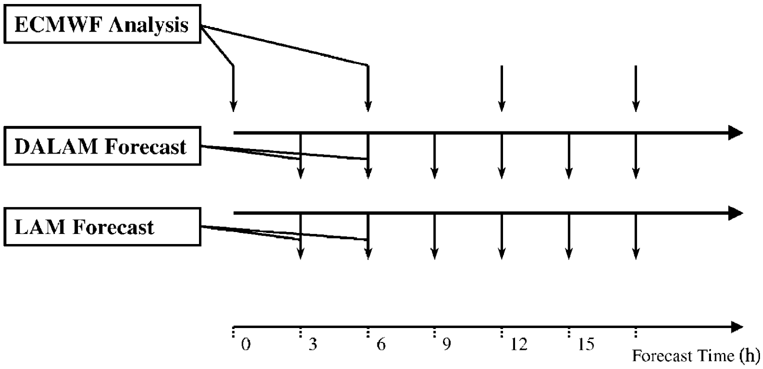

Fig. 1. Scheme of the operational chain used for the simulations. Every 6 hours ECMWF analyses (55 km resolution) are used as initial and boundary conditions for the runs of the DALAM (35 km resolution), which, in turn, provides initial and boundary conditions (every 3 hours) for the simulations of LILAM and BOLAM3 (10 km resolution)

1991). The time scheme in BOLAM3 is split explicit, while the advection scheme is a forward backward second order scheme, stable up to Courant number 2 (Malguzzi and Tartaglione, 1999). It is coupled with a semi-Lagrangian scheme applied to the water species. Gravity modes are described by a forward-backward integration. A fourth-order horizontal diffusion term, based on the ∇^4 spatial operator, is added to all prognostic equations except for the tendency of surface pressure. The Emanuel scheme used in both LILAM and DALAM has been replaced in BOLAM3 by the Kain-Fritsch's CPS (Kain and Fritsch, 1990 and 1992). BOLAM3 uses a new microphysical scheme for the description of water cycle, including a treatment of mixed phase condensate species which uses 5 explicit variables: cloud water, cloud ice, rain, snow and hail/graupel. The simplified approach of the Schultz's NEM (NWP Explicit Microphysics) scheme (Schultz, 1995) is adopted in several aspects.

As already noticed, the simulations of LILAM and BOLAM3 have been performed starting from the initial and boundary conditions provided by DALAM, which in turn derive initial and boundary conditions from the analysis of the ECMWF global circulation model. In Figs. 1 and 2 the schemes of the nesting procedure and of the different integration domains used in this work are presented. ECMWF analysis are provided every 6 hours and used as initial and boundary conditions for DALAM simulations, performed with horizontal resolution of about 35 km. DALAM outputs are saved every 3 hours and made available for the simulations of LILAM and BOLAM3, performed with horizontal resolution of about 10 km.

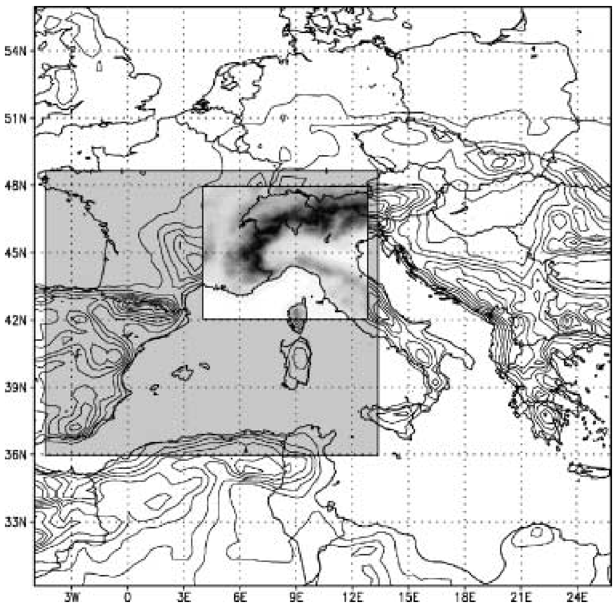

Fig. 2. Integration domain of DALAM. The internal shaded area represents the integration domain of BOLAM3 and LILAM. The external shaded area represents the integration domain used in the *Sim 2* and *Sim 4* simulations. Contours and internal shaded contours denote height of DALAM and LILAM/BOLAM3 orography, respectively (contour interval: 200 m, horizontal resolution: 35 km and 10 km, respectively)

3. The data set and the adopted methodology

Our main interest was centered around the capability of the models in forecasting heavy precipitation fields. This is the reason why we have chosen eleven extreme precipitation events occurred in the northwestern part of Italy between 1984 and 1994 (see Table 1).

Using the observations collected in the station network reported in Fig. 3, the verification has been performed using well known statistical

Table 1. Case studies used for the statistical verification of LILAM and BOLAM3 and number of observed values for each event. The three central columns represent the number of runs of respectively 24, 48 and 72 hours

Case	No. of runs			No. of
study	24 h	48 h	72 h	obs.
22–25 Aug 1984	0	0	1	2561
2 Mar 1985	1	1	1	3308
4 Nov 1986	1	1	1	1840
22 Dec 1989	1	1	2	2987
29 Sep 1991	1	1	1	1902
22–23 Sep 1992	0	0	3	2935
26–28 Sep 1992	1	1	3	3465
22–23 Sep 1993	0	0	3	3957
1 Oct 1993	1	1	2	2010
26 Jun 1994	1	1	2	2832
4–6 Nov 1994	1	1	3	5483

