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Analysis of the precipitation and cloudiness associated with COLs occurrence in the Iberian Peninsula

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With 14 Figures

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Summary

The Iberian Peninsula is one of the regions in the world with higher occurrence of cut-off low systems (COL). The aim of this paper is to analyse the weather events (rainfall and cloudiness layer) associated to COLs in the Iberian Peninsula with tools not previously used: (a) the use of the new multidecadal COLs database developed by Nieto et al (2005) that permit us to study a 41 years period (1958–1998), (b) the checking of the expected weather events (rainfall and cloudiness layer) associated with COLs in a conceptual model (Winkler et al, 2005) and (c) the extensive use of radiosoundings to analyse convective instability in areas inside and close to the COL. Two points of view are used to make the analysis: (1) a source oriented method, when a particular COL is followed and its associated precipitation and cloudiness is analysed over four quadrants in which Iberia was divided and (2) a receptor oriented method, when the precipitation associated to COLs is analysed in given areas, defined by patterns of precipitation. Results reveal that the precipitation and cloudiness patterns associated to COLs in the conceptual model reproduce quite well the main characteristics found over the Iberian Peninsula. The generalized idea that most of the COLs produce intense convective rainfall is show to be misleading. Convective phenomena are important usually when the centre of the COL is located on the Mediterranean region. Most of the rainfall associated with COLs comes from the baroclinic shield; specially in cases located over the west half of the Iberian Peninsula. It is shown that nearly 30% of COLs do not induce any rainfall; most of them located in the southern half of the Peninsula, and mainly during autumn. Only 30% of COLs produce generalized rainfall over the whole analysed territory, being most of them (about 90%) located over the western half of the Iberian Peninsula.

1. Introduction

Cut-off low systems (COLs) are closed cyclonic eddies isolated from the main western stream. These lows are upper and midtropospheric features and consequently they do not need to have a corresponding low at the lower levels of the troposphere (Palmen and Newton, 1969; Winkler et al, 2005). However, sometimes a COL may start as an upper-level trough extending to the surface after its development. Its intensity is higher in the upper troposphere, decreasing downward and being even possible to find anticyclonic circulation at the surface. The disturbances related to the cut-off lows can be recognized as a maximum of potential vorticity (PV) on isentropic surfaces (Hoskins et al, 1985) or as closed geopotential contours with a cold core on isobaric maps (Palmen and Newton, 1969).

In general, COLs produce significant precipitation only when they receive a significant transport of moisture at low and midlevels, then becoming a potentially unstable air mass (Knippertz and Martin, 2005). This instability is quite usual under southward COLs and convective – and sometimes severe – events occur frequently in the affected areas, the severity depending on surface conditions, particularly these related to moisture input. Thus, weather forecasting associated to COLs is particularly difficult, being of outmost relevance the characteristics of the terrain underneath and the presence/absence of a warm sea surface temperature that permits/inhibits the convection. If the conditions are favourable, COLs can produce moderate to heavy rainfall over large areas. Over Iberia the presence of COLs is frequent (Nieto et al, 2005), being often associated with catastrophic weather events like heavy rainfall, hail, storms and floods (Llasat et al, 2005) and the losses derived from the occurrence of these systems can seriously affect the local economy.

The COL conceptual model (Winkler et al, 2005) describes typical life cycles of precipitation and cloudiness for these systems. Figure 1 shows the associated cloudiness in a COL ac-

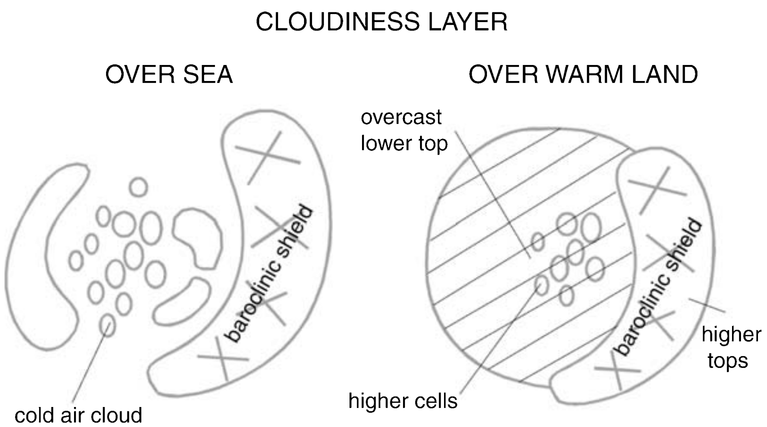


Fig. 1. Main zones of cloudiness in a COL according to the conceptual model when they occur over sea or over land (adapted from Winkler et al, 2005)

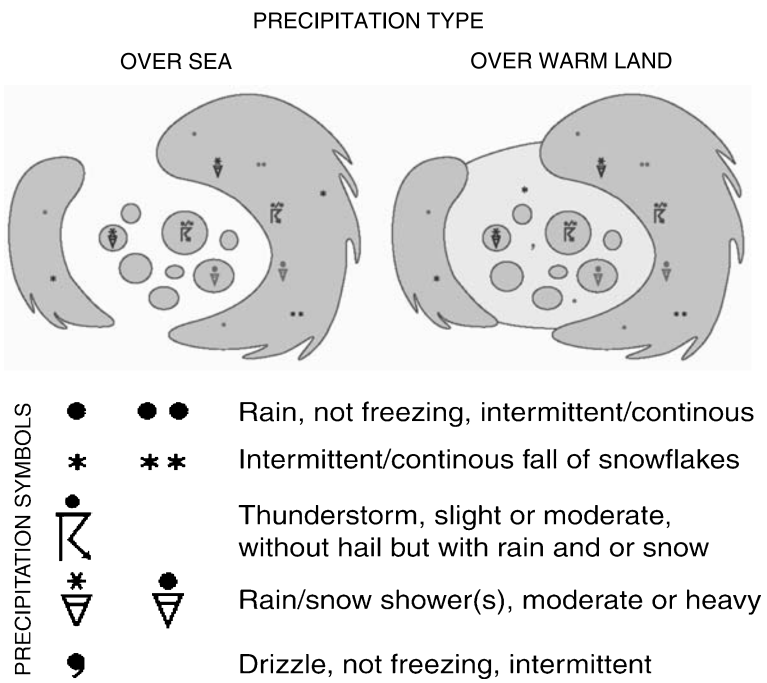


Fig. 2. Synoptic phenomena linked to precipitation associated with COLs over sea or over land, according to the conceptual model (adapted from Winkler et al, 2005)

cording to this model and its dependence of the underlying terrain. Figure 2 indicates the synoptic phenomena linked to precipitation associated with COLs. In general (Kurz, 1998; Winkler et al, 2005), the cloudiness associated to a COL is related to a frontal zone in the advancing edge of the system (baroclinic shield). This cloudiness is thick and has enough developed to produce precipitation. Some fibrous cloudiness may appear in the rearward branch of the upper level trough. Dry air is usual around the trough axis and cold air cloudiness may also exist in this area in the initial stages of the COL life cycle. This cloudiness is produced predominantly by convergence within the mid- and upper levels of the troposphere. In the final stages of COLs lifecycle both cloud bands become stronger. As a consequence of the potentially unstable stratification of the troposphere within the centre of the COL, convective cloudiness can also occur. When a COL occurs over land (Fig. 1) its centre is usually covered by a low cloud layer, suppressing the condition for convective precipitation. Over the ocean (Fig. 1) moisture supplies trigger the convection and the probability of precipitation, being this frequently strong or moderate. According with the conceptual model strong precipitations occur when convective cells are formed in the centre of the COL (Winkler et al, 2005). This occurs frequently in the Iberian Peninsula during autumn, or when COLs occur in subtropical areas, like the Canary Islands, where these systems are especially important for the precipitation regime (García et al, 2001). Although less important than the cloudiness associated with the leading edge of the COL, it is also frequent some cloudiness and light precipitations associated with secondary frontal areas in the rear edge of the system.

Though there are some previous studies of the precipitation and cloudiness associated with COLs over Iberia (Martin León, 2003; Jansá, 2004), these are limited to case studies and published as technical reports of limited scientific diffusion. These studies conclude that the direct connection between COLs and intense rainfall events over Iberia is erroneous. Some particular case studies during a 10 years period – from 1974 to 1983 – (Llasat, 1987; Llasat and Puigcerver, 1987, 1989, 1990) showed that not every COLs produces heavy precipitations over Iberia, and not every heavy precipitation event is triggered by COLs. They found that there was not any kind of precipitation for 67% of days of the COLs they analysed, and when precipitation was developed its distribution was very dependent on the COL position. In general, if the COL centre is over the Southern part of the Iberian Peninsula the highest precipitations occur over the Cantabric coast or over the Northeast quadrant of the Peninsula, and if the COL is over the Eastern Iberian coast the maximum precipitation are recorded at its western part.

