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Abstract. The speed of Atlantic surface depressions, occurred during the autumn and winter seasons and that lead to intense precipitation over Italy from 1951 to 2000, was investigated. Italy was divided into 5 regions as documented in previous climatological studies (based on Principal Component Analysis). Intense precipitation events were selected on the basis of in situ rain gauge data and clustered according to the region that they hit. For each intense precipitation event we tried to identify an associated surface depression and we tracked it, within a large domain covering the Mediterranean and Atlantic regions, from its formation to cyclolysis in order to estimate its speed. "Depression speeds" were estimated with 6-h resolution and clustered into slow and non-slow classes by means of a threshold, coinciding with the first quartile of speed distribution and depression centre speeds were associated with their positions. Slow speeds occurring over an area including Italy and the western Mediterranean basin showed frequencies higher than 25%, for all the Italian regions but one. The probability of obtaining by chance the observed more than 25% success rate was estimated by means of a binomial distribution. The statistical reliability of the result is confirmed for only one region. For Italy as a whole, results were confirmed at 95% confidence level. Stability of the statistical inference, with respect to errors in estimating depression speed and changes in the threshold of slow depressions, was analysed and essentially confirmed the previous results.

1 Introduction

In the last years, considerable research efforts have been devoted to the impact of weather systems on human activities. For what concerns the Mediterranean area see the MEDEX program (Major impact weather in the Mediterranean, http://medex.inm.uib.es). Particularly relevant impact can be associated with weather systems that move slowly, since high rain rates, on a specific area, is established by movement of weather systems across the area (e.g. Frei et al., 2000; Frei and Schär, 2001). The scale of such weather systems can be the synoptic or the smaller one.

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At even smaller scales, the slow movement of storms, such as supercells, makes such weather systems extremely dangerous.

The mobility of mid-latitude weather systems, such as cyclones and fronts, is determined by the planetary pattern of flow as well as by other factors like sea surface temperature, latent heat release and interaction with mountains. In this respect, the Mediterranean region, encompassing the Mediterranean Sea and the mountains surrounding it, is particularly rich of "modulating agents" for the mobility of the mid-latitude weather systems.

Theoretical studies were devoted to understanding the space-time evolution of waves.

Illari et al. (1981), using a theoretical model of a barotropic atmosphere, studied mechanisms determining the mobility of localized unstable disturbances on the planetary circulation. Cessi and Speranza (1985) and recently Speranza (2004) extended such studies for a baroclinic atmosphere.

The basic idea is that two types of instabilities are possible for the growth of a localized unstable disturbance: the so called (from Plasma Physiscs) "convective" and the "absolute" one. In the former type, an initially localized disturbance is advected faster than it grows, and in the latter one the localized disturbance grows more rapidly than it moves. As a consequence, the first type of localized disturbance appears as "moving downstream" and the second is "growing in place". Although those theoretical models are necessarily schematic, they seem to capture some observed mobility features from a diagnostic point of view. After all, there are good theoretical reasons for assuming that the

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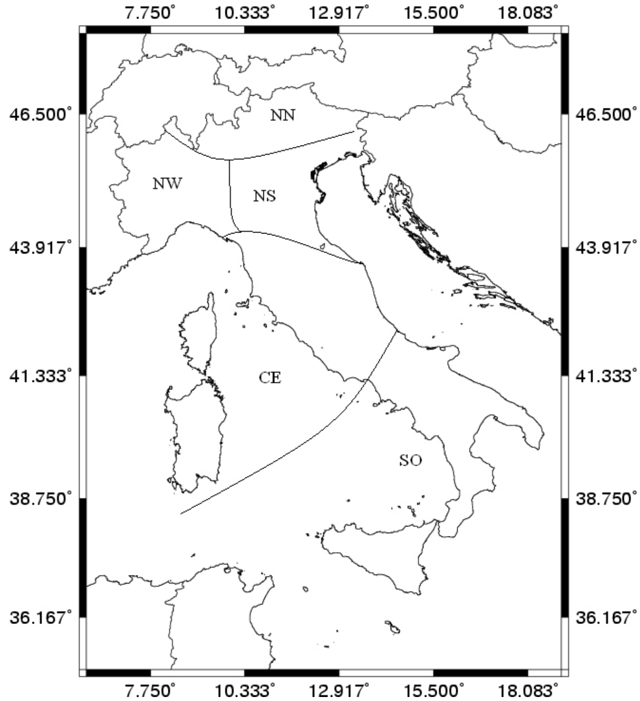

