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Article

Orographic influence on deep convection: case study and sensitivity experiments

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Abstract

The non hydrostatic convection resolving model MOLOCH is employed in order to evaluate its capability to realistically simulate the evolution of the mesoscale convective system responsible for an episode of extremely heavy rainfall and flood over southeastern France (Gard event, 2002). Numerical experiments indicate large sensitivity of modelled precipitation amounts and distribution, due to different cell organization and propagation, to the specification of the initial conditions. Among different experimented initialization times (00, 06 and 12 UTC, September 8) the run starting at 06 UTC is able to predict the development and the almost stationary behaviour of the convective system, at least in the early stage of the event. Additional experiments, aimed at studying the role played by the orography in triggering the convection and controlling its evolution, have been performed in order to characterize sensitivity to ambient wind and orography. Simulations demonstrate that the presence of the orographic barrier is crucial for both triggering and maintaining the mesoscale convective system. Moreover, the location and intensity of precipitation turns out to be sensitive to variations of the mountain height and of the mean meridional wind component. A partial explanation of this behaviour in terms of the Froude number is suggested.

Zusammenfassung

Das nichthydrostatische, die Konvektion explizit berechnende Modell MOLOCH wird angewendet, um seine Fähigkeit, die Entwicklung eines mesoskaligen konvektiven Systems, das für ein extremes Regen- und Überschwemmungsereignis in Südost-Frankreich verantwortlich war, realistisch zu simulieren (Gard-Ereignis 2002). Numerische Experimente zeigen eine große Sensitivität der modellierten Niederschlagsmenge und -verteilung von den vorgegebenen Anfangsbedingungen auf Grund der unterschiedlichen Organisation und Verlagerung der Konvektionszellen. Unter den verschiedenen ausgetesteten Startterminen (00, 06 und 12Z am 8. September) erweist sich die zum 06Z-Termin gestartete Simulation als in der Lage, die Entwicklung und das nahezu stationäre Verhalten des konvektiven Systems zumindest in der Anfangsphase vorherzusagen. Weitere Experimente, die darauf abzielten, die Rolle der Orographie bei der Auslösung und der weiteren Entwicklung der Konvektion zu analysieren, charakterisieren die Sensitivität der Simulation gegenüber dem großräumigen Windfeld und der Orographie. Die Simulationen zeigen, dass das Vorhandensein eines Gebirgszuges sowohl für das Auslösen als auch das weitere Unterhalten eines mesoskaligen konvektiven Systems entscheidend ist. Darüber hinaus erweist sich, dass sowohl Variationen der Gebirgshöhe als auch der meridionalen Windkomponente den Ort und die Intensität des Niederschlags beeinflussen. Eine teilweise Erklärung dieses Verhaltens unter der Verwendung der Froude-Zahl wird vorgeschlagen.

1 Introduction

Heavy precipitation and floods often derive from quasi-stationary convective systems where orography plays an important role in triggering convection and controlling its subsequent evolution. An example is provided by the Gard river severe flood event of 8–9 September 2002 (DUCROCQ et al., 2003), occurred near the southern flank of the Massif Central (France). The distinctive feature of this event is that the mesoscale convective system (MCS) remained nearly stationary in place for many hours. The precipitation maximum was observed at some distance upstream of the mountain main slope, at variance with the climatological rainfall distribution of that region (SCHWARB et al., 2001), characterized by a maximum located over the crest of the Cévennes.

This MCS developed in a low-level pre-frontal meridional (south-westerly at higher levels) flow advecting moist air from the Western Mediterranean. As mentioned above, the very high accumulated rainfall maximum, exceeding 600 mm/24 h, was recorded at about 20–30 km upstream of the Cévennes slope. Convective activity started over the Mediterranean sea during the early morning of 8 September and then moved northward forming a MCS. At 12 UTC the MCS was already affecting the Gard region, and persisted over the same area, at the foothills of the Cévennes ridge, for nearly 24 hours, until a cold front coming from the Atlantic passed over the region. Damages and fatalities occurred as a consequence of the severe flood that affected the Gard basin.

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Over recent years, the problem of quantitative precipitation forecasts (QPF) in cases of severe convective events has been tackled by applying and testing high-resolution non-hydrostatic meteorological models, with grid spacing of a few (1–3) kilometers. Although at such high resolution the approach is still mainly experimental, also due to computing limitations, the reported results appear very encouraging. On the one hand, the capability of reproducing small scale processes (e.g. orographic forcing and microphysics) and explicitly resolving the dynamics of deep convection (CRM: Convection Resolving Model) has allowed to better simulate and forecast the structure and evolution of convective systems, while further improvements are expected from increasing resolution. On the other hand, although a horizontal resolution of a few kilometers is considered sufficient to properly simulate the "large scale" dynamics of organised convection, like MCS or squall lines (WEISMAN et al.,1997), it is still inadequate to predict accurately the turbulent and microphysical processes of deep convection (JAMES et al., 2002; BRYAN et al., 2003) that may have a strong impact on rainfall amount and distribution and system movement. Moreover, the low predictability associated with convective precipitation, as demonstrated by WALSER et al. (2004), poses a limit to the applicability of deterministic high-resolution forecasting and raises important questions related to data assimilation and model initial conditions.

CRMs, besides constituting a tool for very high resolution short-range weather prediction, can be used also for research studies. In the present case, a CRM model (MOLOCH: see below) is employed in order to investigate the role played by the orography in triggering the convection and controlling its subsequent evolution, both under realistic and more idealized conditions.

