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Toward an estimation of the relationship between cyclonic structures and damages at the ground in Europe

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Abstract. Cyclonic systems dominate European and Mediterranean meteorology throughout the year and often induce severe weather in terms of heavy and/or long-lasting precipitation with related phenomena such as strong winds and lightning. Surface cyclonic structures are often related to well defined precipitation patterns with different scales, duration and intensity. Cyclones confined in the upper troposphere, usually referred to as cut off low, may induce instability at lower levels and the development of convective precipitation.

In this work the occurrence of cyclonic events (discriminated between surface ones and cut-off lows) is analyzed and matched with an economic losses database to highlight a relation between the atmospheric structures and the impact on the social environment in terms of casualties and material damages. The study focus on the continental Europe and, based on the ERA-40 reanalysis, two databases of surface cyclones and cut-off lows have been constructed by means of automatic pattern recognition algorithms. The impact on the local communities is estimated from an insurance company record, which provides the location, date and type of the events, as well as related losses in terms of damages and casualties. Results show the relatively high impact of cyclonic structures on human life in Europe: most of the weather induced damages occur close to a cyclonic center, especially during warm months. Damages and human losses are more frequent from late summer to January, and precipitation is the most relevant meteorological damaging feature throughout the year.

1 Introduction

The impact of a meteorological system on the society mainly depends on four factors: 1) severity of the meteorological phenomena, 2) geomorphology, 3) population density and assets value, and 4) promptness of the ground structures to react to the hazard.

The resulting damages are a complex combination of all these factors so that in order to mitigate the effects of hydro-meteorological severe events, a strategic action on any of them is strongly required. While improving numerical weather predictions, with an emphasis on extreme events, is recognized to be of primary importance, an effective losses reduction can only be achieved if the forecast improvements are accompanied by progresses in civil engineering and in the strategies to optimize the reaction of the population to the predicted hazard.

Humans usually modify the land usage to maximize the exploitation of the land resources, which often results in decreasing the capacity of the environment to mitigate natural hazards: this is particularly true in mountainous regions, such as the Alps (Holub and Hübl, 2008), and coastal areas (Barnolas and Llasat, 2007; Barroca et al., 2006).

At the same time, it is well known that the extra-tropical meteorology is often driven by migratory cyclones. At the European scale these synoptic systems (and sub-synoptic, especially in the Mediterranean basin) are often responsible for severe weather, as it has well outlined by a stream of works and research projects (see e.g. MEDEX project for high impact cyclones in the Mediterranean area; http://medex.inm.uib.es). A classification of cloud systems responsible for flood events in Europe has been proposed in Porcù et al. (2003) while, more recently, Homar et al. (2007) have analyzed the sensitivity patterns of high impact weather related to intense cyclones in the Mediterranean basin. This latter study highlights the needs of a more homogenous,

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hopefully adaptive, observations deployment in order to reduce cyclonic systems prediction errors.

In parallel, recent studies on climate prediction indicate that, due to the increase of the green-house-gases forcing, cyclones activity is expected to change in the next century, in terms of both their intensity and track density (Pinto et al., 2007a; Lambert and Fyfe, 2006; Knippertz et al., 2000; Leckebusch et al., 2007). Pinto et al. (2007b) analyzes the economical loss in Europe related to modified climate conditions in the next century: they found that the loss potentials increase as a result of an enhanced number and increased intensity of extreme cyclones.

The present study is aimed at investigating the relation between cyclonic structures and severe weather which leads to economical losses and causalities. Our ultimate goal here is to statistically assess which are the typical synoptic and subsynoptic settings prone to high impact events with damages at the ground. The present study is based on the ERA-40 reanalysis (Uppala et al., 2004). The focus here is on two different types of low pressure systems: the upper-air cyclones, usually known and hereafter named as cut-off lows (CUT) and the surface cyclones (LOW). To investigate the relation between the atmospheric structures and the impact on the environment in terms of casualties and material damages, the CUT and LOW databases are matched with a collection of damages produced by meteorological events. The latter were estimated from an insurance company record (Munich Re), which provides the location, date and type of the events, as well as related losses in terms of damages and casualties.

