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Ensemble sensitivities of the real atmosphere: application to Mediterranean intense cyclones

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ABSTRACT

Ensemble sensitivity has been recently proposed as an alternative cheap approach to sensitivity analysis. We adapt it to compute climatological sensitivity estimates of intense Mediterranean cyclones using a climatology based of the ECMWF ERA-40 fields. A catalogue of 1202 events, objectively detected and classified in 25 clusters, is used in this study. Sensitivity fields are derived for each intense Mediterranean cyclone type by correlating the precursor conditions with the mature cyclones depths. Corrections to the raw sensitivity estimates are applied by means of the correlation coefficient. Further, a normalization based on the climatological spatial variability of the variance of the precursor conditions is used to derive the final sensitivity fields. The 24 h sensitivity information derived for each intense Mediterranean cyclone type is easily interpretable both in amplitude and distribution. A synthetic result combining the sensitivity fields for all 25 intense Mediterranean cyclone classes shows that the evolution of these high-impact systems 24 h prior to its maturity stage depends largely on structures located over Western Europe, the Northern African lands and parts of east North Atlantic. These results are in agreement and complement with previous results obtained with the expensive adjoint model, although further work is needed to objectively verify the results.

1. Introduction

The Mediterranean region is an active cyclogenetic area, frequently affected by cyclones that produce hazardous weather such as strong winds and heavy rain. The European Union devotes many efforts to improve the prediction of these events. Increasing the number and type of observations fed into data assimilation systems is continuously leading to better forecasts. Increasing spatial and temporal resolution of regular standard observations would also arguably reduce analysis errors and improve the numerical forecasts derived from them. However, a simple homogeneous increase of the number and type of in situ observations is an unaffordable approach which is incompatible with an ever-growing pressure from the public and authorities to improve forecast skill while reducing costs and tighting to high efficiency. The Network of European Meteorological Services Composite Observing System project (EUMETNET-EUCOS, http://www.eumetnet.eu.org/conteucos.html) is a relevant example of the European commitment to improve short-range forecasts, optimizing the integrated observing system network across Europe. Sensitivity analysis provides a cheap and efficient approach to explore optimal network configurations. Sensitivity analysis techniques point towards atmospheric features at earlier times that have a relevant effect on a particular forecast aspect of interest. Information derived from such analyses can be very useful to support decision makers regarding the design of an efficient routine observing network and targeted observation strategies. The high-impact weather (HIW) component of these two objectives is an important part of the plan for the second phase of MEDEX (Mediterranean experiment on cyclones that produce HIW in the Mediterranean, http://medex.inm.uib.es). Especially, MEDEX is designed to contribute to the basic understanding and short-range forecasting of HIW events in the Mediterranean, mainly heavy rains and strong winds.

In average, over Europe and for all weather regimes, sensitivities of forecast errors are located mainly upstream of the westerlies, over the Northeastern Atlantic (Marseille and Bouttier, 2000). However, in accordance with the common interest between EUCOS and MEDEX in analysing the sensitivities of HIW, Homar et al. (2006), Homar et al. (2007) and Jansà and Homar (2006) report on the process of building a climatology of short-range sensitive areas for intense cyclone events in the Mediterranean based on adjoint model results. This climatology reveals that areas poorly sampled by the current in situ observing networks, such as most of North Africa, the Mediterranean Sea and the eastern North Atlantic, are important for the short-range forecast of intense Mediterranean cyclones. In the present study, we provide an alternative methodology to build a climatology

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of sensitivities of Mediterranean intense cyclones using an approach not linked to a particular forecasting model or numerical set-up, besides the data assimilation system used to produce the reanalysis fields. Results from this study are intended to complement those in Jansà and Homar (2006) and might ultimately support future decisions regarding the optimization of observational strategies in Europe, accounting also for Mediterranean high-impact episodes.