Fig. 1. Division of Italy in the five precipitation climatological regions as obtained by PCA analysis by Brunetti et al. (2004). (Adapted from Brunetti et al., 2004).

development (unstable growth) and the motion of cyclones are strongly connected: a Charney-Pedlosky study (Charney and Pedlosky, 1963) showed that a depression, developing in a baroclinic region, will remain confined in that region until its mature stage is reached. The movement of mid-latitude cyclones seems to be determined by the mid-level ("steering level") winds, during the phase following the unstable growth, but this is only an impression as remembered, for example, in Carlson (1998) textbook. In fact, the movement of cyclones is continuously determined by evolving interactions between the cyclone and the "surrounding flow".

Rigorous mathematical theories concerning the motion of well formed vortex "singularities" in fluids (mostly based on the so called Hugoniot-Maslov expansion chain) begin to be available, but they still refer to very schematic flow models.

Available observations seem to show that the mobility of depressions is a key factor in determining the development of the associated weather. Often, slow depressions are associated with "major" impact weather in the Mediterranean area (e.g. Nieto et al., 2005). This is evident from observations, although a statistical assessment establishing a connection between the speed of weather systems and their impact on specific areas is still missing. Hurley (1954) investigated inter-relationship between intensity, speed and direction of depressions in the Central United States from 1920 to 1929. A relationship between positions of winter depressions and their speed in the Northern Hemisphere may be found in the paper of Hoskins and Hodge (2002). The Mediterranean area seems fundamentally associated with slower depressions, as suggested by the work of Bell and Bosart (1989).

In this paper, we propose a statistical analysis concerning the mobility of Atlantic pressure lows associated with intense precipitation over Italy. We wish to verify whether a statistical relationship between low speed of depression centres and position within a selected area exists. Since a continuous relationship of the speed value with the geographical position cannot be envisaged, we introduce a threshold of speed value for distinguishing low speeds (hereafter indicated as SLOW). This way, we have a binomial definition of speed categories: speeds below the threshold and those above it. Furthermore, such speeds can be relative to motion within the selected area or out of it. With such a schematic representation of the combination speed-position, we try to identify possible symptoms of the above-mentioned relationship and test their statistical reliability.

In the following Sect. 2 we describe used data and adopted methodology. We specifically devote Sect. 3 to the limitations of our work in view of their relevance in such a preliminary study. In the following Sect. 4 we discuss our statistical results and draw our conclusions in Sect. 5.

2 Data and methodology

The precipitation data set used in this work consists of daily observations from 1880 to 2000, at stations spread over the whole Italy. The set was previously homogenized and checked in order to guarantee adequate data quality (Brunetti et al., 2002, 2004). Brunetti et al. (2004) also found, by applying Principal Component Analysis on the precipitation time series, that Italy can be conveniently divided into five regions: Northwest (NW), Northeast-North (NN), Northeast-South (NS), Centre (CE) and South (SO). Figure 1 shows the five regions as found by Brunetti et al. (2004).

The main purpose of our study is to understand whether a connection between the motion of depressions and intense precipitation exists for the five Italian climatic regions. We define as "intense" those precipitation events in which the estimated amount exceeds the 99th percentile threshold for at least two stations within one of the regions identified by Brunetti et al. (2004).

After selecting the "intense" events, we identified the nearest depression associated with the events, on NCEP mean sea level pressure reanalysis. Such an association is possible because in most Mediterranean heavy precipitation events there is a cyclonic centre not far from the areas where maximum rain is recorded. For example, Jansá et al. (2001) found that for about 90% of cases of heavy precipitation in the western Mediterranean, the centres of the associated cyclones were at least 600 km from the place where heavy rain was recorded. Tracking backward the minimum associated with intense precipitation, we were able to identify the place where cyclogenesis occurred, and then we followed the cyclone centre from its genesis to cyclolysis when possible, or the portion available in the domain of our study for cyclones born and/or died outside.