The paper is organized as follows. In Sect. 2 the data and the recognition algorithms are introduced. Section 3 reports results of the spatial and seasonal distribution of the three databases independently while the matching between the CUT and LOW database with the one of the events with reported damages is presented in Sect. 4. Final conclusions are drawn in Sect. 5.

2 Data and algorithms

This study is based on the Continental Europe. The rectangular domain under study is limited between 30° W–45° E and 20°–60° N on a 2.5°×2.5° grid (31×17 grid-points). The analysis is relative to the five-year period from 1992 to 1996, and is based on the ERA-40 reanalysis, available freely on the ECMWF website (http://data.ecmwf.int/data/d/era40_daily/). The data are at 23 pressure levels (plus surface) every six hours for the period 1957–2001 (see Uppala et al., 2004 for details).

For the analysis, the following ERA-40 fields are considered:

- geopotential height (at the pressure levels: 200, 250, 300 and 1000 hPa);
- temperature and zonal wind at 200 hPa;
- total precipitation cumulated over 6 h at the surface.

For the same period a collection of Events with Reported Damages (ERD) is considered, as recorded in the MRNatCat archive by the Munich Re reinsurance company. This archive collects ERD giving, for each event, the following information: calendar date, location (toponym of the geographical area of interest), type of meteorological forcing (in 5 classes: rain, hail, strong winds, lightning, snowfall), type of damages (e.g. flooded buildings/cellars, crops destroyed, road damaged), and number of casualties. For about one fourth of the ERDs the economic losses, in terms of millions of US dollars, are also listed.

2.1 Detection of cut-off low events

The detection of a cut-off low event (CUT) is carried out adopting a two-step strategy introduced in Porcù et al. (2007) which is in turn a follow-up extension of an automatic objective detection algorithm (Nieto et al., 2005) based on the three main characteristics of the CUT conceptual model. It can be summarized according to subsequent stages, as follows:

1. At each synoptic time, and at the 200 hPa level, a given grid-point is identified as a geopotential minimum if it is a minimum (with a 10 gpm lower threshold) with respect to at least 6 of the 8 surrounding grid-points. Once this set of candidate CUT is identified, only the grid-points showing a change in the direction of the 200 hPa zonal wind at any of the two adjacent grid-points placed northwards are retained.
2. It is required for a CUT to have the equivalent thickness eastward of its central point (computed between 200 and 300 hPa) higher than that at the centre.
3. To finally label the event as a CUT, the grid-point eastward of a the candidate event centre is required to have a thermal front parameter higher than that at the CUT centre. The thermal front parameter measures the change of the temperature gradient in the direction of its gradient.

The database obtained after the application of the automatic algorithm was manually post-processed, following Porcù et al. (2007), according to a subjective analysis to overcome possible tracking problems due to the higher time resolution (6 h) used here, with respect to the daily data used in the original application of the automatic algorithm (Nieto et al., 2005).

2.2 Detection of surface cyclone events

A surface cyclone database has been also constructed by means of an automatic procedure. The criteria used to detect significant low pressure centers close to the surface are similar to those adopted in previous studies (Trigo et al., 1999; Picornell et al., 2001).

The sea-level pressure field is computed from the 1000 hPa geopotential field as p(hPa)=0.121 Z(gpm)+1000, and a grid-point is labeled as a LOW if:

1. It is a sea-level pressure minimum over the eight surrounding grid-points which does not exceed 1020 hPa.

2. The average sea-level pressure gradient over a 7.5°× 10° sub-area is higher than 0.55 hPa/100 km.

The empirical threshold on the gradient was chosen, according to Trigo et al. (1999), in order to eliminate spurious small and weak troughs. The objective detection procedure was applied to the five years under study. No restriction on the minimum life-time of the events was imposed, but events with only a single appearance were removed from the database.

