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Towards a systematic climatology of sensitivities of Mediterranean high impact weather: a contribution based on intense cyclones

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Abstract. One of the multiple approaches currently explored to mitigate the effects of hydro-meteorological hazardous events aims at improving the numerical weather forecasts. Under an ever increasing societal demand for cost cuts and more precise forecasts, targeted observations are currently receiving great attention within the operational weather community. The MEDEX project (http://medex.inm.uib.es) is aimed at improving the forecasts of high impact weather (HIW) in the Mediterranean and, in particular, proposes the creation of a climatology of sensitivities of such episodes. The construction of a comprehensive climatology of sensitivities is hampered by the lack of an exhaustive collection of Mediterranean HIW events.

In this study we contribute with a systematic climatology of Mediterranean intense cyclones. We perform an objective cluster analysis of intense cyclones detected from the ECMWF ERA40 reanalysis using a k-means algorithm and compute the sensitivities for each of the resulting classes. For each cluster, a representative sensitivity field is computed using the MM5 Adjoint Modeling system. The results show that although the sensitive areas for intense Mediterranean cyclones are not particularly confined, it is remarkable how areas poorly sampled by the regular observing networks, such as North Africa, the Mediterranean Sea and the eastern North-Atlantic, are highlighted in the prototype sensitivity maps.

1 Introduction

Operational weather prediction centers are receiving increasing pressure from the public and the authorities to extend and improve the forecasts while reducing costs and increasing efficiency. The European community is strongly committed to accomplish this increased efficiency on the observational component of the weather forecasting process. The Network of European Meteorological Services Composite Observing System project (EUMETNET-EUCOS, http://www.eumetnet.eu.org/conteucos.html) is appointed to optimize the composite observing system at European scale with a view to improve short range forecasts over Europe without increasing significantly the overall cost. The "EUCOS Plan" recognized the necessity to identify data sparse areas around Europe, and more specifically, the first objective of the "EUCOS High Level Design" is to clearly identify the areas where an increased observation effort needs to be implemented in order to improve numerical weather predictions. To this end, the EUCOS programme established as a priority the generation of a climatology of forecast sensitivities. At european scale and in average for all weather regimes, sensitivities of forecast errors are located roughly over the Northeastern Atlantic, in good agreement with the intuitive idea regarding the importance of structures located upstream of the Mediterranean along the climatological mid-latitude westerlies (Marseille and Bouttier, 2000). For the sake of efficiency, decisions regarding the location and deployment time for new observations or regarding the optimization of the permanent component of observational networks should take into special consideration the weather that entails high social impact. There is a special interest in analyzing the sensitivities of high impact weather (HIW) due to the larger associated benefits from better warnings of hazardous weather, supported by the expected forecast improvements.

The "Mediterranean experiment on cyclones that produce high impact weather in the Mediterranean" (MEDEX, http://medex.inm.uib.es) is a subproject of THORPEX endorsed by the "World Weather Research Program" of the "World Meteorological Organization". MEDEX coordinates weather services and research institutions from most countries of the Mediterranean basin. The "MEDEX Scientific Plan" is designed to contribute to the basic understanding and

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short-range forecasting of HIW events in the Mediterranean, mainly heavy rain and strong winds. Being the Mediterranean a region affected regularly by cyclones that produce hazardous weather such as strong windstorms or heavy rains that may produce extreme floods, one milestone within the project is the calculation of sensitive areas where an increase in the number, quality or type of observations would improve the numerical prediction of these episodes.

Provided the common interest between EUCOS and MEDEX, collaboration and support between the two projects were established, and an agreement was formalized that promoted the production of a climatology of short-range sensitive areas for Mediterranean intense cyclone events.

The lack of good databases of Mediterranean HIW events has made the design of a strategy to generate the full climatology of sensitivities of HIW events more difficult. Homar et al. (2006) reported on a first approach that focused on Mediterranean intense cyclones. The cyclones were classified subjectively according to the trajectory of their center and the representative sensitivity of each of the 19 cyclone classes were derived using an adjoint model on a single case belonging to the class. The conclusions presented in Homar et al. (2006) regarding the sensitivity of each cyclone type had limited representativity due to the lack of a constrain that forced the homogeneity of preceding conditions within each cyclone class. In this paper, a second step towards the composition of the climatology of intense cyclones sensitivities is presented. We make use of an objective cyclone classification method that promotes homogeneity of preceding conditions within the classes and therefore it improves how representative the derived sensitivity fields for each cluster are.

The following section discusses the methodological details of this study and some caveats in the databases that need special treatment in the classification and sensitivity computations. Sections 3 and 4 present the results of the clustering method and the sensitivity fields of each cyclone type. The conclusions and a discussion of their implications is presented in Sect. 5.

2 Methodology

In order to build the climatology of short-range sensitivities of high impact weather in the Mediterranean, a well-defined climatology of such events, consistent across the region, should be used as a starting point. As far as we know, the most recent effort to build such a climatology is being carried out within the MEDEX community. However, many difficulties have arisen during the data collection process. The climatology of Mediterranean HIW is currently a list of cases selected by the project members as important and representative of HIW in their region (http://medex.inm.uib.es/data/Selection_cases.htm). This list is not exhaustive and does not include systematic information, neither meteorological nor about the societal impacts, for all events. Thus, since a useful HIW database for our purposes is not currently readily available, alternatives to systematize the identification of HIW are explored.