Sea Level Pressure (hereafter SLP) for the selected events was extracted from the NCEP dataset. The grid (25×25 points) has 2.5° horizontal resolution and covers the Mediterranean and Atlantic regions from 30° W to 30° E and from 10° to 70° N (Fig. 2). The time resolution is 6 h. The NCEP has the longer available gridded dataset, from 1951 to 2000. Limitations associated with this choice will be discussed in the next section. In order to dispose of a statistical ensemble with some degree of homogeneity, the investigation was confined to depressions with genesis over the Atlantic region of Fig. 2. Removal of the seasonal modulation seemed also advisable and therefore, only autumn and winter (from October to March) were considered. In these seasons the Atlantic cyclogenesis is, in fact, more active.

Although from our dataset two types of depressions (Atlantic, Mediterranean) were identified, we used only the Atlantic ones, since the Mediterranean ones were already in the area where "intense" precipitation was recorded and a direct impact of the Mediterranean area on the speed of such systems cannot be easily evaluated. 138 Atlantic depressions, associated with the selected intense precipitation events over the five Italian regions, were taken in account: 14 for NW, 81 for NN, 17 for NS, 19 for CE and 7 for SO.

An "objective" procedure was used to track depressions. The centre of depressions was computed on the basis of the SLP pattern. A description of the procedure can be found in Lionello et al. (2002). The speed of a depression was obtained just by dividing the distance the reconstructed depressions centre runs in the 6 h of the time resolution by the time interval. After tracking depression centres we associated to each position the mean speed during the previous 6 h. Then we clustered the speeds according to positions within or out of an area including Italy and the western Mediterranean basin (Fig. 2), hereinafter referred to as target area.

3 Limitations of the present study

Although high values of precipitation are often associated with "major" impact events – in particular flooding – an actual risk for population and territory is not their necessary consequence. Specifically, not all the events of precipitation selected as intense correspond to flooding events. On the other hand, long series of precipitation observations are readily available, while not the same can be said of hydrological observations. Moreover, precipitation series tend to be more reliable than hydrological ones since they are less influenced by human evaluation of damages. As a consequence, we choose to use precipitation in our first statistical exploration of the problem in question.

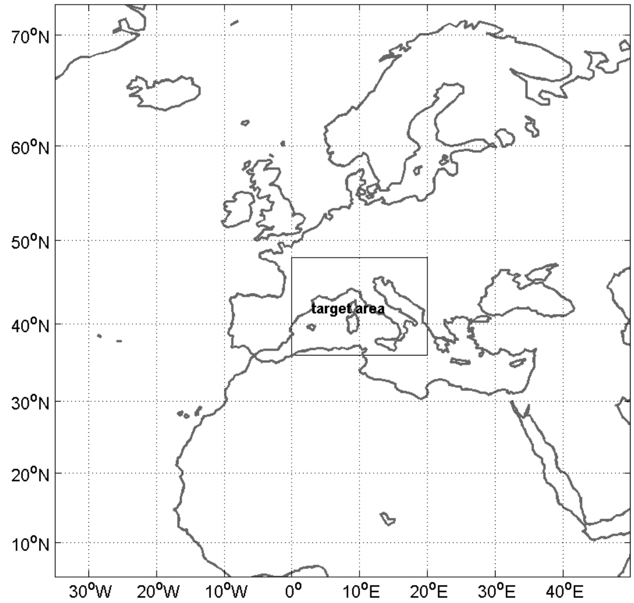

Fig. 2. The domain used for tracking the centres of depressions associated with "intense" precipitation over Italy. The rectangle within the domain is the area where a relationship between SLOW speeds of depression centre and "intense" precipitation over Italy is searched for.

As already remarked, it is problematic to establish a direct causality connection between slowing down of depressions and "intense" precipitation over specific regions. Besides obvious geographic factors, like mountains, other agents may be involved in the process. Just to mention one of such an agent, latent heat can be a key factor in determining the speed of the weather systems as, for example, shown by Reeves and Lackmann (2004) in the analysis of the mobility of a front.

In trying to understand whether a possible relationship between position of depressions, leading to intense precipitation over Italy, and their speed can be traced from statistical analysis, some a priori limiting factor must be considered.

First of all, in the present work we do not take into consideration precipitation along the path of depressions, due to a lack of precipitation data along depression paths, especially over sea.