3 Spatial and seasonal distribution of ERD and cyclonic systems

As a first step, the spatio-temporal characteristics of the three databases are analyzed independently. The spatial distributions of the LOWs, CUTs and the ERDs are shown in Fig. 1 over a 5°×5° grid.

The distribution of LOWs (Fig. 1a) shows local peaks over the Gulf of Genoa, the Atlas Mountains, and the south eastern Mediterranean (see also Trigo et al., 1999 for comparisons). For the CUT distribution, two local peaks are coincident with the LOW distribution (Gulf of Genoa and Atlas Mountains), while North Atlantic appears to be the most active area for CUT occurrence, with secondary peaks over Iberian peninsula and Aegean Sea. The distribution of the 268 ERDs is clearly peaked over Alpine region. This may be partially due to a bias which may affect the ERD database. Munich Re is in fact based in Germany so that, not surprisingly, much reported events are relative to central Europe. Anyhow the whole Alpine region is known to be prone to hydro-geological hazards (see e.g. Bacchi and Ranzi, 2003). For these reasons the ERD database is used here in a “positive” way: the CUT or LOW event is searched only in the presence of an ERD. Consequently, the present analysis on CUT/LOW – ERD relation is not expected to be affected by an eventual underestimation of the ERD occurrence in some regions of our domain.

The observed peak of ERD occurrences over the Alpine region highlights an inherent limitation of the present coarse spatial scales analysis. Most of the reported Alpine ERDs are very likely due to mesoscale (and smaller) structures, that may be linked to the synoptic setting via complex multiple scales interaction mechanisms. Similar synoptic patterns, such as southerly flow (Asencio et al., 2003), are prone to be locally forced and lead to high impact weather (Rudari et al., 2004) in combination with orographic mechanisms (Rotunno and Ferretti, 2003) and channeling (Tripoli et al., 2002). A weak synoptic disturbance can be forced locally by a wide variety of different mechanisms (Rockwell and Maddox, 1988), often driven by ground physiography. Numerical studies (Homar et al., 2002) mentioned processes like orographic upslope, boundary layer convergence, outflows from nearby convective systems and jet-streak induced ageostrophic circulation as the main contributors in the western Mediterranean to convection initiation and triggering. The focus of this study is limited to the synoptic structures, while its extension to the finer scales may be addressed in a future work.

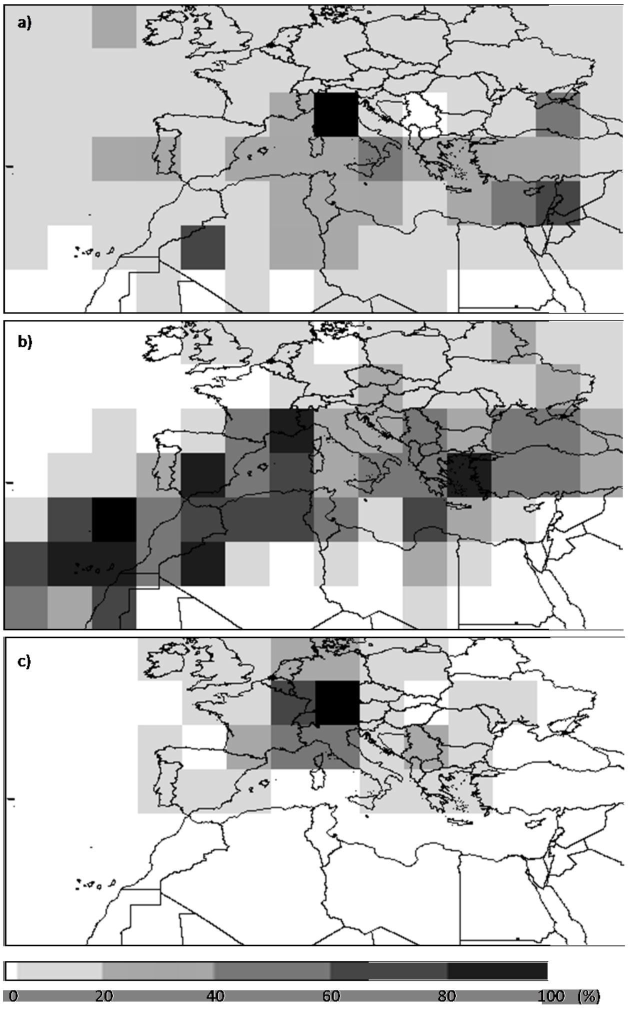

Fig. 1. Spatial distributions of LOWs **(a)**, CUTs **(b)**, and ERDs **(c)**. Values are normalized with the maximum number of occurrences.

