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The Role of Mathematics in the Understanding of the Dynamics of Meteorogical Situations that Produce Heavy Rain over the Spanish Mediterranean Zone

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Abstract

Globally, floods and flash floods are the natural hazards that annually produce the greatest number of fatalities as well as economic losses. Mainly in autumn, the Spanish Mediterranean zone is affected by these meteorological phenomena. The most common meteorological situation that produces such episodes can be characterized at surface by an European anticyclone and a weak cyclone located on the Algerian coast that induce humid easterly winds impinging on the Spanish Mediterranean coast. At the middle and high troposphere a cold cyclonic centre is usually located to the south or southwest of the Iberian peninsula, producing southwesterly flow over the western Mediterranean. The conceptual model that can be devised from the synoptic situation attributes an important role to the orography, being the factor that provides enough lifting to the humid low level parcels to trigger convection. Evaporation from the sea is responsible for the high amount of water vapor that carries the flow associated with the pressure gradient produced by the European anticyclone and the Algerian low. We have verified the validity of this conceptual model by means of numerical simulations of several cases of torrential rain combined with a factor separation technique. In order to analyze the role played by the high-level disturbance, we apply numerical techniques aimed at isolating the ingredients that contribute to the development of convection and intense rain. In particular, we investigate the role of Potential Vorticity nuclei, associated with the upper-level cold low, through numerical experiments. Initial conditions in the model are thus soundly perturbed by modifying the Potential Vorticity field after applying an inversion technique. The results confirm that the high-level Potential Vorticity is responsible for the development of an easterly low-level jet. The interaction of such circulation and the orography determines where the heavy rain focuses.

1 Introduction

The distribution of floods that take place around the world every year, as well as the economic and human live losses attributed to these adverse phenomena, reveal their enormous impact on human life and property (see `http://www.dartmouth.edu/~floods/`). In the northern hemisphere, this impact is manifestly higher in south and southeast Asia, with remarkable persistency also over Central America and the Caribbean Sea. Nevertheless, there is a belt surrounding the Earth at around 45°north latitude that is also strongly affected by this type of hazardous phenomena. The Mediterranean region lays in this belt and the lands that surround the western Mediterranean Sea are especially inclined to this type of catastrophic situations. This belt also covers North America, mainly its Eastern half, where death tolls are lower than average, although with very important economic losses (Figure 1).

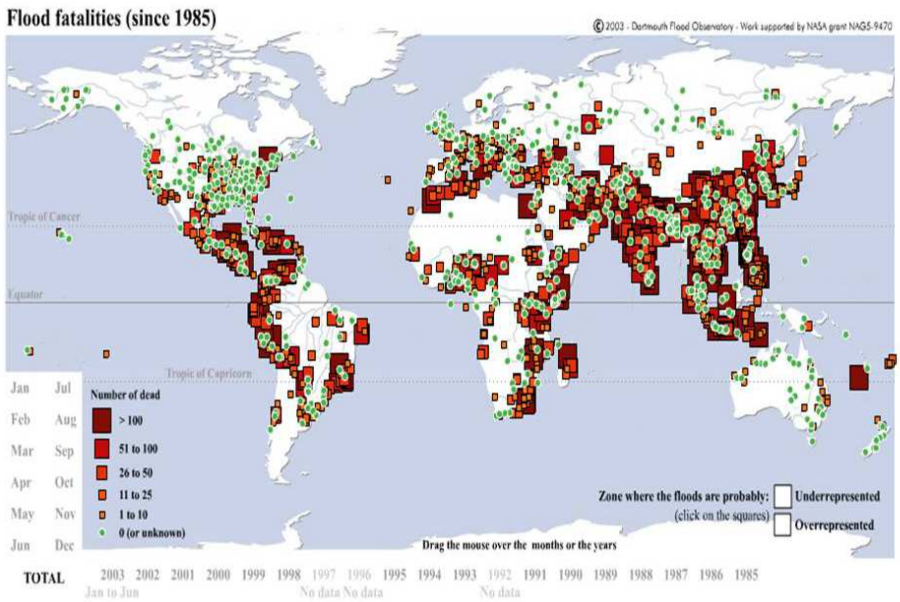

Figure 1.— Human live losses from 1985-2003 produced by floods (from Dartmouth Flood Observatory, `http://www.dartmouth.edu`)

Rainfalls that give place to floods are generally produced by convective clouds, so called cumulonimbus. There are diverse reasons and meteorological systems that can develop deep convection. In southeast Asia, tropical cyclones need to be considered but it is also a zone favored by convergence inside the intertropical convergence zone. In south Asia and interior lands of India and China, the summer monsoon, with a very important contribution of humid and warm air, moves the Indian Ocean intertropical convergence zone to the interior of the continent. In Central America and the Caribbean Sea, tropical cyclones are again the main cause. The aforementioned flood-prone mid-latitude belt includes the convective cloud clusters developed in favorable environments, which are linked to the mid latitude circulation and triggered by mesoscale systems or by orographic systems when they interact with the humid currents.

The UFDA/CRED International Disaster Database from the University of Louvain (`www.em-dat.net`) shows that in Spain, during the period 1953-2007, 22 important floods were registered, with 1280 people died, 740.000 people affected and economic losses estimated at 7.800 M$. These flood- producing intense rains (often exceeding 200 mm in 24 hours or less) take place principally in the coastal Mediterranean zone and mainly during the autumn (Romero et al. 1998, Figure 2). There are references of hazardous floods in the region since the Middle Age, such as the case of Palma (Balearic Islands) of October 14, 1403 in which more than 5000 persons died (Grimalt 1989). The Biescas's case (Aragon) occurred on August 7, 1996 and with 87 casualties (Romero et al. 2001) is one of the most destructive of the all recent events.

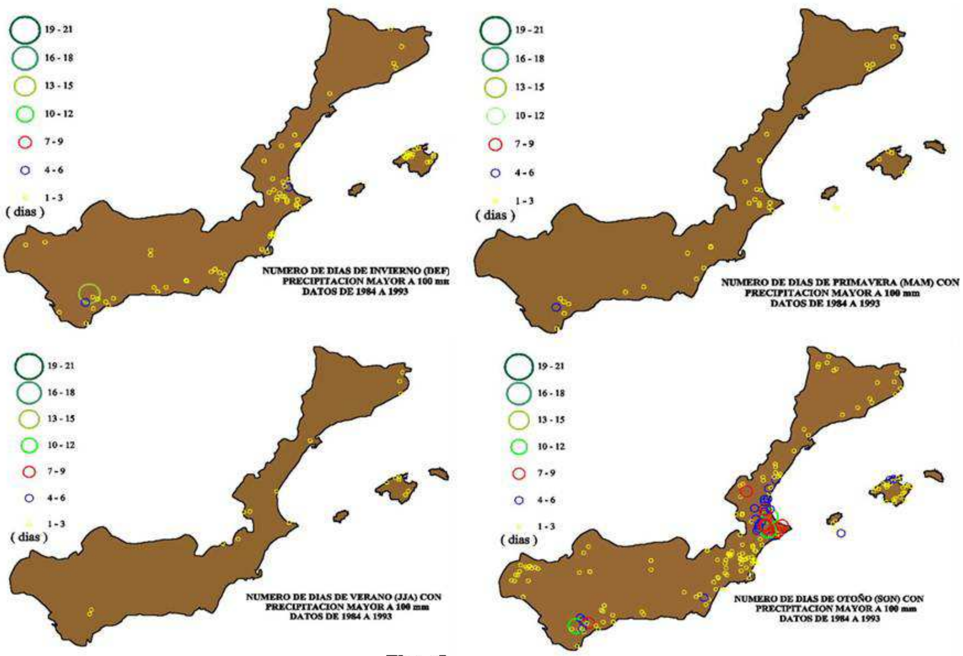

Fig.- 2

Figure 2.— Number of days with precipitation greater than to 100 mm during the period 1984-1993 in Mediterranean Spain (from Romero et al. 1998)

The aim of this article is to show how Mathematics allows us to analyze the physical mechanisms involved in the development of the meteorological situations that produce heavy rain in the Spanish Mediterranean zone. It also allows us to verify a conceptual theory, previously introduced by Miró-Granada (1974) and Llasat (1987) on the formation of these rains. In addition, the ability of meteorological mesoscale numerical models to reproduce such situations is assessed. The understanding of the limitations of numerical models and, at the same time, of the physical mechanisms involved in the development of the heavy rains episodes, become decisive to carry out accurate forecasts and to be really useful and valuable in civil defense.