A natural approach is to use the strong link between HIW and intense cyclones. Although most of Mediterranean HIW events are linked to cyclones (Jansà et al., 2001), not all of these cyclones are intense. However, intense cyclones are naturally associated with HIW. In an attempt to identify events that produce high impact in the Mediterranean, while admitting the inadequacy of the available HIW databases, we use the intense cyclones as a first contribution towards a more exhaustive climatology including all types of HIW events. Indeed, a cyclones database has been constructed under the MEDEX framework (publicly available at http://medex.inm.uib.es) and it is used here to identify types of intense cyclones. The cyclones catalogue is based on the Reanalysis fields from the European Center for Medium-Range Weather Forecast (ERA-40, Uppala et al., 2005) and characterizes the size, position, intensity, depth and path of all sea-level pressure cyclones within a domain that covers the Mediterranean region (see Fig. 1). The detection and tracking algorithms, as well as the characterization methods used to build the database, are thoroughly described in Picornell et al. (2001) and Campins et al. (2006).

Intense cyclones in this study are selected as those cyclonic systems with maximum circulation exceeding $7\times10^7\,\mathrm{m^2s^{-1}}$ and a lifetime of at least 24 h. The intensity measure is computed as an area integral of the geostrophic vorticity at 1000 hPa over the area around the cyclone's center with positive geostrophic vorticity. Using this definition and threshold for the intensity values, 1359 intense cyclones in 1349 days were detected by the automatic algorithm in the study domain over the 45 years period covered by the ERA-40 data (September 1957 to August 2002). This implies a mean frequency exceeding 30 intense cyclones per year, which agrees well with the order of magnitude of the average number of significant cyclones per year that one might allegedly assume to occur over the entire Mediterranean. The upper panel in Fig. 1 depicts the number of cyclones that achieve maximum intensity within an area of $2.25°\times2.25°$. The highest frequency of intense cyclones is located south of the Alps, which is consistent with the results of Petterssen (1956) that highligted the southern alpine flank (i.e. Gulf of Genoa and Northern Adriatic Sea) as the most cyclogenetic area in the Mediterranean. The areas with persistent occurrence of mature intense cyclones arise to the south and southeast of the most cyclogenetic areas. Indeed, most of the cyclones that achieve maximum intensity over the Adriatic and Thyrrenian are likely of alpine origin. Cyprus, Turkey and the Black Sea are also well known cyclogenetic areas, unlike the Ionian Sea which is also highligted in Fig. 1 as a region with a high occurrence of mature intense cyclones. As opposed to all other zones prone to the occurrence of intense cyclones, the maxima obtained over north Africa

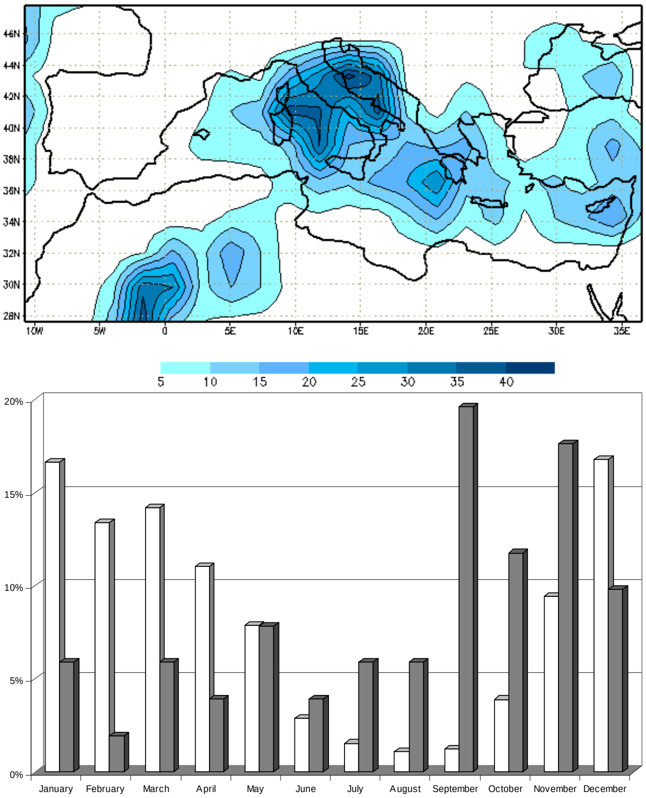

Fig. 1. Upper panel) Number of intense cyclones over the 45 years ERA-40 period at mature stage per squares of 2.25°×2.25°. Lower panel) Monthly frequency of intense cyclones in the ERA-40 analysis 1957–2002 (white) and monthly distribution of episodes in the MEDEX "list of selected cases" (grey).

mostly represent large thermal lows that fit the criteria of circulation but do not have high vorticity or strong winds associated with them. Indeed, most of the north African intense cyclones develop during summer while the average monthly distribution of Mediterranean intense cyclones show maximum frequencies during the winter months (lower panel in Fig. 1). In this regard, most of the actual dynamical cyclogenesis occurring over North Africa that lead to an intense cyclone, produces eventually a mature intense cyclone over the Mediterranean Sea, being accounted for over that area, and not so over the North African plateau. These population of intense cyclones that are not linked to high impact weather will require a special treatment at the later classification stage.