The distributions of CUT, LOW and ERD along the year is presented in Fig. 2a. The distribution of LOWs appears rather flat, with two weak peaks in April–May and September, in agreement with the low seasonal impact on Mediterranean LOWs found in Trigo et al. (1999). On the contrary, the CUT occurrence is more frequent in warm months: more than the 60% of the total number of CUT events occurred

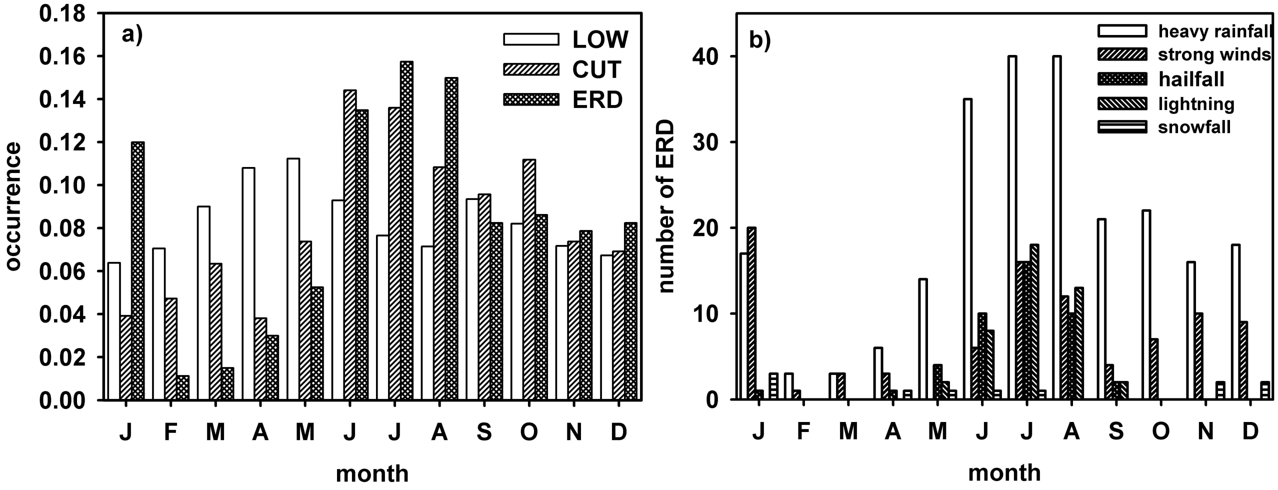

Fig. 2. Monthly distribution of: **(a)** fractional occurrence of LOWs, CUTs and ERDs; **(b)** occurrence of different types of meteorological event.

in five months (June to October). The ERD distribution is strongly peaked during the summer (June to August) and January, with a drop during February-March-April.

In Fig. 2b the monthly occurrence of the different types of meteorological events is reported (multiple types are allowed for any single ERD). Heavy rain systematically represents the major source of damages, while hail falls and lightning are frequent in summer and snowfall in winter. Strong winds events are also well distributed with a relatively pronounced peak in January. Considering these results in the light of the "Alpine peak" found in the spatial distribution of ERDs (see Fig. 1c), a large number of ERDs is likely due to summertime thunderstorms in the Alpine region.

