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Orographic triggering of long lived convection in three dimensions

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Summary

A significant fraction of the occurrences of intense flash floods is due to quasi-stationary or long-lived convection that may insist on the same place for many hours, producing high values of accumulated precipitation. One of the elements that favour the initiation and anchoring of the convective system (MCS) is the orography. In one of the most severe floods (Gard basin in southern France, 8-9 September 2002), the orography of the Massif Central played a rather unusual role, favouring the onset and maintenance of the MCS at some distance upstream of the main orographic slope. In the present work the initial atmospheric conditions of this event have been largely idealized, taking horizontally uniform values for wind, temperature and humidity profiles, and a simplified isolated orography representing the sole Massif Central. A convective system is initiated in the non-hydrostatic simulations, embedded in a quasi-stationary solution of flow over the orography. It is shown that the triggering of convection occurs in the convergence zone immediately upstream of the orographic obstacle, at an altitude comparable with the mountain height. The subsequent growth of the mesoscale convective system is associated with a slow eastward drift, with the intense precipitation located upstream of the mountain and with the formation of a gust front that propagates against the incoming basic flow. Sensitivity experiments show that the development of convection critically depends on mountain height and moisture content. Although the results obtained in such idealized conditions do not reflect all the observed characteristics of the real event, they contribute to clarify the role of the orography in triggering and maintaining strong convection.

1. INTRODUCTION

The predictability of flash floods triggered by strong atmospheric convection is generally low, due to the short time scales of convective instability, so that NWP short range forecasts, even at very high resolution, need to be complemented by nowcasting techniques based on rainfall observations at a few hour time scale (Collier, 2007). However, orography may trigger convective cells in the same place for a comparatively long time, associated with the time scale evolution of the larger scale flow, and then may increase predictability in some cases (Cosma et al, 2002). In addition, orography can modify the impinging flow in such a way that the formation of quasi-stationary or slow moving convective cells or mesoscale convective systems (MCS) is favoured. Some of the most intense local flood events are due to quasi-stationary MCS's that insist on the same place for many hours, producing high amounts of accumulated precipitation.

Orographic convective triggering and maintenance of quasi-stationary convection can occur through several different mechanisms, including forced uplift on the upstream slope, flow blocking, formation of convergence areas in the orographically modified flow upstream and downstream, differential heating, lee waves etc. The complexity of the orographically modified flow, including turbulence interacting with precipitation microphysics (Rotunno and Houze, 2007), makes it necessary to simplify the general problem in order to better understand the underlying mechanisms. For example, in the case of conditionally unstable flows over idealized two-dimensional mesoscale orography, different convective regimes were identified by Chu and Lin (2000), Stein (2004), and Chen and Lin (2005a). In the first regime, convection propagates upstream together with the downdraft-generated density current, while in the second regime quasi-stationary convection over the mountain crest or its nearby slopes is attained.

The purpose of the present work is to generalize the study of the interaction between the onset of severe convection and orography to three dimensions, but keeping the basic flow essentially two dimensional. The original motivation was inspired by the previous observational and numerical studies (Delrieu et al, 2005; Chanchibault et al, 2006; Anquetin et al, 2006; Davolio et al, 2006 and 2007; Ducrocq et al, 2008; Nuissier et al, 2008) of one of the most severe floods that occurred on 8 and 9 September 2002 in the Mediterranean region, namely in the Gard basin, located south-east of the Massif Central, in southern France. In this case, a MCS insisted over nearly the same area for more than 12 hours, undergoing different stages of evolution during which the larger scale atmospheric circulation changed considerably. A combination of factors, including the arrival of a cold front from the west, favoured the persistence and rejuvenation of the convective system in place. The low level upstream convergence and lift induced by the Massif Central played a role in triggering the convection, while the convective downdraft and associated low level cold outflow appeared to interact with the orography in the mature stage of the MCS, influencing the subsequent evolution of the system. The idealized study presented here addresses the first stage, during which convection was initiated, and remained at some distance upstream of the main orographic slope, before the arrival of the cold front.

In the Gard event the orography of the Massif Central played a rather unusual role, considering that the climatological maximum of precipitation is located on the upstream slope of the Massif, in the Cevennes area (Cosma et al, 2002). It is well known, in general, that both stratiform and convective orographic precipitation tend to occur over the upstream slope of a ridge, but with the location and amount of precipitation being subject to important modifications depending on the type of orographic flow regime and on the vertical and horizontal transport of liquid and frozen water species. The flow regime depends on the Froude number, computed taking into account the possible occurrence of saturated air volumes (Miglietta and Buzzi, 2001; Miglietta and Rotunno, 2005; Rotunno and Houze, 2007).

This paper is structured as follows: the model setup is described in Sect. 2; the reference and sensitivity experiments are presented and discussed in Sect. 3 and 4, respectively, and a summary is given in Sect. 5.