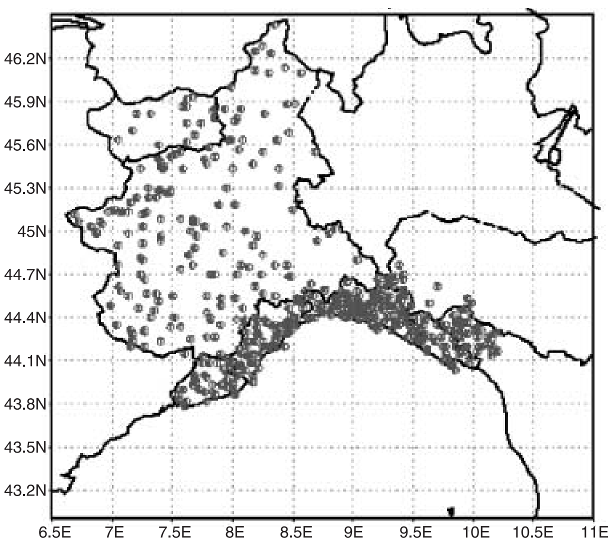

Fig. 3. Scheme of the observation network used for the statistical analysis. Precipitation values are available as 1 hour accumulated values. Not all the stations are available in all the experiments. Also refer to Table 1

indices for precipitation (Wilks, 1995; Anthes, 1983; Anthes et al, 1989). Results can be considered statistically significant, being the number of independent events of the order of several thousands. Models' statistical outputs have also been compared with the "no skill forecast", obtained by assuming that the probability to correctly forecast a given precipitation amount is equal to the product between the probability that the considered precipitation amount is forecasted and the probability that the considered precipitation amount occurs, which corresponds to the assumption of completely independent events (joint probability as product of probabilities). Note that we have identified the latter probability (occurrence of the given precipitation amount) with the corresponding frequency in the considered period and not with the corresponding climatological frequency.

Except for the two events of November 1986 and December 1989, both of which exhibited no particularly heavy precipitation, all the case studies have been characterized by a meridional flow associated to a deep trough over Western Europe, by a sea-level pressure low over the western Mediterranean Sea or the Gulf of Biscay, and by a strong and stable anticyclonic structure over the Balkan region and Eastern Europe. This configuration leads to a south or south-westerly flow of warm and humid air from African regions towards the northwestern part of Italy. The orography of this region, characterized by the double presence of the Apennines and the Alps, represents a very efficient triggering mechanism for convective phenomena and consequently for heavy precipitation events.

The eleven case studies taken into account are not to be considered a significant sample of the synoptic conditions and precipitative events that characterize the northwestern part of Italy. They are rare events with an annual frequency of the order of unity. Therefore it should be stressed that the conclusions of this work are to be considered valid only for the evaluation of the capability of models to simulate heavy precipitation and cannot be generalized to different scenarios. However, one of the main aims of mesoscale modelling is the possibility to forecast correctly extreme events: for this reason a test on these case studies can lead to useful information.

The statistical analysis is performed using observations obtained from a rain gauge network. The number of observations is variable from case to case, but always of the order of one hundred. Most of the available stations are placed in Liguria and Piedmont regions (Fig. 3). The total number of pairs of observed and forecasted values is of the order of one hundred thousand. Yet, not all the values can be considered independent, because it may happen that the same observed values were compared to the simulated ones more than once, due to the different forecast

	For	Not For
Obs	a	c
Not Obs	b	d

Fig. 4. Scheme of the contingency table: for every considered rain threshold *a* is the number of correctly forecasted event, *b* is the number of times the event was forecasted but not observed, *c* is the number of times the event occurred but was not forecasted and *d* is the number of times the absence of the event was correctly forecasted

time. An estimate of the number of independent values available for the statistical verification can be obtained by dividing the total number by three, 3 being the maximum number of predicted values that can be related to the same observed value.

The statistical analysis has been performed using the commonly adopted indexes: *threat score* (*TS*), *bias* (*B*) and *false alarms* (*FAR*), computed from the *Contingency Table* reported in Fig. 4 and defined respectively as (Wilks, 1995):

$$TS = \frac{a}{a+b+c}, \tag{1}$$

$$B = \frac{a+b}{a+c}, \tag{2}$$

$$FAR = \frac{b}{a+b}. \tag{3}$$

The precipitation values, available as 3 hours accumulated precipitation amounts over the stations reported in Fig. 3, have also been averaged in space and time. More precisely, we have compared the observed and forecasted spatial mean values over four ligurian sub-regions (Fig. 5) as well as 12 hours accumulated values for the original data.

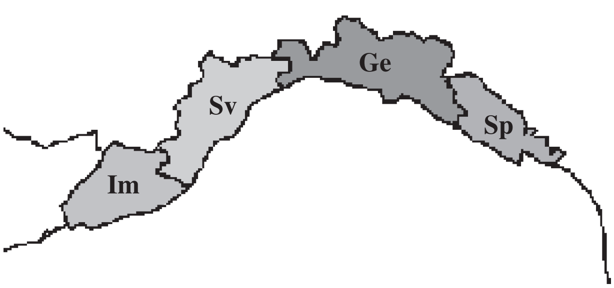

Fig. 5. The four subregions of Liguria: Imperia (Im), Savona (Sv), Genova (Ge) and La Spezia (Sp)

The threat score and the false alarms indexes have also been computed for the "no skill forecast" case. As already pointed out, we have considered the frequencies of the observed and forecasted values relative to the event under consideration, characterized by precipitation values much higher than the climatological mean.

The spatially averaged data have also been used to calculate correlation and rank correlation values, defined respectively as (Wilks, 1995):

$$r_{xy} = \frac{\mathrm{cov}(x,y)}{s_x s_y} \tag{4}$$

and

$$r_{\mathrm{rank}} = 1 - \frac{6\sum_{i=1}^{n} D_i^2}{n(n^2-1)}, \tag{5}$$

where n is the total number of pairs of forecasted (x) and observed (y) values and D_i is the rank difference between x and y. This provides useful information about the capability of the models to forecast precipitation patterns. More precisely, the correlation coefficient (also known as "Pearson product – moment coefficient of linear correlation") is calculated when one wants to highlight the linear relationship between the two sets of data x and y. Unfortunately, strong but nonlinear relationships between the two variables x and y may not be recognized by this coefficient. Furthermore, it can be extremely sensitive to one or a few outlying point pairs. In order to avoid these problems, the Spearman rank correlation coefficient can be used. This is simply the Pearson correlation coefficient computed using the ranks of the data instead of the data themselves.