2 Previous works

Forty years ago, Jansà (1966) reveals the importance in the western Mediterranean of the meteorological non frontal systems. He also indicates that the effects (rainfall, etc) of these systems are glaringly disproportionate in relation to what can be identified on the meteorological maps. Especially he refers to the "cutoff lows", generally undetected on surface maps but identifiable in the mid troposphere, though very hardly (at that time) as consequence of the lack of radiosounding observations.

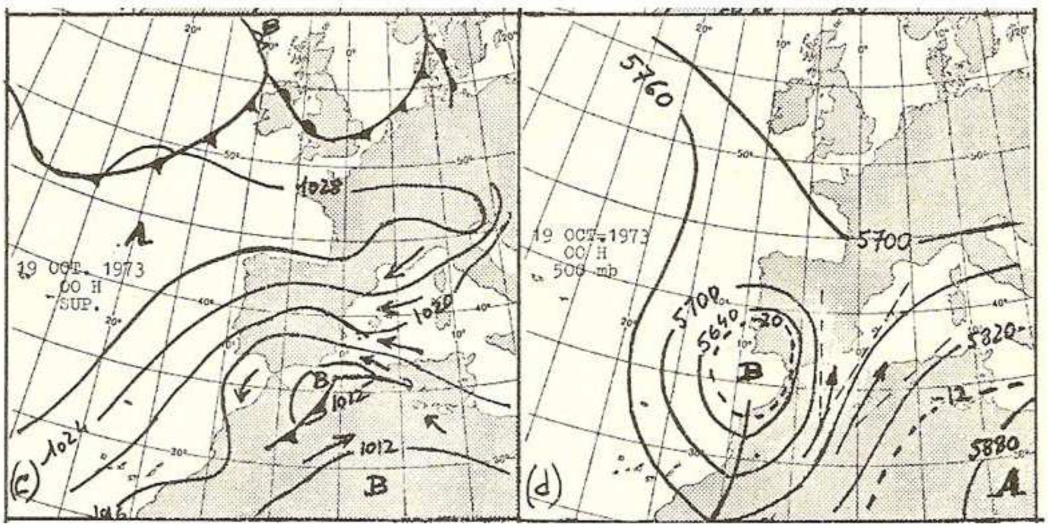

Figure 3.— Meteorological situation on 19 october 1973 at 00 UTC at surface and 500 hPa (from Miró-Granada 1974).

Miró-Granada (1974) presents in detail the meteorological situation in which intense rains took place on October 19-20, 1973 in the province of Granada (Figure 3). At surface, there are high pressures on central Europe and a low over the Algerian coast. The combination of both systems produced a flow that impinged on the Mediterranean Spanish coast close to Andalusia. It is evident on the weather maps - according to the thermal wind relation - the warm air advection towards the Spanish coast. The presence of high sea surface temperatures along the easterly wind path allowed the author to assume strong evaporation from the sea that would lead to high relative humidity to the air approaching the Iberian Peninsula. At mid and high tropospheric levels, a closed depression with cold nucleus was identifiable over the gulf of Cadiz. The author presupposed that the difluence of the isohipses on the Andalusian coast would carry divergence and therefore upward vertical motion that would had favored the convection. The orography would be the uplift mechanism for the low level very humid particles to reach its level of free convection.

García-Dana et al. (1982) analyze the meteorological situation that gave place to very intense rains in the province of Valencia on October 20, 1982. The meteorological situation at large scale was similar to the one previously described: a low over the Algerian coast and high pressures over central Europe producing easterly flow on the western Mediterranean that impinged the Levantine coast. At mid tropospheric levels, there was a closed depression with cold nucleus over Alborán Sea, with difluence of the isohipses on the Valencia coast. The authors assume the orography is high enough to trigger the convection that, for this case, was organized as a Mesoscale Convective Complex (MCC, Maddox 1981, Figure 4).

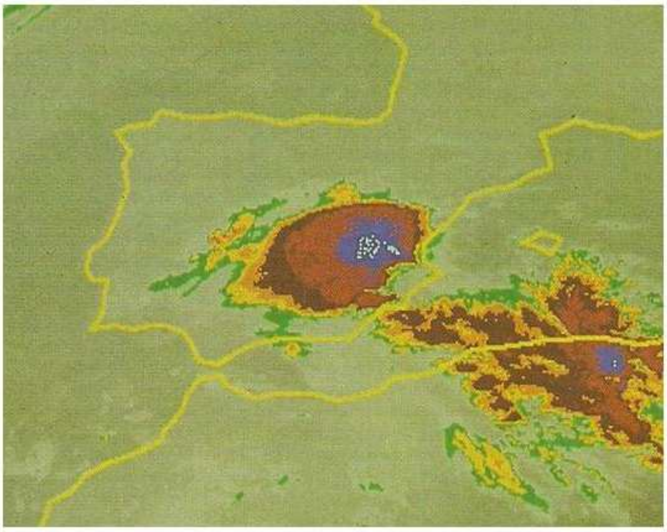

Figure 4.— IR Meteosat image on 20 October 1982 at 06 UTC. A MCC is located over Valencia.

Llasat (1987) studies different cases of torrential rain in Catalonia. The meteorological situation at the large scale is very similar to the described previously but in these cases the surface moist flow impinges the Catalan coast. The author presents a conceptual model (Figures 5) that can be applicable to the whole Mediterranean coast. This conceptual model includes: a) intense flow at surface from the east that is very humid after undergoing intense evaporation from the sea in its path towards the Spanish coast; b) temperature inversion at low levels that retains the water vapor close to the surface; c) depression at high levels that brings Atlantic humid air that favors the abundance and efficiency of the rainfall; d) the coastal orography provides the lifting mechanism to the surface particles to overcome the inversion and to trigger the convection. The suitable interaction of the humid flow with the orography determine the location of the rainfall.

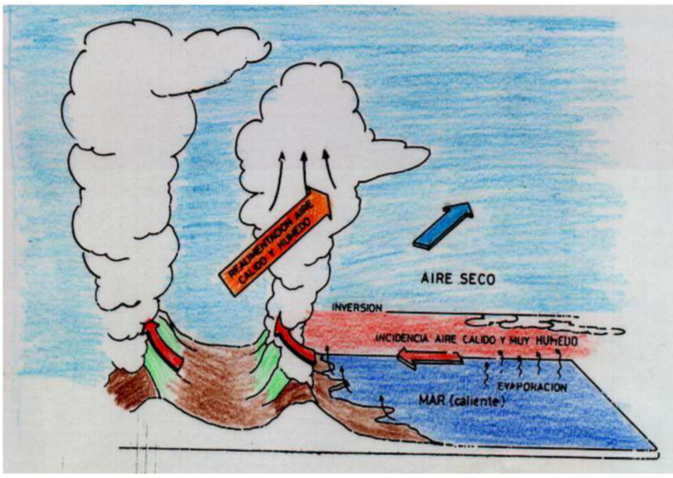

Figure 5.— Conceptual model of the mechanisms that operate in the development of heavy rain in the Spanish Mediterranean area (from Llasat 1987)

3 Statistical study of daily rainfall patterns versus meteorological situations

The aim is to determine objectively the characteristic meteorological situations that produce heavy rain on the Spanish Mediterranean area (Catalonia, Valencia, Murcia, Andalusia and Balearic islands). Here the methodology is shortly presented, more details can be found in Romero et al (1998, 1999a, 1999b).

We start constructing a data base of daily precipitation using 410 raingauges for the period 1964-1993. The density and spatial coverage of the network is quite satisfactory (Figure 6). Next, we define as torrential days those days that present rainfalls exceeding 50 mm in at least 2% of stations (8 stations). This criterion yields 449 days (15 days per year on average), 44.8% belong to the autumn season, 35.2% to winter, 14.9% to spring and 5.1% to summer.

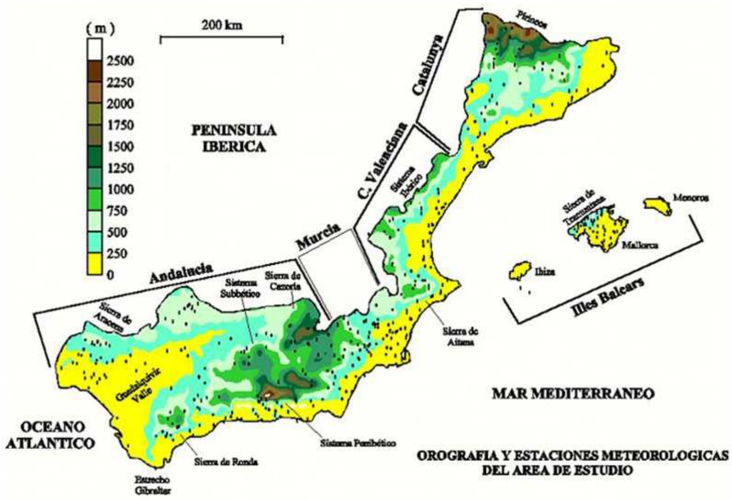

Figure 6.— Raingauges that conform the daily rainfall data base from 1964 to 1993 (from Romero et al. 1998)

The approach followed to derive the typical daily precipitation patterns consist in subjecting the T-mode (day-by-day) correlation matrix to principal component analysis (PCA) and carrying out cluster analysis (CA) on the most important extracted components. Since axes in the T-mode represent precipitation maps (points represent time series), days participating with similar loadings will be clustered together. Applying the simple scree test of Cattell (1966) 15 PCs are retained which account for 68.5% of the total variance. For the cluster analysis, the k-means method (Anderberg 1973) is used.

