

OROGRAPHIC ROLE IN THE TEMPORAL AND SPATIAL DISTRIBUTION OF PRECIPITATION. THE CASE OF THE INTERNAL BASINS OF CATALONIA (SPAIN)

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Abstract

This paper is a contribution to the analysis of the high rainfall distribution in regions with a complex orography. First of all, a general introduction about the specific features of the Mediterranean meteorology has been provided, making specific reference to the influence of topography. In the second place, a preliminary summary of the state of the art about the kind of research related with the orographic role in rainfall production and distribution has been made. Afterwards, the watershed made up of the Internal Basins of Catalonia (Spain) is presented, showing the rainfall monitoring system in real time (SAIH project and meteorological radar).

1. Introduction

Local meteorology and climate can be considered as an interaction between the intrinsic atmospheric processes and the geographical substratum. The more geographically defined a specific region is, the more defined is its specific meteorology and climate. In this sense, the Mediterranean region is one of the best geographically defined regions in the world (Fig.1). Its very name means “in the middle of lands” and reminds us that it is surrounded by an almost continuous barrier of mountains, with crest heights between 1500 and nearly 5000 m. Besides this, the warm surface and deepest water of the Mediterranean sea (permanent temperatures above 13°C), combined with its specific geographic situation (extra-tropical and sub-tropical influences may alternate and even coincide) and its position between the cold Euro-Asiatic lands and the warm lands of Africa, constitute a suitable permanent framework to favour the existence of a specific Mediterranean air mass (Jansà, J.M., 1966; Jansà, A., 1997).

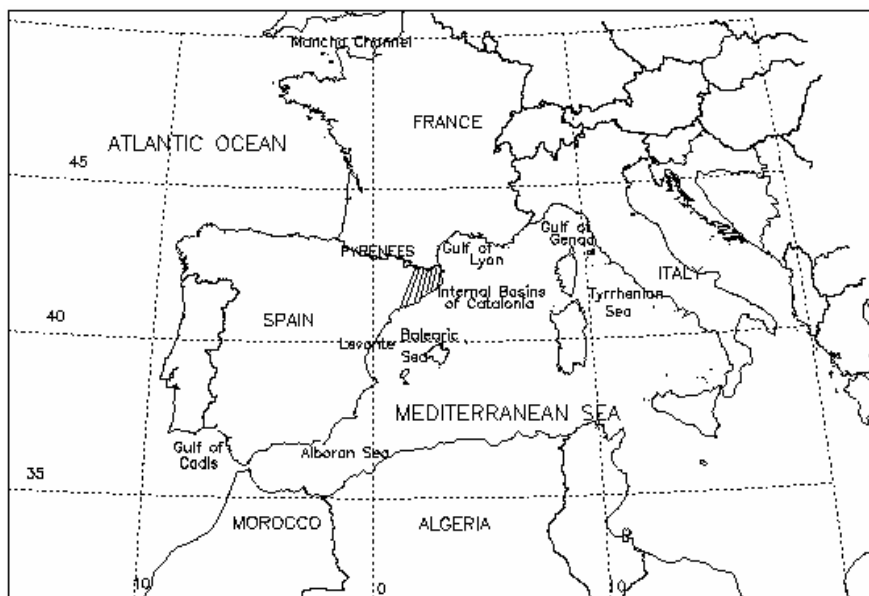


Figure 1. Map of the west Mediterranean Area showing Catalonia and the location of the Internal Basins of Catalonia (CIC).