2. MODEL SETUP

In the present work, the initial atmospheric conditions have been largely idealized and a simplified isolated orography has been considered as a smoothed representation of the Massif Central. The vertical profiles of wind, temperature and humidity, defining the initial and the lateral boundary conditions of the simulations, were derived from the ECMWF operational analysis at 06 UTC of 8 September 2002. This turned out to be the best initiation time, as compared with the analyses of 6 hours before and after, for obtaining realistic simulations of the event (Davolio et al, 2007). The profiles were computed by sampling the atmospheric variables over an area located in the Gulf of Lion, upstream - with respect to the low level meridional flow - of the Massif Central, and averaging on a domain of 2°x2° centred around 42° N, 4.5° E. A slight vertical smoothing was applied to the variables.

Two models with different resolution were employed. The hydrostatic BOLAM model (Malguzzi and Tartaglione, 1999; Buzzi and Foschini, 2000) was first used to integrate the initial state on a relatively large domain (1200 x 1200 km), with horizontal resolution of 12 km and 40 hybrid levels, fixed lateral boundary conditions. Since the thermal wind relationship requires a horizontal temperature gradient that is incompatible with stationary conditions, due to differential advection in the presence of wind turning with height, the planetary rotation was set to zero. The orography was derived by smoothing to some extent the Massif Central (obtained from the 1 km resolution UGGS DEM) and flattening the surrounding mountains, namely the Alps and the Pyrenees. The elimination of the Alps and Pyrenees has important effects on the local flow dynamics, suppressing horizontal and vertical features that may have affected the evolution of the MCS in the real case. However, as mentioned above, this was done in order to simplify the approaching flow and to study its interaction solely with the Massif Central orography. In most of the experiments, a transition from sea (south) to land (north; the "coastline" is indicated by a horizontal line in Fig. 3) was prescribed in order to simulate the presence of the Mediterranean sea. In the model this was done by imposing appropriate values of roughness for heat, moisture and momentum over sea and land.

The BOLAM model was run without atmospheric radiation, convective parameterization and surface fluxes of heat and moisture, while boundary layer turbulence and stratiform precipitation parameterizations were kept active. Starting from the reference profiles of humidity derived from the ECMWF analysis, limited portions of condensation developed over the mountain without significant precipitation. If convective parameterization were activated in the model, precipitation would occur due to the conditional instability of the basic state, whose CAPE is about 1500 J/kg.

The non-hydrostatic MOLOCH model (Drofa and Malguzzi, 2004; Malguzzi et al, 2006) was nested into the BOLAM grid over a domain of 500x500 km, using initial conditions derived from the BOLAM output after a quasi-stationary flow over orography was reached (12 hours). The model used full physics (except radiation) and fixed boundary conditions. Earth rotation was also neglected, for consistency with the BOLAM dynamics. The orography was prescribed with a more detailed representation of small scales, as allowed by the model finer grid spacing, namely 2.5 km in the horizontal with 50 hybrid vertical levels. The non-hydrostatic integrations were carried on for seven hours, in order to capture the formation of convection and its subsequent evolution. This time span is much larger than the time scale (less than one hour) typical of isolated convection and is comparable with the duration of the first phase (about ten hours) of the real event (Davolio et al, 2006). The purpose of the high-resolution non-hydrostatic experiments is to study the conditions that allow the initiation of convection, with particular regard to the atmospheric vertical profiles of wind, temperature and humidity, and to the role played by the orography in modifying the upstream flow. It is clear, however, that one cannot directly compare the life cycle of the simulated convective system with that of the event that motivated this work, mainly due to the imposition of uniform and stationary conditions and to the absence of rotation and baroclinicity. More realistic (including semi-idealized) experiments were already presented and discussed by Chancibault et al (2006), Anquetin et al (2006), Davolio et al (2006, 2007), Ducrocq et al, 2008.

3. THE REFERENCE EXPERIMENT

The BOLAM model has been applied first to compute a flow solution in quasi-equilibrium with the isolated topography and the constant lateral boundary conditions that are defined by the initial profiles. This is a necessary step to avoid flow adjustment nearby the orography and associated gravity wave radiation, which would have an artificial effect on the development of convection in the high resolution simulations. In order to better highlight the flow modifications induced by the orography, a BOLAM run with flattened topography has also been performed. In this case, mainly due to some internal diffusion acting in the model, the equilibrium fields differ only slightly from the initial condition. Figures 1 and 2 show the vertical profiles of relative humidity, wind, and vertical velocity at the end of the two runs with and without orography. The profiles are obtained by averaging over an area upstream of the mountains that corresponds to the location where convection is initiated in the subsequent high resolution run. This area is indicated by the small square in Fig. 3. The differences between the profiles with and without mountain reflect the effect of the orography in the near upstream region: the relative humidity (Fig. 1) is larger in the presence of the mountain, in a layer between 500 and 2000 m, which is directly affected by the orographic uplift. The vertical velocity (Fig. 2) has a oscillating structure in the vertical, suggesting the presence of a mountain wave, but its magnitude is small due to the partial blocking of the flow upstream, where near stagnation conditions are met. The difference between the two wind profiles (Fig. 2) clearly reflects the orographic retardation and deviation of the flow, visible in the layer below 1000 m. The Froude number NH/U is larger than unity at low levels (its estimated value is around 2), consistently with the instauration of a 'flow around' regime (see also Davolio et al, 2006).