4. Statistical results and discussion

Considering the false alarms, threat score, and bias reported in Figs. 6–8, it is clear that both BOLAM3 and LILAM performances are much better than those of the no skill forecast. Although a direct comparison with other models is not made here, it is important to notice that the values obtained for the two models considered in this work are comparable to those computed for other models reported in literature (see, for instance, Gyakum et al, 1996).

A tendency of LILAM to overestimate and BOLAM3 to underestimate the number of

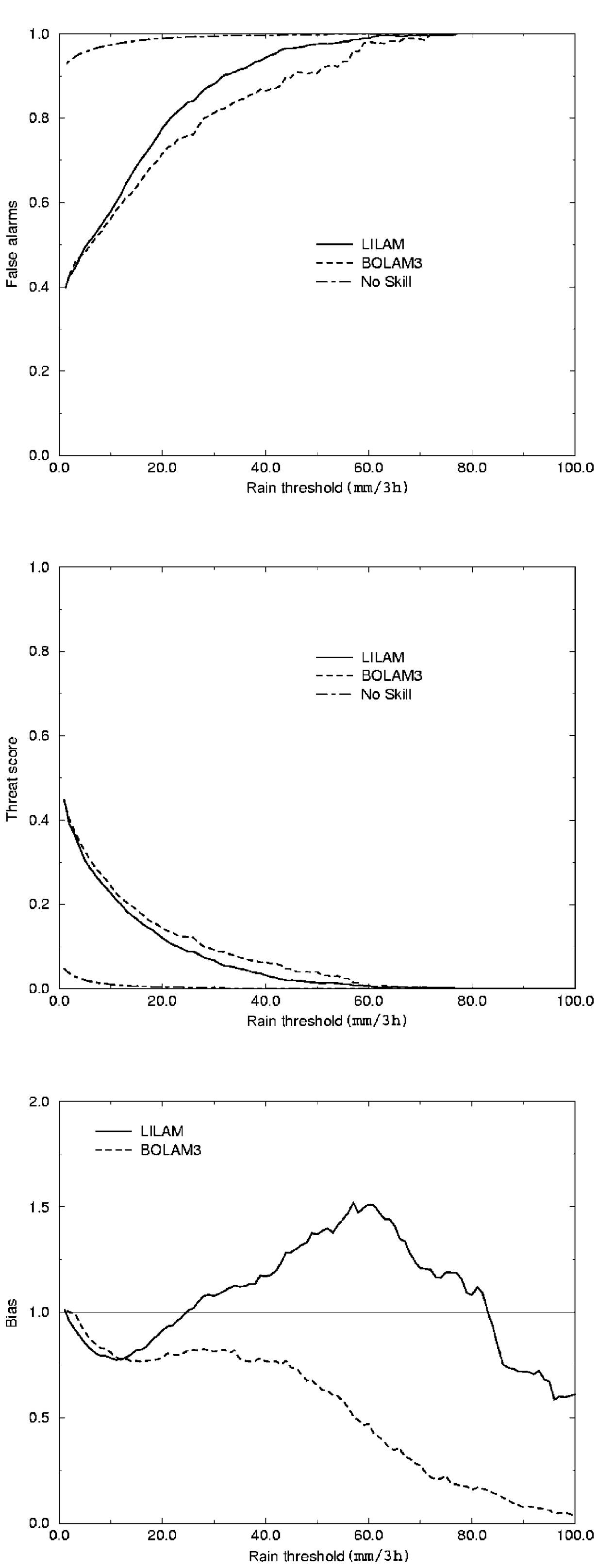

Fig. 6. *False alarms*, *threat score* and *bias* for LILAM, BOLAM3 and the "*no skill*" *forecast* (see text for explanation), for 3 hours accumulated precipitation