In order to classify the 1349 days into homogeneous classes we use the non-hierarchical k-means classification algorithm (Anderberg, 1973), as implemented in the R package (R Development Core Team, 2006). The set of prototype intense cyclones is derived by subjecting the T-mode (day-by-day) correlation matrix to principal components analysis (PCA), reducing the problem size while keeping significant variance (above 97%), and then carrying out cluster analysis (CA) on the most important extracted components. That is, days participating with similar loadings on the extracted components are clustered together. This approach is aimed at joining days with similar distribution of the classifying fields rather than similar actual values, ensuring a classification independent of the seasonal variation of the absolute values of the fields. The aim of the clustering process is to obtain classes of intense Mediterranean cyclones with similar 48 h lead-time sensitivity fields. The sensitivity fields depend greatly on the preceding synoptic situation, as well as the location of the mature cyclone. Consequently, the classification will be based on fields characterizing the location of the cyclone at the time of maximum intensity as well as the fields that characterize the situation preceding that time. Here, two rounds of classification were used (Table 1).

Table 1. Fields, number of principal components (PCs) and number of clusters. First round used Sea Level Pressure (SLP) over the Mediterranean at the time of maximum intensity of the cyclone (t_{max})whereas the second round also used geopotential height at 500 hPa (H) and temperature at 850 hPa over the whole domain, 24 h prior to t_{max}. The number of clusters in which each of the 16 classes obtained from round 1 were divided was subjectively decided between 1 and 5 subclasses by visual inspection of the results for each test (see text for details).

Round	Fields	# PCs	# Clusters
1	SLP t_{max} MED	25	16
2	SLP t_{max} MED H 500 hPa t_{max}-24h T 850 hPa t_{max}-24h	15 10 10	1–5 each from round 1

The first round is intended to regionalize the database so that cyclones that achieved maximum intensity on the same area, get clustered together. Sea-level pressure at the time of maximum cyclone intensity over an area that covers the entire Mediterranean is used as classifying field for this first round. The decision about the adequate number of clusters was made subjectively based on visual inspection of various tests. None of the objective indexes that were tested was useful in guiding this process, so the final decision of defining 16 clusters was made based on human judgement. The resulting clusters included a representation of all the classical types of Mediterranean intense cyclones. Thus, after the first round, cyclones belonging to one cluster happen to achieve maturity over the same region in the Mediterranean. This does not ensure homogeneity of preceding conditions, and so the existence of a unique representative field of sensitivities for each of these classes is highly unlikely. As mentioned before, the large thermal north African cyclones typical of summer months are included in the database due to the size of the cyclone rather than its intensity. Fortunately, these cyclones get clustered together at this first round, and their characteristics can be assessed specifically. Most of these cyclones

Table 2. Intense cyclone clusters as derived from the two rounds of k-means clustering. Dates of the closest members to the centroid are formatted as YYYYMMDDHH.

CL #	Name	# Members (%)	Closest member
1	Balearic Sea	124 (11)	1971013112
2	Tyrrhenian I	12 (1)	1979092406
3	Tyrrhenian II	24 (2)	1969020412
4	Tyrrhenian-Adriatic	51 (4)	1987011206
5	Adriatic I	110 (9)	1971021706
6	Adriatic II	128 (11)	1999012906
7	Sicily I	77 (7)	1959031306
8	Sicily II	70 (6)	2001011406
9	Ionian-Aegean	109 (9)	1994013000
10	Greece	55 (5)	1980010312
11	Cyprus	90 (8)	1992121500
12	Turkey	67 (6)	1988030918
13	Black Sea	74 (6)	1966121506
14	Atlantic	73 (6)	1982011200
15	North-West Africa I	27 (2)	1978050418
16	North-West Africa II	15 (1)	1974041906
17	North-West Africa III	21 (2)	1973032212
18	Libya	52 (4)	1974042500
	Total	1179	

are shallow, being detectable only up to 700 hPa while most of the 1359 intense Mediterranean cyclones of the database are deep, achieving the 300 hPa level. In addition, the average maximum winds associated with these 96 north African cyclones is 11.7 ms $^{-1}$, much lower than the average maximum winds for the complete dataset, 17.2 ms^{-1}. Owing to these differences, this whole class is discarded from the later analysis.

For the sake of more homogeneous groups in terms of preceding atmospheric conditions, the second round of classification also takes into account the fields of geopotential height at 500 hPa and temperature at 850 hPa over the entire domain valid 24 h prior to the time of cyclone maturity. Each first-round cluster were divided from 1 (no division) to 5 subgroups. All results from the second round of classification were analyzed subjectively and the most appropriate number of subgroups for each first-round cluster were subjectively decided using the criteria of minimizing the final number of classes and maximizing the homogeneity of the fields within each cluster. For most of the first-round clusters, the second step was very useful to refine the cluster by eliminating outliers that were very easy to identify in the high order division tests. As an example, the centroid of first-round cluster number 4 shows a cyclone over Sicily and contains 72 members. The second round test that divides this in 2, shows one subgroup with 70 members and the other with 2 members with intense cyclones shifted to the west and very different 24 h preceding fields than those of the 70 members subgroup. Thus, the final cluster of Sicily cyclones was chosen to be the first subgroup, discarding the 2 outliers from the latter sensitivity analysis.