The humidity profile shows quasi-saturated conditions near 3000 m, with lower relative humidity, around 80%, below this level. In order to develop convection in the non-hydrostatic model, it has been necessary to modify the humidity profile bringing the relative humidity of the PBL from ~ 80% to more than 90%. Hence, in the MOLOCH run the initial field of specific humidity is increased by about 13%, clipping at saturation. This modification implies that the two humidity maxima in Fig. 1 reach saturation. This is consistent with the enhancement of the low level humidity in the numerical studies of the real event through assimilation of surface and radar data, in order to obtain realistic precipitation amounts at the correct position (Chancibault et al, 2006; Davolio et al, 2007). Moreover, in the present case in which baroclinic effects associated with the eastern side of the synoptic scale trough are suppressed, the spontaneous triggering of convection is hindered by the absence of large scale ascending motions.

Figure 3 shows the wind field at the lowest model level (80 m above the surface) after one hour, prior to the initiation of convection. A stagnation area is clearly visible on the south-eastern flank of the Massif Central, where the low level flow is impinging the steeper part of the slope. The existence of a flow-around regime is indicated by the pronounced diffluence of the wind field around the mountain and by the reverse flow north of it. The possible reduction of the effective Froude number due to the reduction of static stability, owing to condensation effects, can be considered as small at this stage, since only a thin cloud with no significant precipitation appears above and near the mountain top. This implies that the artificial humidity enhancement does not change the nature of the orographic flow regime before convection is initiated.

Subsequently, deep and organized convection develops in a region located at the foot of the mountain, on its southern side, and then drifts to the east, detaching from the orography as the precipitation-induced downdraft grows and a density current propagates to the south-east. Figure 4 shows the total precipitation, accumulated over a period of seven hours. The occurrence of strong convection, associated with the onset and growth of a MCS near the south-eastern flank of the mountain, is reflected by the accumulated precipitation field. Convection starts at about 1.5 hours after the initial time at the foot of the slope, in the area marked by the squared frame shown in Fig. 3, and then propagates to the east (see Fig. 5). Inside the area delimited by the 8 mm isohyets in Fig. 5, partial splitting into two main precipitating cells (not shown) takes place after about four hours of integration. The whole MCS persists throughout the run and is still active at the end of it, having produced its own gust front (Fig. 6) that propagates nearly to the opposite direction of the low level wind. The main updraft feeding the system is apparent in Fig. 7, corresponding to the edge of the gust front, while the downdraft is confined on its north-western side. At this stage, the basic south-easterly inflow does not reach the mountain, being deflected by the presence of the MCS outflow which acts to "shield" the orography from the large scale flow, so that no more upslope flow is present (compare Fig. 6 with Fig. 3).

The eastward drift of the convective system can be counteracted by adding an easterly perturbation to the reference wind profile, at low and middle tropospheric levels, of 5-6 m/s. This modification, however, does not seem to be justified by the wind profiles observed in the real event.

4. SENSITIVITY EXPERIMENTS

The reference experiment described in Sect. 3 has been repeated by varying the humidity profile and the mountain elevation, in order to determine the sensitivity of this particular type of orographic convection to basic state parameters. The orography has been multiplied by a factor H which is varied in the range from 0.7 to 1.5. The specific humidity profile used as initial and boundary condition for the MOLOCH simulation has been derived by the BOLAM final profile after multiplication by a factor Q, which is varied in the range from 1.10 to 1.155, without exceeding saturation. For each value of H, the BOLAM model has been run to provide initial conditions to the non hydrostatic model consistent with the modified orography. Results are summarized in Fig. 8, where crosses (dots) mark the experiments in which convection is (is not) found to occur in the high resolution model. The reference case corresponds to H=1.0 and Q=1.137. The "convection" and "no convection" regimes can be neatly separated, clearly indicating that higher orography gives rise to convection in dryer profiles.

A comparison with other investigations of flow regimes in two and three dimensions (e.g. Cosma et al, 2002; Stein, 2004; Chen and Lin, 2005a and 2005b) is not straightforward, due to the different mountain geometries, non uniform saturation conditions that, in our case, makes it difficult to apply the concept of moist Froude number, and the assumption of vertically uniform wind considered in such studies. Nevertheless, our results are consistent with the above for what concerns sensitivity to mountain height, inflow moisture, Froude number, and CAPE ranges. Regime II as defined by Chen and Lin (2005a) describes quasi-stationary convection over the upstream slope of the mountain or above its top, while regime I (blocking) describes upstream propagation of convection. The parameter range of our experiments corresponds to regime II (CAPE about 1500 J/Kg and Froude number that is somehow less/more than critical in the dry/moist case) described by Chen and Lin (2005a and 2005b) and Stein (2004), the latter two papers dealing with a three dimensional mountain representing the Alps. Our results are, however, intermediate between regime I and II, since the convective development occurs ahead of the mountain slope without upstream propagation. The presence of vertical wind shear, not included in the aforementioned studies, favours the onset of organized convection and affects its propagation.