Although the present case study does not pertain to the Alpine area, the theoretical and experimental reference framework is that proposed in a number of recent MAP (Mesoscale Alpine Programme) studies of convectively unstable flows in the presence of orography. A number of such studies (CHU and LIN, 2000; STEIN, 2004; CHEN and LIN, 2005a) have addressed the general problem of convection development and propagation in the presence of orography in more or less idealized environments. CHEN and LIN (2005b) identify four different regimes as a function of the moist Froude number, defined as $F = U/Nh$ (where U is a measure of the wind speed, h is a typical height of the mountain and N is the static stability, taking into account the effect of moisture in case of saturation). Three regimes were already identified in both 2 and 3-dimensional experiments of conditionally unstable airflow over a mesoscale mountain ridge (CHU and LIN, 2000; CHEN and LIN, 2005a): (I) flow with an upstream propagating convective system, (II) flow with a quasi-stationary convective system locked near the mountain crest, (III) flow with both convective systems defined in (I) and (II). The fourth regime, recently identified (CHEN and LIN, 2005b), is characterized by a long lasting orographic stratiform precipitation system over the mountain. STEIN (2004) recovered the first two regimes in a more realistic 3-dimensional framework.

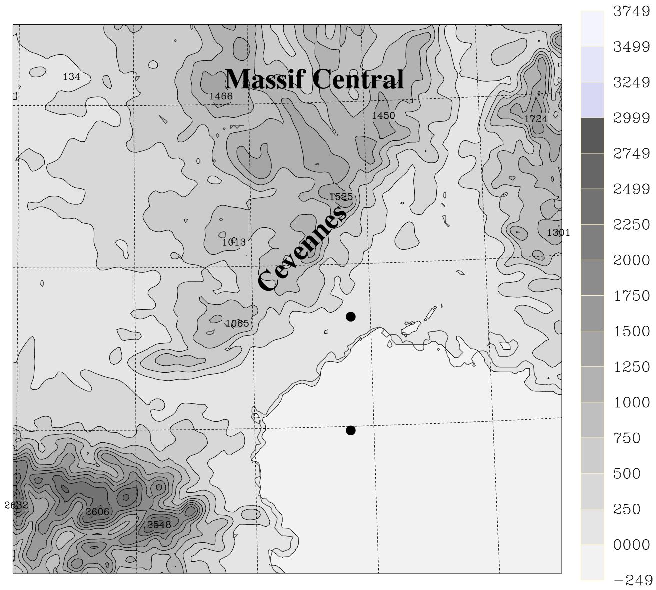


Figure 1: MOLOCH integration domain and orography. Shading and contour interval is 250 m. Coastal lines are drawn using the land-sea mask contour 0.5. The two dots indicate the position of the vertical profiles shown in Fig. 3. Geographical features referred in the text are indicated.

The aim of the present study is to characterize the dynamical properties of the convective event of the Gard flood, especially in relation to the role played by the orography, and to determine if the development and evolution of the MCS can be identified with some known regime of convective propagation in the presence of orography. In particular, the effects of mountain height and impinging flow speed are investigated, with reference to the influence of the Froude number on flow regimes.

In Section 2 the model is described. Results of simulations of the Gard flood are presented in Section 3. Section 4 is devoted to idealized experiments with modified orography and wind speed and in Section 5 a summary is given.

2 The modelling systems

The non-hydrostatic model MOLOCH, developed at ISAC-CNR, is based on the fully compressible set of equations with prognostic variables (pressure, temperature, specific humidity, horizontal and vertical velocity components, turbulent kinetic energy (TKE) and four water species) represented on the lat-lon rotated,