The severity of hazards in terms of human losses is reported in Fig. 3, where the total number of casualties for month (Fig. 3a) and the fraction of ERDs with reported casualties (Fig. 3b) are shown. Most of the casualties occurred from August to January and very few cases are reported during the rest of the year. Given the relatively short period of study, the distribution of the number of casualties is biased by the exceptional event reported in Biescas (Spain) in August 1996, where 86 people died in a single event. The fraction of ERDs with casualties shows a peak in September and October and high values for November, December and January, with lowest values during May to August. The values from February to April have less significance, due to the low number of ERD occurred. Unfortunately, data for economic losses cannot be considered because the small number of reported economic figures makes the statistics poor and dominated by few events with very high reported losses, such as the Piedmont flood in 1994, when a total loss of about 12 500 billion of US dollars was reported.

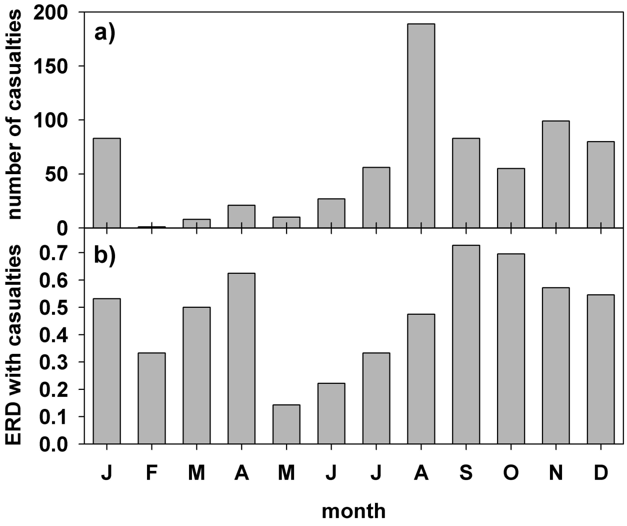

Fig. 3. Monthly distribution of: **(a)** number of casualties, and **(b)** the fraction of ERDs with reported casualties.

4 Database matching: co-location of LOW, CUT and ERD

After the independent analysis of the spatial and seasonal characteristics of the three databases, the co-occurrence of meteorological events (LOW and/or CUT) and ERD is considered. The different databases are matched along the following criteria. On a day by day basis and for each entry in the ERD database, the presence of a LOW and/or a CUT over the 2.5°×2.5° grid is searched. For 256 ERD (out of 268) a coincidence in the CUT or LOW database was found. The distance of the location of the ERD from the closest cyclonic center (LOW or CUT) is computed and plotted in

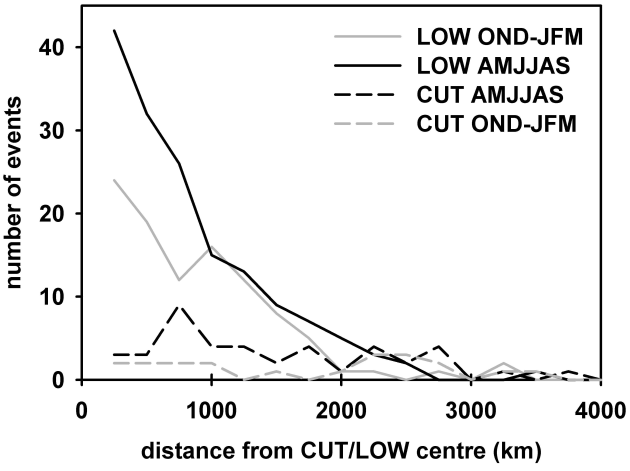

Fig. 4. Distribution of ERDs with respect to distance to the closer LOW (solid lines) or CUT (dashed lines), for warm months (AMJJAS, black lines) and cold months (OND-JFM, grey lines).

Fig. 4. The analysis was split in two subsets discriminating "warm" (April to September) and "cold" months (October to March) to see if the monthly variability showed in Fig. 2 is present even when analyzing the distance of the ERD from the related cyclonic center.

Most of the ERDs (89%) occurs at a distance lower than 1500 km from a LOW center, which is a reasonable length scale for a front surface in European cyclonic systems. A lower amount of ERD events appears linked to CUT development although the small peak at around 750 km may be directly related to precipitation induced by the CUT which usually tends to occur close to CUT center (Porcù et al., 2007). Other ERDs cluster at distances larger than 2000 km from the CUT center: for these cases no direct link with the CUT can be supposed. In warm months the ERDs tend to occur closer to the cyclonic center (being either CUT or LOW), while in the cold months the distance between ERDs and LOWs is larger and the link between CUT and ERD seems to be weaker.