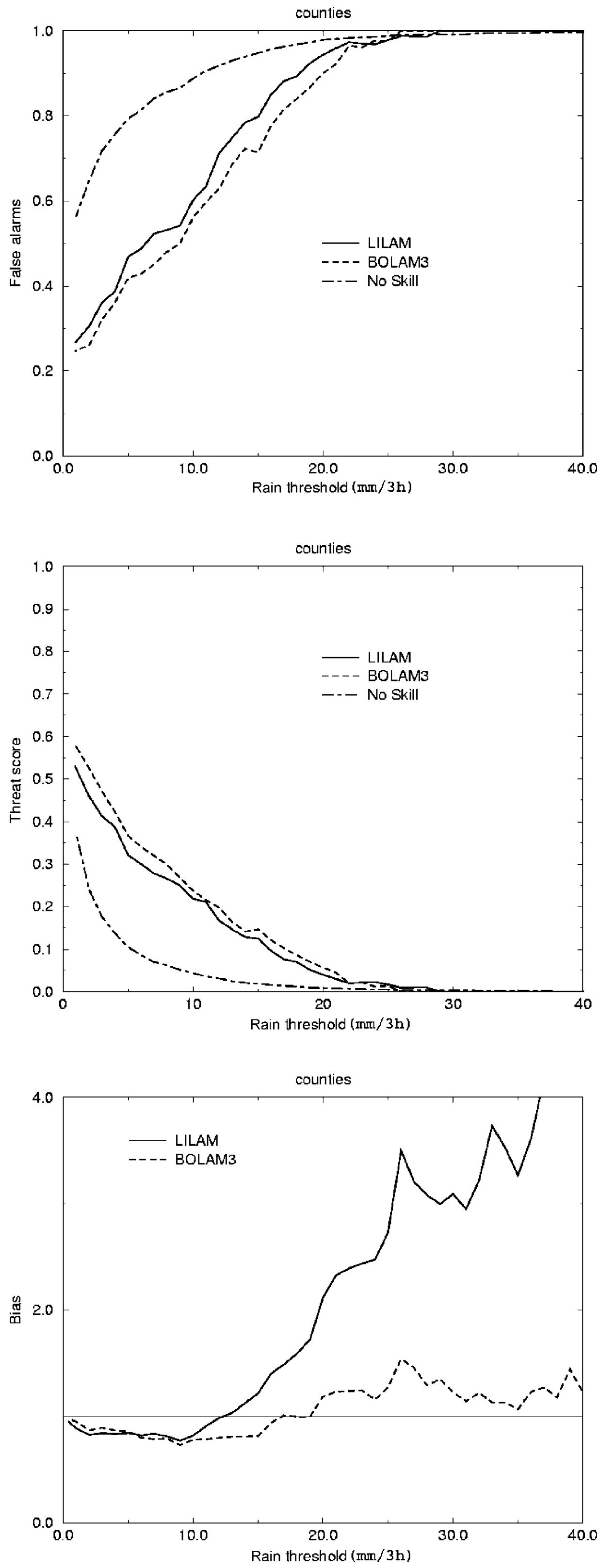

Fig. 7. *False alarms*, *threat score* and *bias* for LILAM, BOLAM3 and the "*no skill*" *forecast* (see text for explanation), for 3 hours accumulated precipitation averaged over the four Ligurian subregions

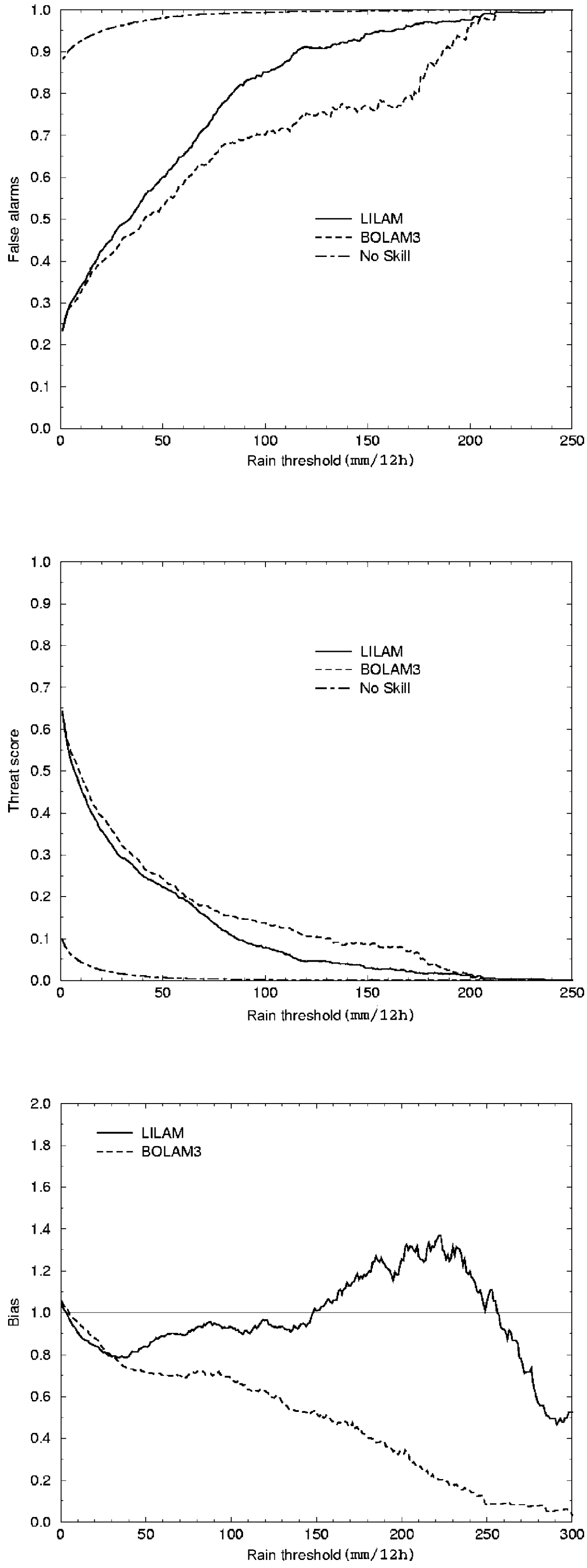

Fig. 8. *False alarms*, *threat score* and *bias* for LILAM, BOLAM3 and the "*no skill*" *forecast* (see text for explanation), for 12 hours accumulated precipitation

precipitation events for mid-high threshold values can be easily inferred from the indices. The analysis of the indices computed both with spatially and time averaged values suggests that part of BOLAM3's underestimation can be associated with the spread of the precipitation patterns. Observing Fig. 7, it is possible to note that the use of the spatially averaged values instead of the station values leads to a remarkable increase in the bias of BOLAM3, which is now much closer to the optimal value ($B = 1$) for every threshold. It is also important to note that the decreasing values of the bias with increasing rain thresholds may be explained as follows. The spatial resolution of the model, of the order of 10 km, forces the precipitation output to be an averaged value over a surface of $10 \times 10\,\text{km}^2$. When the rain threshold increases, the possibility that the leading physical phenomena consist of convective activity also increases. Spatial scales of convective cells are much smaller than the considered model resolution; therefore, also for a perfect forecast, precipitation outputs of the model are a smoothed value of the observed one. The fact that the bias computed for the spatially averaged values is near to the optimal bias confirms this interpretation. Yet, it is not possible to give a similar interpretation for LILAM, as the averaged forecasted precipitation values are much higher than the observed ones.