Depressions may produce intense precipitation over Italy even when their centres are outside the target area considered (see Fig. 2). For example, a trough associated with a depression having its centre over British Isles caused the 1994 Piedmont flood (see, for example Buzzi et al., 1998; Doswell et al., 1998): this flow configuration leads to air from the southeastern Mediterranean flowing against the mountains surrounding the northern Mediterranean. In other events, a part of the moisture is observed to flow from the Atlantic region (e.g. Reale et al., 2001). Hence, in order to define causes and effects of heavy rainfall, the analysis of the moisture sources as well as the analysis of other precursors

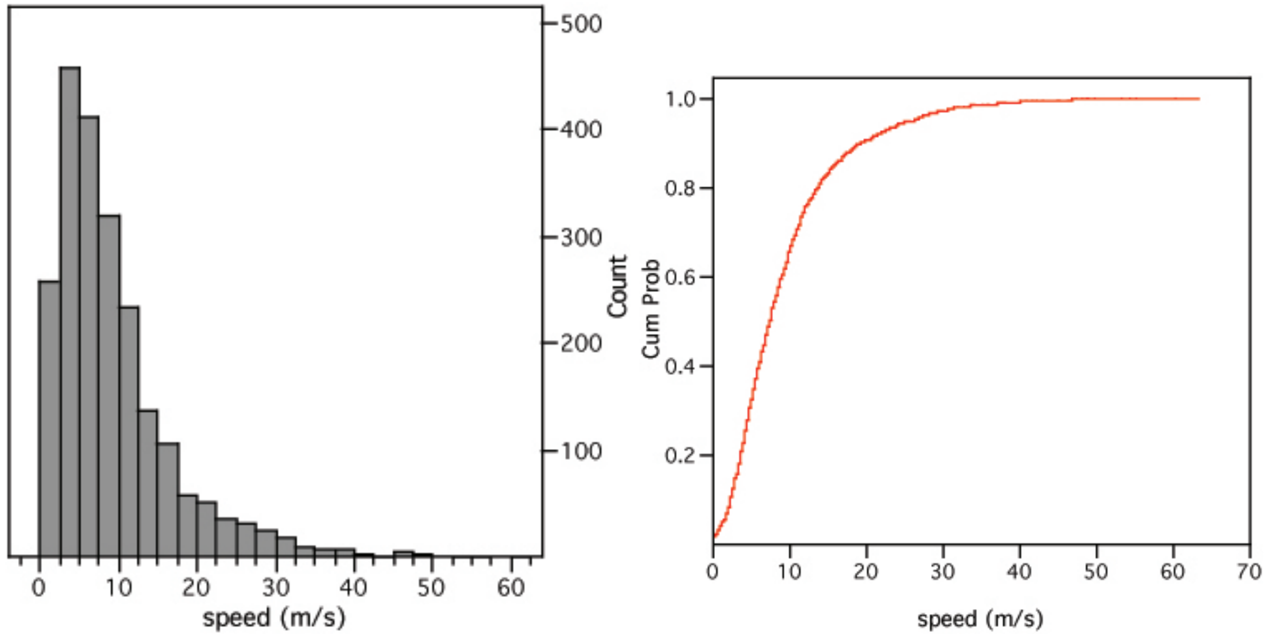

Fig. 3. Histogram and cumulative distribution function of the number of depressions centres (over all the 5 regions in which Italy was divided) with respect to their speed.

associated with intense precipitation (see, for example, Massacand et al., 1998) should be performed. Many factors can make a depression potentially dangerous, but the investigation of such factors is not proposed in this paper.

Moreover, estimates of mobility may depend on both the nature of data and the tracking algorithm. Because of the coarseness of the space-time resolution of the gridded fields used in this study, the error in the overall speed of depressions can be quite large. An estimate of such an error is of the order of one grid step over the considered time step, i.e. 2.5° in 6 h (about 250 km in 6 h or about 12 ms^{-1}). Although the definition of depression speed is admittedly rough, other studies with the same space-time grid (e.g. Nieto et al., 2005; Zhang et al., 2002), or with an even coarser one (Hoskins and Hodge, 2002) provided significant statistical results in the analysis of climatology of storm tracks in the Northern Hemisphere. In this paper, we also propose an analysis of the impact of this error on the proposed statistical inference. In fact, with respect to the focus of this paper, i.e. joint statistics of mobility and intense precipitation statistically stratified with geographical location, the outlined limitations proved to have limited impact. It is possible that some small Mediterranean baric depressions could not be caught due to the coarseness of NCEP grid. Among the depressions associated with intense precipitation over Italy, many Mediterranean depressions were found. For reasons discussed in the previous section, these depressions were not included in the analysis presented here. It will be useful, in the future, to analyse other dataset, like the ERA-40 one.