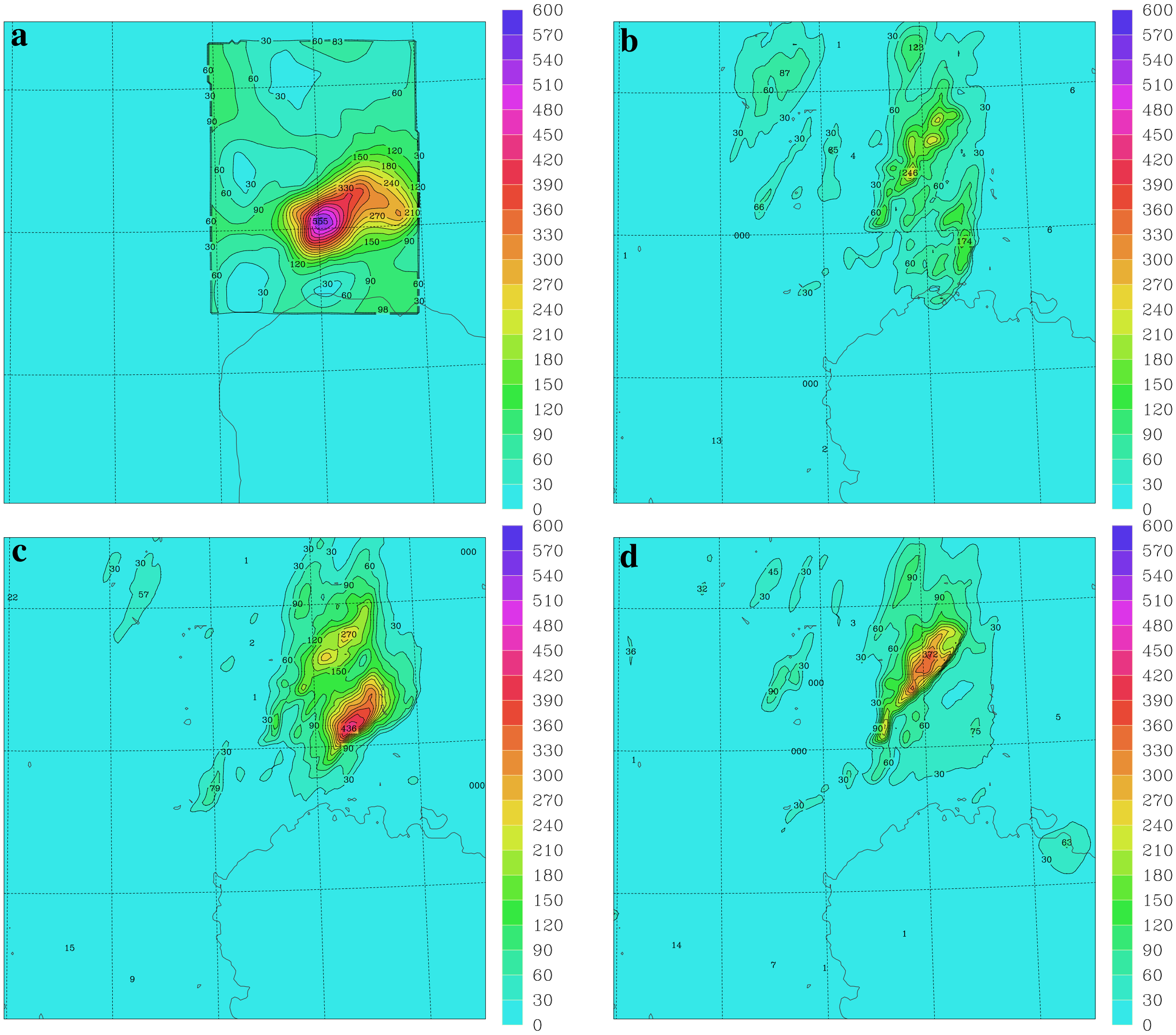


Figure 2: 24-h accumulated precipitation at 12 UTC, 09 Sep. 2002 analysed observation (a) and simulations initialized at 00UTC (b), 06 UTC (c) and 12 UTC, 8 Sep. 2002 (d), respectively. Shading and contour interval is 30 mm.

Arakawa C grid (170x170 grid points, with spacing of 0.02 degree for the present study). Model dynamics are integrated in time with an implicit scheme for the vertical propagation of sound waves, while explicit, time-split schemes are implemented for the remaining terms. Horizontal wave propagation is forward-backward. Three-dimensional advection is computed using the accurate Weighted Averaged Flux (WAF) scheme (BILLET and TORO, 1997). Small horizontal fourth order diffusion is included to prevent energy accumulation on the shorter space scales. The lower boundary condition over topography is imposed using terrain following vertical coordinates which relax smoothly to horizontal surfaces away from the earth surface. These coordinates are implicitly defined by:

$$\varsigma = H\left(1 - e^{-\frac{z-h\left(1-\frac{\varsigma}{H}\right)}{H}}\right), \quad h(x,y) < z < \infty$$

where $H = \frac{R_d T_0}{g}$ is the density scale height.

Model “physics” include a cloud and precipitation microphysical scheme, a sub-grid turbulence parameterization scheme, a four-layer vegetated soil model, and a computation of atmospheric radiation processes.

The microphysical scheme is based on the parameterizations proposed by DROFA and MALGUZZI (2004). The physical processes determining the time tendency of specific humidity, cloud water/ice and precipitating water/ice are divided into “fast” and “slow” ones. Fast processes involve transformations between specific humidity and cloud quantities and are computed every advection time step. Temperature is updated by imposing exact entropy conservation at constant pressure. Fall of precipitation is computed with the stable and dispersive backward-upstream scheme with terminal velocities depending on concentration.

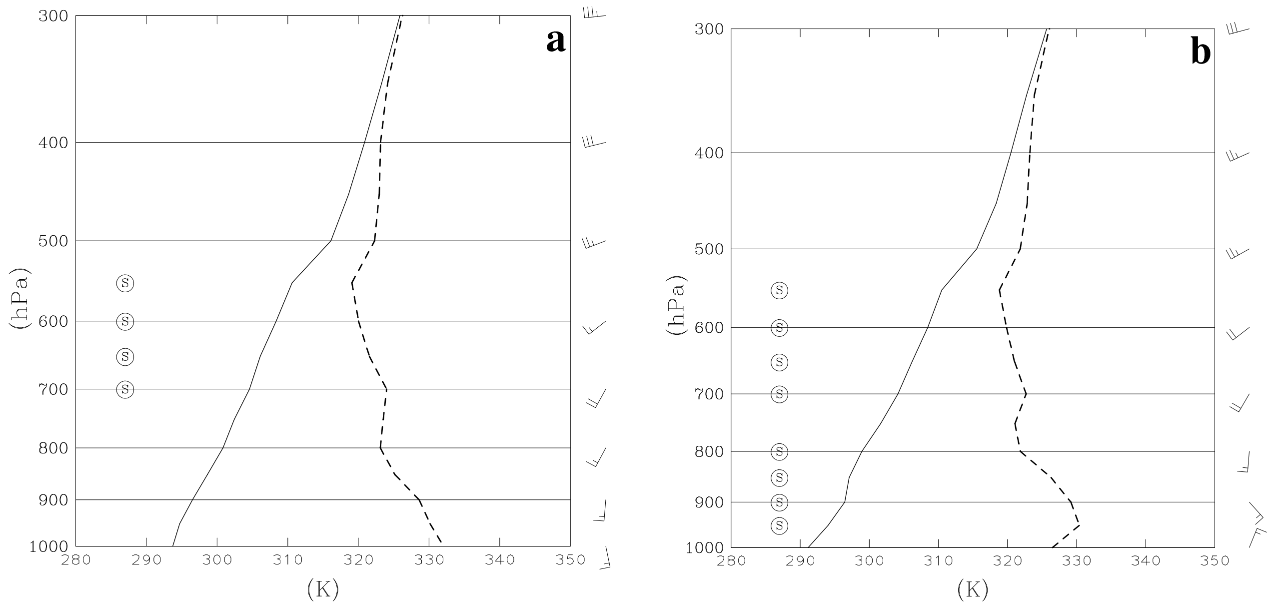


Figure 3: Vertical profiles of potential temperature (solid line), equivalent potential temperature (dashed line) and wind, at 09 UTC, September 8, 2002 for the simulation initialized at 06 UTC (time of convective activity initiation) corresponding (a) to a point over the sea and (b) just inshore, ahead of the orography (for the exact location, see Fig. 1). Half barb: 2.5 m/s; full barb: 5 m/s. Circles marked with "S" (on the left) indicate saturated layers.