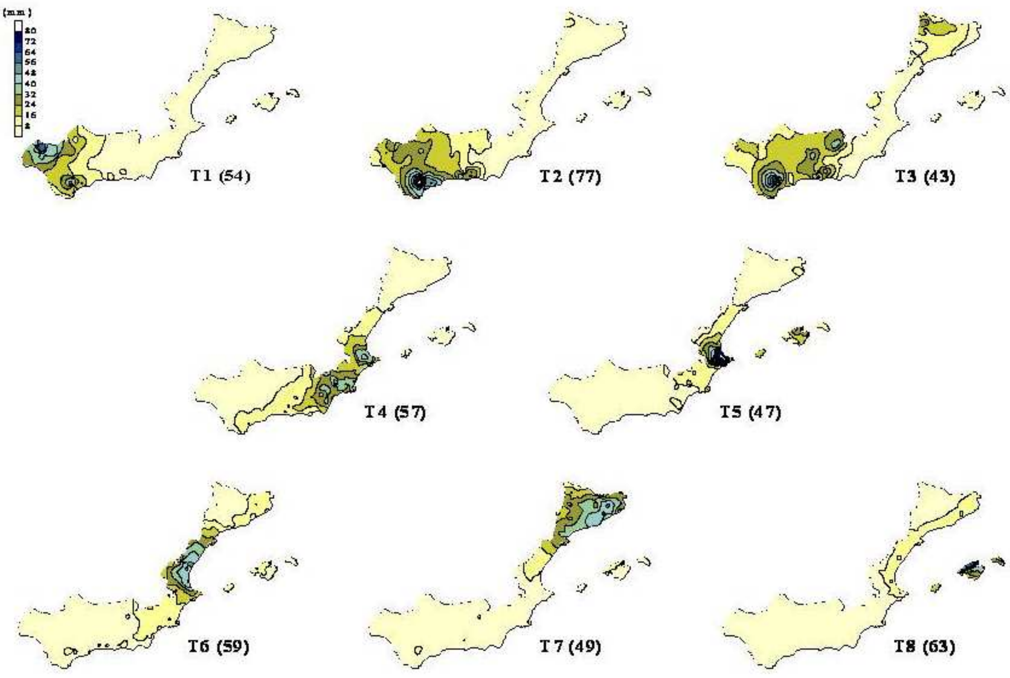

Figure 7.— Torrential rainfall patterns (from Romero et al. 1999a)

Figure 7 shows the 8 torrential pattern (TP) groups obtained. It stands out clearly the preference of heavy precipitations for coastal areas and interior mountainous zones. The TPs reflect the dominant role exerted by the topography for the spatial distribution of rainfalls.

The data used to carry out the objective classification of meteorological situation associated with torrential precipitation patterns are the ECMWF grid analyses of geopotential height, temperature, relative humidity and horizontal wind components at 11 standard pressure levels available at 00.00, 06.00, 12.00 and 18.00 UTC. The spatial resolution is 0.75°in both latitude and longitude. The temporal coverage is from 1984 to 1993. During that decade 1275 days were identified as significant rainfall days (days in which at least 5% of the raingauge stations registered more than 5 mm) in Mediterranean Spain. Among these, 165 attain the category of torrential days. The classification of the atmospheric circulations thus utilizes 1275 circulations patterns. As daily rainfalls correspond to the

07.00-07.00 UTC time interval, we select the synoptic situation at 18.00 UTC, since this is approximately the central time in the 07.00-07.00 interval.

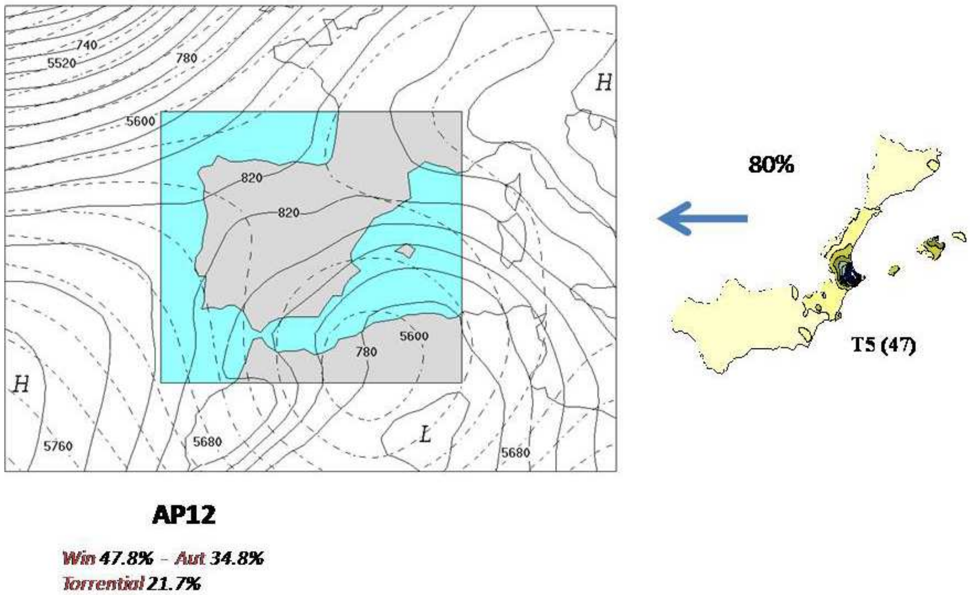

Figure 8.— Example of an atmospheric circulation pattern (AP12) and the most related torrential rainfall pattern (T5). In the atmospheric circulation pattern the full lines represent 925 hPa isohipses and dashed lines 500 hPa isohipses. Small area is the selected area to calculate the correlation matrix. The AP12 is torrential in 21.7% of the cases. The T5 appears in 80% of AP12 situations (from Romero et al. 1999b)

The classification is carried out using data within the interior window extending between 33.75°and 45.75°N and between 11.25°W and 06.00°E. The window then comprises 408 grid points (see Figure 8), and its dimensions are consistent with the mesoscale nature of the rainfall patterns and the strong dependence between the basic flow and the local topography. The 1275 circulation patterns are classified by subjecting the T-mode (day by day) correlation matrix of the data to PCA and then carrying out CA of the days based on the retained principal component loadings using the k-means method. When more than one field is considered, e. g. geopotential heights at two levels, PCA is carried out for each level and a unique CA applied to the total set of collected loadings. The methodology is applied to all relevant data, but the most satisfactory results are obtained from a combination of the circulations at 500 and 925 hPa.

Application of the scree test of Cattell (1966) suggests the retention of 6 PCs for 500 hPa (accounting for 96.7% of the variance) and 8 PCs for 925 hPa (95.7% of the total variance). Thus, 14 variables are used in the CA. Solutions involving 7, 11 and 19 clusters appear as the best associations. The last solution was finally considered since it presents a relatively simple and meaningful collection of patterns. These clusters are referred to as atmospheric patterns (AP).

Table 1 shows how the set of 165 torrential days are distributed amongst the derived 19 atmospheric patterns and also how, for each AP, the torrential events distribute among the 8 TPs.

An example of the relation between AP and TP can be seen in Figure 8. The most torrential APs for the Murcia, Valencia, Catalonia and Balearic Islands are characterized in the middle troposphere by closed cyclonic circulation or shortwave troughs located in the south of the domain. At low levels they exhibit a significant level of warm advection towards some area of Mediterranean Spain, in concordance to the meteorological situation described in the previous section.