The objective of this paper is to analyse the weather events (rainfall and cloudiness layer) associated to COLs in Iberia with tools not previously used, namely: (a) the use of the new multidecadal COLs database developed by Nieto et al (2005) that allow us to study a 41 years period (1958–1998), b) to characterize the amounted weather events (rainfall and cloudiness layer) associated with COLs in a conceptual model (Winkler et al, 2005) and c) the extensive use of radiosoundings to analyse convective instability in areas inside and close to the COL.

2. Data and methodology

Data: The daily multidecadal Northern Hemisphere COL dataset (41 years, 1958–1998) from Nieto et al (2005) was used. A brief description of the method used to identify COLs is also included in this issue (Nieto et al, 2006). The region of study is centred on the Iberian Peninsula; therefore we have restricted our analyses to those COLs that occur in a box from 30° to 50° N and from 15° W to 10° E. To analyse the weather events associated with COLs, data of precipitation and cloudiness from the main stations of the INM (Spanish National Meteorology Institute) were used. These dataset cover the area of the Iberian Peninsula (except Portugal) and Balearic Islands, with 69 stations for the precipitation and 50 for the cloudiness (Fig. 3). The studied period was from 1958 to 1998 for precipitation data, and from 1973 to 1998 for cloudiness due to dataset availability. Daily precipitation corresponds to the 24 hours-period beginning at 07UTC. The whole COLs' dataset without seasonal split was used for the global compute of precipitation and cloudiness.

Radiosounding data from IGRA –Integrated Global Radiosonde Archives– from the National

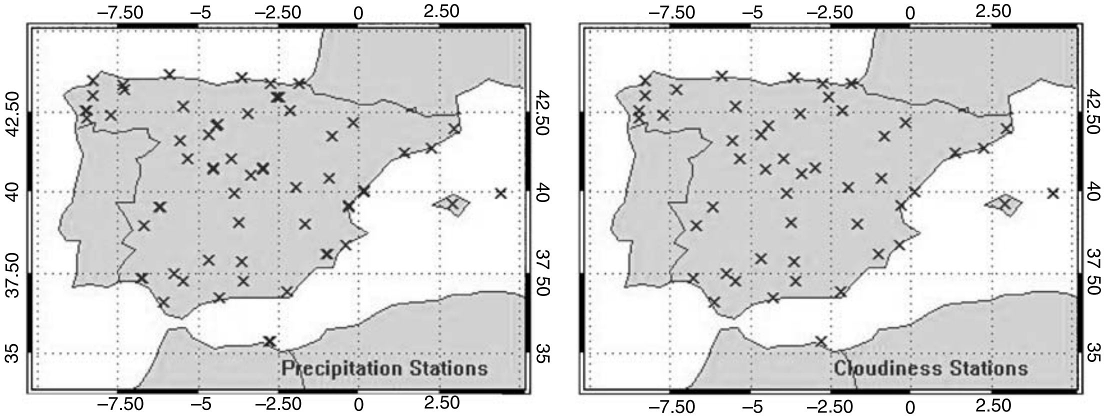


Fig. 3. Geographical distribution of INM's stations for precipitation and cloudiness

Climatic Data Center (Durre et al, 2006) were used to characterize the vertical profile of the COLs and calculate their instability. IGRA consists of quality-assured soundings at over 1500 globally distributed stations. The dataset was created by merging data from 11 different sources with varying period of records and for different areas of coverage. The overall period of record spans from 1938 to present, however, many stations present much shorter time series. The observations include pressure, temperature, geopotential height, dewpoint depression, wind direction, and wind speed at standard surface, tropopause, and significant levels. IGRA is the most comprehensive radiosonde available dataset (Durre et al, 2006). Its temporal and spatial coverage is the most complete over the United States, Western Europe, Russia and Australia. In this study, we used data only from stations in the box from 32.5° to 50° N and from 12.5° W to 10° E. Table 1 gives details of the radiosonde stations used in this study, such as their position, elevation or WMO code (the official station code from the World Meteorological Organization).

Methodology: Two criteria were used to study the precipitation and cloudiness associated to COLs over the Iberian Peninsula.

– The first criterion is a source oriented method, when a particular COL was followed and its associated precipitation and cloudiness analysed directly over four quadrants in which Iberia was divided (Fig. 4).
– The second one is a receptor oriented method, when the precipitation associated to COLs was analysed in given areas. These areas were classified by using precipitation climatological patterns (Fig. 10).

Table 1. Description of the radiosonde stations used. The latitude and longitude are in decimal degrees. (WMO: the World Meteorological Organization Code of each radiosonde station)

Radiosonde station listing

WMO	Name	Localization	Elevation (m)	Latitude	Longitude
7645	NIMES/COURBESSAC	France	62	43.87 N	4.40 E
8001	A CORUÑA CITY	Spain	67	43.37 N	8.42 W
8023	SANTANDER CITY	Spain	65	43.47 N	3.82 W
8221	MADRID/BARAJAS	Spain	582	40.45 N	3.55 W
8301	PALMA DE MALLORCA	Spain	39	39.55 N	2.60 W
8430	MURCIA CITY	Spain	62	38.00 N	1.17 W
8495	GIBRALTAR (CIV/MIL)	Gibraltar (UK)	5	36.15 N	5.35 W
8521	FUNCHAL/MADEIRA	Portugal	55	32.68 N	16.77 W
8579	LISBON/GAGO COUTINHO	Portugal	105	38.77 N	9.13 W
16560	CAGLIARI/ELMAS (AFB)	Italy	1	39.25 N	9.05 E
60155	CASABLANCA/ANFA	Morocco	62	33.57 N	7.67 W
60390	DAR-EL-BEIDA/HOUARI	Algeria	25	36.72 N	3.25 E

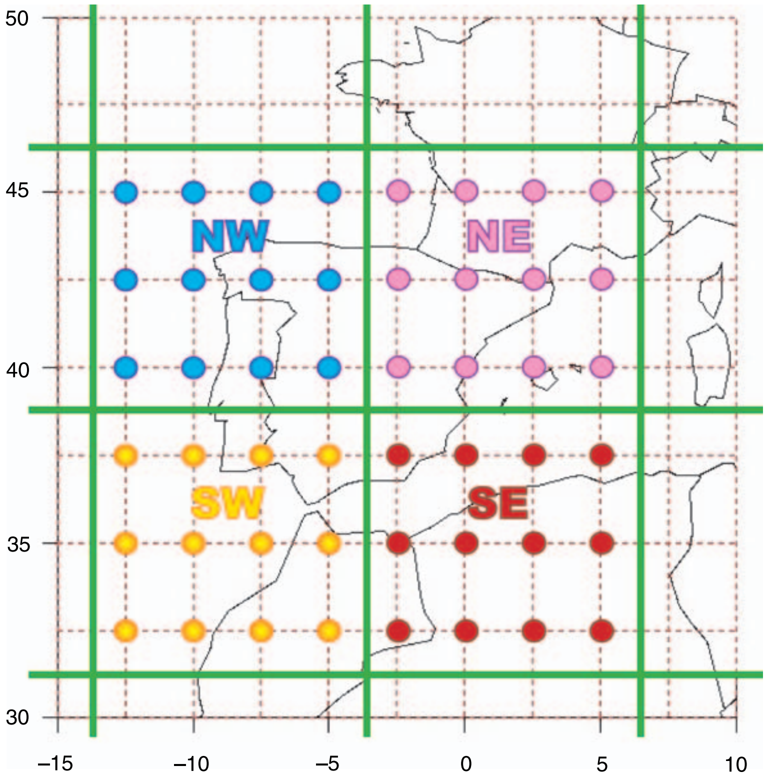


Fig. 4. Regionalization of the Iberian Peninsula in four quadrants to evaluate the precipitation and the cloudiness layer depending on the position of the COLs

For both approaches the region of study was divided in boxes of 2.5° × 2.5° (Fig. 4). The average precipitation and cloudiness layer associated for the first day of occurrence of every COL was calculated for each box.

3. Results

3.1 Analysis of the precipitation and the cloudiness layer depending on the COLs position (source oriented)

In this approach, the Iberian Peninsula was divided into four quadrants: Northwest (NW), Northeast (NE), Southwest (SW) and Southeast (SE) (Fig. 4). For the period covered by precipitation data (1958–1998) there were 28 COLs identified over NW, 13 over NE, 34 over SW and 20 over SE. For the shorter period covered by cloudiness data (1973–1998), these were 17 COLs located over NW, 7 over NE, 24 over SW and 16 over SE. The analysis was performed from two distinct approaches. The first one consisted in calculating accumulated mean precipitation in every 2.5° × 2.5° boxes associated to all the COLs that occurred within a given quadrant (Fig. 5). The highest absolute values for COLs over the NW quadrant occurred within the box 42.5°–45° N to 0°–2.5° W (Basque Country), accumulating more than 85 mm. The NE COLs left the highest precipitation (more than 30 mm) over the box delimited between 40°–42.5° N and 0°–2.5° E (Catalonian region). For COLs over SE and SW quadrants the highest precipitation was obtained for the box east of the Gibraltar Strait.