The turbulence scheme is based on a E-l closure where the subgrid turbulent kinetic energy (TKE) is predicted. Surface turbulent fluxes of momentum, specific humidity and temperature are computed by the classical Monin-Obukhov theory with Businger (Holtslag) functions in the unstable (stable) case. The mixing length is computed from the TKE (DEARDORFF, 1980) in the stable atmosphere and from the BOUGEAULT and LACARRERE (1989) method, modified by ZAMPIERI (2004), in the unstable environment. A four-layer soil model describes the evolution of water and heat fluxes, including vegetation effects (PRESSMAN, 1994).

The computation of atmospheric radiation is based on the ECMWF scheme (MORCRETTE et al, 1998), including the RRTM model (MLAWER et al., 1997).

The MOLOCH performance in cases of strong precipitation was already evaluated for a number of different case studies (RICHARD et al., 2002; BUZZI et al., 2004; MARIANI et al., 2005).

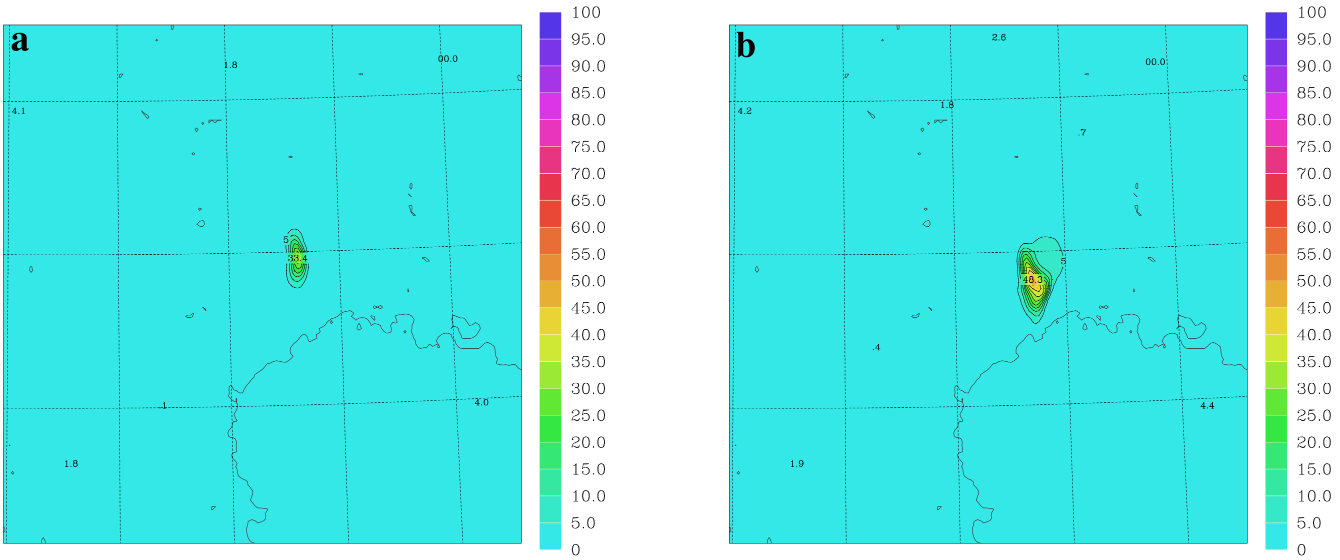
MOLOCH (integration domain shown in Fig. 1) is nested into the hydrostatic model BOLAM (for a description see DAVOLIO and BUZZI, 2004) which in turn is driven by the ECMWF analyses.

3 Sensitivity to the initial conditions

The observations[1], analysed on the MOLOCH grid (Fig. 2a), show an area of very intense precipitation, summing up to 555 mm in 24 hours (the analysis smoothes out the actual maximum of 690 mm). Three different stages can be identified in the episode contributing to such very large accumulation (DELRIEU et al., 2005; CHANCIBAULT et al., 2006). During the first 12 hours, till 00 UTC, September 9, the MCS developed and remained almost stationary over the Gard region. Then, during the night, the system moved slightly northward. Finally, during the early morning of September 9, the cold front that passed rather quickly over the area was associated with additional convective rain that contributed to the flood, but after the frontal passage convection was eventually suppressed.

Different simulations were initiated at 00, 06 and 12 UTC, September 8, 2002, respectively, in order to analyse the impact of different initial conditions on the precipitation forecasts. Although the three initial conditions derive from the same continuous assimilation cycle of ECMWF and are only 6 hours apart, the accuracy of the simulations varies widely among the experiments. The run initiated with the 06 UTC analysis (Fig. 2c) gives the best reproduction of the characteristics of the MCS, particularly in the first phase of its evolution. In this case the simulated MCS develops near the coast, moving slowly northeastward and then becoming nearly stationary over the Gard region. During the first 12 hours the simulated precipitation pattern is located very close to the observed maximum, but the amount is slightly over-predicted in comparison with the analysed observations. In the following stage the model places the precipitation too much to the north, in correspondence to

[1]Gridded precipitation data, analysed with kriging over the Gard region, were kindly provided by Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE) – Grenoble (Fr), in the framework of the HYDROPTIMET project, INTERREG IIIB (Medocc Programme).