Table 1.—

Atmospheric pattern	Torrential days	% of total	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8
AP1	8	15.7	25.0	62.5	12.5	0.0	0.0	0.0	0.0	0.0
AP2	8	11.3	37.5	25.0	25.0	0.0	0.0	0.0	0.0	12.5
AP3	21	25.0	33.3	52.4	4.8	4 8	0.0	4.8	0.0	0.0
AP4	16	15.2	25.0	31.3	12.5	0.0	0.0	6.3	24.9	0.0
AP5	10	17.2	20 0	50.0	0.0	10 0	0.0	10.0	0.0	10.0
AP6	18	23.1	0.0	22.2	0.0	33.3	11.2	33.3	0.0	0.0
AP7	2	2.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0
AP8	6	7.9	0.0	16.7	0.0	0.0	0.0	16.7	66.6	0.0
AP9	3	3.5	0.0	0.0	66.7	0.0	0.0	0.0	0.0	33.3
AP10	3	10 7	0.0	0.0	0.0	33.3	33.3	33.3	0.0	0.0
AP11	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AP12	5	21.7	0.0	0.0	0.0	0.0	80.0	0.0	0.0	20.0
AP13	25	37.9	0.0	4.0	0.0	32.0	20.0	24.0	8.0	12.0
AP14	11	19.6	0.0	0.0	0.0	36.4	27.3	27.3	0.0	9.0
AP15	8	32.0	0.0	0.0	0.0	12.5	0.0	62.5	0.0	25.0
AP16	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AP17	7	13.5	0.0	0.0	0.0	14.3	71.4	0.0	0.0	14.3
AP18	4	4.7	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0
AP19	10	11.5	0.0	0.0	0.0	0.0	10.0	10.0	10.0	70.0
Total	165	12.9	10.9	20.6	6.1	13.9	12.7	15 8	7.9	12.1

a Also shown as a percentage of the total number of significant days; in bold percentages greater than 20% .

4 Analysis of the synergy orography-sea evaporation.

4.1 Case description and objective

On 9 and 10 October 1994, heavy rain was registered in Catalonia that produced important floods with substantial damage to houses, routes and railways. In addition, 8 people lost their lives. Figure 9 shows the accumulated precipitation collected in Catalonia during October 10. In south Catalonia more than 450 mm fell during the two days episode. At the beginning of the event, the meteorological situation at low levels (Figure 10a) was characterized by an anticyclone located north of Italy and a low to the southwest of Spain with a trough along the Algerian coast. Over the western Mediterranean the flow is from the southeast. Warm advection forms over the Valencia and Murcia coasts. The same pattern can be identified at 850 hPa with a southerly low level jet (LLJ) pointing towards Valencia. At mid tropospheric levels (Figure 10b) a trough with cold core is located to the southwest of Spain producing southwesterly winds over the eastern Spanish Mediterranean coast. The situation evolved slowly in the subsequent hours and warm advection, as well as the LLJ, pointed towards Catalonia. The meteorological situation accomplishes the synoptic pattern included in the conceptual model presented before. Numerical simulations provide an opportunity to test the validity of the conceptual model and this is the objective of the present section. A more complete study of the case can be found in Ramis et al (1998).

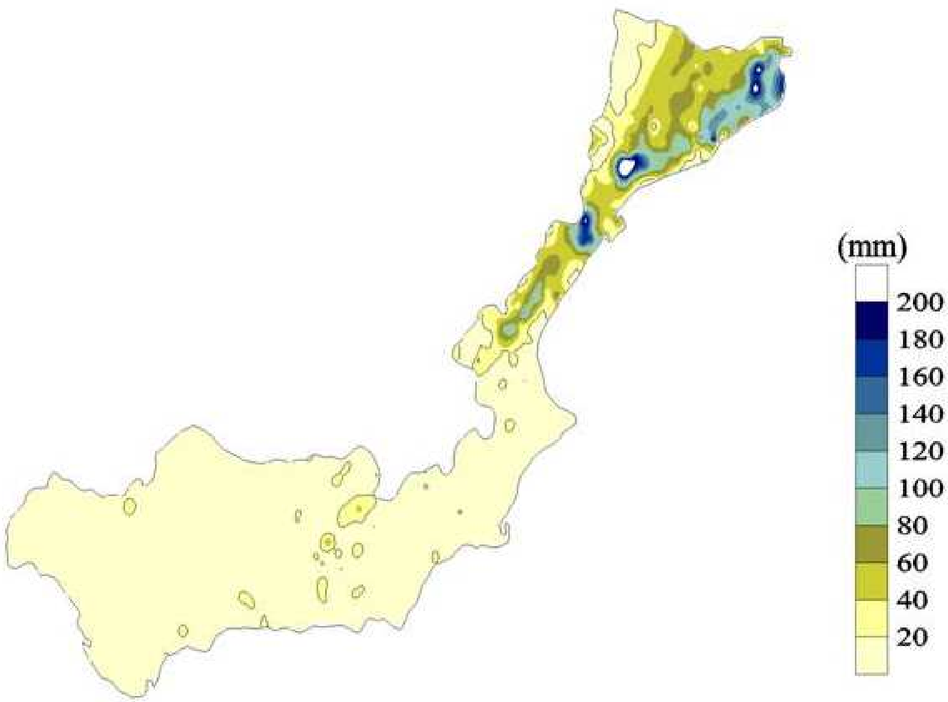

Figure 9.— Accumulated precipitation in Catalonia from 07 UTC 10 October to 07 UTC 11 October 1994 (from Ramis et al. 1998)

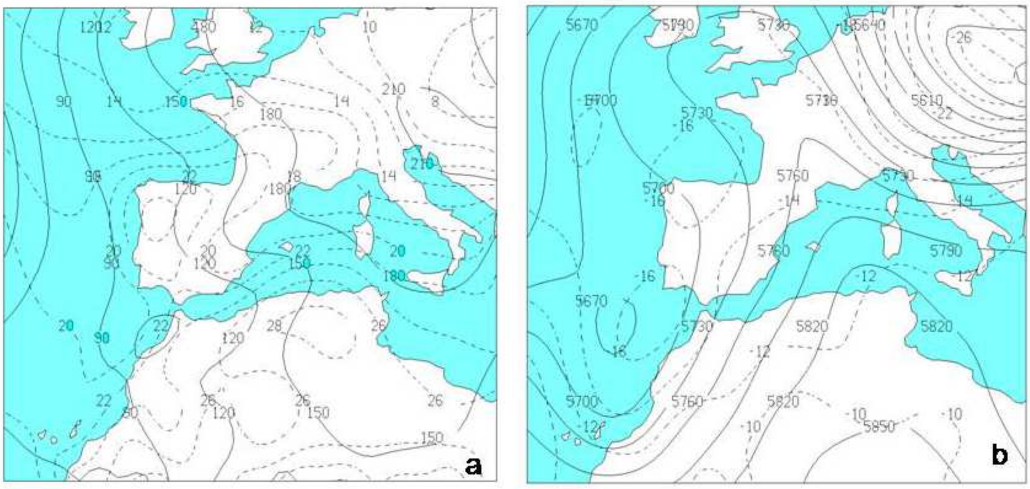

Figure 10.— Meteorological situation on 9 October 1994 at 12 UTC at 1000 and 500 hPa (from ECMWF analysis)

4.2 Numerical experiments

The numerical model developed by Nickerson et al (1986) was used. The cumulus convection parameterization scheme of Kain and Fritsch (1990) was included. A set of experiments were carried out for 9 and 10 October 1994 in order to test the capability of the model to simulate the event and to assist the assessment of the main physical processes that controlled the occurrence of the heavy rain. Initial and boundary conditions were provided by the ECMWF analysis. The model domain covers 1800 × 1800 km^2 (Figure 11), horizontal resolution is 20 km. Thirty levels in the vertical have been included. We consider the coastal topography and the evaporation from the sea as the key factors responsible for the focalization of the heavy rain. Table 2 summarizes the four experiments performed.

Following the factor separation technique developed by Stein and Alpert (1993), the outputs (in our case rainfall) of the four experiments may be combined to yield the isolated effects on the rainfall field by the orography, evaporation from the sea and their synergism:

1. Effect of the orography $F_1^* = E_1 - E_0$.
2. Effect of the sea evaporation $F_2^* = E_2 - E_0$.
3. Effect of the interaction orography- sea evaporation $F_{12}^* = E_{12} - (E_1 + E_2) + E_0$.