On the other hand, the Mediterranean region presents some specific meteorological features. The most important are: a great concentration of

cyclogenesis, the heaviest extra-tropical rainfall events (even up to 800 mm in 24 h) and very strong local winds (Mistral-Tramontane, Bora, Etesians, etc. with 40 or even 50 kt of sustained speed. (Jansà 1997)

These characteristic meteorological factors, combined with these well-defined geographical features means that we can speak of a specific Mediterranean Meteorology (Jansà, 1966; Reiter, 1975), in which orography plays a decisive role. The two primary meteorological effects that appear almost continuously are (Jansà, 1997):

a) The formation of a particular low-level Mediterranean air mass, 1500-2000 m thick, warm and wet from autumn to spring and relatively cold and wet in summer, with the coastal lines and the mountain barriers forming quite permanent frontal boundaries. As a consequence, its vertical thermodynamic profile shows, usually, convective potential instability; the cooling of the upper layer and/or the lifting of the whole air column can release the latent convective energy, giving rise, if the other conditions are present, to heavy rains (Llasat and Puigcerver, 1992; Llasat *et al.*, 1996). A second consequence is the formation of low-level fronts when external air enters it, closely following the gaps between the mountains or flowing over the mountain ranges.

b) The appearance of lee depressions as well as the creation of low level potential vorticity nuclei, as a consequence of the interaction of the air-flow with the mountainous barriers. Hundreds of lee-depressions have been identified every year (Radinovic, 1978; Genovés *et al.*, 1997), affecting the local winds as well as, in the last analysis, rainfall production and distribution (Ramis *et al.*, 1994). The highest concentration of Mediterranean cyclogenesis corresponds to the Genoa region, with a secondary maximum located in the Catalan-Balearic sea and the Gulf of Lyon (Jansà, 1986). Other relative maxima are the Cyprus and Aegean region (Flocas and Karacostas, 1994) and the Adriatic Sea (Ivancan-Picek and Tutis, 1996).

2 Orography and heavy rainfalls in the Mediterranean meteorology

Seasonal distribution of heavy rain events in the Mediterranean (mainly in the west and central part) shows a maximum in late summer or autumn. This reveals the significant role of the Mediterranean air mass, warm and with very high water content during this epoch of the year, that favours the existence of a strong convective instability

A distinction between three kinds of heavy rain events and floods can be made:

a) Short-lived peaks of very intense precipitation, for which the local

amount of rainfall is nevertheless not usually very high (usually, less than 50 mm). This kind of event needs great instability.

b) Relatively large amounts of precipitation can be accumulated from rain of moderate intensity but falling over a long period (usually 100 or 150 mm approximately). In this case intense dynamic disturbances are needed.

c) Heavy rain sustained for several hours with large amounts of total precipitation (200-500 mm). This kind of event needs convective instability, large feeding of warm and wet air from low levels, and a mechanism to force air ascent to release the potential instability or to destabilise the air column.

The conceptual model (Llasat and Puigcerver, 1992; Jansà *et al.*, 1995, 1996) shows during the previous days a long anticyclonic situation over the Mediterranean, which favours the formation of a Mediterranean air mass and the accumulation of water vapour. Usually, the presence of any Mediterranean low or a convergence line organises the differentiated air currents as well as internal low frontal boundaries (Jansà *et al.*, 1996, have identified the presence of a cyclonic centre in 79% of 721 heavy rain cases in the Mediterranean Area). The intersection between the tip of a warm-wet current and a thermal-humidity boundary is the best place for reaching or releasing the convective instability and for developing large convective clouds that produce heavy rain. If the situation remains quite stationary the accumulated rainfall can reach very large amounts (i.e., 28 September-5 October 1987 in Catalonia, Ramis *et al.*, 1994). Another possibility is to substitute the low internal boundary by a mountain barrier that stops and forces the ascent of the warm-wet current (i.e., 6-8 November 1982, NE of Spain and S of France, Llasat, 1993). Usually, both variants appear combined and it is difficult to assess the contribution of each factor, having in mind the synergetic effects between them.