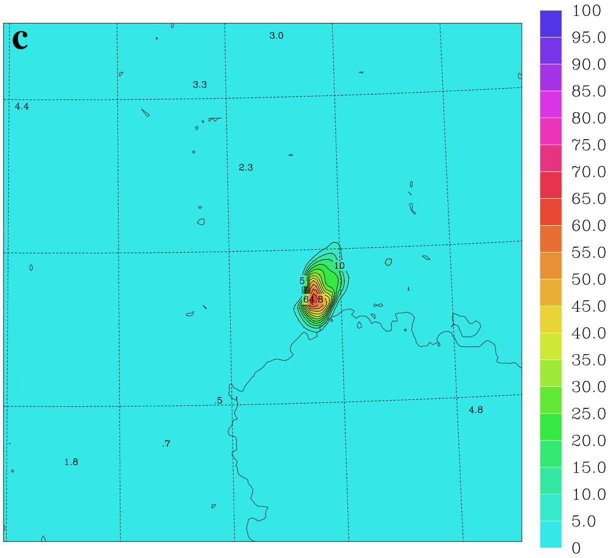


Figure 4: 2-h accumulated precipitation at 11 UTC, September 8, 2002 (triggering phase). (a) Experiment with orography reduced by a factor 0.5; (b) control run; (c) experiment with orography increased by a factor 1.5. Shading and contour interval is 5 mm. All the experiments are initialized at 06 UTC, September 8, 2002.

the main slope of the Cévennes. In the final stage of the event, the model realistically reproduces the progression of the front and forecasts additional intense frontal precipitation over the Gard region.

Neither the experiment starting at 00 nor the one starting at 12 UTC (Fig. 2b and 2d, respectively) develop the convection over the plain. Instead, in both cases the convective activity appears to be directly triggered by the orographically forced uplift and the resulting precipitation pattern is displaced several tens of km northward, over the Massif Central. Moreover, the simulation initiated at 00 UTC displays a large underestimation of the rainfall amount. The simulations seems quite accurate only in the final phase, when the large scale dynamics becomes dominant and the MCS starts moving south-eastwards along with the incoming cold front.

From the analysis of the observed low-level wind field it appears that an area of pronounced convergence just inshore is present at the time of convective activity initiation. The south-south-easterly low level flow from the Mediterranean Sea (Fig. 3a) turns abruptly (Fig. 3b), becoming north-easterly ahead (south-east) of the orographic barrier, nearly parallel to the terrain contours. Only the experiment starting at 06 UTC correctly reproduces this feature. The deflection of the low-level flow coming from the sea, due to the presence of the orography (Massif Central and Cévennes), seems therefore to be directly associated with the initiation of convection. The orography in this case strongly influences the flow at some distance upstream, exerting a blocking action possibly associated with flow reversal and a low level stable layer (e.g. MIGLIETTA and BUZZI, 2004; STEIN, 2004). This aspect has been further investigated by means of idealized sensitivity experiments presented in the next Section.

3.1 Idealized experiments

Two set of experiments were performed in order to investigate the role of the orography in triggering and maintaining the convective system, looking for a possible explanation in terms of concepts of orographic flow regimes (upstream blocking versus non-blocking), depending on the Froude number, and of regimes of convection development and propagation in the presence of orography (STEIN, 2004; CHEN and LIN, 2005b).

All the simulations considered in this Section were initialized at 06 UTC, 8 September, using the same atmospheric conditions, but modifying the height of the model orography over the central part of the domain (the Alps and the Pyrenees remain unchanged). The height of the topography of the Massif Central and surrounding areas has been varied by multiplying it by different factors, ranging from 0.25 to 1.5. Simple considerations based on the Froude number suggest that transitions between orographic flow regimes can be also obtained by changing the intensity of the wind speed across the orographic slope. Having this in mind, a number of additional experiments have been made by adding or subtracting a barotropic component (1–2 m/s), in geostrophic equilibrium, to the initial and boundary conditions, leaving the orography unchanged.

Two different phases of the MCS evolution have been investigated. First, the triggering phase has been analysed, in the interval between 9 and 11 UTC of September 8, when the convection started over land. Then, dealing with the mature phase of the system, the whole 12 hour period between 9 and 21 UTC has been considered.

During the triggering phase, in the experiment where the height of the Massif Central is reduced by a factor of two, the convection develops several kilometres to the north (Fig. 4a) with respect to the control simulation (Fig 4b). The rainfall intensity is lower (33 instead of 48 mm in 2 hours) and localized in correspondence to the main mountain slopes. At variance with the control simulation, the south-easterly flow in the lower troposphere is only weakly deflected during the first hours as the orography is not able to effectively block it. Therefore, after a few hours the low-level wind becomes oriented across the orographic barrier and the convection is triggered further downstream. When the height of the Massif Central is enhanced by a factor 1.5, precipitation is more intense (65 mm) and accumulates more to the south (Fig. 4c), over the plain. In general, by varying the orography height (multiplying it by a factor between 0.25 to 1.5), the precipitation pattern tends to move upstream with increasing intensity. A similar behaviour in terms of rainfall location is obtained by changing the meridional wind component (not shown): by decreasing the wind speed, the precipitation pattern tends progressively to move upstream but, in this case, the maximum rainfall intensity is obtained in the control experiment.