The second point of view was analogous but calculating the relative precipitation, defined as the contribution (in percentage) of precipitation in a box to the precipitation in the whole area of study with precipitation data, associated to COLs in each quadrant (Fig. 6). For the NW quadrant the Basque Country box collected 20% of the total precipitation. On the other hand for the NE quadrant the Catalonian box represented more than a half of the total precipitation (60%). For the SE and SW COLs the box over eastern Gibraltar Strait collected 30% and 20% of precipitation, respectively. It is worth mentioning that while the maximum of absolute precipitation occurred for NW COLs and in particular in the box over the Basque Country, the maximum precipitation in percentage was obtained for COLs located over NE sector and,

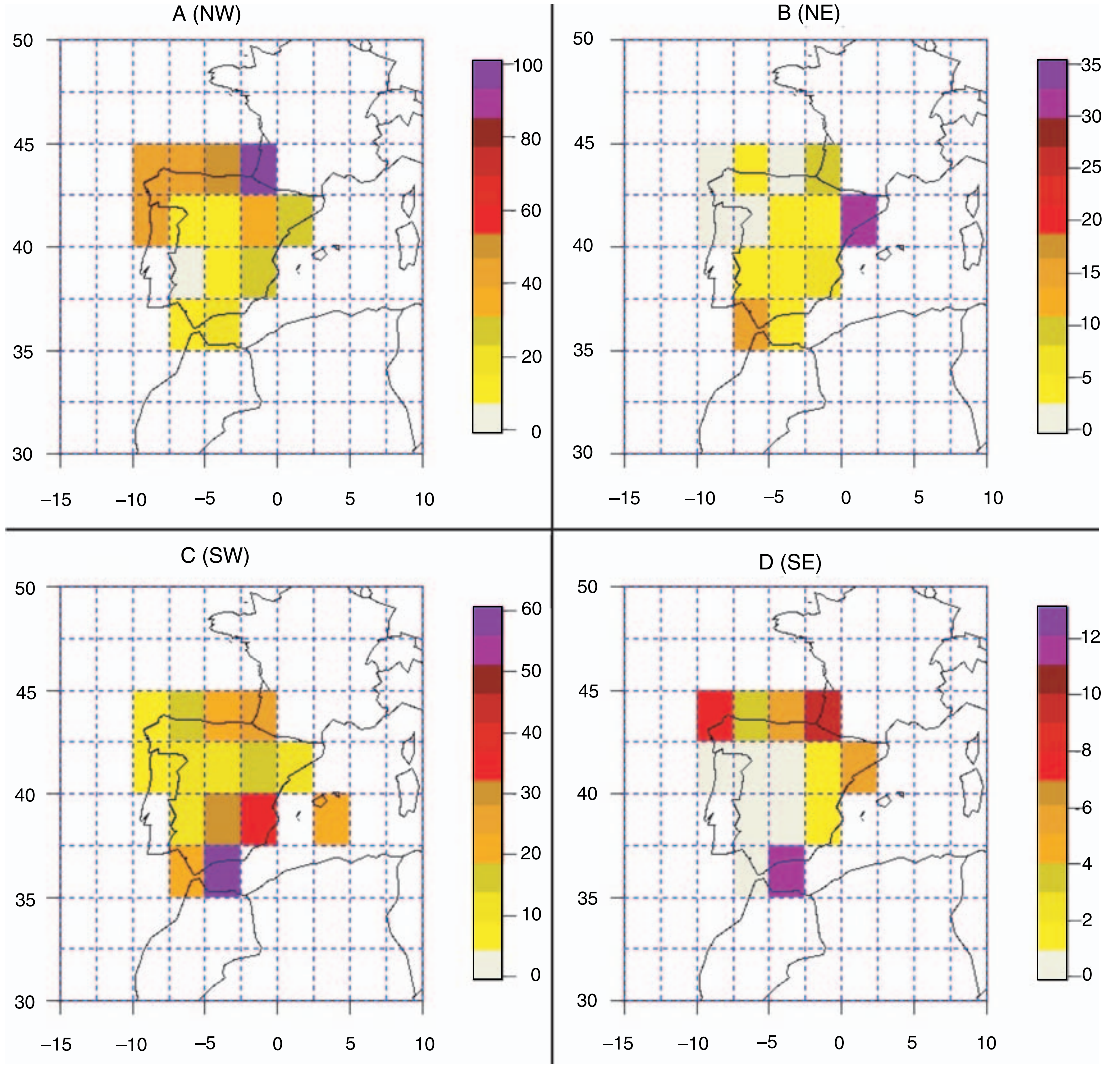


Fig. 5. Accumulated mean precipitation (mm) for the COLs that occur over each quadrant for the period from 1958 to 1998. (**a**) Northwest, (**b**) Northeast, (**c**) Southwest, and (**d**) Southeast

in particular, in the box over Catalonia. A combined view of both figures (Figs. 5 and 6) reveals that the lowest precipitation associated to COLs for any quadrants occurred over the centre of the Iberian Peninsula. An interesting result is also the moderate precipitation over the Cantabric coast for SE COLs that will be discussed next.

Most of the previous results can be explained attending to the characteristics of the conceptual model of COL (Winkler et al, 2005). Some individual examples are displayed in Fig. 7 to support the following staments:

– For NW COLs: the precipitation occurs in the zone of the leading baroclinic shield -leading front zone that coincides with Mediterranean coast and most oriental zone of Cantabric coast-, and in the centre of COL. This last case could be due to convective cells or also to the fact that there could be closed geopotential height contours at 1000 hPa surface associated to the COL; 42% of the systems for the European sector were closed in surface, see Nieto et al (2005).
– For SW COLs: the precipitation is mostly associated with the baroclinic shield (area from Gibraltar Strait up to the Balearic Islands for COLs in this quadrant). Important precipitation values have been also detected in northern Iberia due to westerlies fluxes associated

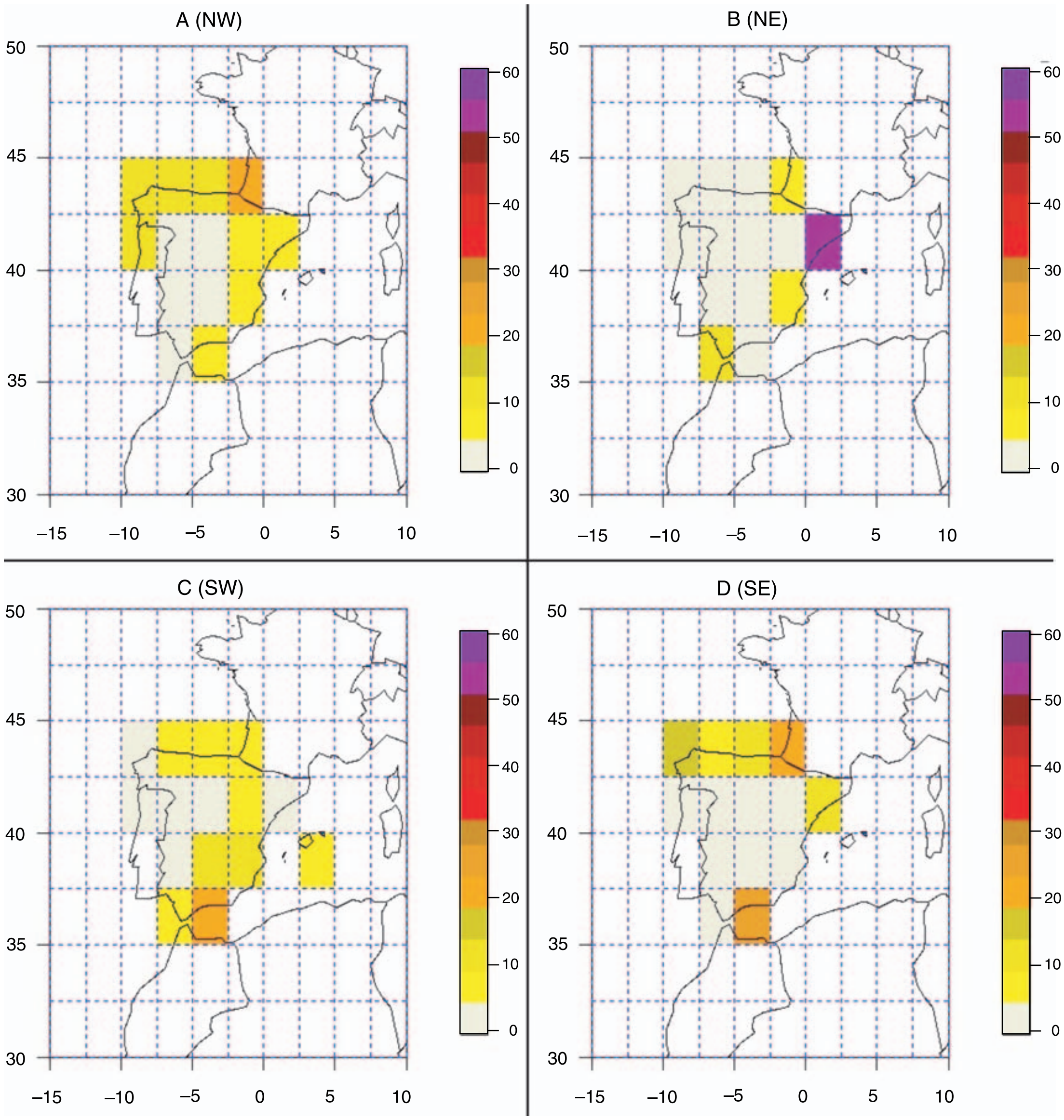


Fig. 6. Relative precipitation (%) associated with COLs that occur over each quadrant for the period from 1958 to 1998. (**a**) Northwest, (**b**) Northeast, (**c**) Southwest, and (**d**) Southeast