The difference between precipitation biases of the two models can be explained on the basis of two different aspects. First of all, the Emanuel convective parameterization scheme is used in LILAM, while the Kain-Fritsh scheme is used in BOLAM3. The Emanuel scheme shows some indication of "instability" which also causes a high number of false alarms. The Kain-Fritsh scheme seems to be more "stable", producing smoother rain fields, sensibly reducing the number of false alarms, along with a reduced capability of simulating the very extreme events. The second aspect is represented by the newly implemented microphysical scheme in BOLAM3. The improvement given by the explicit description of the microphysical quantities leads to a better distribution of the precipitation patterns both in time and space. In particular this is due to the new possibility to horizontally advect the water species in the considered layer, the result being a delay in the fall of the water itself.

While the better false alarms indexes of BOLAM3 can be interpreted as a further evidence of the above mentioned facts, the better threat score indexes produce new information, which demonstrates that BOLAM3 is more efficient in forecasting precipitation patterns both in space and time.

This result is confirmed also by the analysis of the correlation and the rank correlation.

In Tables 2 and 3 the sixteen correlation coefficients for LILAM and BOLAM3 are shown, respectively. They are computed using the observed and forecasted values obtained with a spatial average over the four subregions of Liguria: Imperia (Im), Savona (Sv), Genova (Ge) and La Spezia (Sp) (Fig. 5). One would expect the highest values along the diagonals (Im vs. Im and so on) and the minimum values for the furthermost Provinces (Im vs. Sp and Sp vs. Im). Although this happens on the whole, one can note, both for LILAM (Table 2) and BOLAM3 (Table 3), a correlation coefficient, between forecasted values in Savona and observed values in Genova, higher than the correlation coefficient between observed and forecasted values within a same Province. This fact, although less visible in the more reliable rank correlation coefficient, could be interpreted as a tendency of the model to shift precipitation patterns westward from Genova to Savona, with respect to reality. However, coefficients along the diagonal in tables relative to BOLAM3 are much higher then those relative to LILAM, indicating a sensible improvement of BOLAM3 simulations with respect to those of LILAM.

These results can partly be ascribed to the influence of the lateral boundary conditions. As a matter of fact, as we shall see in the following section, when simulations are performed on a larger domain, and, therefore, when the importance of the boundary condition is reduced, this error decreases.

Table 2. LILAM correlation and rank correlation for 3 hours cumulate precipitation values

	Im	Sv	Ge	Sp
Corr (Rows:Obs Col:Fc)				
Im	0.52	0.47	0.31	0.21
Sv	0.37	0.42	0.26	0.13
Ge	0.34	0.55	0.28	0.08
Sp	0.19	0.19	0.29	0.29
R-corr (Rows:Obs Col:Fc)				
Im	0.71	0.66	0.48	0.43
Sv	0.62	0.67	0.46	0.36
Ge	0.61	0.66	0.58	0.50
Sp	0.60	0.50	0.53	0.60

Table 3. BOLAM3 correlation and rank correlation for 3 hours cumulated precipitation values

	Im	Sv	Ge	Sp
Corr (Rows:Obs Col:Fc)				
Im	0.59	0.54	0.41	0.24
Sv	0.44	0.50	0.29	0.15
Ge	0.45	0.56	0.42	0.21
Sp	0.20	0.17	0.33	0.39
R-corr (Rows:Obs Col:Fc)				
Im	0.73	0.68	0.60	0.56
Sv	0.66	0.70	0.55	0.45
Ge	0.61	0.64	0.66	0.59
Sp	0.56	0.47	0.57	0.66

5. The Brig flood

In the statistical analysis performed in the previous section we have pointed out several changes in the performances of LILAM and BOLAM3 models. In particular, we tried to understand the changes in the behavior of the two models in terms of the different schemes used. In this section we investigate the influence of other two aspects on the BOLAM3 model: the integration domain and some modification to the convective parameterization scheme.

For this purpose we studied the behavior of the BOLAM3 model performing several simulations of one of the case studies considered in the last section, each time introducing a new feature in the code. A suitable test for the model is represented by the event of 22–24 September 1993, the well known "Brig flood", from the name of the Swiss town seriously affected by the flood.

Between the 22nd and the 24th of September 1993 a number of mesoscale convective systems caused heavy precipitation events in the area between Pirenees and southwestern Alps, and produced major floods. Precipitation maxima of more than 200 mm in 24 h were registered in Barcelona, 50–100 mm on the southwest part

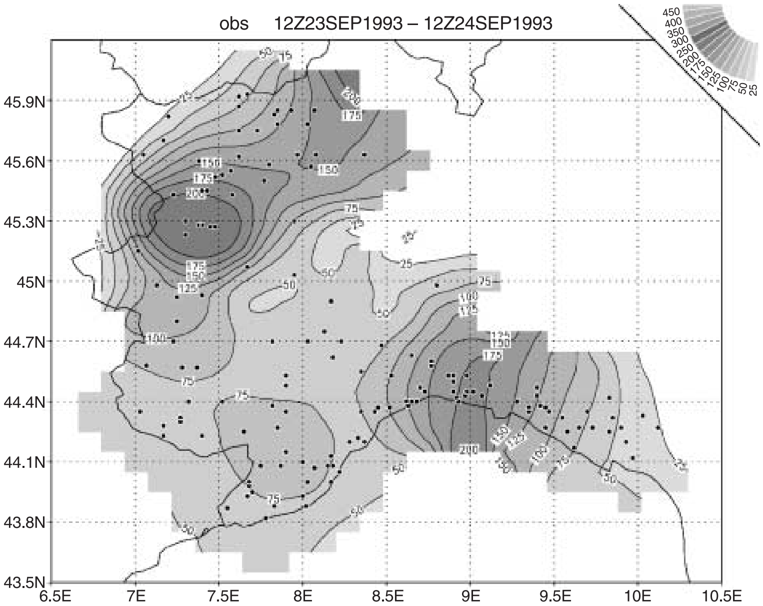

Fig. 9. Observed 24 h accumulated precipitation amounts (mm) at 12 UTC of September 24, 1993. Contour intervals are of 25 mm below the 200 mm threshold and of 50 mm above

of France (400 mm on Cape Corse), and 100–200 mm on southwestern Alps (Benoit, 1996). A detailed representation of the observed precipitation pattern over the entire area can be found at the MAP Data Centre (Frei and Schär, 1998, http://www.map.ethz.ch), where 24 h precipitation sum analyses for the whole Alpine arc are available.