4 Statistics of speed of Atlantic depressions in the selected area

The estimator (histogram) of the probability density function (pdf) and its cumulative distribution function (cdf) for the overall speed of the selected depressions are shown in Fig. 3. Discriminating "speed regimes" is an arbitrary matter. In this first statistical inspection, in order to maintain things as simple as possible, we choose to distinguish slow speeds on the basis of quantiles of the speed distribution. The basic motivation for such procedure is that although histograms, like the one in Fig. 3 may change depending upon the number of bins, quantiles are not dependent on bins themselves. We choose the first quartile (96.5 $km\,h^{-1}$ or 4.47 ms^{-1}) as the value separating slow speeds (hereafter indicated as SLOW) from the rest. Having chosen the first quartile, SLOW speeds are particularly infrequent. The reduction to just two speed categories (SLOW and NON-SLOW, i.e. all the rest) is useful since it allows systematic use of the binomial distribution for testing the significance of the statistical results. A typical contraindication of such a pdf discretization consists in the potential instability of the statistical results with respect to changes in the adopted threshold.

Table 1 displays the number and frequency of slow speeds for the cases a) cyclone centre within the target area, b) cyclone centre outside the target area. Results are reported for all clusters of events, with the events classified according to the region in which intense precipitation was recorded. The table also displays the result obtained considering all Italian

Table 1. Number of positions, associated with SLOW speeds and their percentage with respect to all observed positions (TOTAL) observed in the selected area and out of it for three different thresholds (4.26, 4.47 and 4.61 ms^{-1}) . Number is shown for the five regions in which Italy was divided and for Italy as a whole. Percentages are approximated at the first decimal digit.

	In the target area			Out the target area		
Italian Region	NUMBER OF SLOW with thresholds 4.26, 4.47, 4.61 m/s	TOTAL	% SLOW on TOTAL	NUMBER OF SLOW with thresholds 4.26, 4.47, 4.61 m/s	TOTAL	% SLOW on TOTAL
NW	24, 27, 31	117	20.5, 23.1, 26.5	25, 32, 33	130	19.2, 24.6, 25.4
NN	27, 29, 31	101	26.7, 28.7, 32.7	128, 134, 151	652	19.6, 20.5, 23.1
NS	75, 80, 87	212	35.7, 37.7, 41.0	34, 38, 40	161	21.1, 23.6, 24.8
CE	23, 24, 24	82	28.0, 29.3, 29.3	70, 73, 74	273	25.6, 26.7, 27.1
SO	13, 15, 17	48	27.1, 31.2, 35.4	13, 13, 14	87	14.9, 14.9, 16.1
ITALY	162, 175, 192	560	28.9, 31.2, 34.3	270, 290, 312	1303	20.7, 22.3, 24.0

events together. The results give evidence that when the selected depressions have centre in the target area the associated speeds have higher frequencies of slow values than when they have centre outside. This result is evident for almost all regions but the NW one.

Figure 4 shows an example of the spatial distribution of positions associated with SLOW speed (red circle) and NON-SLOW speed (green circle). It concerns the NS region that is the region with the highest frequency of slow speed cases within the target area.

We have to investigate, though, whether the obtained results are significant. Specifically, we want to test the hypothesis that frequencies higher than 25%, shown in Table 1, are statistically reliable. Since for any position of its centre, a depression has only two states, SLOW or NON-SLOW, and we can use the binomial distribution under the hypothesis of independence of events and stationary probability.

At this point, the probability p to have a SLOW speed can be estimated by using the relative frequency of the SLOW speeds over all the possible speeds in the entire domain chosen for the analysis. This way, p is equal to 0.25. Therefore assuming that frequency of SLOW speed is always 0.25, we can compute the likelihood of an outcome (i.e. the number of SLOW speeds) high at least as the observed one. This means that we can use the classical expression for the binomial probability:

$$P(\text{slo} \geq \text{obs}) = \sum_{\text{slo}=\text{obs}}^{\text{tot}} \binom{\text{tot}}{\text{slo}} 0.25^{\text{slo}} (1-0.25)^{\text{tot}-\text{slo}} \quad (1)$$

Where “slo” indicates the number of SLOW speeds that we may have and obs is the number of the observed ones in the Mediterranean area; “tot” is the number of total observed speeds. Results of Eq. (1) are shown in Table 2. Results are significant only for the NS region and for Italy as a whole.