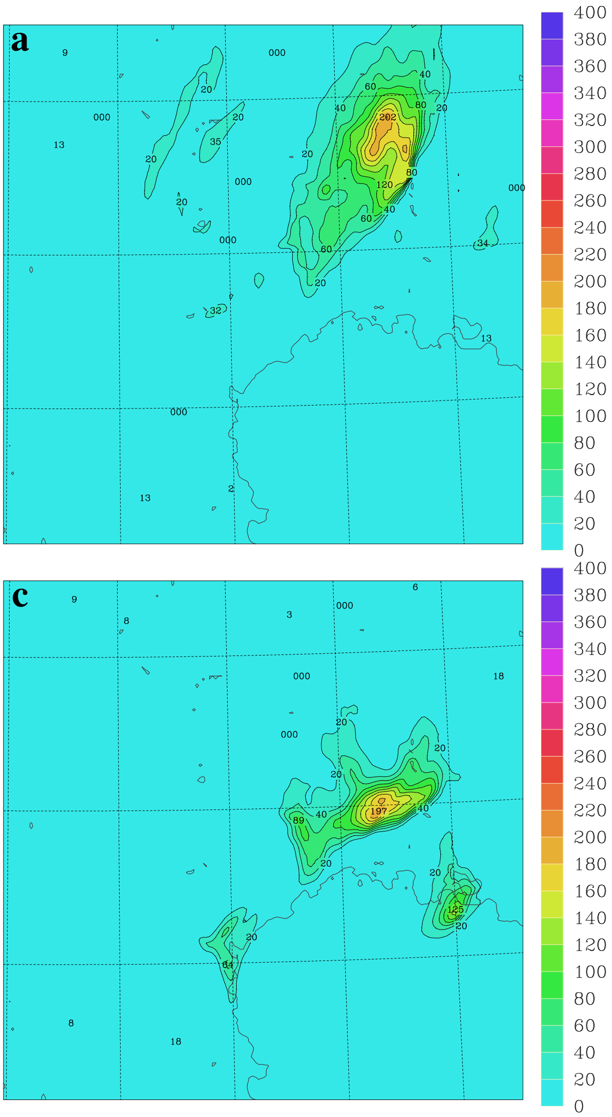
Variations of orography height produce the same effects also during the mature phase: an increase in intensity and an upstream displacement of the pattern of precipitation as the orography is raised (not shown). At variance with the triggering phase, a sort of saturation effect for maximum rainfall amount is found in this stage: an increase of orography height larger than a factor of 1.25 does not produce a further increase in rainfall intensity.

When the wind speed across the orography is increased by 2 m/s (Fig. 5a) the precipitation is produced well to the north with respect to the control run (Fig. 5b), over the Massif Central relief, and the intensity is remarkably lower (202 instead of 329 mm in 12 hours). On the other hand, if the meridional wind intensity is decreased by 2 m/s (Fig. 5c), the convective system remains stationary over the plain, but several kilometers upstream with respect to the control simulation. Again the maximum precipitation is obtained in the control experiment: in this case the analyzed wind is the one that maximizes precipitation.

In order to provide a more detailed view of the sensitivity experiments, the results have been plotted together in terms of the Froude number. Its value is only indicative because of the degree of arbitrariness in defining a mean mountain height h, a typical wind speed U impinging the mountain and a representative buoyancy N. The chosen values are, respectively, 1200 m, 8 m/s and 0.012 s^{-1} for the reference experiment. The last two parameters are evaluated upstream of the orographic barrier (Fig. 3a), averaging in height over a depth of 1500 m above the ground. The external parameters that are imposed in the experiments are only U and h while N may change depending on the flow regime that is established. Therefore, the choice of a constant N is intended only to define a “reference Froude number” characterizing the basic state, which may not correspond to the local value.

The rainfall location (latitude) during the triggering phase, as a function of the Froude number, is plotted in Fig. 6a (note that the control run corresponds to a value of F^{-1} = 1.8 on the x-axis). For higher value of the Froude number (lower orography or higher wind speed) the convection is triggered more to the north. For smaller value of the Froude number (higher orography or lower wind speed) the convection develops further upstream. This is consistent with the general concept of flow regimes upstream of the orography based on the Froude number: the larger is the dimensionless mountain height (i.e. the inverse of Froude number) the stronger is the blocking action, associated with flow reversal and convergence. Therefore, the convection is triggered upstream of the mountain chain, in association with a flow that seems to undergo a gradual transition from a flow over to a blocked or even reversal regime.

When the mature phase of the MCS is analysed with the same method, the results are more ambiguous (Fig. 6b). The behaviour of the MCS cannot be understood only by assuming that the characteristics of the flow are



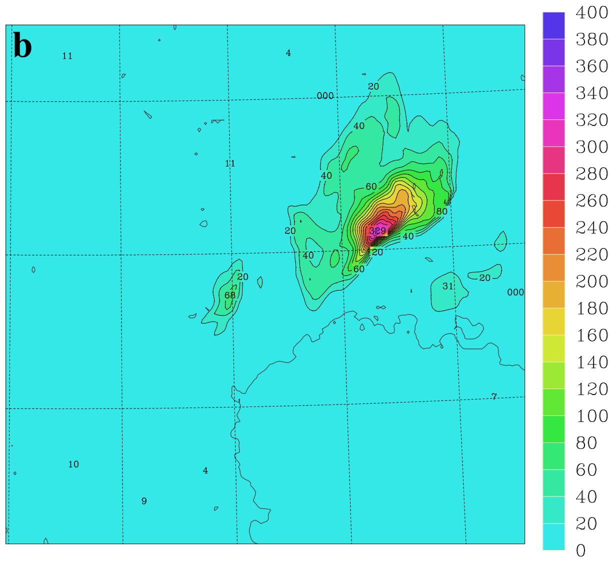


Figure 5: 12-h accumulated precipitation at 21 UTC, September 8, 2002 (mature phase). (a) Experiment with meridional wind speed increased by 2 m/s; (b) control run; (c) experiment with meridional wind speed decreased by 2 m/s. Shading and contour interval is 20 mm. All the experiments are initialized at 06 UTC, September 8, 2002.

a function of the Froude number alone. It is clear that the fully developed MCS strongly perturbs the upstream basic flow. In order to better understand the nature of this phenomenon, the interaction between the MCS circulation and orography has to be analyzed, including the formation and role played by the cold pool ahead of the orography itself and the effect of the intensity of the upstream flow which feeds the updraft.

A comparison with previous three-dimensional idealized studies of convection propagation in the presence of orography (STEIN, 2004; CHEN and LIN, 2005a) is difficult due to the different orography geometry and large scale flow variability. In CHEN and LIN (2005a) the initial flow is uniform and directed perpendicularly to the ridge-like orography. Stein (2004) started from an uniform atmosphere and southerly wind condition, although employing a realistic alpine orography. In the present case the real southeasterly low level flow is oriented across the orography but not exactly perpendicularly, and it turns southwesterly at higher level becoming even parallel to the orographic barrier at 700 hPa. However, it seems that this case represents a convective regime somehow intermediate between the upstream propagating and quasi-stationary regimes. The most distinctive feature, however, is that instead of being locked near the mountain crest, the convection occurs at some distance upstream of the mountain main slopes.