4.3 Results for 10 October

Figure 11 presents the spatial distribution of the rainfall as simulated by the model for the 10 October (experiment E_{12}). A coastal band of more than 40 mm, resembling the observed pattern, is forecast by the model from central Valencia to northern Catalonia. Although peak values up to 100 mm appear in Catalonia, precipitation is underestimated. When considering the basic simulation E_0, less than 10 mm are given by the model in the

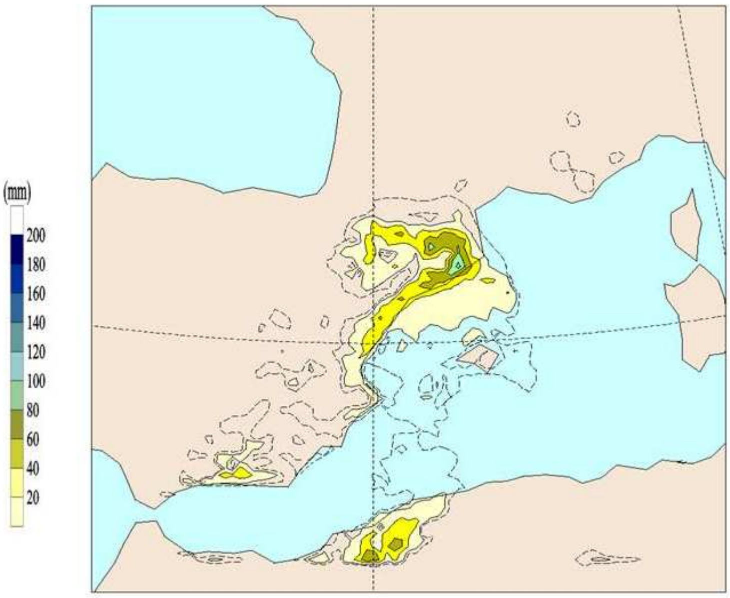

Figure 11.— Simulated precipitation from 06 UTC 10 October to 06 UTC 11 October 1994 (from Ramis et al. 1998)

Table 2.—

Experiment	Orography	Sea Evaporation
E_0	NO	NO
E_1	YES	NO
E_2	NO	YES
E_{12}	YES	YES

area of interest. This means that the considered factors should be fundamental for the rainfall distribution and amounts.

The isolated effect of the orography results very important (Figure 12a) since it practically explains the forecast rainfall in all zones except in coastal Catalonia and over the sea. The effect of the evaporation from the sea is essentially positive but weak and helps to explain the rainfall structure depicted in Figure 11 south of the Balearic Islands. The effect of the interaction orography-evaporation (Figure 12b) results to be the most important for explaining the rainfall north of the Balearic Islands and in particular the coastal maxima of Catalonia. Correspondingly, its action is suppressive downstream over interior lands. Then, evaporation increases the relative humidity of the air parcels flowing over the Mediterranean and the coastal mountains provide the lifting mechanism to develop convection.

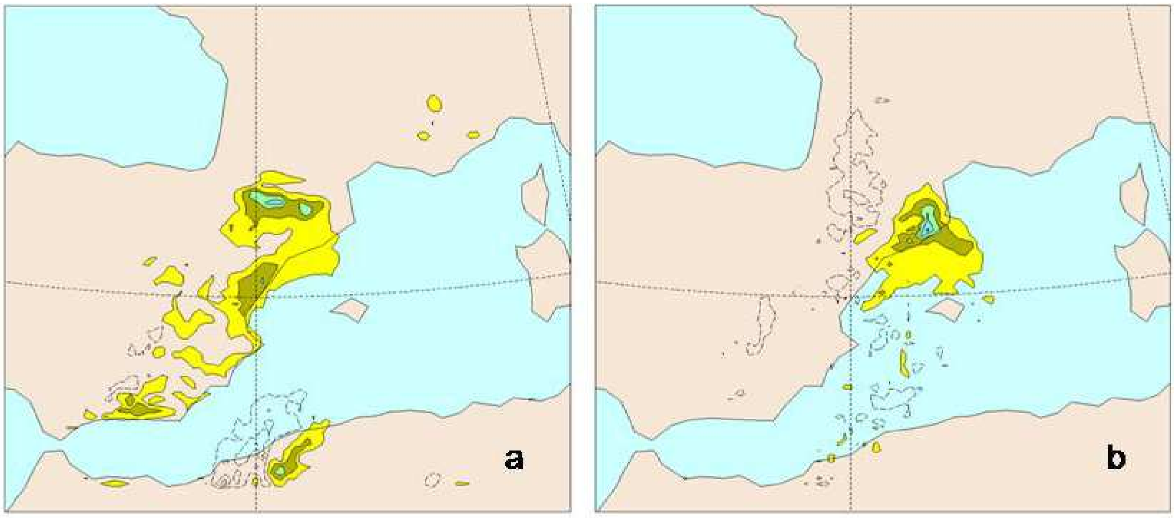

Figure 12.— Effect of the orography (a) and of the synergy between orography and evaporation from the sea (b) on the precipitation field (from Ramis et al. 1998)

5 Action of upper levels on the focalization of heavy precipitation

5.1 Case description and control simulation

The aim of this section is to answer the question: What is the role of upper levels dynamics in heavy rain events? To accomplish this analysis we have used a torrential precipitation event that affected eastern Spain from 21 to 24 October 2000. Total accumulated rainfall higher than 500 mm was registered at some locations (Figure 13), with values up to 300 mm in a 24 hours period. Here we present a short description of the case and the most important results; for a detailed study see Homar et al (2002).

Figure 14 presents the meteorological situation at surface and upper troposphere. At surface, high pressures over Europe and low pressures over Africa produce initially southerly flow over the western Mediterranean which was gradually backing to southeast/east and increasing the speed with a long fetch over the sea. Warm advection over eastern Spain is also identified. At middle troposphere a cut off low developed south of the Iberian Peninsula associated with a notable nucleus of Potential Vorticity (PV) easily identifiable at 300 hPa. Then the meteorological situation can be classified as very representative of this kind of events. Satellite pictures show a MCC located over the Valencia coast (Figure 15).

The analysis of the case has been made by means of numerical simulations. Experiments were performed using the MM5v3, a full non-hydrostatic mesoscale model (Grell et al., 1995). Three domains were used to cover the wide range of scales of interest in this study. The coarse domain (7290 km × 9090 km), with a resolution of 90 km is used to reproduce the large scale aspects of the event. The second domain has a 30 km resolution

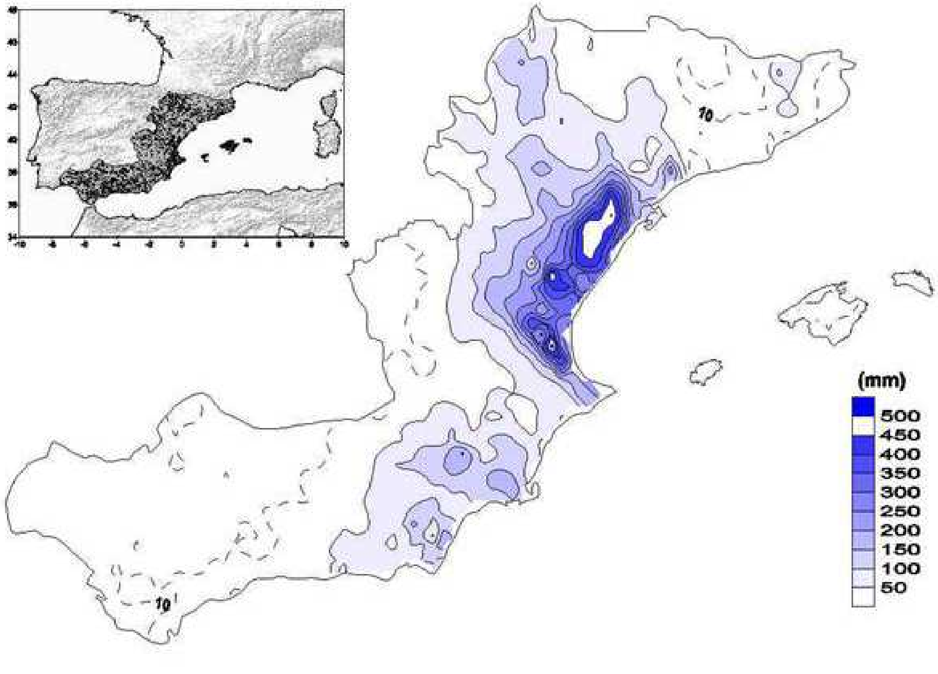

Figure 13.— Accumulated rainfall from 21 to 24 October 1994 in eastern Spain (from Homar et al. 2002)

and the fine domain has 10 km grid spacing and covers the eastern Iberian Peninsula and the Balearic Islands (1080 km × 1080 km) (Figure 16). The three domains interact by means of a two-way nesting strategy. Simulations for the coarse domain were 90 h long, from 20th at 12.00 UTC to 24th at 06.00 UTC. Simulations for domains 2 and 3 started on 22th at 00.00 UTC and extended 54 h ahead, until 24th at 06.00 UTC. The convective parameterization from Kain and Fritsch (1990) has been considered. Microphysics scheme for moist processes from Tao and Simpson (1993) has been included as well as the subgrid processes scheme of the planetary boundary layer from Hong and Pan (1996). Sea level temperature (SST) remains constant during the simulation. A radiation scheme, which accounts for long and shortwave interactions with the clouds and clear air, is also included (Benjamin 1983).