Less frequent are the cases of Mediterranean heavy rains produced by dynamically driven cases, usually related to deep cyclogenesis, that produce a deep and continued large-scale ascent. In these cases continuous moderate rain from stratified clouds with alternating heavy rain periods can occur. Sometimes the large scale forcing combined with orographic forcing can produce heavy rain in some places, for hours, even without convection. The cyclone itself provides the vigorous warm-wet feeding current to maintain the heavy rain for the necessary time to accumulate large amounts of precipitation (i.e. 18-19 October 1978, 500 mm in points of mountainous area of Majorca, Grimalt, 1992)

3 Main research lines about the influence of orography in rainfall distribution

Analysis of orographical influence in rainfall distribution constitutes nowadays an important and frequent line of research. In general, we can classify the different studies into three types according to their point of view, methodology and objectives. The more common are those related with specific case studies (mainly related with heavy rainfalls). Secondly, we find projects devoted to analysis of the orographic influence in the generation, triggering and distribution of rainfall, usually from a meteorological and physical point of view; this is the case of some studies made in the MAP project or cyclogenesis projects, with the final objective of improved forecasting for mountainous areas. Finally, we find studies that focus on modelling of rainfall space and time distribution, usually to improve some hydrological models and the management of water resources. In this last case stochastic methodologies as well as statistical ones are used. Some examples of each kind of study are shown next.

3.1 Orography in the heavy rainfall case studies

It is frequent to find references to the role played by orography in heavy rainfall events. This is the case of the flash flood that occurred in Biescas, Huesca (Spain) in the Central Pyrenees on 7 August 1996. The flood completely destroyed a camp site that was situated between two small gullies which overflowed. Of a total of 630 persons registered at the camp site, 183 sustained injuries of greater or lesser seriousness and a further 85 died in less than 45 minutes. The maximum precipitation was 269.3 mm in 24 hours, with 226.5 mm in only three hours (15-18 GMT) and 152.9 mm between 16 and 17 hours GMT. The focusing of the convection can be explained by taking into account the relationship between the mountains and the dominant flow at low levels. In fact, the slow shifting of the system as a consequence of the weak wind and the formation of new cells in the opposite direction to the movement of individual cells, combined with winds blowing perpendicularly to the ranges of more than 2000 m elevation, brought about the quasi-stationary nature of the system. So then the mature individual cells always arose over the vicinity of Biescas, thus explaining the great amount of precipitation recorded (for more information see Riosalido et al, 1997; Riosalido, 1998).

Between the 28 September and 5 October 1987, 431 mm were recorded in Barcelona (Catalonia, Spain). In this occasion the main role of the Pyrenees was related with the generation of a strong orographic dipole, giving rise to a strong meso-high over Catalonia. As a consequence of this high, the synoptic south-easterly wind at low levels was substituted near the Catalan coast by a westerly wind

and a convergence line was developed over the Mediterranean sea, off Catalonia. The situation remained quasi-stationary for a few days and the continuous vertical forcing of the convective unstable wet air gave rise to generation of an MCS (Ramis *et al.* 1994). The rainfall distribution over land clearly shows the effect of the coast and the Littoral mountain range, with the maximum values between the coast and the mountain. On the other hand, in the November 1982 event (408 mm in 24 h in parts of the Pyrenees) the high mountains were responsible of the triggering of instability. Besides other synoptic and mesoscale characteristics, highest rainfalls will be recorded near the Littoral range (maximum altitude, 500 m) or near the Pyrenees range (altitudes between 1000 and more than 3000 m) in function of the vertical distribution of the convective instability over the Catalano-Balearic sea (Llasat and Puigcerver, 1992).

Obviously, orography plays an important role in the floods that occur in the North of Italy. This is the case of the Versilia event, in the Tuscany region, on 19 June 1996. On that occasion, heavy precipitation over twelve hours occurred (maximum accumulated value 478 mm). Strong potential instability with large CAPE values, low-level jet mainly driven by the local topography; synoptic forcing was very weak and therefore the local mesoscale conditions were responsible for the outbreak of the convection (Frontero *et al.*, 1997). In the case of the 26-28 September 1992 event, with floods in the Rousillon (France) and Liguria (Italy) regions, the mountain littoral ranges over which the wind impinged perpendicularly triggered the convection which remained latent over the Mediterranean sea, with high CAPE values, strong quasi-geostrophic vertical forcing, water vapour nourishment and instability in low and medium levels (Llasat *et al.*, in press)