4 Conclusions

A set of high resolution simulations of a very intense MCS that affected southeastern France, leading to a severe flood, has been performed in order to evaluate the capability of the MOLOCH convection resolving model in simulating the episode and in order to study the influence of the orography and of the upstream flow parameters on the convective initiation and subsequent evolution. The QPF accuracy is found to be very sensitive to the initial condition, as can be expected in a case of

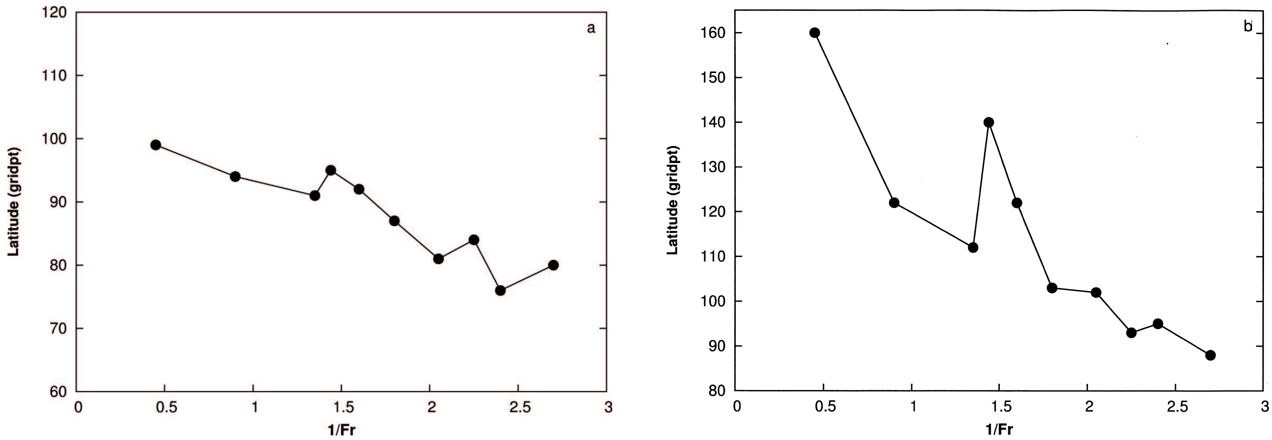


Figure 6: Position of the rainfall maximum (latitude express in terms of grid points) as a function of the inverse of the Froude number for (a) the triggering and (b) the mature phase of the mesoscale convective system. The control run corresponds to a value of 1.8 on the x-axis.

strong convection. In particular, the main characteristics of the MCS, which remained almost stationary for several hours over the Gard catchment region, at some distance upstream of the Cévennes (Massif Central) are reproduced by the simulation initialized at 06 UTC, 8 September. This simulation is in good agreement with the observations during the first phase of the event, but at later stage the rainfall is displaced too much to the north. In the final phase of the event, the passage of the cold front, simulated precipitation occurs again over the Gard region, consistently with observations. The use of a different time for the initial condition (00 or 12 UTC) produces larger errors also in the initial stage, while the precipitation associated with the cold front is more predictable.

Model simulations show that convection is triggered as a consequence of the low level flow deflection exerted by the orography, which takes place at short distance from the coast. The presence of the orography is a key ingredient in this flood case. An investigation of the importance of the orographic blocking effect, with respect to convection development and propagation, has been carried on by varying the dimensionless mountain height. Several experiments have been performed modifying the Massif Central height or the wind speed of the impinging flow. It turns out that the concept of flow blocking depending on the Froude number can be useful in the early stages of the MCS evolution, when modifications are week, or in cases of stratiform flow and shallow convection (KIRSHBAUM and DURRAN, 2004). Once the MCS has developed to full amplitude, its interaction with the orography is probably determined by dynamical processes, more complex than those associated with orographic flow regimes.

A direct comparison between the evolution of the MCS and the results obtained in more idealized studies of convection propagation in the presence of mesoscale mountains is difficult, not only due to the different geometry and large scale flow variability, but also due to the high spatial variability of the stratification parameter that enters in the definition of the Froude number. The present case does not seem to strictly resemble any of the regimes so far identified in the literature, being somehow intermediate between a flow with an upstream propagating convective system and with quasi-stationary convection locked near the mountain crest.

Acknowledgements

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References

BELJAARS, A. C. M., A. S. M. HOLTSLAG, 1991: On flux parameterization over land surface for atmospheric models. – J. Atmos. Sci. **30**, 327–341.

BILLET, S. J., E. F. TORO, 1997: On WAF-type schemes for multi-dimensional hyperbolic conservation laws. – J. Comput. Phys. **130**, 1–24.

BOUGEAULT, P., P. LACARRERE, 1989: Parameterization of the orography-induced turbulence in a mesoscale model. – Mon. Wea. Rev. **117**, 1872–1890.

BRYAN, G. H., J. C. WYNGAARD, J. M. FRITSCH, 2003: Resolution requirements for the simulation of deep moist convection. – Mon. Wea. Rev. **131**, 2394–2416.

BUSINGER, J. A., J. C. WYNGAARD, Y. IZUMI, E. F. BRADLEY, 1971: Flux-Profile Relations in the Atmospheric Surface Layer. – J. Atmos. Sci. **28**, 181–189.

BUZZI, A., S. DAVOLIO, M. D’ISIDORO, P. MALGUZZI, 2004: The impact of resolution and of MAP reanalysis on the simulations of heavy precipitation during MAP cases. – Meterorol. Z. **13**, 91–97.