A total of 18 types of episodes that produce intense cyclones in the Mediterranean on 1179 different days were finally derived (Table 2). A description of the results of the classification is presented in Sect. 3. In order to obtain a representative sensitivity field for each of the 18 clusters, we select the most similar member to the cluster centroid, that is, the closest member of the cluster to the centroid in the space of PC loadings. Then, the sensitivity fields for this closest member are calculated using the MM5 Adjoint modeling system (Zou et al., 1997, 1998).

The adjoint model (L^*) is a tangent linear operator that traces back in time the gradients vector of a response function ($\nabla_{\boldsymbol{x}} J$) with respect to the forward (standard nonlinear) model fields ($\boldsymbol{x}$), along forward model trajectories in phase space (see Errico, 1997, for an introduction to adjoint techniques in numerical weather prediction). As a result, the gradients of the response function, defined at a forecast time, with respect to the model fields at an earlier time (usually the initial conditions time) are obtained:

$$\nabla_{\boldsymbol{x}} J|_{t=t_0} = L^* \, \nabla_{\boldsymbol{x}} J|_{t=t_f}$$

where t_0 is the initial conditions time, t_f the forecast time when the response function (J) is defined. These fields ($\nabla_{\boldsymbol{x}} J|_{t=t_0}$) inform about the changes in the forecast that will be obtained for a certain perturbation to the model fields, which is commonly referred to as the sensitivity of the forecast to the model fields:

$$\Delta J|_{t=t_f} = \nabla_{\boldsymbol{x}} J \cdot \boldsymbol{\Delta x}|_{t=t_0}$$

where $\boldsymbol{\Delta x}$ is a perturbation to the initial conditions and $\Delta J|_{t=t_f}$ is the linear estimate of change in the response function J derived from the sensitivity field $\nabla_{\boldsymbol{x}} J|_{t=t_0}$.

The selection of J is a key point in the construction of the climatology of sensitivities. Any sensible comparison between different sensitivity fields must be done using the same response function. Otherwise, we would need to make use of balance relationships which would allow for quantitative comparison among them. Since all episodes considered in this study are connected to an intense cyclone, we define as response function the 48 h forecast of the pressure perturbation field at the 3 lowest σ model levels over an area centered on the predicted cyclone minimum pressure. Note that the location of the predicted cyclone may differ from the location in the cluster centroid. In consequence, the response function will be defined based on the position of the predicted cyclone of the closest member to the centroid, as opposed to the cyclone center on the centroid fields. This allows to better capture in the sensitivities of the physical processes leading to the predicted cyclone. Besides, although humidity involves highly nonlinear processes that hamper the applicability of the adjoint model (Vukićević and Errico, 1993), we turn on the adjoint of the explicit moisture parameterization (Dudhia, 1989) in the adjoint model run because it is an influential factor in many Mediterranean intense cyclonic events that must be considered in the sensitivity calculations. For a more detailed description of the adjoint model and its application to a Mediterranean cyclone, see Homar and Stensrud (2004). The adjoint model computes the gradients of the response function with respect to each model field on the initial conditions.

A way of summarizing the results is to compute the average over all fields and vertical levels, which provides a good perception of the most sensitive regions, hiding in all information about the sensitivity of the response function to different levels or fields and resulting in a quantity with non-physical units ([Pressure units]/["IC units"], Homar and Stensrud, 2004). This simple averaging over vertical levels and over wind components, temperature, pressure perturbation and specific humidity is the standard product, hereafter referred to as "sensitivity". This product is used to summarize the complete set of gradients for each case and to facilitate the comparison among different regions and classes. The interpretation of such an index is analogous to a sensitivity field but extrapolable to the vertical levels: high values of "sensitivity" highlight areas where changes to the fields of U,V,T,PP or q at some (undetermined with this field) level in the vertical will produce significant changes to the response function (i.e. central sea level pressure in the predicted intense cyclone).

Since the response function for each case is defined following a common criteria, the comparison of results among classes is possible. In addition, further calculations are attempted in order to obtain a single summarizing map that sketches the most important areas of sensitivity for the intense Mediterranean cyclones. The sensitivity fields and the results derived from them are presented in Sect. 4.

3 Clustering results

The results obtained from the double round of k-means clustering algorithm show a diverse typology of cases that cover very well the entire Mediterranean region (Fig. 2). On the western basin, the *Adriatic* (*I* and *II*) is the most frequent type of intense cyclone in the Mediterranean with more than 200 events in the database (∼20%). This is consistent with the climatological fact that the Genoa Gulf is the most cyclogenetic area in the Mediterranean (Petterssen, 1956) and most of the cyclones that achieve maximum intensity over the Adriatic, are likely to originate in that area. Classes *Adriatic I* and *II* differ in the location of the sea level pressure cyclone center but also on the 24 h preceding conditions. Both types of intense cyclone develop under the presence of a deep trough at 500 hPa that extends from north Europe down to North Africa and a ridge over the eastern north Atlantic. However the mean trough is deeper and shifted to the east for the *Adriatic II* cases than those grouped in class *Adriatic I*. Therefore, the classes are not merged into a single one to prevent the two different sensitivity fields to be smoothed out. The other type of cyclones that lay from the Balearic Sea to the Adriatic are represented by classes 1 to 4, under very different configurations of sea-level pressure highs over the Atlantic (upper row and left panel of second row in Fig. 2).