The stability of an air parcel to (small) vertical displacements has been examined to better understand why a given parameter set may lead to atmospheric convection. The stability properties have been evaluated from the vertical profiles of temperature and humidity after one hour of integration of the MOLOCH model, prior to the (possible) initiation of convection. The profiles have been computed by horizontal averaging over the area, located just upstream of the orography, indicated by the frame in Fig. 3. At each model level, the virtual temperature of an air parcel, adiabatically lifted by 350 m (corresponding roughly to the distance between two vertical levels at 2000 meters), is computed and compared with the virtual temperature of the environment at the new altitude. In this process, the hypothesis is made that the lifted parcel retains liquid water or ice (reversible uplift), since, in the very early (linear) stages of convection development, the occurrence of precipitation can be neglected. The computation is actually done by conserving the entropy of a mixture of air, water vapour, liquid water, and ice, consistently with the MOLOCH parameterization of microphysical processes. The results are shown in Fig. 9 for a subset of experiments, located around the neutral curve in Fig. 8, whose parameters H and Q are reported in the figure. The convective cases (dashed lines) systematically show increased buoyancy in the vertical layer limited between the mountain top and the 3000 m level (similar results are obtained by considering larger vertical displacements). The indication that, in the early stage, convection is initiated at altitudes above the mountain top is confirmed by inspection at Fig. 10, where a meridional cross-section of equivalent potential temperature and tangent velocity is shown after two hours of integration, for the reference case. Inspection at cloud contents (not shown) indicates that the cloud base forms just above the 2000 m level.

After the first convective cell has developed its downdraft and cold pool, with associated gust front, a MCS forms whose subsequent evolution depends on the propagation of the gust front itself. Although the system progresses to the east, the orography still influences its propagation by confining the gust front, as suggested by comparing experiments with different mountain heights.

5. CONCLUSIONS

This work has been inspired by deep convection episodes associated with flash floods in the vicinity of orography, in particular by the Gard event of September 2002. The purpose was to investigate the onset and evolution of mesoscale convective systems originated by conditionally unstable, upstream uniform flow interacting with an isolated orography.

Numerical experiments were performed, in which a basic flow profile was extracted from the ECMWF analysis at the beginning of the event. The simulated convective systems are long lived and move slowly eastwards against the low level flow, developing their own cold pool and gust front generally more intense than those observed in the real event. They are not stationary, however, unless a suitable modification of the wind profile is introduced. This indicates that the model setup is capable of describing the basic mechanisms for the orographic convective triggering, while the conditions that lead to quasi-stationarity of the convection require more complex flow configurations than those modelled in this work.

The orography acts both as to trigger and to determine life cycle and intensity of the MCS. The height of the mountain must be sufficiently large, for a given humidity content, for the onset of convection. For a given orography height, convection develops if the humidity of the basic profile is increased above a given threshold. A well defined curve separating convective regime from quiescent flow upstream of the mountain has been identified. The buoyancy computed with water loading turns out to be a useful instrument to understand what is going on in the early stages of evolution. Initially, convection arises at relatively high altitudes, above and upstream of the mountain top, in an environmental stratification which is determined by the interaction between the orography and the incoming flow. Subsequent intensification of convection is caused by the interaction of the cold pool which propagates against the mean flow itself.

The most drastic simplifications of the model dynamics was the neglect of large scale changes over the course of the simulations, the use of horizontally uniform upstream conditions and the assumption of vanishing planetary rotation. The latter was necessary in order to maintain a realistic vertical wind shear, which is known to be an important factor determining convection strength and organization, neglecting at the same time the associated horizontal temperature gradients that are needed to maintain thermal wind equilibrium with rotation. Although the elimination of baroclinicity is unrealistic for the synoptic scale dynamics, it is commonly accepted as a simplification for studying the convective development on relatively short space and time scales.

In spite of the above limitation, the area south-east of the Massif Central, where strong low level flow deviation and stagnation are reproduced as a response to the orographic forcing, is the location where strong convection develops in the numerical experiments. The triggering of convection occurs without artificial local perturbation, within the orographically modified flow, near or within the convergence area upstream of the obstacle, and in a position, with respect to the mountain, that corresponds to the location of intense convection observed in the Gard case. More generally, evidence supported by the present and other investigations suggest that the physical and dynamical processes highlighted in this work can be considered as typical of the events of MCS generation and evolution embedded in moist flows impinging upon orography.

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FIGURE CAPTIONS

Fig.1: Vertical profile of relative humidity computed at the end of the BOLAM simulation with and without mountain. The profile is computed from temperature and specific humidity horizontally averaged over a region upstream of the mountain (see text).