In Fig. 9, the 24 hours accumulated precipitation observed by the available rain gauges between 23rd 12 UTC and 24th 12 UTC of September is reported. Starting from the analysis of the 00 UTC of the 22nd of September, we have produced four 72 hours forecasts, obtained with the modification described below:

Sim 1: control simulation, made with the standard version of BOLAM3 model, with 64×60 horizontal grid points and 30 σ levels, an horizontal resolution of 0.10 degree and a time step of 90 seconds.

Sim 2: large domain simulation, based on a domain four times larger than the control simulation domain, centred to include a larger portion of the upstream/inflow region (Fig. 2).

Sim 3: modified convection simulation on small domain, obtained by modifying the Kain-Fritsh convection scheme as suggested by Spencer and Stensrud (1998).

Sim 4: performed by applying the two modifications of *Sim 2* and *Sim 3* simultaneously.

Figure 10 shows the 24 hours cumulated precipitation forecasted by the control simulation (*Sim 1*) between 12 UTC of the 23rd of September and 12 UTC of the 24th. Comparison with the observed values, reported in Fig. 9, allows us to confirm what already pointed out in the statistical analysis presented in the previous section. Indeed there is a tendency of the model to shift the precipitation pattern from Genova towards Savona, roughly 50 km to the west.

The integration domain used in all the simulations performed for the statistical analysis (equal to that of the control simulation) is certainly smaller then optimal. Therefore the effect of the lateral boundary conditions strongly control the evolution of the forecast. As a consequence, the effect of the errors of the low resolution model providing the lateral boundary conditions is amplified when using a small nested domain. The use of a larger integration domain is important for a correct description of the physical phenomena. The simplest way to understand the influence of the lateral boundary conditions on the results obtained in this work is to enlarge the integration domain of the model. The integration domain of *Sim 2* simulation is shown in Fig. 2. The choice of an area clearly not centered is due to the characteristics of the Brig flood: a feature of this event is the development of a deep cyclone over the Balearic Islands which moves towards the Ligurian Sea, imbedded in a general southwesterly flow.

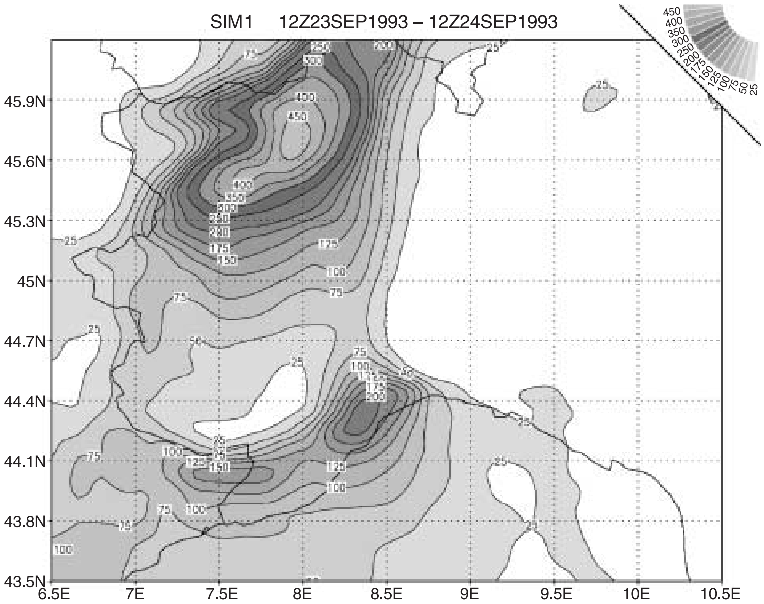

Fig. 10. 24 h accumulated precipitation amounts (mm) at 12 UTC of September 24, 1993 forecasted by the *Sim 1* run. Contour intervals are the same of Fig. 9

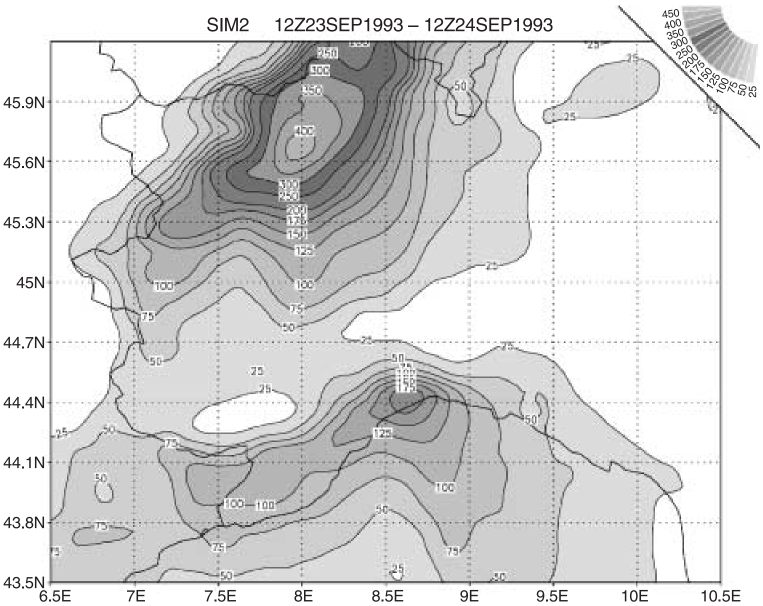

Fig. 11. 24 h cumulated precipitation amounts (mm) at 12 UTC of September 24, 1993 forecasted by the *Sim 2* run. Contour intervals are the same of Fig. 9