The position of each ERD relative to the closest LOW/CUT center, for warm and cold months, is plotted in Fig. 5. A clear asymmetry can be noted in the warm months for both the CUTs (Fig. 5a) and the LOWs (Fig. 5b). The first is elongated along the east-west direction, with a small cluster very close to the center, slightly moved to the south-east. The second presents a populated cluster of events very close to the center and scattered points to the south of the LOW center. The cold months distribution are quite different: few ERDs are close to the center of the CUTs, while most of them are very far, more than 2000 km apart (Fig. 5c). The distribution of ERDs around the LOW center for the cold months (Fig. 5d) is more symmetric with only few events found at long distances. This latter distribution indicates the high probability of having an ERD close to a LOW center and in the region usually swept by a typical cold front structure, that is to the south of the synoptic system center.

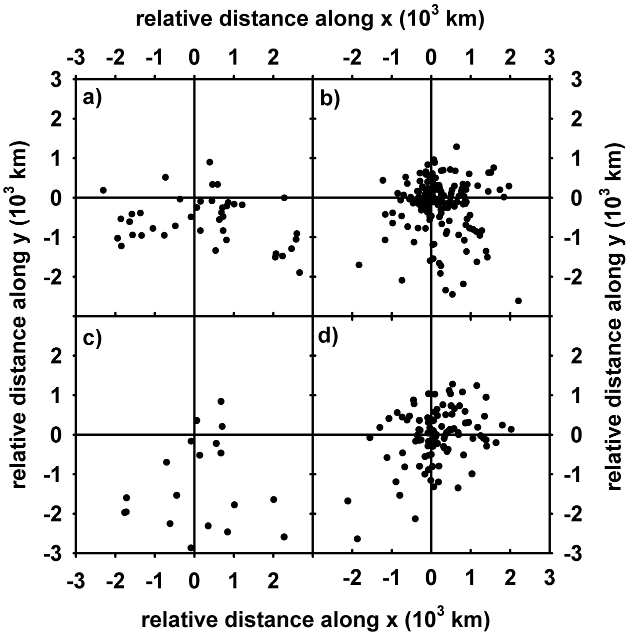

Fig. 5. Distribution of ERDs with respect to the center of: CUT for warm months **(a)**; LOW for warm months **(b)**; CUT for cold months **(c)**, and LOW for cold months **(d)**.

Since heavy precipitation is present in almost all the ERD (see Fig. 2b), in Fig. 6 the ERA-40 total cumulated rainfall for the days where an ERD occurred was plotted, relatively to the CUT or LOW center for the warm months. The peak of cumulated precipitation appears located to the south of the LOW center and most of the cases of associated rainfall is very likely due to the cyclonic developments in its warm sector (Fig. 6a). The cumulated rain for the CUT cases is elongated along the east-west direction, with a relative peak slightly moved to the south-east with respect to the CUT center. For the cold months the distribution, not shown, is more flat, without defined structures.

5 Conclusions

In this study, a statistical approach was followed to investigate the link between two typical meteorological synoptic structures, the cut-off low (CUT) and the surface cyclones (LOW), and the impact on the human activities at the ground. The work focused on the European continent and for the 5 years period 1992–1996. Three databases were constructed, collecting the occurrence of CUTs, LOWs and ERDs. The formers are constructed through automatic algorithms based on the ERA-40 reanalysis, while the ERD database comes by the reinsurance company Munich Re.