Cyclones that achieve maximum intensity over Sicily represent also a large portion of the population (13%), developing under two different synoptic SLP patterns (left and middle panels of third row in Fig. 2). *Sicily II* cyclones form under the influence of a high pressure system over Europe that produces strong south and south-easterly winds over Greece and the Adriatic basin. Class *Sicily I* differs from *Sicily II* in the presence of a weak pressure high between Azores and Canary Islands as oposed to the general cyclonic flow over the Atlantic part of the domain for class *Sicily II*.

Regarding the cyclones of the central basin, the *Ionian-Aegean* class is the most frequent type (9%) and together with the *Greece* cyclones produce strong winds (e.g. Bora) over the Adriatic basin. Further to the east, the *Cyprus*, *Turkey* and *Black Sea* clusters represent a 20% of the total population and typically form under a synoptic trough aloft over eastern Europe that extends south towards the Ionian Sea.

As shown in Fig. 1, the area over which the intense cyclones were detected from the ERA-40 database included a narrow strip of the Atlantic Ocean. Consequently, a number of Atlantic cyclones slipped in the climatology. As expected, these cases were clustered together by the k-means algorithm and could have been easily removed from the study. However, many of these situations produce strong winds and precipitation over Mediterranean Spain (Romero et al., 1999) and so even though the cyclones are not Mediterranean, the entailed impacts affect the Mediterranean and so they are eventually considered in this study. The preceding conditions for these cyclones are characterized by deep Atlantic troughs aloft progressing eastwards towards western Europe.

The last four classes resulting from the two rounds of classification are North-African systems that are associated with high impact weather, either by being associated with strong winds (Libyan depressions) or by being responsible for easterly moist flows that impinge the Tunisian, Algerian and Spanish coasts, producing deep moist convection and heavy precipitation. The preceding conditions for these events usually show a deep cold trough at mid levels extending down to North Africa which generates a large baroclinic region where the intense cyclone rapidly develops.