to the general circulation. Some SW COLs are located southern enough from the Cantabric coast and the precipitation in this region is probably due to other systems to the northern edge of COLs.

– For NE COLs: the highest precipitation amounts occurring over north-eastern Iberia (Catalonia region) coincide with the centre of the COLs, being of convective type. In the second important area, the Gibraltar Strait, the precipitation is due to westwards sea flows of the own COLs, especially for those closed in surface.

– For SE COLs: the precipitation over the Mediterranean area is due to the strong moisture advection, which is caused by the easterly sea flows over the northern part of the COL in the Catalonian area and by the westerly sea flow in the zone of the Gibraltar Strait. Another region of important precipitation is detected over the northern coast of Iberia, probably due to general circulation westerly flows that prevail over the isolated COLs, as commented for SW COLs.

Figure 8 shows the analysis for the mean cloudiness (in oktas) associated with COLs located in

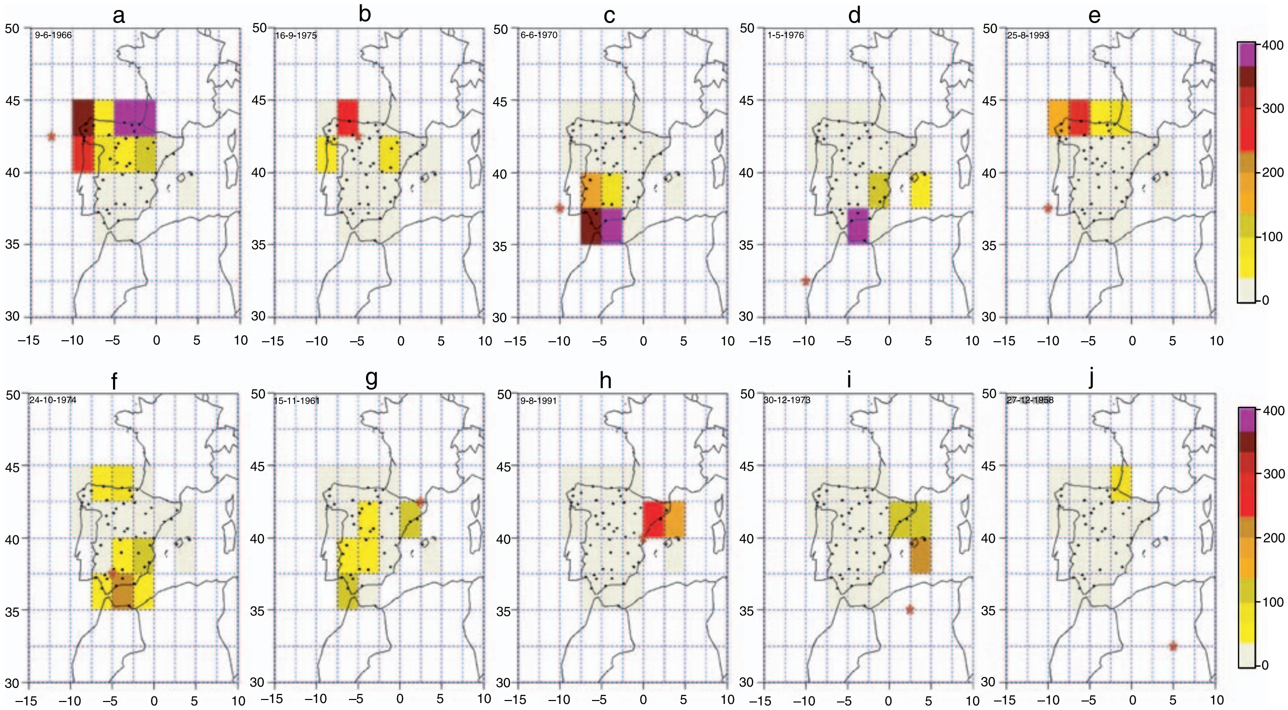


Fig. 7. Examples of individual COLs that indicate different patterns of mean precipitation (mm) depending on COL position. COLs are indicated with a red asterisk. (**a**) NW COL that provides precipitation associated with the baroclinic shield; (**b**) NW COL with high precipitation in its centre; (**c**) and (**d**) SW COLs that bring precipitations associated with the baroclinic shield; (**e**) SW COL that induces precipitation in the northern Peninsula due to westerlies fluxes associated to the general circulation; (**f**) SW COL that brings precipitation in its centre; (**g**) NE COL that provides convective precipitation in its centre and over the Gibraltar Strait due to eastward sea flows of the own COL; (**h**) NE COL that induces convective precipitation in its centre; (**i**) SE COL that brings precipitation over the Catalonian area due to the easterly sea flows of the northern part of the COL; (**j**) SE COL hat provides precipitation over the northern Peninsula

each quadrant. It should be empathised that it is particularly difficult to extract general results for SW and SE quadrants, because there are few systems over land.

Attending to the conceptual model of COLs it is possible to verify that:

- For NW COLs: the maximum mean of cloudiness is detected over the Cantabric region (more than 6 oktas) and it is due to the cloudiness associated with the centre of the COLs. The cloudiness detected eastward to the centre of the COLs is due to clouds associated with the leading baroclinic shield.
- For SW COLs: the mean cloudiness associated with the centre of the COLs is difficult to assess because there are few systems over the Peninsula. Nevertheless, cloudiness associated with the baroclinic shield is observed in the area of Gibraltar Strait (more than 6 oktas). The other area with important cloudiness, the Cantabric coast, is due to cloudiness associated with systems linked to general circulation that overpass the isolated COLs.
- For NE COLs: As for NW COLs, the maximum cloud coverage is directly located under the centre of the COLs. It is not possible to analyse the cloudiness associated with the baroclinic development due to lack of information in the corresponding area, but it is possible to analyse the cloudiness that is formed in the rear part of the COLs. So, the maximum of cloudiness over the eastern Cantabric (from 6 to 7 oktas) could be due to the cloudiness under the centre of NW COLs or to the cloudiness associated to the rear part of the COLs placed in the eastern part of the NE quadrant.
- For SE COLs: The maximum mean of cloudiness is located in northern Iberia (3–4 oktas). It is probably due to frontal systems.

Figure 9 shows examples of individual COLs supporting this reasoning.