Figure 11 shows the 24 hours cumulated precipitation values for *Sim 2*, in which the domain has been enlarged to contain a larger portion of the upstream region, as specified above. The improvement in the localization of the precipitation pattern, now closer to the observed pattern, can be noticed especially in the Ligurian area, where the rain field structure now presents only one maximum between Genoa and Savona, shifted eastward in the direction of the observed maximum of about a quarter of degree. It is also possible to observe that the entire structure over Liguria is correctly moved eastward with respect to *Sim 1*, with a nearly doubled amount of precipitation over the eastern part of the region, and that the precipitation maximum are slightly lower than those of the control run, with a larger spread of the pattern.

We have already pointed out that in the scenario of flood events over Liguria the correct simulation of convective phenomena is, without exceptions, of extreme importance. During the comparison between the performances of the Emanuel convective scheme of LILAM and the Kain-Fritsh scheme of BOLAM3, described in Sect. 4, we found that in this context the

Kain-Fritsh scheme is more reliable but seems to underforecast the intensity of the most severe events. This means in particular that we have to face the problem of parameterizing long lived convective cells. Both the Emanuel and the Kain-Fritsh scheme include the parameterization of convective downdrafts. Spencer and Stensrud (1998) have pointed out that convective downdrafts form in new convective cells with a delay of the order of 30 minutes. Following the suggestions of Spencer and Stensrud, we performed a new simulation of the Brig flood event, with a modified Kain-Fritsh scheme. The triggering of the downdrafts has been enabled only after the second consecutive call to the convective scheme, that is about 30 minutes after the first call.

Precipitation amounts of this simulation are shown in Fig. 12. It is not possible to notice any remarkable difference with respect to the control run (*Sim 1*). A good way to understand if this result is due to an integration domain, too small to contain the relevant portions of the mesoscale development of these features, is to apply simultaneously the modifications of *Sim 2* and *Sim 3* in *Sim 4*. The analysis of the forecasted precipitation values of the *Sim 4* run (Fig. 13) confirms the

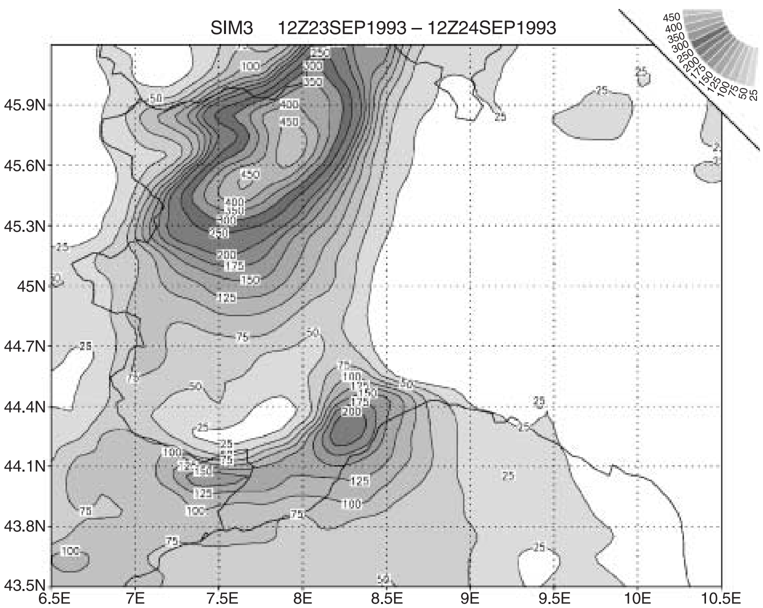

Fig. 12. 24 h accumulated precipitation amounts (mm) at 12 UTC of September 24, 1993 forecasted by the *Sim 3* run. Contour intervals are the same of Fig. 9

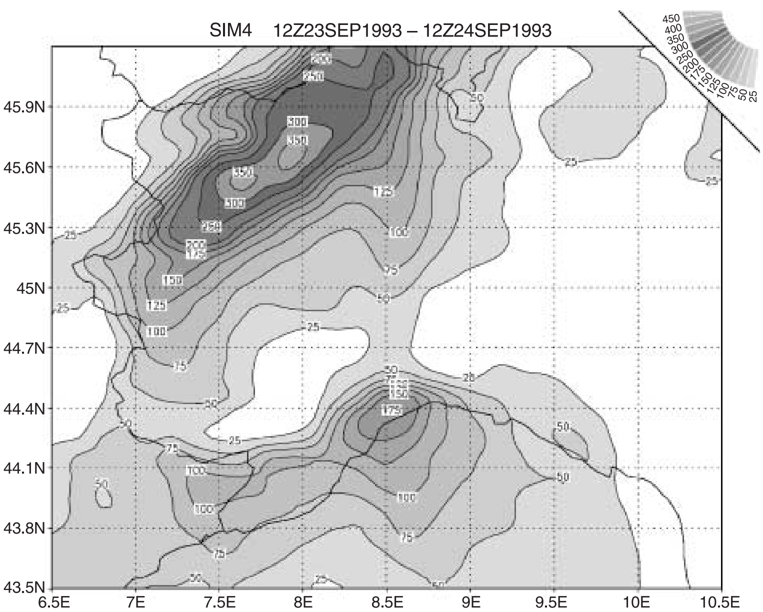

Fig. 13. 24 h accumulated precipitation amounts (mm) at 12 UTC of September 24, 1993 forecasted by the *Sim 4* run. Contour intervals are the same of Fig. 9

results obtained for *Sim 2*. Moreover it is now possible to observe an improvement of the forecasted precipitation pattern over the western part of the Alps. In particular, a tendency to produce an elongated precipitation pattern over Piedmont, with a NE–SW axis and two distinguished maxima, reveals the efficacy of the Spencer and Stensrud modifications in producing a more realistic precipitation pattern.