Fig.2: Same as Fig. 1, but for wind and for vertical velocity (cm/s). Wind barbs in the left (right) portion of the figure refer to BOLAM simulation with (without) mountain. Half barb stands for 2.5 m/s, full barb for 5 m/s.

Fig.3: Horizontal wind at the lowest model level after 1 hour for the MOLOCH reference experiment described in Sect. 3. Maximum vector is 5.0 m/s; winds below 0.2 m/s are not drawn. Topography contours every 250 m. Tics indicate model resolution. The horizontal line indicates the coastline (see text). The small square indicates the area where convection starts and where vertical profiles upstream of the mountains are computed (see text).

Fig.4: 7-hour accumulated precipitation (contour interval is 10 mm) for the MOLOCH reference experiment.

Fig.5: Time evolution of the 8 mm (hourly) precipitation contour for the MOLOCH reference experiment. The labels indicate the simulated time in hours.

Fig.6: Same as Fig. 3, but after 6 hours of integration. Maximum vector is 7.9 m/s.

Fig.7: Vertical velocity field at 850 hPa after 6 hours of integration. Contour interval is 0.4 m/s. Negative contours are dashed.

Fig.8: Diagram summarizing the results obtained in the sensitivity experiment. H and Q indicate, respectively, the multiplying factors of orography and specific humidity field at the initial time.

Fig.9: Parcel *minus* environmental virtual temperature for an air parcel lifted adiabatically from the level reported in the y-axis. Vertical displacement of 350 m with water loading included. Dashed (continuous) lines refer to experiments in which convection (no convection) has occurred. Environmental vertical profiles of temperature and humidity are computed by horizontally averaging over the box indicated in Fig. 3.

Fig.10: North-south cross section showing equivalent potential temperature (contour interval 2 ºK) and tangent velocity after 2 hours of the reference experiment with H = 1.0 and Q = 1.137. The section is taken along the dashed line sketched in Fig. 7.

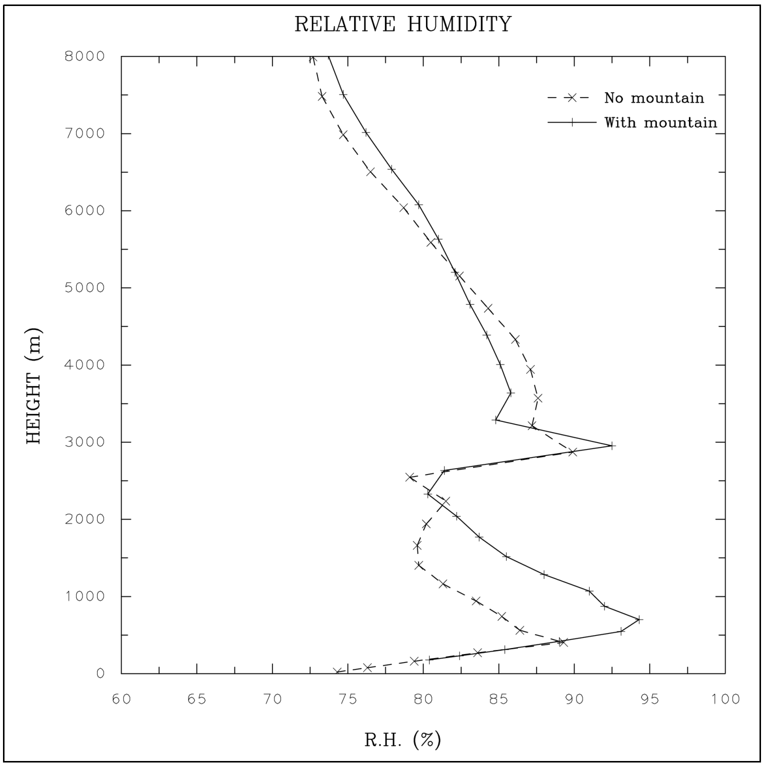
RELATIVE HUMIDITY
No mountain
With mountain
HEIGHT (m)
0
1000
2000
3000
4000
5000
6000
7000
8000
60
65
70
75
80
85
90
95
100
R.H. (%)