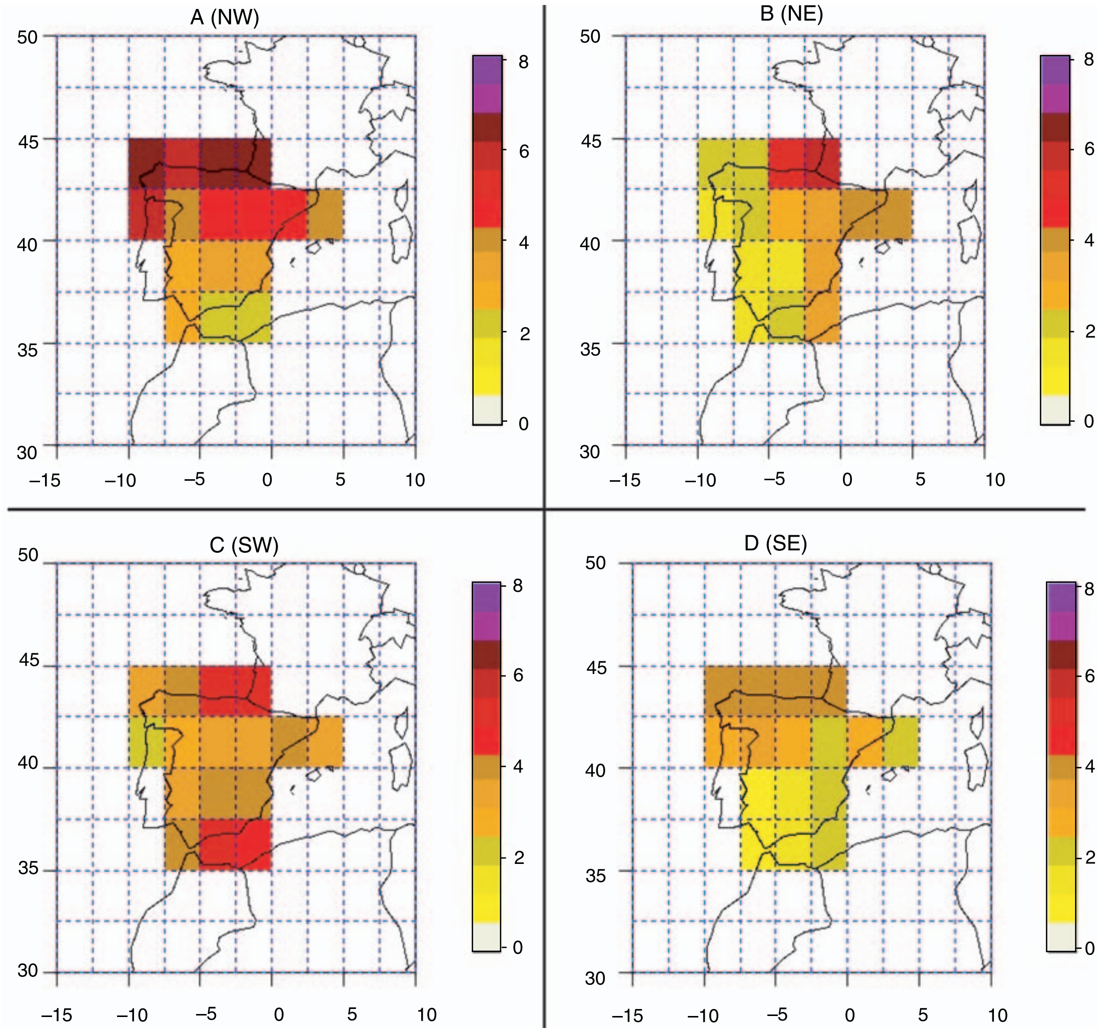


Fig. 8. Cloudiness layer (oktas) for COLs over each quadrant for the period from 1973 to 1998. (**a**) Northwest, (**b**) Northeast, (**c**) Southwest, and (**d**) Southeast

3.2 Analysis of precipitation attending to a climatological division of the Iberian Peninsula (receptor oriented)

During the last decade, a number of papers have addressed the different precipitation regimes in Iberia by using Empirical Orthogonal Functions (Rodríguez-Puebla et al, 1998), Principal Component Analysis (Serrano et al, 1999; Esteban-Parra, 1998) or conglomerate analysis (Muñoz-Díaz and Rodrigo, 2004a, b). The number of different precipitation patterns and regions varies among authors and seasons but a division in three zones, as those defined by Esteban-Parra (1998), can be considered an excellent summary of the regional variability of the precipitation inside Iberia. Thus, their approach has been adopted in this paper. Figure 10 shows the selected areas: (a) a North region including the Cantabric coast and Galicia, (b) a South-centre region that includes the centre of the Peninsula and Andalusia, and (c) the East-Mediterranean region. For every COL we computed the mean accumulated precipitation in each region. According to the definition of the World Meteorological Organization (WMO), a rainy event is considered when the record is higher than 0.1 mm Gallego (2004), and Gallego et al (2005) classified the precipitation over Iberia, defining as "light rain" all those events where precipitation does not surpass 2.5 mm per day. Following this approach, when the mean value of the accumulated precipitation for any of the three regions was below this threshold we considered that this COL

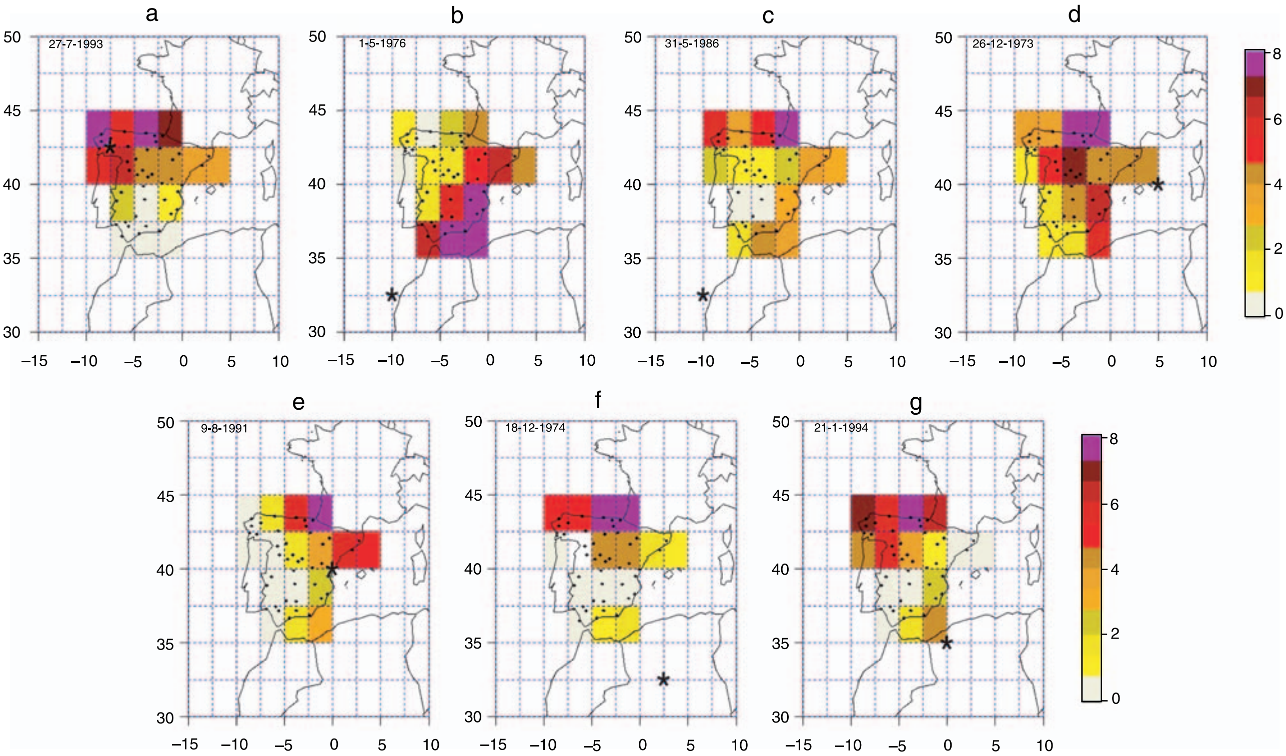


Fig. 9. Examples of individual COLs that indicate different patterns of mean cloudiness layer (oktas) depending on COL position. COL centres are indicated with a black asterisk. (**a**) Cloudiness layer associated to the centre and the baroclinic shield of a NW COL; (**b**) cloudiness layer associated to the baroclinic shield (violet boxes to the East of the Gibraltar Strait) for a SW COL; (**c**) cloudiness layer over Cantabric area associated with a front that overcomes a SW COL; (**d**) cloudiness layer associated with the rearward front in a NE COL; (**e**) Cloudiness layer associated with the centre of a NE COL; (**f**) and (**g**) cloudiness associated to SE COLs

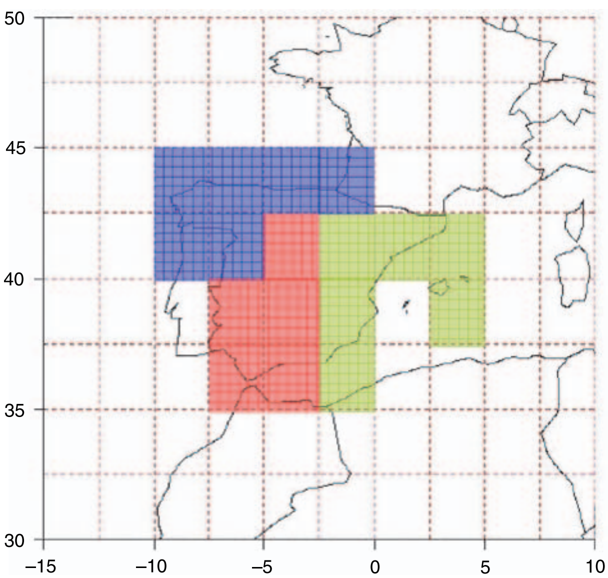


Fig. 10. Regionalization of the Iberian Peninsula in three precipitation regions based on the study of Esteban-Parra et al (1998): the Northern region (blue), the South-centre region (red) and the East-Mediterranean region (green)

did not produce significant precipitation over the whole Iberian Peninsula (from now "null precipitation"–NP). If the precipitation over some of the regions was higher than 2.5 mm we defined a three-step procedure to assign to every COL its region of preferred precipitation:

- The mean precipitation was calculated for each region.
- The region with the highest mean value was chosen.
- If the mean precipitation for the other two regions exceeded 20% of the mean value of the region with the highest precipitation, we considered that this COL provides a "generalized precipitation" (GP) over Iberia. Else wise, we assigned the region with the highest precipitation to the COL.