CHANCIBAULT, K., S. ANQUETIN, V. DUCROCQ, G. M. SAULNIER, 2006: Hydrological evaluation of high resolution precipitation forecasts of the Gard flash-flood event (8-9 September 2002). – Quart. J. Roy. Meteor. Soc., in print.

CHEN, S. H., Y. L. LIN, 2005a: Orographic effects on a conditionally unstable flow over an idealized three-dimensional mesoscale mountain. – Meteor. Atmos. Phys. **88**, 1–21.

—, —, 2005b: Effects of moist Froude number and CAPE on a conditionally unstable flow over a mesoscale mountain ridge. – J. Atmos. Sci. **62**, 331–350.

CHU, C. M., Y. L. LIN, 2000: Effects of orography on the generation and propagation of mesoscale convective systems in a two-dimensional conditionally unstable flow. – J. Atmos. Sci. **57**, 3817–3837.

DAVOLIO, S., A. BUZZI, 2004: A nudging scheme for the assimilation of precipitation data into a mesoscale model. – Wea. Forecasting **19**, 855–871.

DEARDORFF, J. W., 1980: Stratocumulus-capped mixed layer derived from a three dimensional model. – Bound.-Layer Meteor. **18**, 495–527.

DELRIEU, G., V. DUCROCQ, E. GAUME, J. NICOL, O. PAYRASTRE, E. YATES, P. E. KIRSTETTER, H. ANDRIEU, P. A. AYRAL, C. BOUVIER, J. D. CREUTIN, M. LIVET, S. ANQUETIN, M. LANG, L. NEPPEL, C. OBLED, J. PARENT-DU-CHÂTELET, G. M. SAULNIER, A. WALPERSDORF, W. WOBROCK, 2005: The catastrophic flash-flood event of 8-9 September 2002 in the Gard region, France: A first case study for the Cévennes-Vivarais Mediterranean hydrometeorological observatory. – J. Hydrometeor. **6**, 34–52.

DROFA, O. V., P. MALGUZZI, 2004: Parameterization of microphysical processes in a non hydrostatic prediction model. – Proc. 14th International Conference on Clouds and Precipitation (ICCP). Bologna, Italy, 1297–1300.

DUCROCQ, V., K. CHANCIBAULT, F. HABETS, S. ANQUETIN, 2003: Mesoscale modelling of a flooding storm. Application to the extreme flood of Gard. – Proc. of the 5th Plinius Conference on Mediterranean Storms. Ajaccio, France, 43–52.

JAMES, R. P., G. H. BRYAN, J. M. FRITSCH, 2002: The effect of turbulence-resolving grid spacing on convective precipitation. – Proc. of the International Conference on Quantitative Precipitation Forecasting, Reading, UK, **65**.

KIRSHBAUM, D. J., D. R. DURRAN, 2004: Factors governing cellular convection in orographic precipitation. – J. Atmos. Sci. **61**, 682–698.

MARIANI, S., M. CASAIOLI, C. ACCADIA, M. C. LLASAT, F.PASI, S. DAVOLIO, M. ELEMENTI, G. FICCA, R. ROMERO, 2005: A limited area model intercomparison on the “Montserrat-2000” flash-flood event using statistical and deterministic methods. – Natural Hazard and Earth System Sciences **5**, 565–581.

MIGLIETTA, M. M., A. BUZZI, 2004: A numerical study of moist stratified flow regimes over isolated topography. – Quart. J. Roy. Meteor. Soc. **130**, 1749–1770.

MLAWER, E. J., S. J. TAUBMAN, P. D. BROWN, M. J. IACONO, S. A. CLOUGH, 1997: Radiative transfer for inhomogeneous atmosphere: RRTM, a validated correlated-k model for the longwave. – J. Geophys. Res. **102** D, 16663–16682.

MORCRETTE, J. J., S. A. CLOUGH, E. J. MLAWER, M. J. IACONO, 1998: Impact of a validated radiative transfer scheme, RRTM, on the ECMWF model climate and 10-day forecasts. – ECMWF Technical Memo **252**.

PRESSMAN, D. J. A., 1994: Chislennaja model’ gidrotermicheskikh processov v pochve kak chast’ skhemy mezomasshtabnogo prognoza (A numerical model of hydrothermical processes in soil as a part of a mesoscale weather forecast scheme). – Meteorologiya i gidrologiya (Meteorology and Hydrology) **11**, 62–75.

RICHARD, E., N. ASENCIO, R. BENOIT, A. BUZZI, R. FERRETTI, P. MALGUZZI, S. SERAFIN, G. ZÄNGL, J. F. GEORGIS, 2002: Intercomparison of the simulated precipitation fields of the MAP IOP 2B with different high-resolution models. – Proc. of the 10th Conference on Mountain Meteorology, Park City, Utah, 167–170.

RITTER, B., J. F. GELEYN, 1992: A comprehensive radiation scheme for numerical weather prediction models with potential applications in climate simulations. – Mon. Wea. Rev. **120**, 303–325.

SCHWARB, M., C. FREI, C. DALY, C. SCHÄR, 2001: Mean annual precipitation throughout the European Alps 1971–1990. – In: Hydrological Atlas of Switzerland, Plate 2.6. Available from: Landeshydrologie und Geologie, 3003 Bern.

STEIN, J., 2004: Exploration of some convective regimes over Alpine orography. – Quart. J. Roy. Meteor. Soc. **130**, 481–502.

WALSER, A., D. LÜTHI, C. SCHÄR, 2004: Predictability of precipitation in a cloud-resolving model. – Mon. Wea. Rev. **132**, 560–577.

WEISMAN, M. L., W. C. SKAMAROCK, J. B. KLEMP, 1997: The resolution dependence of explicitly modeled convective systems. – Mon. Wea. Rev. **125**, 527–548.

ZAMPIERI, 2004: Comparison among first, second and third order CBL models. – Proc. of the 16th Symposium on Boundary Layers and Turbulence, Portland, Maine, August 9 –13, 2004.