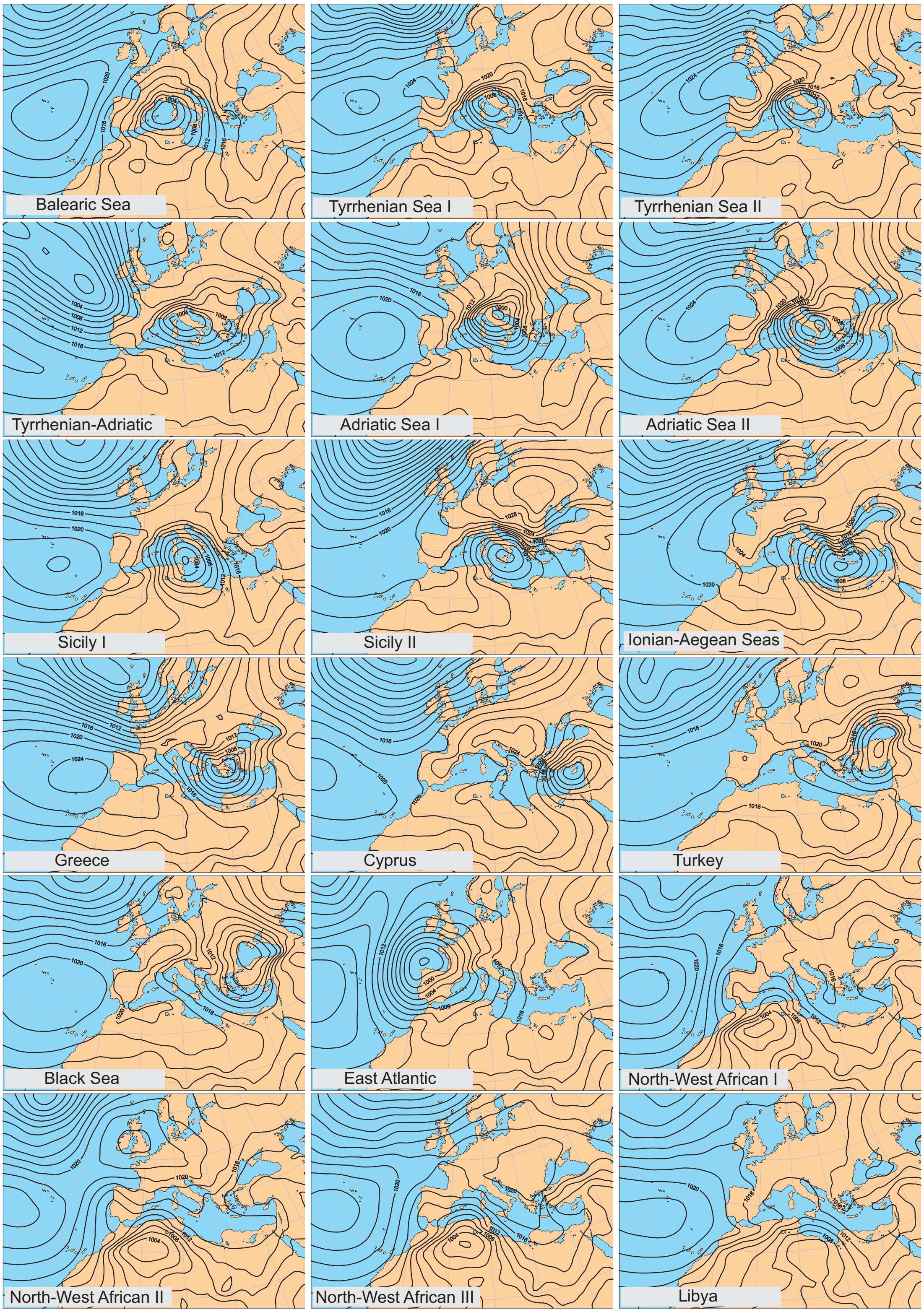

Fig. 2. Mean sea-level pressure for each of the 18 clusters.

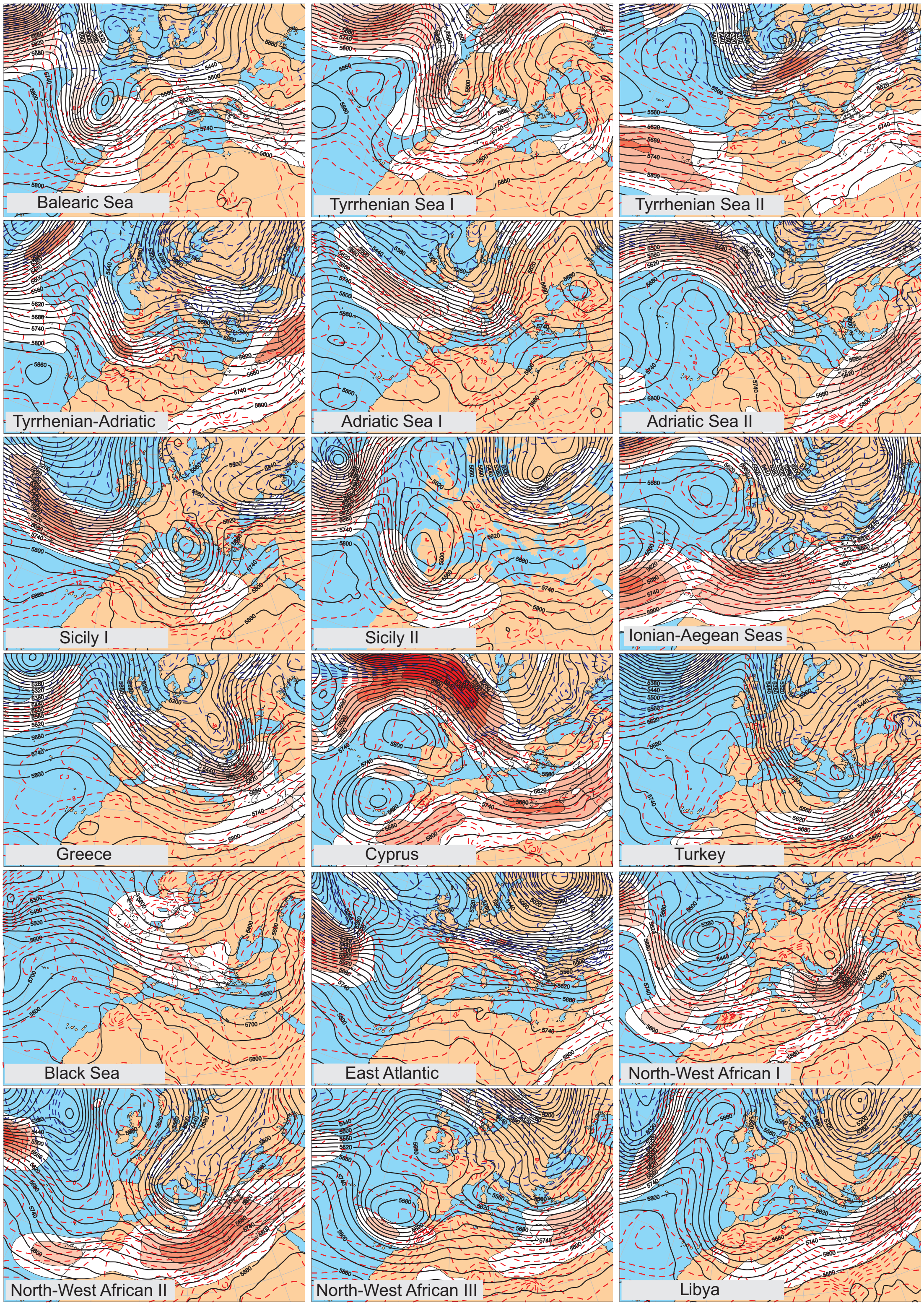

Fig. 3. Representative normalized sensitivity to initial conditions for each of the 18 intense cyclones shown in Fig. 2. Normalization refers to the area over which the response function is defined. Actual values for this field are unphysical (see text for details). Darker areas show higher sensitivities. Geopotential height (m) at 500 hPa and Temperature (°C) at 850 hPa valid at the same time are also depicted for reference.