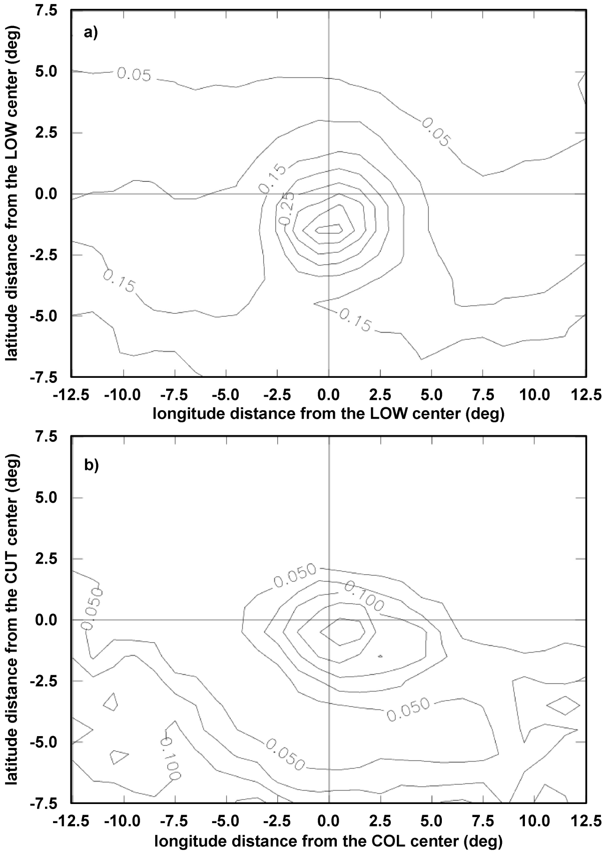

Fig. 6. Normalized cumulated ERA-40 precipitation with respect to the LOW **(a)** and CUT **(b)** centers for warm months.

In the first part of the study the databases were analyzed independently to highlight the main spatio-temporal features of each of them. In relation to their geographical distribution it has been found that: (1) the LOWs show clear peaks over the Gulf of Genoa, south-eastern Mediterranean and the Atlas mountain, (2) the CUTs peaks are over the Gulf of Genoa, Aegean Sea, and the North Atlantic, and (3) the ERDs are more frequent in the Alpine region, where steep mountains and narrow valleys may enhance the destructive potential of any severe weather system. The typical small size of the river catchments and their quick time response to intense precipitation episodes contribute to make a prompt warning particularly difficult.

The time distributions have revealed that: (1) the LOWs are more homogeneously distributed throughout the year, (2), the CUTs show a seasonal cycle, with most (60%) of the events occurring during five months (June to October) and, (3) the ERDs are concentrated from May to January, when the major source of damages is represented by heavy precipitations. The human losses due to ERDs occur more frequently from August to January, when the 83% of the total number of casualties and the 74% of the ERDs with human losses are found.

The joint analysis of spatial and seasonal ERD distributions indicates that a large number of ERDs is probably induced by warm season convective mesoscale, or smaller, systems in the Alpine region. Further studies are necessary in order to resolve these relevant smaller scale features; the use of regional or cloud resolving models may be crucial at that stage.

The intersection of the databases has revealed that almost all the ERDs occurred when a cyclonic system is present in the target area. Most of the ERDs appear at a distance from the cyclonic center lower than 1500 km, indicating that the possible relationship between cyclonic development and damages at the ground is very likely. This is particularly true for the LOWs: most of the correspondent ERDs (61%) occur very close to the center (within a 750 km radius), and a further significant fraction (28%), at distance between 750 and 1500 km from the LOW center, are distributed in the area where the cyclone cold front is usually present. In the case of the CUT systems the relation with the ERD can only be weakly established; the ERD centers are often found quite far from the CUT centers. This is probably related to the fact that the weather at lower levels is not always influenced by the upper air vortex. Finally, we remark that with this approach we have been able to only a statistical assessment of the large scale features, while it is well known that finer scales mechanisms, such as orographic or differential heating forcing, boundary layer convergence and jet-streak induced ageostrophy, have often a leading role in triggering severe events, especially when convection is involved.

It might turn to be interesting to extend the analysis outlined in this work to larger geographical areas and/or longer period. At the same time, quantitative evaluation of the damages potentially related to cyclonic systems is also expected to be useful in the context of climate prediction. These problems will be addressed in future works.

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