Thus, for example, counting 15 or more SLOW speeds, with the threshold 4.47 ms^{-1}, is not particularly unlikely for the South region (see Fig. 5 that shows the spatial distribution of the positions, for the SO region, with the associated SLOW and NON-SLOW speeds). For almost all regions but the NS, the observed success rate is not a strong evidence of the impact of the position within the target area on speeds of depressions that produced intense precipitation over those regions. Only for the NS region, under the above considered

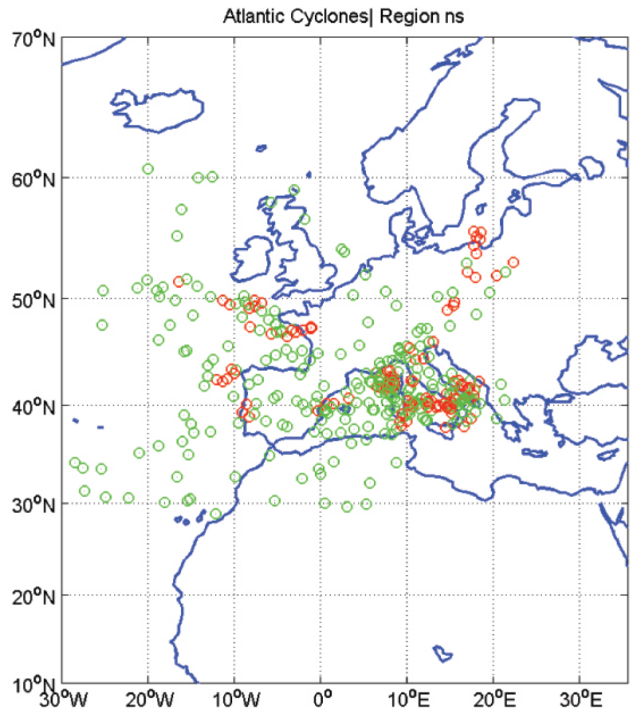

Fig. 4. Spatial distribution of positions of depression centres associated with “intense” precipitation occurred over the NS region. Red (Green) circles denote a SLOW (NON-SLOW) speed of the depression centre during the preceding 6 h.

Table 2. Binomial probability of the speed to assume a number of SLOW values at least as high as the previously computed one, as a function of the threshold defined as the 25th percentile. Values lower than 1.0, have only the most significant digit, for other numbers only the first decimal digit is shown.

Region	Threshold=4.26 (m/s) Probability %	Threshold =4.47 (m/s) Probability %	Threshold=4.61 (m/s) Probability %
NW	89.2*	71.7*	38.9
NN	38.0	22.5	5.1
NS	0.04	0.0002	0.00002
CE	30.0	22.0	22.0
SO	42.0	20.0	7.0
ITALY	2.0	0.05	0.00006

* it is not necessary since the percentage of observed SLOW speeds is lower than 25%.

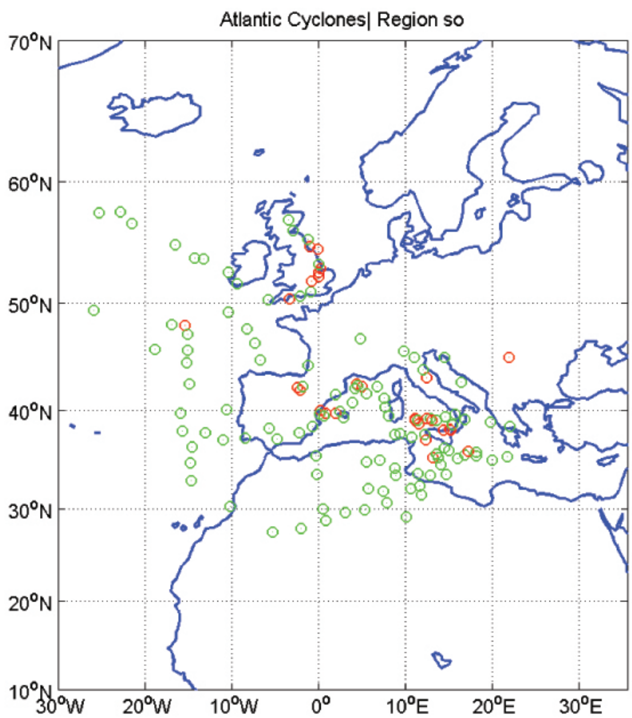

Fig. 5. As Fig. 4, but for the South (SO) region.

hypothesis and limitations, results are statistically significant with a confidence level of 99%. For other regions the confidence level of 95% is not reached.