Sometimes, orography does not play any role. This was the case on 12 September 1996, in the Balearic Islands, when a quasi-tropical /CISK cyclone 150 km in diameter crossed the Islands just over Majorca. The latent heat release was the main cause but due to low precipitation efficiency rainfall was not very heavy. An external synoptic forcing was responsible for the convergence from the outset: a cut-off low in high levels, a cyclogenesis in the Algerian sea and very warm water (Gili *et al.*, 1997). On the other hand, in Eastern Mediterranean countries, where high rainfalls with more than 100 mm/24 h are a strange phenomena, the role of orography is secondary or null in rainfall production. For instance, an extreme rainfall event (maxima of 44 mm/day in the Balkans and Asia Minor) over the Black sea, Ukraine and Russia occurred from 28 March 28 to 1 April, 1995. The event started when a secondary cyclonic eddy was formed in a deep trough over the North of Italy and passed to the Adriatic sea, but the main factor was a frontogenetically-driven circulation (Chakina and Berkovich, 1997).

3.2 Orography in meteorological models and projects

The importance of orography in cyclones and cyclogenesis location in Mediterranean areas has been shown by Genovés *et al* (1997) after application of the HIRLAM mesoscale analysis model (0.5° network). A first quantitative statistic assessment of the weight of the orographic factor (OFA) in Mediterranean cyclone generation is given by the expression:

$$OFA = -\vec{v} \cdot \nabla h$$

The OFA distribution shows absolute maxima in the lee of high mountain ranges, where the most intense mesolows are detected. The majority of them are stationary and only a few of them develop into great cyclogenesis when a high-level disturbance approaches.

In this line we might locate the studies made by Alpert (Alpert, 1986, Alpert and Shafir, 1989) at mesoscale, making specific reference to the wind topography interaction and using data from meteorological radar. Their model assumes that orographic precipitation can be calculated from the water vapour convergence caused by the mechanisms of air ascent and precipitation as a consequence of synoptic convergence. An easy model is that proposed by Weson and Marjory (1994) that considers the changed water content in a cloud column. In this line, Palmieri (1992) proposes a model to evaluate the orographic effect on precipitation in function of the altitude and slope of the mountain, the speed that the air that impinges on the mountain and the precipitable water mass

But, nowadays, the most important European project related with the role of orography in weather phenomena is the MAP (Mesoscale Alpine Programme). Although the project deals with other meteorological phenomena, the fact that natural disasters in the Alpine region are linked to strong precipitation events has forced consideration to be given to improvement of rainfall forecasting, one of the main objectives. Indeed, the first primary scientific objective is “to improve the understanding of orographically influenced precipitation events and related flooding episodes involving deep convection, frontal precipitation and runoff”. After a multi-year preparatory phase which will end this year, a 13-month observation period will start, followed by a 2-year evaluation phase. Besides this, the project is linked with the results of preliminary projects, such as ALPEX (Alpine Experiment, 1981-1982 /GARP, 1986) or PYREX (Pyrenean Project, Bougeault *et al*, 1993) or present projects such as GEWEX (Global Energy and Water Cycle Experiment).

3.4 Analysis and models of rainfall distribution and orography for hydrological applications

One objective of the FRIEND-AMHY project of UNESCO is rainfall regionalisation in Alpine and Mediterranean countries. In relation with this project, two programmes have been developed over the French Alps, pointing to the knowledge of the conversion factors from the rainfall in valleys to rainfall at high altitudes, in order to have a detailed but regional cartography of the rainfall (Desurosne and Leblois, 1997). At regional scale, the IdF-Sud/Est programme has been carried out by Cemagref (Lyon and Grenoble), EdF, IMG-LTHE of Grenoble and Région Rhône-Alpes. Rainfall data have been recorded at different time steps between 1h to 24 h for 66 raingauges placed from the Jura mountains to the Mediterranean sea. From 1997, extension towards the Italian Alps has been made. The second programme has been developed at basin scale by Cemagref, since 1986. The TPG (Transect de Pluviographes pour l'analyse et la modélisation des Gradients Pluviométriques d'altitude) contemplates 23 raingauges from Lyon to the Belledonne massif covering a distance of 100 km with altitude increasing from 500 m to 3000 m in a W-E direction. In this case data are only available from May until October.