From now on, we will assign a code to every type of precipitation. When the precipitation is NP type the code will be 1, for precipitation over Northern region it will be 2, for South-centre region it will be 3, for East-Mediterranean region it will be 4 and when for GP it will be 5.

This analysis was made in two different ways, first we studied the type of precipitation associated to COLs placed in the quadrants defined in Fig. 4 and then we studied the geographical distribution of those COLs producing each type of precipitation.

Figure 11 shows the number of COLs for each quadrant and the percentage of them that induce precipitation of the different types (in blue boxes) for the period 1958–1998. COLs occur mainly in the western half of the Iberian Peninsula (65.25%), with a maximum in the SW quadrant (36.78%). The percentages of COLs for the rest of the sectors are 27.47% (NW), 21.05% (SE) and 13.68% (NE). Most of COLs that occur in *the NW quadrant* induce precipitation over the northern region (46.40%) or GP (32.10%), being the former probably associated with development in the centre of the COL. The precipitation in the Mediterranean region (7.20%) is due to the leading front zone of the COL (baroclinic shield). It is interesting to note that the flows associated with NW COLs do not produce precipitation in the centre-south region of the Iberian Peninsula. COLs over *the NE quadrant* bring mainly null or not significant precipitation (46.10%), although almost the fourth part of these COLs (23.10%) provides precipitation over the Mediterranean region. This precipitation could be convective, since it is associated to the centre of the COLs. Identical percentages (7.70%) of these COLs produce precipitation over the northern region and over the south-centre region; and 15.40% of them produce GP. COLs over *the SW quadrant* induce mainly general precipitation (47.10%); being also important the percentage that produce null or not significant precipitation (20.60%). Precipitation in the northern region (17.60% of the COLs) are due to the frontal areas associated with the general circulation from the west that overcome the isolated COLs. Precipitation over the Mediterranean and South-centre regions (8.80% and 5.90% respectively) is associated with the baroclinic shield. Most COLs that occur over *the SE quadrant* (50%) do not produce significant precipitation. Precipitation values over the Mediterranean zone (15%) and over the south-centre zone (20%) are probably associated to the own COLs circulation, while fronts associated with the general circula-

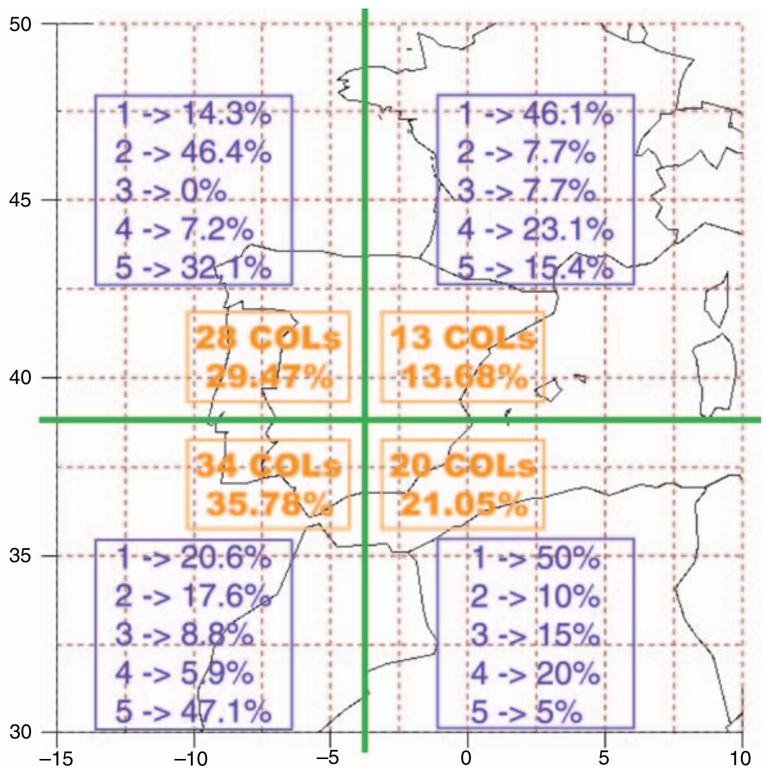


Fig. 11. Scheme of precipitation types for the period from 1958 to 1998 that COLs provide attending to their position. Blue boxes: percentage of COLs that produce precipitation over the Northern region (represented with 2), the South-centre region (3), the East-Mediterranean region (4), for null precipitation (1) and when the precipitation is generalized over the whole Peninsula (5). Orange boxes: number and percentage of COLs situated in each quadrant

Table 2. COL distribution attending to the affected precipitation region

	NW	SW	NE	SE
Null	14.8%	25.9%	22.2%	37.1%
Northern	59.1%	27.3%	4.5%	9.1%
South-centre	0%	42.9%	14.2%	42.9%
East-Mediterranean	18.2%	18.2%	27.3%	36.3%
Generalized	32.1%	57.1%	7.2%	3.6%

tion from the west seem to be responsible for the precipitation produced by the 10% of these COLs over the northern region.

Table 2 summarizes the geographical distribution of COLs producing each type of precipitation and Fig. 12 shows in detail this information, indicating for every grid point the number of COLs and the season in which they are produced. An example can help us to read Fig. 12, the following legend appears in the coordinates 32.5° N–12.5° W for NP type: SXXF, which means that over this grid-point four COLs occur, one in spring (S), two in summer (X) and another one in autumn (F). In general, COLs which do not bring important precipitation (NP, type 1) occur mainly over the SE region, representing 37.1% of the total COLs, followed by the SW region that represents 25.9%, the NW region with 22.2% and finally the NE with 14.8%. COLs that produce rainfall over the Northern region (type 2) are mostly placed over NW quadrant, representing 59.1% of the cases and over the SW quadrant (27.3%). Thus, precipitation over the Northern region is mainly due to the COLs that occur over the western half of the Peninsula (86.4%) particularly during summer (43.75% of the cases). The number of COLs bringing precipitation over the South-centre region (type 3) is quite reduced; most of them occur in the southern half Iberia (85.8%) and mainly during winter or spring (42.9% of the cases for each season). COLs producing precipitations over the East-Mediterranean region (type 4) are placed mainly over the SE quadrant (36.3%). Finally, when the precipitation is generalized (GP, type 5), the COLs are overwhelmingly located over the western half of the Peninsula (89.2%) and occurring mostly during spring (about the half of the cases) and autumn (21.4% of the cases), being summer the less favoured season (10.8%).

3.3 Analysis of the convective instability in areas associated to the COL

CAPE, or Convective Available Potential Energy, is the vertically integrated buoyancy of a parcel between the LFC (Level of Free Convection) and the EL (Equilibrium Level). The CAPE is related with convective developments, so we used this variable as an orientated measure of convectivity. The CAPE for the first day of a COL was computed using radiosonde data from IGRA. The existence of CAPE indicates that upward motion will occur, as long as air is lifted to the LFC. When CAPE values fall between 0 and 1000 J/kg the convection is possible but the instability is not enough to produce precipitation, values between 1000 and 2500 J/kg indicates a moderate instability and the convection is likely, with values over 2500 J/kg the air mass becomes very unstable and strong convection is very likely. Figure 13 shows the CAPE for the available radiosonde data closest to the COL centre (inside a box of 7.5° × 7.5°, being the COL the central point). Soundings with less than 10 levels were rejected. Numbers inside each quadrant in the Fig. 13 indicate the number of individual COLs, with different colours for each quadrant. Tables next to each quadrant correspond to the results for the COLs inside that quadrant. The analysis was done for the different types of precipitation defined in the previous section (null precipitation, generalized precipitation and precipitation over the Northern, East-Mediterranean and Southern-centre regions). For the South-centre region no radiosonde station was found near the core of the COLs.