Fig. 1

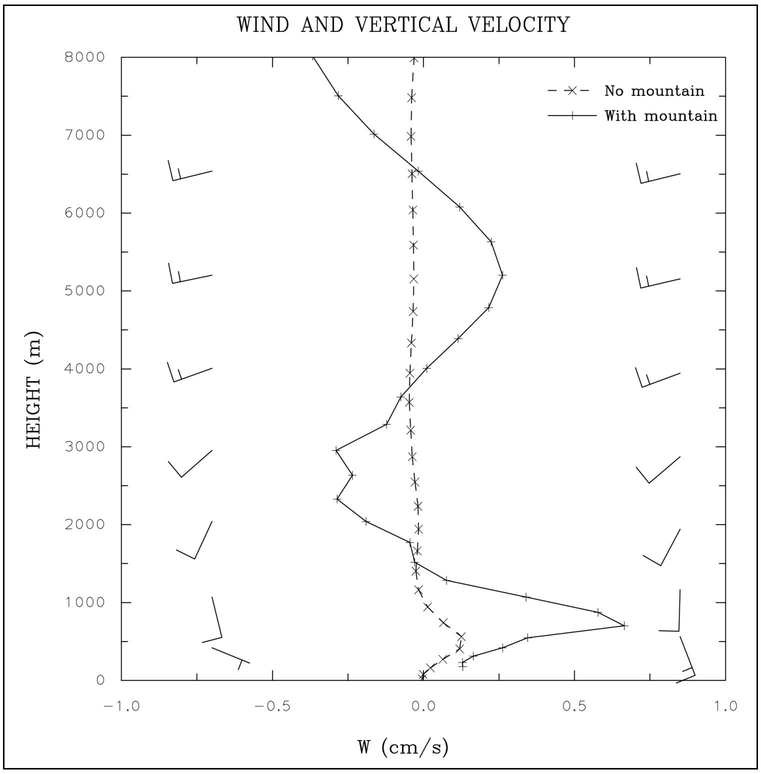
WIND AND VERTICAL VELOCITY
No mountain
With mountain
HEIGHT (m)
0
1000
2000
3000
4000
5000
6000
7000
8000
−1.0
−0.5
0.0
0.5
1.0
W (cm/s)

Fig. 2

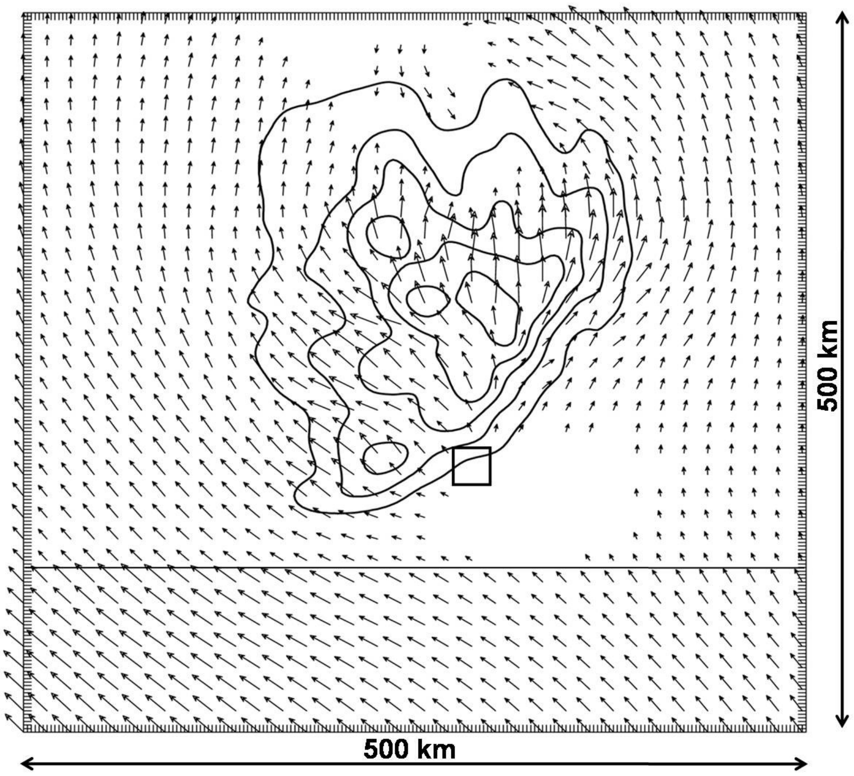
500 km
500 km

Fig.3

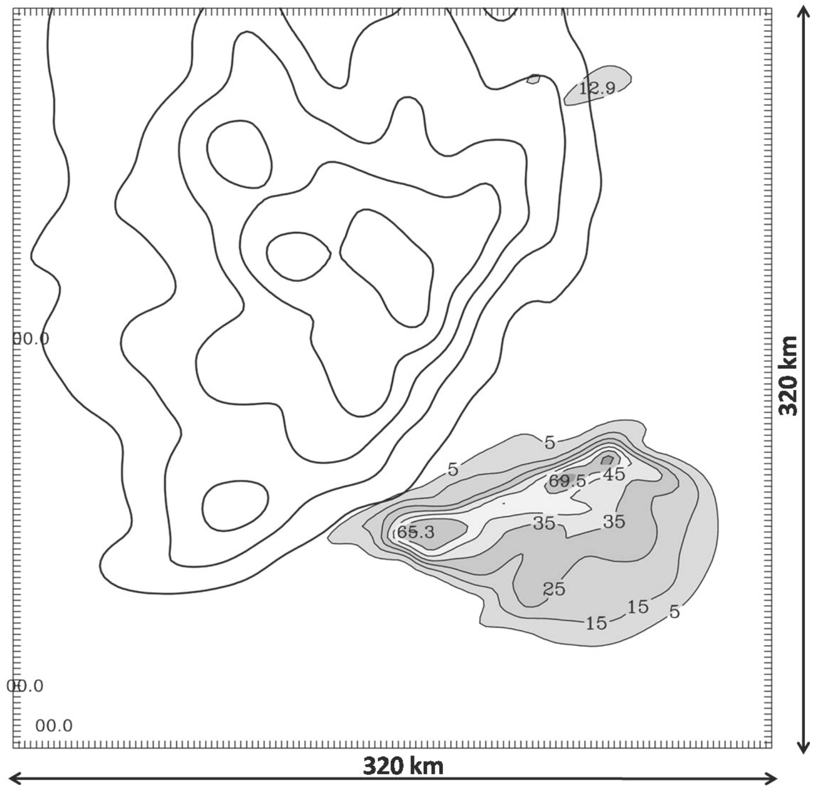
12.9
00.0
5
5
69.5
45
65.3
35
35
25
15
15
5
00.0
00.0
320 km
320 km