The main results of the two programmes show the need for making a prior classification of the perturbations before trying to model the spatial rainfall distribution (i.e., the precipitation features associated with perturbations from the W - the most frequent- is completely different from the heaviest that occur in summer by thunderstorms mainly developed into S or SW flows). The application of a synthetic model to the rainfall intensities shows that the local factor influence is more important in estimation of the quantiles of long duration of rainfall (i.e. 24 h) than for quantiles of short duration (i.e. 1 h), independently of their return period. As a consequence, the influence of relief over the Montana quantiles is different for the different time steps: regional for rainfalls of short duration; regional and local for rainfalls of long duration. For a long duration, the maximum accumulated rainfall is found near the mountain peaks, although on some occasions other local features can affect this distribution (i.e., in the Chartreux range, the precipitation rainfall associated with local thunderstorms increases with altitude up to 1000 m, but, above this level, they decrease). It is thus possible to make a synthetic model of rainfall rates in the pre-Alpine range, using the equations proposed in the IdF/Sud-Est programme and one coefficient per massif.

Recent results obtained from a CICYT Spanish project for a pluviometric transect near the Llobregat mouth shows the maximum accumulated rainfall near the high altitudes and the maximum intensities near the valley (Llasat et al, 1997). Similarly, an analysis made from 6 floods between 1992 and 1993 with more than 100 mm of accumulated rainfall in each of them, over the Soca river watershed (Slovenia-Italy), corroborates those results. This basin of 3450 km² is divided into 25 sub-watersheds

from 3 to 182 km² and with mean altitudes between 50-1319 m. Rainfall data are collected daily at 50 rainfall stations (7 of them with recording) and 8 gauging stations, located in Italy and Slovenia.. The results show that on large flat areas, rainfall cells are situated randomly, but in the mountainous areas the orographic effect leads to more rainfall at higher altitudes. Daily raingauge data and daily mean sub-watershed rainfall data were cross-correlated, showing that the linear regression between the different sub-watershed samples is better for high rainfall (Brilly, 1997)

The Spanish contribution to rainfall regionalization in the AMHY-FRIEND project has been made on the basis of 2231 pluviometric stations (Ferrer and Ardiles, 1994; Ferrer, 1997). The schema used was the one termed “index variable”, which assumes a single a-dimensional law within the region re-scaled by means of a local factor. The index rainfall method has also been applied at national scale in Great Britain (Reed, 1992). The local scale factor, usually the mean, can be estimated at the site of a meteorological station by means of the AMS sampling mean, though it has to be extrapolated to points without records. Two types of procedures are used: a) in zones of gentle topography and good density of pluviometric stations, by using simple spatial interpolation techniques; b) in zones of complex topography or with a low density of stations, relationships must be established with the main variables: altitude, degree of exposure to winds and distance from the coast. Of interest in this respect are the papers by Philips et al., 1992 using co-kriging techniques with a digital terrain model, and Ferrari et al., 1990 which used logarithmic correlation with altitude. Other studies made using empirical relations are, for instance, those of Bleasdale and Chan (1972) and Spackman (1994), who even use equations for the adjustment with more than 31 coefficients.

4. The case of the Internal Basins of Catalonia: characterisation of the rainfall distribution

The Internal Basins of Catalonia (C.I.C.) are situated in the north-eastern part of the Iberian Peninsula, and cover an area of 16000 km² (Fig. 2). The rainfall and gauge data are obtained in real time from the SAIH (Sistema Automático de Información Hidrológica) of Junta d'Aigües of the Generalitat de Catalunya. The rainfall network is comprises 125 tipping-bucket automatic raingauges with a rainfall overttuning of 1.0 mm and the precipitation is accumulated and recorded every 5 minutes. Data are available since January 1996.