In the control experiment, initial and boundary conditions for the coarse domain are constructed from the global analysis of the NCEP available at 00.00 and 12.00 UTC which are reanalyzed at the model resolution using surface and upper air observations. NCEP weekly analysis also provides SST.

The model has been able to simulate the convective activity which produced the torrential rainfall with remarkable accuracy (Figure 17). The simulated precipitation distribution resembles the observed precipitation distribution and significant precipitation is simulated over north Valencia and south Catalonia.

The control simulation reproduces the cutoff low development as well as the persistent

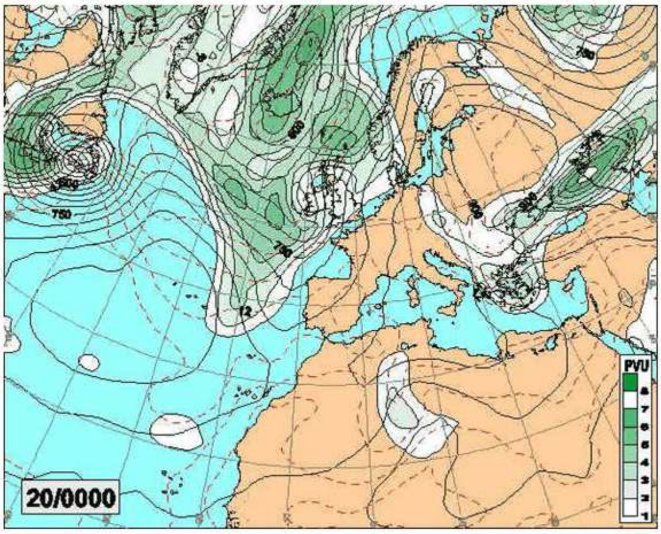

Figure 14.— Meteorological situation on 20 October 1994 at 00 UTC at surface (full lines represent isobars) and PV at 300 hPa (shaded) (from Homar et al. 2002 using NCEP analysis)

easterly low-level flow. Figure 18 summarizes the evolution of such synoptic scale structures. A LLJ is clearly identified over the sea, from the Libyan coast to eastern Spain, with 48 hours averaged 1000 hPa winds higher than 12 m/s. The presence of warm and moist air at low levels generated convective instability over the area. Figure 19 shows a wide area over the sea showing convective unstable profiles, with remarkable negative vertical gradient of equivalent potential temperature around 850 hPa. High values of precipitable water (PW) are also available to feed the convective systems ahead of the LLJ, necessary to maintain the precipitation efficiency. Subsynoptic lifting mechanisms are essential to develop the convective systems and these mechanisms are favored where the large scale upward motion is promoted. For this case, dynamic forcing for upward motion is weak at the synoptic scale over the region of interest as it is calculated using the Q-vector formulation of the w-equation (Hoskins and Pedder 1980). However, opposition to subsynoptic upward motion mechanisms is neither found at the synoptic scale. Orographic upslope flow, convergence ahead of the LLJ or convergences produced by the sea-land drag difference appear as possible subsynoptic lifting mechanisms.

5.2 Sensitivity experiments

In order to perform a first evaluation of the role of the cutoff low present at upper levels during the entire episode, a new experiment was done. To modify the strength of the cutoff, the PV inversion technique of Davis and Emanuel (1991) was used. The method consist of resolving the geopotential (ϕ) and streamfunction (ψ) from a system

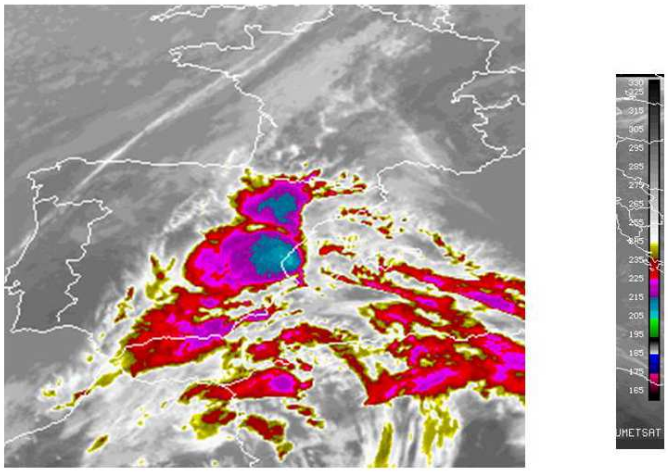

Figure 15.— IR Meteosat image on 10 October 1994 at 06 UTC (from EUMETSAT)

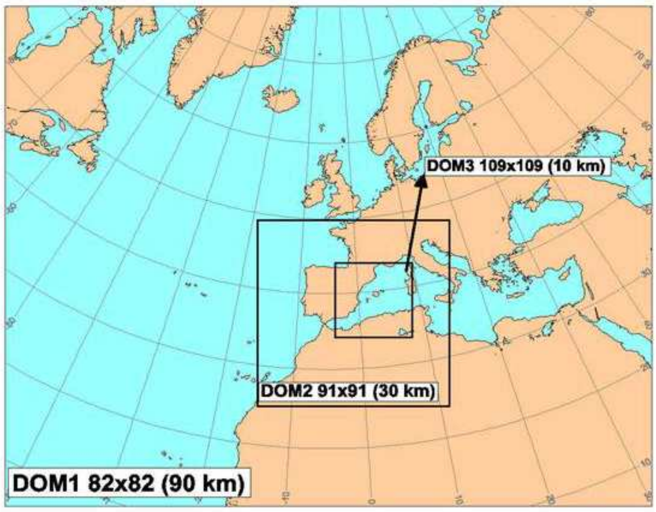

Figure 16.— The three domains used in the numerical study (from Homar et al. 2002)

formed by the Charney (1955) nonlinear balance equation

$$\nabla^2\phi = \nabla \cdot f\nabla\psi + 2m\left[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2} - \left(\frac{\partial^2\psi}{\partial x\partial y}\right)\right]$$

and an approximate form of the Ertel Potential Vorticity (PV, q)

$$q = \frac{g\kappa\pi}{p}\left[(f + m^2\nabla^2\psi)\frac{\partial^2\phi}{\partial\pi^2} - m^2\left(\frac{\partial^2\psi}{\partial x\partial\pi}\frac{\partial^2\phi}{\partial x\partial\pi} + \frac{\partial^2\psi}{\partial y\partial\pi}\frac{\partial^2\phi}{\partial y\partial\pi}\right)\right],$$

where g is the gravity, $\kappa = R/Cp$, the vertical coordinate π is the Exner function $C_p(p/p_0)^k$, p is the pressure, f the Coriolis parameter and m denotes the map-scale factor.

From an instantaneous distribution of PV and with appropriate boundary conditions, the three dimensional distributions of ϕ and ψ are obtained. Dirichlet upper and bottom boundary conditions are used following the hydrostatic condition. Lateral boundary

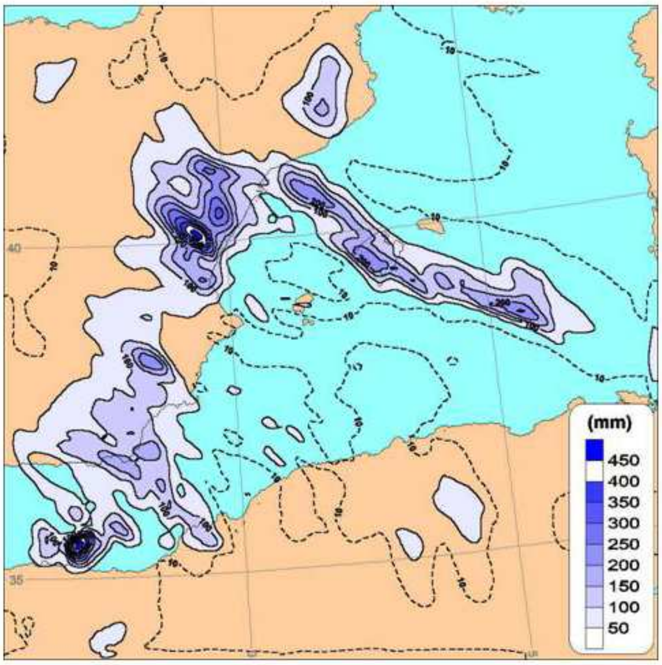

Figure 17.— Accumulated precipitation obtained in the control experiment (from Homar et al. 2002)

conditions are introduced through the geopotential and streamfunction values. The balanced fields obtained from the inversion process (using a relaxation method) are notably accurate, even at large Rossby numbers, due to the accuracy of the nonlinear balance condition used. Further the tridimensional temperature field is obtained by using the hydrostatic assumption, whereas the relative humidity is left unmodified in this process. Using this method, the dynamical structures of an instantaneous atmospheric state can be modified without introducing spurious mass and wind fields imbalances.