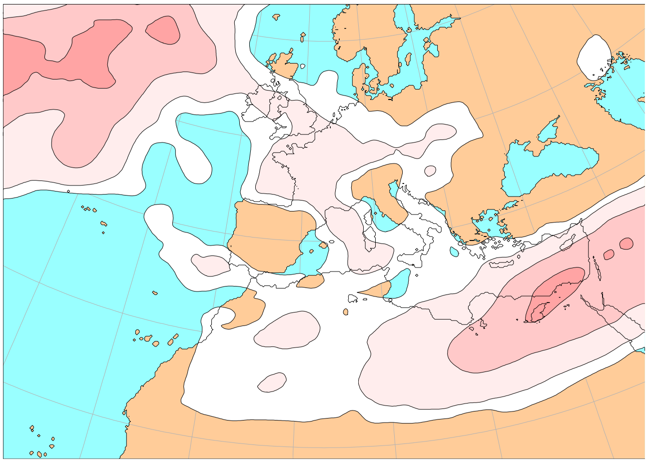

Fig. 4. Average of 48-h sensitivities to central cyclone pressure weighted by the intense cyclone frequency within the database. Darker colors indicate higher sensitivities.

4 Sensitivity fields

For each of the classes listed in last section, the sensitivities of the prototype cyclogenetic development are computed using the adjoint model on the closest member to the cluster centroid (see Table 2 for the dates). As one could expect, there is a wide range of areas that are influential on the 48 h development of intense Mediterranean cyclones. Figure 3 show the normalized sensitivity (i.e. the averaged sensitivity per area unit of the response function) for the 18 cyclone types. Sensitivity patterns tend to focus on strong gradients on the temperature and height fields, confirming its relevance on the future evolution of the situations and eventual cyclone development. Although this link between mid-levels mass fields gradients and subsequent low-level cyclogenesis can be directly inferred from the quasi-geostrophic tendency equation, without the need for running an adjoint model, the adjoint fields provide a more detailed sensitivity field. The adjoint sensitivities not only provide valuable information pointing to specific zones of the dynamic structure that one might infer from dynamical conceptual models, but also highlight other areas of the domain, sometimes even downstream of the cyclone, that pose challenging questions regarding the dynamical factors involved in the intense cyclone development.

The cases affecting the Western Mediterranean (three top rows in Fig. 3) show most of the sensitivity over the Atlantic but also unveiling lower, but significant, values extending eastward along the westerlies belt up to the eastern boundary of the model domain. It is noteworthy how in cases were the westerlies are split, the adjoint model emphasizes both branches of the flow, as in the *Tyrrhenian Sea II or* Sicily II cases. The cases of *Tyrrhenian-Adriatic and* Adriatic II are particularly interesting due to the important sensitivity obtained downstream, over the Eastern Mediterranean. This might be interpreted as a reflection of the crucial role played in this particular cases by downstream structures that remain quasi-stationary during the cyclogenetic and maturing stages of the intense cyclone, thus interacting with the main trough.

Cyclones developed over central and eastern Mediterranean are mostly sensitive to the North-African regions and the Mediterranean Sea. A particular picture is produced by the *Cyprus* cyclones, that are sensitive both to the mid-level advection of northwestern cold air and its interaction with the subtropical jet detected over north-Africa. This is indicated by the adjoint highlighting sensitive areas over northern Europe and the Atlantic, together with north-African regions. Regarding the north African cyclones (*North-West Africans and* Libya), sensitive areas are also obtained over the westerlies, with special attention on downstream areas, with the Eastern Mediterranean being specially influential, arguably due to the aforementioned blocking effect.

The mosaic of results shown in Fig. 3 is summarized by computing a mean over all 18 cyclone types, weighted by the relative frequency of each type within the database, shown in Table 2. This provides a single figure intended to inform about the climatological areas where the prediction of intense Mediterranean cyclones is most sensitive (Fig. 4). This plot highlights the areas over the eastern North Atlantic and the Eastern Mediterranean as important for the 48-h prediction of intense Mediterranean Cyclones. The Atlantic signal agrees with the sensitive area obtained by Marseille and Bouttier (2000), that used a target area centered over the Mediterranean and considered all types of weather situations. However, the persistently high sensitivity areas found over the eastern Mediterranean, mostly downstream of the area of interest, must be interpreted as a result of two different effects: the aforementioned influence of downstream structures on the evolution of the trough that is dynamically linked to the cyclogenesis (as in classes *Adriatic Sea II* or *Libya*), and also the direct dynamical effect of upstream structures on the cyclone formation (as in classes *Cyprus* and *Turkey*). These effects are highlighted in the climatological picture because the four classes mentioned represent almost a third of the total population, thus having an important weight in the mean sensitivity field. Beside the two main regions, also continental Europe, the Mediterranean Sea and North Africa emerge as climatologically sensitive areas for the 48-h forecast of intense Mediterranean cyclones. Remarkably, the southwestern part of the domain is not emphasized as sensitive although the *Tyrrhenian Sea II, Ionian-Aegean Seas* and *North-West African* classes show some sensitivity to that region. This is a benefit of the weighted mean, that highlights the areas where the most frequent cyclone classes show sensitivity and so provides a better guidance to support decisions regarding the efficiency of new observational strategies.