Fig. 4

Fig. 5

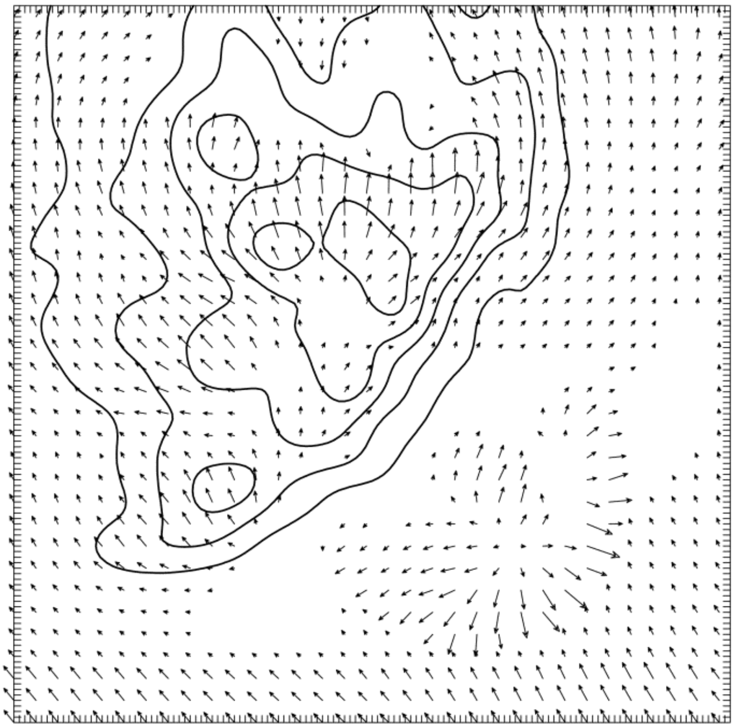

Fig. 6

Fig. 7

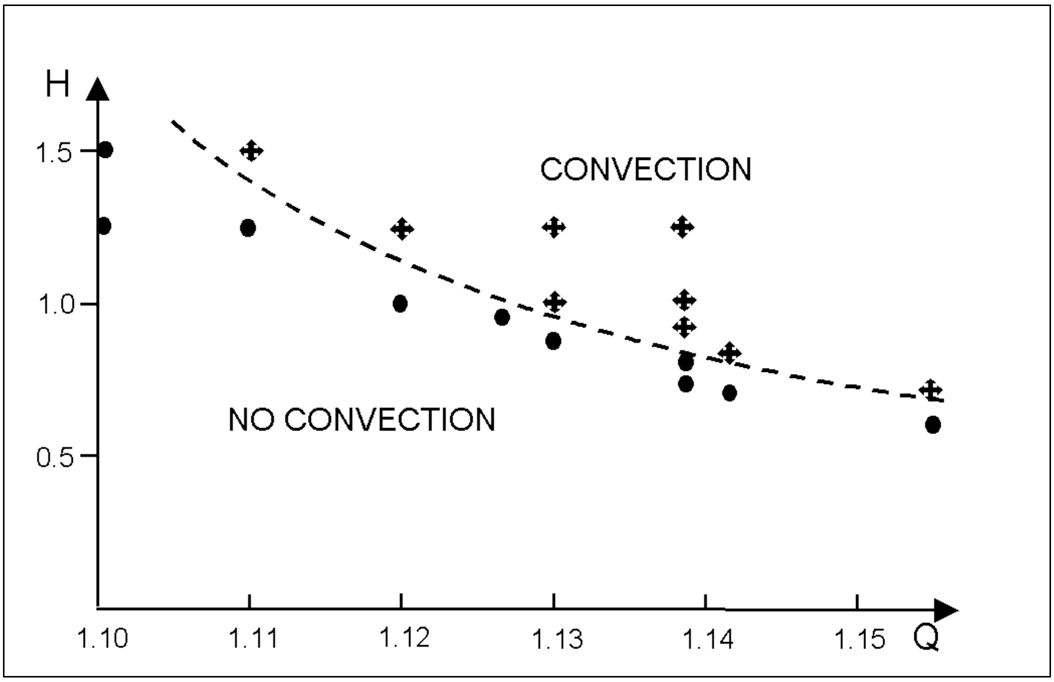

Fig. 8

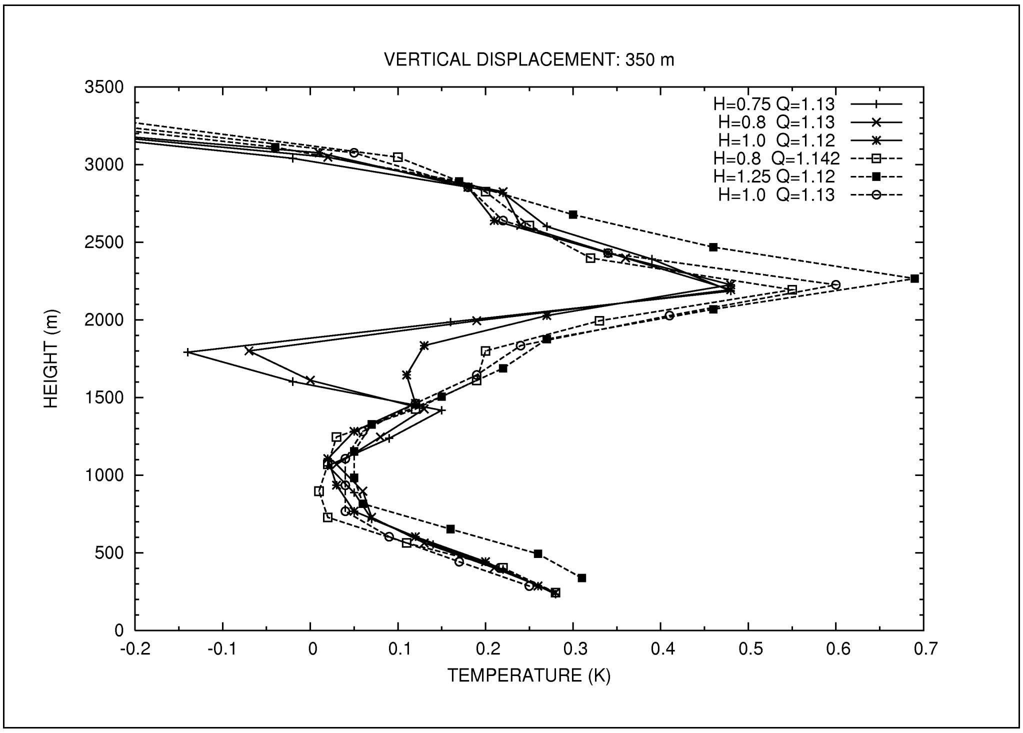
VERTICAL DISPLACEMENT: 350 m
HEIGHT (m)
TEMPERATURE (K)
H=0.75 Q=1.13
H=0.8 Q=1.13
H=1.0 Q=1.12
H=0.8 Q=1.142
H=1.25 Q=1.12