When analyzing Italy as a whole, the result is again significant, with a confidence level of 95%. But a consideration is necessary in this case: for the target area, the region NS contributes to about 40% of the TOTAL speeds and about 50% of the SLOW speeds of Italy as a whole. Consequently, the result for Italy as a whole may be due to the result obtained by the NS region.

Although some reasonable assumptions can be made concerning the unknown error distribution of speed (for example, the distribution can be assumed as skewed, since the value of speed is always positive) a parametric model is not available. Consequently, we produced a bootstrapped confidence interval for the chosen threshold (the first quartile). In order to reduce uncertainty on the confidence interval, we produced 10 000 bootstrap samples.

The confidence interval for the first quartile of the distribution (4.47 ms^{-1}) derived by means of the bootstrap approach is [4.26, 4.61] ms^{-1}. The corresponding confidence level is 0.9.

Results of counting with the extremes of the confidence interval are shown in Table 1. For a 95% confidence level, the overall results are the same as obtained with 4.47 ms^{-1} as a threshold. The confidence levels change as shown in Table 2. The NN region for a 4.61 ms^{-1} threshold displays a confidence level of approximately 95%. This might be an indirect indication about the type of Atlantic cyclones that affect the Northeast area of Italy.

Use of the upper and lower values of the confidence interval associated with the adopted threshold still correspond the first quartile. We also considered what happens if we introduce a threshold corresponding to a different percentile. No substantial change was observed in the results when the threshold remained close to 25th percentile, i.e. performing the same calculations with thresholds up to 21st and 29th percentile.

5 Conclusions

After computing the distribution of speeds of Atlantic depressions leading to intense precipitations over Italy, velocities corresponding to a bottom percentile were classified as SLOW and the rest NON-SLOW. The depressions were split into five subsets depending on the region that they affected with the associated intense precipitation and tracked within a large area covering the Mediterranean and Atlantic regions from 30° W to 30° E and from 10° to 70° N. The frequency of SLOW speeds within a smaller area including Italy and the Mediterranean region (target area – see box in Fig. 2) was statistically higher than that of the SLOW speeds observed within the entire domain, but the statistical reliability, with a 99% confidence level, is confirmed only for the NS region and with a 95% confidence level for Italy as a whole. This provides a statistical evidence of the possible slowing down of Atlantic depressions when they reach the target area, at least for some of depressions considered.

The obtained statistical results are stable, considering the threshold at the first quartile. Results remain stable when the upper and lower values of the confidence interval, computed by applying a bootstrap technique, are used at the first quartile threshold. Moreover, even changing (within reasonable limits) the percentile threshold the results remain stable.

The result of our research seems to be in agreement, at least for the NS region, with previous studies such as the one of Bell and Bosart (1989) that found that formation points and dissipation areas of cut off lows, were very close over the Mediterranean area, indicating a low mobility of those systems.

Certainly, an higher resolution dataset (for example by using ERA-40 dataset) or including the investigation of vorticity can allow to catch more cyclones and give further information of the impact of the Mediterranean area on the movement of such systems.

The proposed, very preliminary, analysis encourages further investigation not only in statistical terms, but also concerning the dynamical processes determining the speed of depressions and their position, as well as the connection of their mobility with precipitation.

Slow speeds of depressions cause persistent weather systems (depressions-self and/or their frontal systems) imposing a high probability of heavy precipitation Frei and Schär (2001). Knowledge of impact of Mediterranean on depression speeds, and hence on the persistence of some type of depressions, is strictly connected with the necessary and sufficient conditions to have an “extreme” precipitation event. For example Llasat and Puigcerver (1990) showed that cold pools (often associated with Atlantic depressions) are neither necessary nor sufficient for the occurrence of heavy rainstorms, at least over the Iberian Peninsula. The conclusions obtained in this work, although not absolutely exhaustive, confirm that such necessary and sufficient conditions (analyzed here through the association between a target area and depression speeds) are not easy to demonstrate.

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