The main result is that the CAPE is lower than 1000 J/kg in most of the cases, so important convection similar to that found inside convective cells is not expected in the centre of the COLs. Only four COLs (11.8% of COLs) show CAPE higher than 1000 J/kg, all during summer, as expected, but with different precipitation effects. Two of them occur in the NW quadrant, associated to precipitation over the Northern region. They are signed by the "code COL" 2 and 4. The precipitation left by these COLs is not higher than 75 mm. The other two cases are located over the NE quadrant, over the Balearic Islands, but the precipitation detected for each case is different. In one case the precipitations over Iberia and

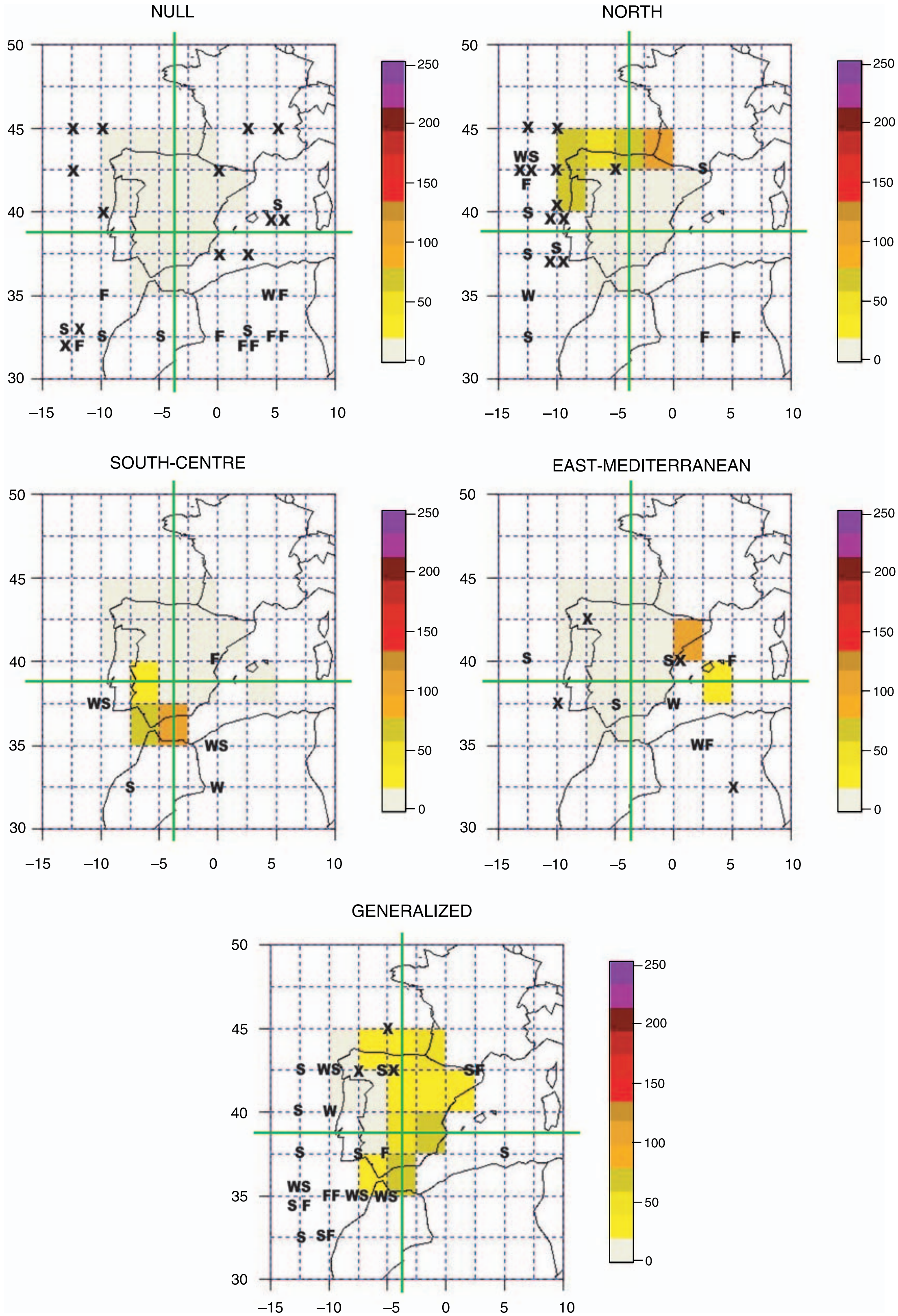
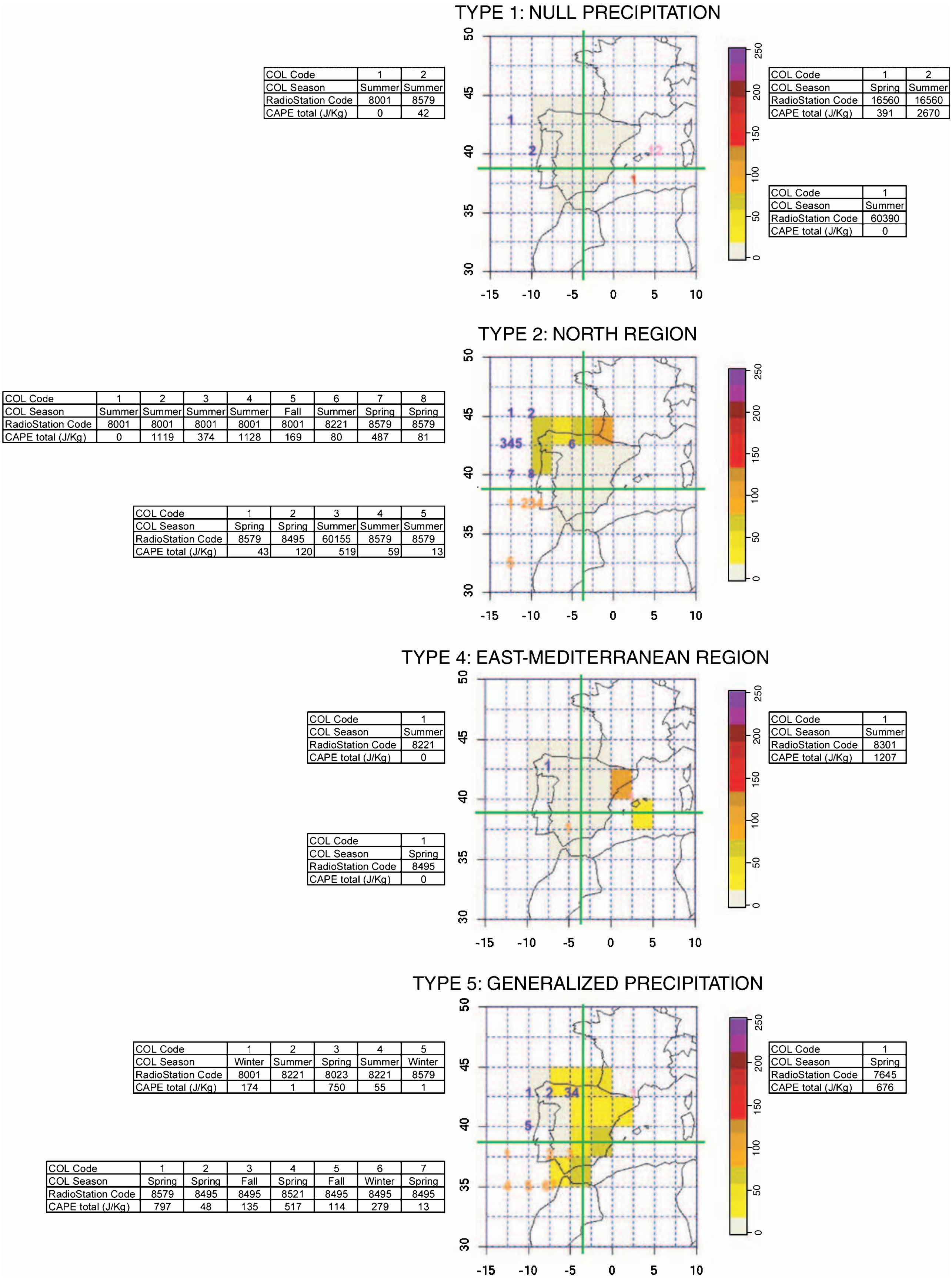


Fig. 12. COL distribution and accumulated precipitation (mm) for the different regions of precipitation over the Iberian Peninsula. COLs are represented by their season, so if the COL occurs in winter it is marked with "W", in spring with "S", in summer with "X" and in fall with "F"



TYPE 1: NULL PRECIPITATION

COL Code	1	2
COL Season	Summer	Summer
RadioStation Code	8001	8579
CAPE total (J/Kg)	0	42

COL Code	1	2
COL Season	Spring	Summer
RadioStation Code	16560	16560
CAPE total (J/Kg)	391	2670

COL Code	1
COL Season	Summer
RadioStation Code	60390
CAPE total (J/Kg)	0

TYPE 2: NORTH REGION

COL Code	1	2	3	4	5	6	7	8
COL Season	Summer	Summer	Summer	Summer	Fall	Summer	Spring	Spring
RadioStation Code	8001	8001	8001	8001	8001	8221	8579	8579
CAPE total (J/Kg)	0	1119	374	1128	169	80	487	81