As has been said before, high rainfall events in Mediterranean countries are usually produced by convective events. The analysis of the convective rainfall contribution in the Internal basins of Catalonia and their relationship with the

orography has been made by using the β parameter (Llasat, 1998) calculated following the expression:

$$\beta_{L, \Delta T} = \frac{\sum_{i=1}^N I(t_i, t_i + \Delta T) \theta(I - L)}{\sum_{i=1}^N I(t_i, t_i + \Delta T)}$$

in which T is the time-interval of accumulation of the precipitation, expressed in minutes (5-minutes), N is the total number of T integration steps into which the episode is subdivided,

$I_L(t_i, t_i + t)$ is the precipitation measured between t_i and $t_i + t$ divided by t, that is, the mean intensity in the said interval expressed in mm/min or mm/h and

$\theta(I-L)$ is the Heaviside function defined as:

$\theta(I-L) = 1$ if $I > L$

$\theta(I-L) = 0$ if $I < L$

$\theta(I-L) = 1$ if $I = L$

where L takes the value of 35 mm/h.

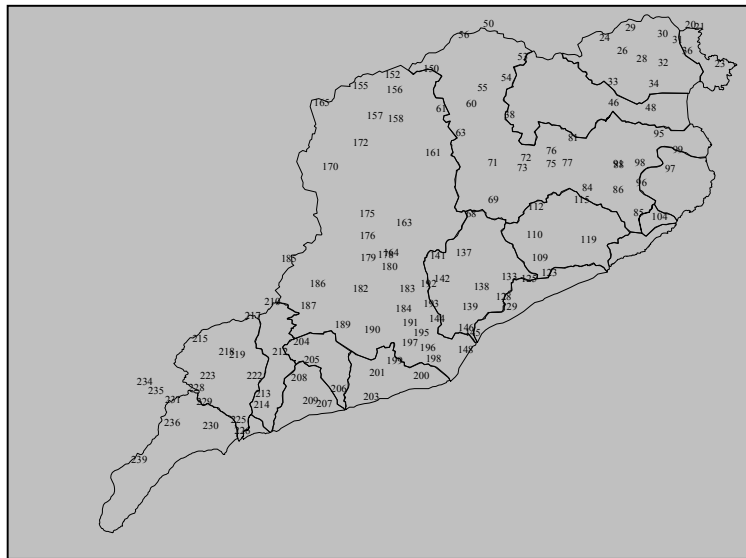


Figure 2. Raingauges network of the SAIH of the Internal Basins of Catalonia.

Figure 3 shows the accumulated rainfall distribution in the CIC between 1996 and 1998. Values above 900 mm are placed over the Pre-littoral and Transversal mountain range and the Pyrenees. Figure 4 shows the β distribution for the period January 1996–December 1998. Maximum values above 0.2 (that is to say, more than 20% of the 5-minute intensities recorded during the three years surpassed 35 mm/h) are located near the Prades mountain range and over the Alt Empordà, a plain zone situated in the E lee of the Pyrenees range. It is interesting to note the differences between the two distributions, mainly the strong convective contribution on the coast, in the lee of the Littoral mountain range.

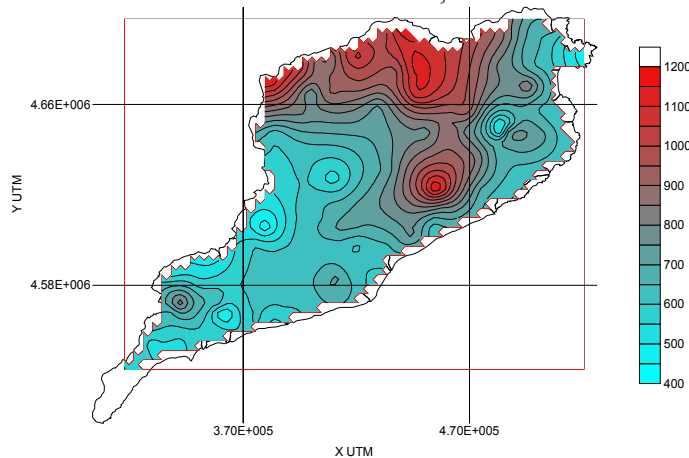


Figure 3. Average annual rainfall distribution in the Internal Basins of Catalonia (1996-1998).