For the present study the identification of the PV structure associated with the cutoff low is first done, then its intensity is diminished and the inversion process is performed to obtain the geopotential and streamfunction fields corresponding to the modified PV field. The modified initial conditions for the numerical simulation are obtained following the scheme represented in Figure 20. The effect of weakening this PV anomaly is to diminish the trough intensity by reducing the vorticity field and to weaken the stability at the anomaly level by warming below and cooling above the perturbation. Figure 21 shows the PV, geopotential height and temperature at 300 hPa of the new initial conditions.

A simulation using the modified fields on 20 October at 12 UTC as initial conditions was performed. A very important change in the accumulated precipitation field with respect to the control experiment is obtained (Figure 22). Highest amounts over land are 30 mm. This reveals a high sensitivity of the precipitation amounts to the intensity of the upper level trough for this event. The upper level cutoff low developed by this simulation is weaker and lays further west compared to the control simulation. In addition, the

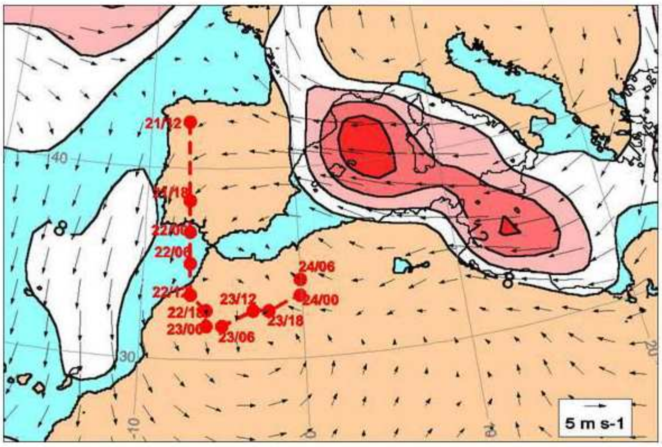

Figure 18.— Mean winds at low levels (m/s, contours are isotachs) and position of the trough at upper levels (dots) in the control simulation (from Homar et al. 2002)

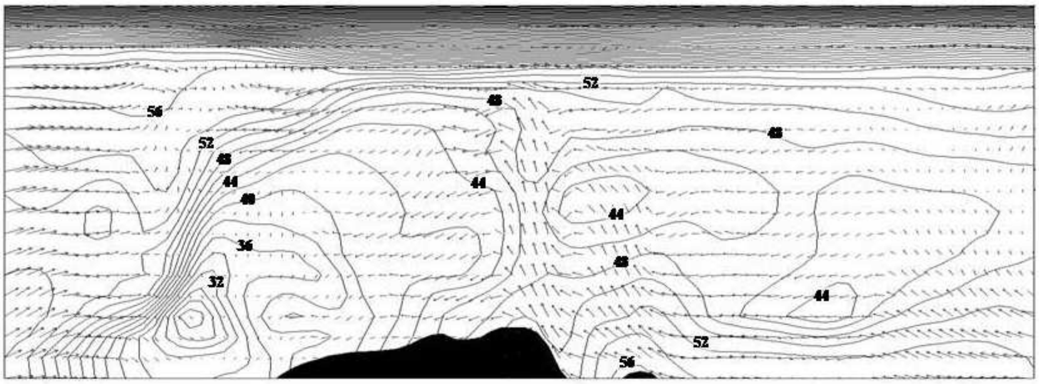

Figure 19.— Zonal vertical cross section along the Iberian Peninsula. Isolines represent EPT and show the existence of potential instability over the Mediterranean. The action of the orography on the wind field is depicted (from Homar et al. 2002)

LLJ over the Mediterranean is not developed in this simulation (Figure 23). As a result of the modification of the surface flow, large differences in the latent heat flux from the Mediterranean are obtained (up to values of 250 W m-2). Then, the influence of the upper level cutoff low is not a direct upward motion forcing over the area of precipitation, but indirect through the enhancement of the easterly flow over the western Mediterranean, producing the LLJ. Likewise, the PW over the eastern Iberian Peninsula and Balearic islands evolves in a very different way in the weakened trough simulation compared with the control experiment (Figure 24). The modification in the mid and low level circulation modifies the evaporation from the Mediterranean and the humid air transport toward the area where heavy precipitation occurred.

Two additional experiments were performed. Both identical to the control experiment but in the first the latent heat flux from the sea was not included (noLHF experiment) and in the second a flat orography has been considered (noORO experiment). The objective

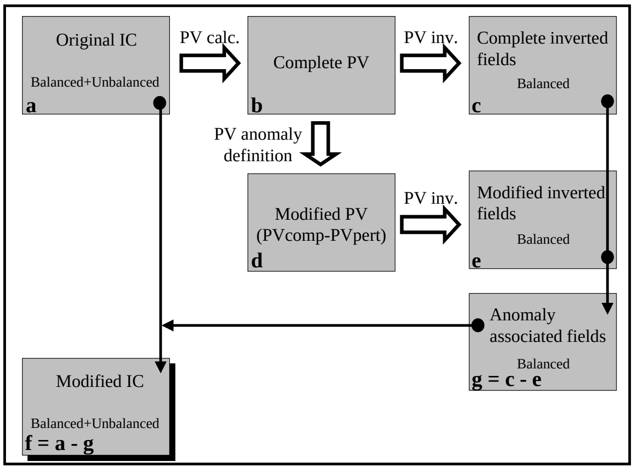

Figure 20.— Scheme of the process followed to modify initial conditions for the numerical experiment (from Homar et al. 2002)

was to analyze the importance of the evaporation from the sea to maintain precipitation during several days and the effect of the Spanish coastal orography as convection triggered through upslope forced flow.

In both experiments the LLJ is also obtained, but in the noLHF experiment the obtained accumulated precipitation is much weaker than in the control experiment. Maximum quantities are 50 mm over Valencia. A temporal evolution of the effect of the lack of evaporation on the PW can be seen in the Figure 24. When no orographic lifting is present, the precipitation is substantially lower and the rainfall structures are not concentrated along the coastal lands as in the control experiment (Figure 25). That demonstrates the important action of orography as a lifting and focusing mechanism. The evolution of the PW in the region is very similar to the control run (Figure 24). When no orographic uplift is considered, other weaker mechanisms emerge in the simulation, though much less efficient, as convergences at low levels in the exit region of the LLJ.

In summary, the numerical experiments performed reveal the capital influence of upper level cut off low intensity and location for generating an easterly LLJ over the Mediterranean. The continuous supply by the LLJ of moisture resulted in high values of precipitable water over eastern Spain. A crucial effect can be attributed to evaporation for the continuous replenishment of water vapor in the lower troposphere. The coastal ranges of the eastern Iberian Peninsula have emerged as primary convection triggering agents, focusing the precipitation on complex terrain regions.