COL Code	1	2	3	4	5
COL Season	Spring	Spring	Summer	Summer	Summer
RadioStation Code	8579	8495	60155	8579	8579
CAPE total (J/Kg)	43	120	519	59	13

TYPE 4: EAST-MEDITERRANEAN REGION

COL Code	1
COL Season	Summer
RadioStation Code	8221
CAPE total (J/Kg)	0

COL Code	1
COL Season	Summer
RadioStation Code	8301
CAPE total (J/Kg)	1207

COL Code	1
COL Season	Spring
RadioStation Code	8495
CAPE total (J/Kg)	0

TYPE 5: GENERALIZED PRECIPITATION

COL Code	1	2	3	4	5
COL Season	Winter	Summer	Spring	Summer	Winter
RadioStation Code	8001	8221	8023	8221	8579
CAPE total (J/Kg)	174	1	750	55	1

COL Code	1
COL Season	Spring
RadioStation Code	7645
CAPE total (J/Kg)	676

COL Code	1	2	3	4	5	6	7
COL Season	Spring	Spring	Fall	Spring	Fall	Winter	Spring
RadioStation Code	8579	8495	8495	8521	8495	8495	8495
CAPE total (J/Kg)	797	48	135	517	114	279	13

Fig. 13. CAPE (in J/kg) for COLs associated to the different types of precipitation over the Iberian Peninsula. Each COL is indicated by a code number and data tables close to each quadrant refer to COLs occurred on that quadrant. Tables include information about each COL: its season, its radiostation code, and its CAPE

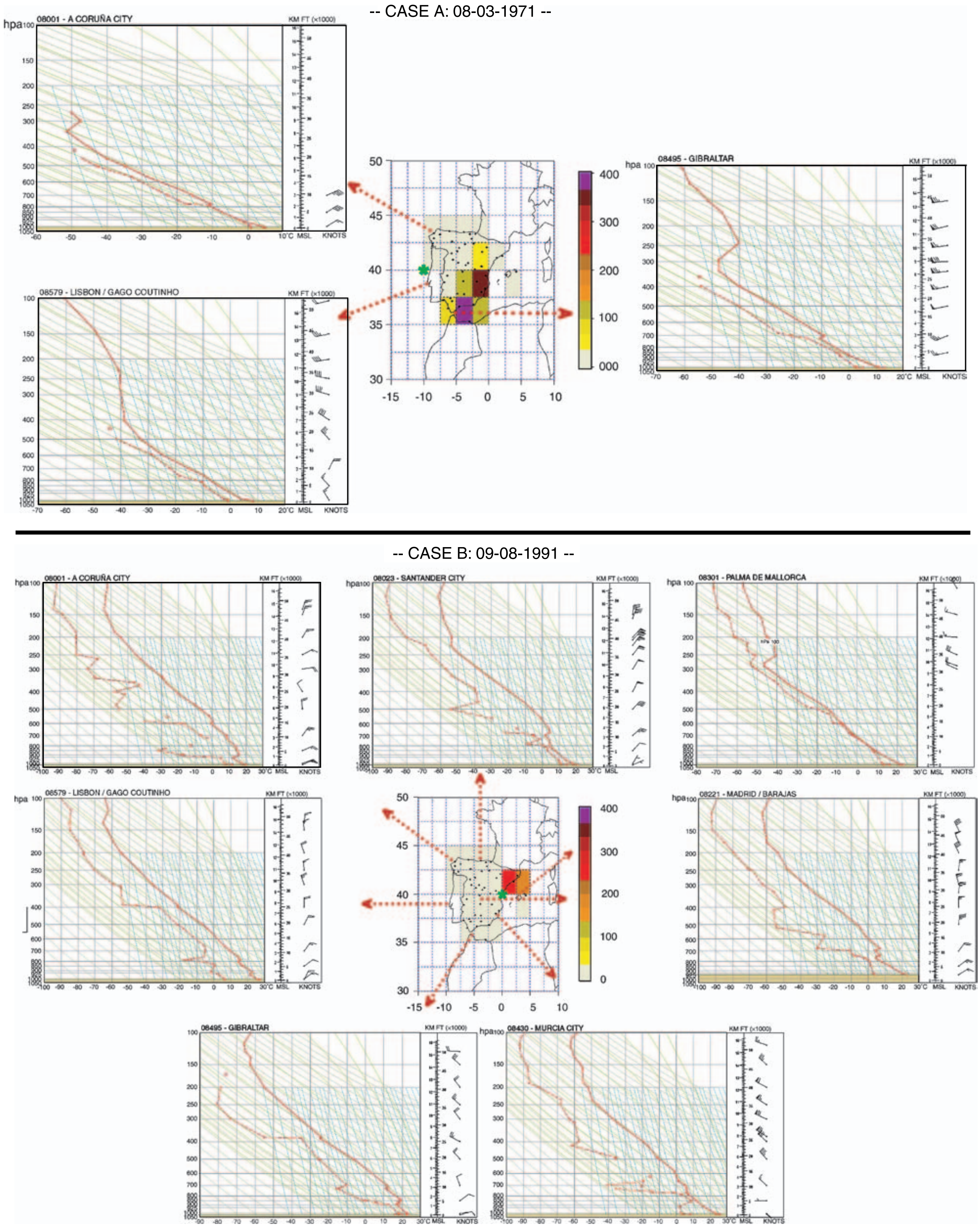


Fig. 14. Analysis of the instability by radiosoundings for the two main kind of precipitation associated to COLs (the lines indicate: in green the saturation adiabats, in brown the dry adiabats and in dashed blue saturation mixing ratios). In case A the precipitation is associated with the baroclinic shield. In case B the precipitation is associated with convective instability

Balearics is null ("code COL" 2), although the CAPE is very high, 2670 J/kg. The instability is enough to create convective activity and to bring moderate precipitation, but the radiosonde data comes from a station far from our region of study (station code 16560 in Table 1, belonging to Italy). In consequence, the limitation of our precipitation data to the Iberian Peninsula does not permit us to analyze the precipitation in the convective area of this COL. The other COL with high CAPE produces precipitation over the East-Mediterranean region (type 4). The amount is about 100 mm and the radiosonde station is close to the box where the precipitation is registered. In this case the precipitation detected is clearly associated to the core of the COL and its origin is convective.

To compare the different types of precipitation associated to COL attending to the conceptual model, we study two particular cases of COLs for different seasons. Figure 14 (case A) illustrates a COL that induces precipitation associated with the baroclinic shield and (case B) a COL with convective precipitation near to its core. The COL position is marked with a green asterisk and the location of the corresponding radiosonde stations is indicated with a red arrow and identified also with their names and codes. Radiosoundings are displayed using emagrams. In case A, the COL occurs during March (winter) and the precipitation is clearly due to baroclinic instability associated with the leading front linked to COLs (see Figs. 1 and 2). The radiosoundings indicate that the air mass is stable in the three analysed stations but the vertical wind shear in the Gibraltar radiosounding (on the right side of the graphic) increases with the altitude. This is a clear signal of baroclinic instability. Case B corresponds to summer and the single radiosounding showing convective instability is the one measured at Palma de Mallorca, inside the core of the COL. The CAPE value in this radiosounding is 1207 J/kg that indicates convective instability in this region, causing moderate to high precipitation, about 250 mm over the box from 40°–42.5° N to 0°–2.5° E.

4. Conclusions

This study analyzes the rainfall and cloudiness patterns associated to COLs in one of the areas of the world where COLs are more frequent, the Iberian Peninsula. The results reveal new and interesting properties of COLs affecting the Iberian Peninsula and allow us to validate for long period some results previously documented in case studies. The main conclusions can be summarized as follow:

- The COL precipitation patterns in Iberia are adequately reproduced by the COLs conceptual model.
- It is demonstrated that the generalized idea that all the COLs leave intense convective rainfall is clearly false for most of the COLs occurred in the Iberian Peninsula.
- Rainfall amounts on the Mediterranean zone linked to COLs are due principally to COLs located over this region (more than 60%). Their quantity and the convective instability of the COLs centres indicate that they are mainly due to convective phenomena produced in the centre of the COLs.
- Most of the rainfall associated with COLs results from the baroclinic shield; especially in cases located over the west half of the Iberian Peninsula.
- In some cases (about 12.5% of the total systems) the rainfall linked to COLs detected in the Peninsula is not directly due to the COL system but to its effects in the west general circulation. This is characteristic of isolated COLs located over the southern half of the Iberian Peninsula, that bring rainfalls over the northern Iberian coast caused by the transition of fronts associated with the general flow that overcomes the COLs.
- Almost 30% of the COLs do not bring any rainfall, most of them located in the southern half of the Peninsula, and mainly during autumn.
- Another 30% of COLs produce generalized rainfall over the whole analysed territory, being most of them (about 90%) located over the western half of the Iberian Peninsula.

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