6. Conclusions

The contribution offered by this work is mainly related to the evaluation of the impact following the introduction of new schemes in the code of the BOLAM model. This work can be divided in two main parts:

(1) a first part, related to the statistical comparison between BOLAM3 and LILAM based on the observed precipitation values of 11 case studies between 1984 and 1994;
(2) a second part (Sect. 5) in which attempts are made to understand the reasons of the statistical behavior pointed out in the first part have been done making use of different simulations of the Brig flood.

In the first part, we have enphasized the marked improvement of the BOLAM3 with respect to its previous version LILAM. In particular two features have emerged:

(1) the differences, at times quite strong, which are observed in the precipitation amounts forecasted by the two models allow us to conclude that both the substitution of the Emanuel convective scheme with the Kain-Fritsh scheme and the introduction of the new scheme for the explicit representation of the microphysical species in the clouds can be considered a relevant improvement;
(2) the analysis of the spatial correlation coefficients for the precipitation values observed and forecasted by the two models shows a marked decrease of the systematic error as shown by the tendency to move precipitation patterns westwards over Liguria.

The results obtained in the first part of the work have been the starting point for the simulations described in Sect. 4. Some of these have been performed over a larger domain as compared to the one usually employed: results permit to ascribe parts of the errors in the location of the precipitation patterns to the critical role of the externally provided boundary conditions.

Applying the modifications of the Kain-Fritsh CPS suggested by Spencer and Stensrud (1998) regarding the downdrafts triggering the CPS, seems to confirm what they presented in their article. In particular, the delay in the triggering of the convective downdrafts leads to the reduction of the spread of the forecasted precipitation pattern. The fact that this benefit is observed only when a larger domain is used re-emphasizes the importance of the nested integration domain, with the larger nest both reducing the influence of possible errors at the boundaries and allowing the model to develop its own dynamical processes on the mesoscale.

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References

Anthes RA (1983) Regional models of the atmosphere in middle latitudes. Mon Wea Rev 111: 1306–1335

Anthes RA, Kuo Y-H, Hsie E-Y, Low-Nam S, Bettge TW (1989) Estimation of skill and uncertainty in regional numerical models. Quart J Roy Meteor Soc 115: 763–806

Arena N et al (1998) A comparison between BOLAM3 and LILAM Limited Area Models in forecasting rain fields in case of extreme events. MAP Newsletter 9: 14–15

Benoit R (1996) Case 2: Brig. MAP Data Centre

Bougeault P, Binder P, Buzzi A, Dirks R, Houze R, Kuettner J, Smith RB, Steinacker R, Volkert H (2001) The MAP Special Observing Period. Bull Amer Meteor Soc 82(3): 433–462

Buzzi A, Fantini M, Malguzzi P, Nerozzi F (1994) Validation of a Limited Area Model in cases of mediterranean cyclogenesis: Surface fields and precipitation scores. Meteorol Atmos Phys 53: 137–153

Buzzi A, Foschini L (2000) Mesoscale meteorological features associated with heavy precipitation in the southern alpine region. Meteorol Atmos Phys 72: 131–142

Buzzi A, Malguzzi P (1997) The Bolam III model: recent improvements and results. MAP Newsletter 7: 98–99

Buzzi A, Tartaglione N, Malguzzi P (1998). Numerical simulations of the 1994 Piedmont flood: Role of orography and moist processes. Mon Wea Rev 126: 2369–2383

Emanuel KA (1991) A scheme for representing cumulus convection in large scale models. J Atmod Sci 48: 2313–2335

Frei C, Schär C (1998) A precipitation climatology of the Alps from high-resolution raingauge observations. Int J Climatol 18: 873–900
Geleyn JF, Hollingsworth A (1979) An economical analytical method for the computation of the interaction between scattered and line absorption of radiation. Contrib Atmos Phys 52: 1–16
Gyakum JR et al (1996) A regional model intercomparison using a case of explosive oceanic cyclogenesis. Wea Forecast 11: 521–543
Haltiner GJ, Williams RT (1980) Numerical prediction and dynamic meteorology, 2nd edn. Wiley, NY
Kain JS, Fritsch JM (1990) A one-dimensional entraining/detraining plume model and its application in convective parameterization. J Atmos Sci 47(23): 1784–1802
Kain JS, Fritsch JM (1992) The role of the convective "trigger function" in numerical forecasts of mesoscale convective systems. Meteorol Atmos Phys 49: 93–106
Lehmann R (1993) On the choice of relaxation coefficients for Davies' lateral boundary scheme for regional weather prediction models. Meteorol Atmos Phys 52: 1–14
Louis JF, Tiedtke M, Geylen JF (1981) A short history of operational PBL parametrization at ECMWF. In ECMWF Workshop on PBL Parametrization, Reading, UK, pp 59–79
Malguzzi P, Tartaglione N (1999) An economical second order advection scheme for explicit numerical weather prediction. Quart J Roy Meteor Soc 125: 2291–2303
Ritter B, Geleyn JF (1992) A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. Mon Wea Rev 120: 303–325
Schultz P (1995) An explicit cloud physics parameterization for operational numerical weather prediction. Mon Wea Rev 123: 3331–3343
Spencer PL, Stensrud DJ (1998) Simulating flash flood events: Importance of the sub-grid representation of convection. Mon Wea Rev 126: 2884–2912
Volkert H (2000) Heavy Precipitation in the Alpine Region (HERA): Areal rainfall determination for flood warnings through in-situ measurements, remote sensing and atmospheric modelling. Meteorol Atmos Phys 72: 73–85
Wilks DS (1995) Statistical methods in the atmospheric sciences: An introduction. Academic Press, 467 pp

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