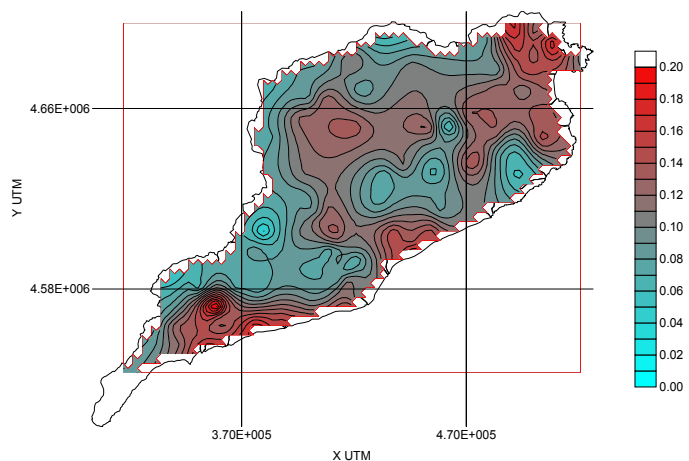


Figure 4. Convective rainfall distribution in the Internal Basins of Catalonia (1996-1998).

According with the pluviometric and β champs and with their evolution along the event, it is possible to distinguish between three types:

a) Precipitation produced by rainfall bands

Usually these bands have a movement direction from S/SW to N/NE. The orography has an important role in the accumulated rainfall distribution showing the highest values in the south lee of the Pyrenees, pre- Pyrenees and Prades range ($h > 1000$ m).

b) Precipitation produced by isolated convective cells

The greatest part of these events are associated with mechanical and thermal convection during the warm season of the year. Maximum accumulated rainfall is recorded over the Pyrenean and Pre-Pyrenean region, but the highest intensities can be recorded near the littoral range ($h < 500$ m). The events are very convective and high intensities are recorded. The rainfall distribution is very irregular

c) Precipitation produced by a uniform precipitation champ

Associated with easterly air flow over Catalonia at low and medium levels of the troposphere. Important orographic effect of the Prelittoral range showing a major accumulated precipitation over the oriental lee rather than over the occidental lee ($500 < h < 2000$ m). Although usually these are non-convective events, catastrophic high rainfall events sometimes occur within this framework.

Summary

This contribution shows some research lines related with the influence of orography on rainfall distribution and generation, that has an important role in Mediterranean Meteorology. Considering the main objective of the study and its methodology, it is possible to classify them into three types. The more common are those related with specific case studies (mainly related with heavy rainfalls). In the second place we find the models and projects devoted to analysis of orographical influence in the generation, triggering and rainfall distribution, usually from a meteorological and physical point of view, as for instance the MAP project. Sometimes they include case studies and their final objective is to improve forecasting in mountainous areas. Finally, we find the studies directed towards modelling the rainfall space distribution, usually to improve hydrological models and the management of water resources. In this last case stochastic methodologies as well as statistical ones are used.

With the final objective of modelling orographic effect on rainfall distribution in the Northeast of Spain, the paper includes recent results obtained from the SAIH automatic rain gauge network in the Internal Basins of Catalonia. Following analysis of all the rainfall events recorded between 1996 and 1998, it proved

possible to distinguish three types of meteorological situation in which the different mountain ranges had a specific role. Analysis of each kind of situation using meteorological radar has now started. The INM (Spanish National Meteorological Institute) radar in Catalonia, is located near the city of Barcelona. It is a S-band radar ($\lambda= 10\text{cm}$) that operates in two modes, normal and doppler, storing the images in normal and doppler mode every 10 minutes.

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