The use of a common framework to compute the sensitivities of all intense cyclone classes allows to perform additional comparison among them. The root mean squared (RMS) of the "artificial" sensitivity fields shown in Fig. 3

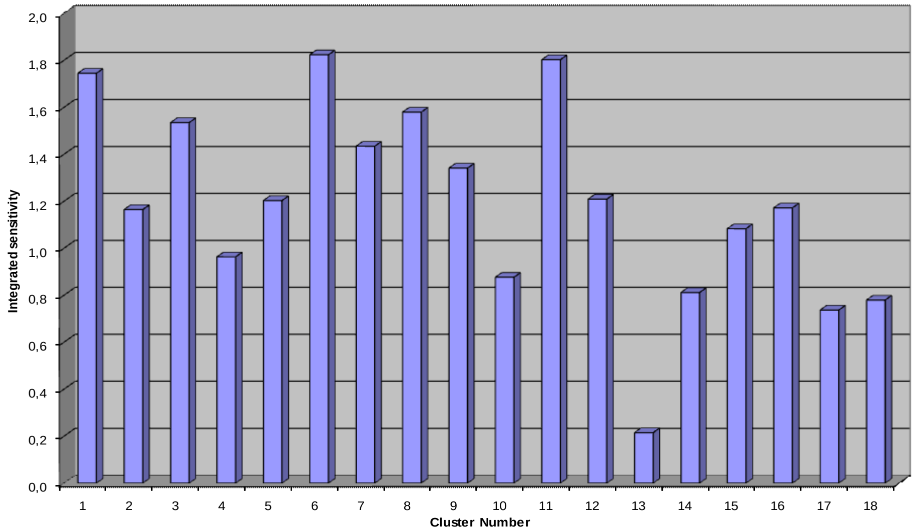

Fig. 5. Root mean squared of the sensitivity field for each intense cyclone cluster. This is a vague estimate of cyclone's central sea-level pressure predictability that allow for sensible comparison among the clusters (see text for details).

gives an integral estimate of the predictability of each class. Provided that the sensitivity field is artificial, the RMS has not physical meaning, but the comparison among them provides a good measure of the relative predictability of each cyclone class compared to the others. Everything else being equal (e.g. the analysis error), a cyclone class showing larger RMS sensitivity means that, in average, the 48-h forecast of those cyclones will change more than another class showing less sensitivity under similar perturbations (or initial conditions errors). Therefore, the larger the integrated sensitivity (i.e. the RMS *sensitivity*), the lower the predictability. Figure 5 shows how the 48-h central pressure forecast for some classes are more than twice as sensitive to initial conditions as others. *Adriatic Sea II*, *Cyprus* and *Balearic Sea* cyclones show the largest sensitivities, whereas the *Black Sea*, *East Atlantic*, *North-West African III* and *Libya* arise as the most 48-h predictable intense cyclones in the dataset.

5 Conclusions

This paper reports on the first step towards building a systematic climatology of sensitivities for Mediterranean high impact weather. Provided the lack of complete and consistent databases of damaging weather events in the region, we perform a first contribution by focusing on intense Mediterranean cyclones.

We classify intense cyclones accounting for not only the location of the cyclone center at the time of maximum intensity but also for the tropospheric situation preceding the events. The use of atmospheric fields 24 h before the cyclones achieve mature stage in the classification process is intended to cluster together those cyclones that not only become mature over the same location in the Mediterranean but also originate from a similar precursor atmospheric pattern. Then for each of the 18 intense cyclone classes, the sensitivity of the pressure field around the center of the cyclone is computed using an adjoint model. The closest member to each cluster centroid is used as the representative member of each class. The adjoint sensitivity calculations are set up using a common framework for all classes that allows later comparison and averaging among the individual sensitivity fields.

Given the climatological sensitivity results, summarized in Fig. 4, future decisions regarding the optimization of the observational strategies with regard to Mediterranean weather should put special attention to the North Atlantic, the north African countries (particularly the easternmost regions) and the Mediterranean Sea. These areas emerge as determinant for the 48 h forecast of intense Mediterranean cyclones and are systematically not well sampled by the operational observation networks. Continental Europe and the British Isles are also emphasized by the results but these regions are routinely well sampled by operational networks. Increasing the number and quality of routine observations over north Africa and the Mediterranean Sea will likely be also beneficial for forecast times shorter than the 48 h analyzed in this study.

Future work along this research line will focus on the use of the cluster centroid to produce the sensitivity fields, instead of a particular member of the cluster. Furthermore, the robustness of the sensitivity fields should be tested by using other response functions that can characterize the cyclonic circulation (such as vorticity or total energy) and also by performing experiments with the standard forward model that test the sensitivity estimates computed by the adjoint. Once the sensitivity fields can be tested and verified, further results such as the vertical structure of the sensitivity patterns or partial summarizing of results by Mediterranean regions will also be derived.

These results are currently being analyzed within the EUCOS programme community and further research lines are being tackled to increase the reliability and the typology of events that will eventually build up the climatology of sensitivities of Mediterranean high impact weather.

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