6 Conclusions

Several aspects of the heavy rain episodes that occur over eastern Spain have been presented. The main general conclusions can be listed as:

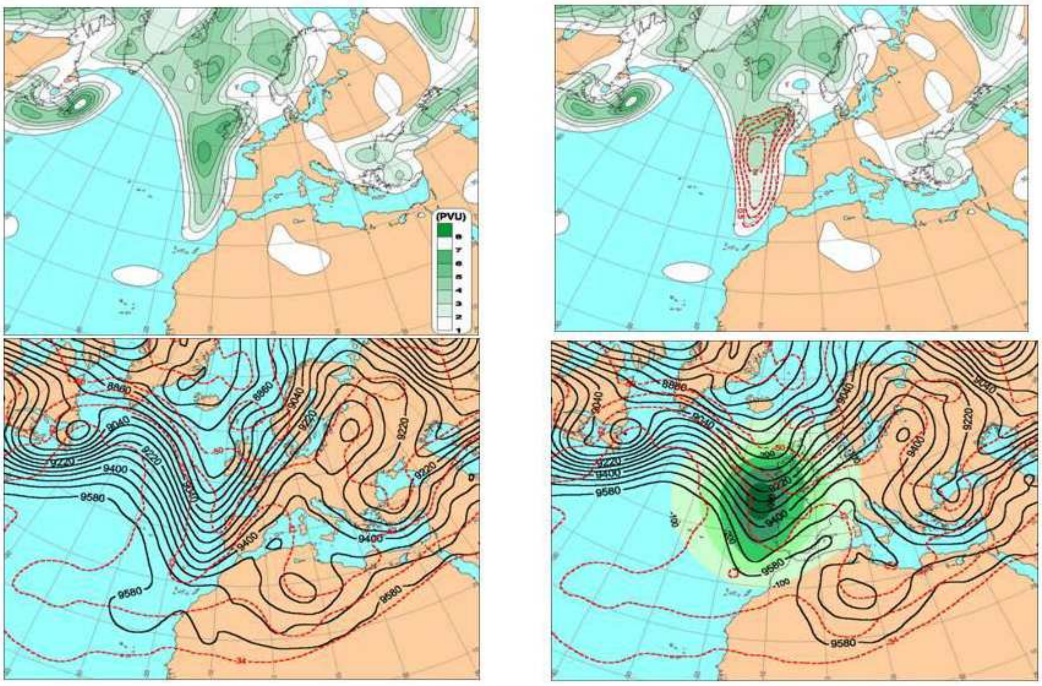

Figure 21.— Left: PV (up) and isohipses and isotherms (down) at 300 hPa corresponding to the control experiment. Right: PV (up) and isohipses and isotherms (down) at 300 hPa corresponding to the experiment with the upper level trough diminished (from Homar et al. 2002)

Objective classification of daily rainfalls and atmospheric circulations, using PCA and CA, results in a good methodology to link atmospheric patterns with rainfall spatial structures. These findings, combined with the outputs from Climate Models, can help determine future aspects of the spatial distribution of precipitation in Mediterranean Spain, a statistical downscaling methodology.

The conceptual model that describes the most important factors that act in the heavy rain episodes over the Spanish Mediterranean zone (orography and evaporation from the sea) has been confirmed. The use of meteorological numerical model outputs, processed through a factor separation technique has demonstrated that the synergy between the considered factors is the most important effect to explain the spatial distribution of the heavy rain.

By means of numerical model simulations and the PV inversion technique we have demonstrated that the action of the upper-level disturbance lying to the south or southwest of the Iberian peninsula in the cases of heavy rain in Mediterranean Spain, becomes decisive in the dynamics of the meteorological situation. Such disturbance acts indirectly by favoring the formation of a LLJ which transports huge amounts of water vapor toward the coastal regions. When the moist LLJ interacts with the orography, convection and heavy rain are promoted.

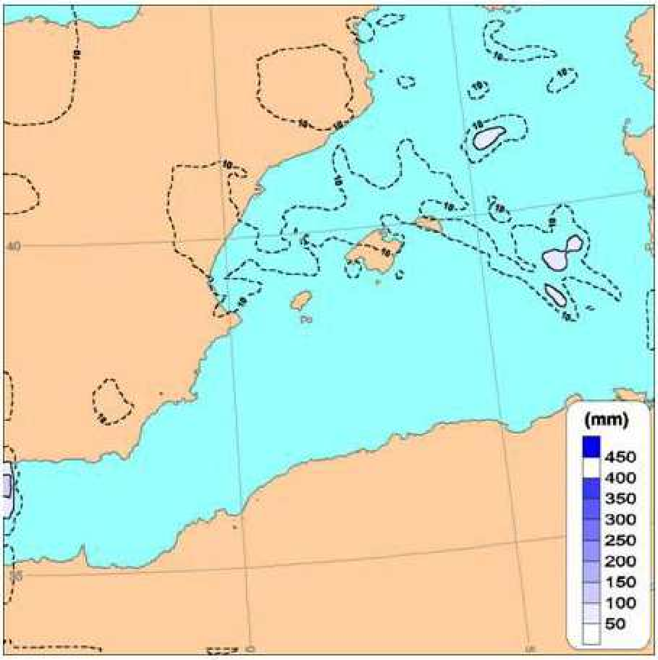

Figure 22.— Accumulated precipitation obtained with the experiment with the upper level trough diminished (from Homar et al. 2002)

Acknowledgements

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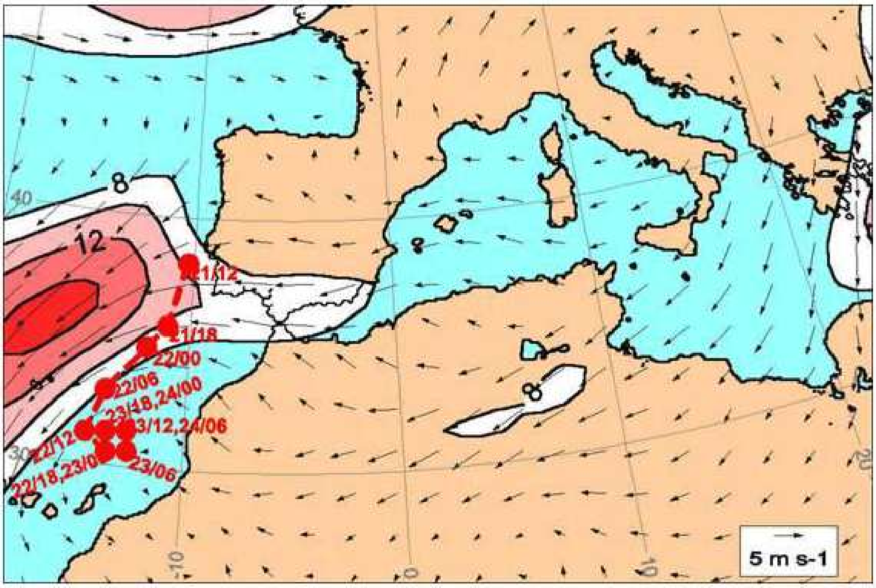

Figure 23.— Mean winds at low levels (m/s, contours are isotachs) and position of the trough at upper levels (dots) in the simulation with the upper level trough diminished (from Homar et al. 2002)

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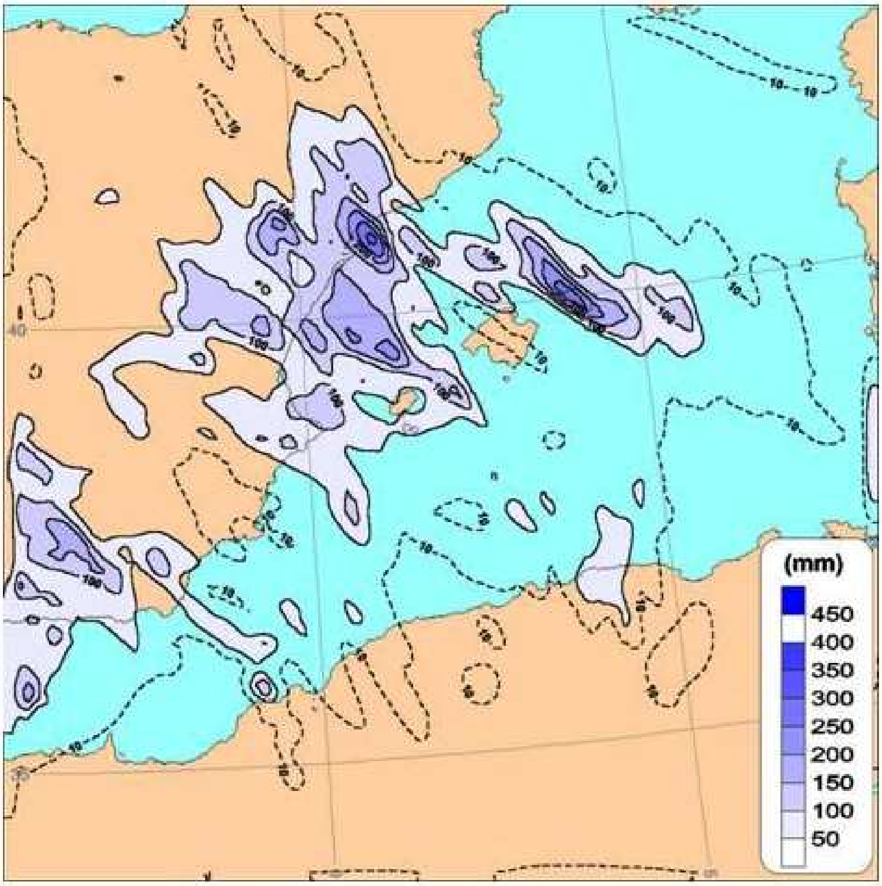

Figure 25.— Accumulated precipitation obtained with the noORO experiment (from Homar et al. 2002)

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