H=1.0 Q=1.13
0
500
1000
1500
2000
2500
3000
3500
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Fig. 9

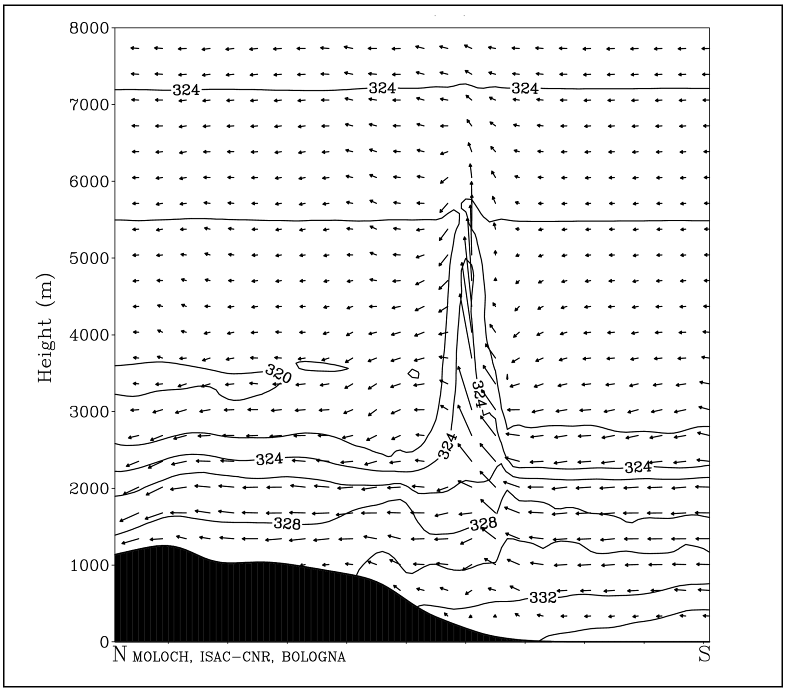
Height (m)
0
1000
2000
3000
4000
5000
6000
7000
8000
324
324
324
320
324
324
324
324
328
328
332
N
MOLOCH, ISAC–CNR, BOLOGNA
S

Fig. 10