A number of methods have been proposed to estimate the effects of any given perturbation to the initial conditions onto a specific aspect of the forecast ('response function', J). The traditional sensitivity analysis techniques track the effects of perturbations throughout the numerical forecast, obtaining the non-linear sensitivities of all forecast fields to the particular set of perturbations initially designed. Under the strong assumption of linearity on the effect of individual unitary perturbations on J (Martin and Xue, 2006), the number of simulations required to characterize the entire model space is proportional to the number of input variables times the number of gridpoints. This 'brute-force' procedure implies a great number of simulations to find the modification that maximizes the change in the response function. In practice, this method has been used to calculate two-dimensional sensitivity fields to a limited number of variables (Martin and Xue, 2006).

Adjoint models are a more efficient alternative to the 'brute-force' approach. Tangent-linear adjoint models follow a phase-space trajectory that is tangent linear to the basic non-linear state evolution and trace back in time the gradients of the response function with respect to the model state (Errico, 1997). These models produce a tangent-linear estimate of the sensitivities of a forecast aspect to the initial and boundary conditions fields. Certainly, the tangent-linear character of the operator limits the validity of its results to timespans in which the non-linear model evolves perturbations quasi-linearly (e.g. linear regime). This interval may extend up to 48–72 h for smooth integrated response functions but it is not longer than 12–18 h when diabatic processes affect J (Homar and Stensrud, 2004). As a consequence, the selection of the response function is a more delicate matter in adjoint sensitivity studies than in other methods because some forecasted features such as rainfall or convective systems severely hamper the tangent-linear approximation. When a highly diabatically influenced response function is to be analysed, a proxy, typically found on a precursor larger-scale dynamical structure, is preferred.

On the other hand, techniques such as the ensemble transform (ET; Bishop and Toth, 1999) and ensemble transform Kalman filter (ETKF; Bishop et al., 2001) may be considered as sensitivity analysis tools because they are useful to identify regions where additional observations are most likely to produce the largest error reduction at forecast time. Both ET and ETKF are used in targeted observations campaigns (Szunyogh et al., 2000,2002) as they produce a quantitative prediction of the likely impact of any feasible set of supplementary observations by estimating the difference between the dispersion of a forecast that includes the targeted observations and one that does not.

Recently, a new approach to sensitivity analysis, based on ensembles of forecasts, has been proposed. This ensemble sensitivity technique uses sample statistics to identify linear relationships between forecast aspects and initial conditions. This technique was described by Hakim and Torn (2008) and explored by Ancell and Hakim (2007; hereafter AH07). They found that ensemble sensitivity provides estimates of the impact of initial condition changes to a forecast metric without additional model integrations if an ensemble of analyses and forecasts is available. Within this theoretical framework, we propose to calculate ensemble sensitivities of the atmosphere, not by using ensembles of simulations but by means of the climatology of Mediterranean intense cyclones available from Jansà and Homar (2006), which is based on the reanalysis fields from the European Center for Medium-Range Weather Forecast (ERA-40; Uppala et al., 2005). The ensemble of prior and posterior fields is built upon days in the ERA-40 in which similar intense cyclones were detected. The differences among similar events provide the required diversity for the AH07 method. In addition, we compare these results to analogous adjoint sensitivities obtained by Jansà and Homar (2006).

The following section describes the climatology of Mediterranean intense cyclones used in this study and discusses the methodological details of the ensemble sensitivity analysis proposed. Section 3 presents the sensitivity fields of one cyclone type and some global results, as well as their comparison with the analogue adjoint sensitivity fields. Conclusions and final remarks are given in Section 4.

2. Methodology

2.1. Climatology of Mediterranean intense cyclones

The original sensitivity calculation method proposed by AH07 stablishes linear statistical bonds between a number of forecasted fields and their precursor conditions. The sets of perturbed initial conditions and forecast fields are obtained from standard ensemble forecasting systems. With the aim of computing climatological sensitivity estimates with no dependence on a particular forecasting system except for the first-guess fields in the data assimilation cycle of ERA-40, we propose to apply the AH07 technique directly to analysis fields instead of ensembles of forecasts. In particular, we put the proposed technique to test by using a climatology of Mediterranean intense cyclones available from the MEDEX project data sets (Jansà and Homar, 2006).

The climatology used in this study is based on a database of Mediterranean cyclones objectively detected on the ERA-40 reanalysis fields. The database catalogues all sea level pressure (SLP) cyclones in the Mediterranean region detected over the

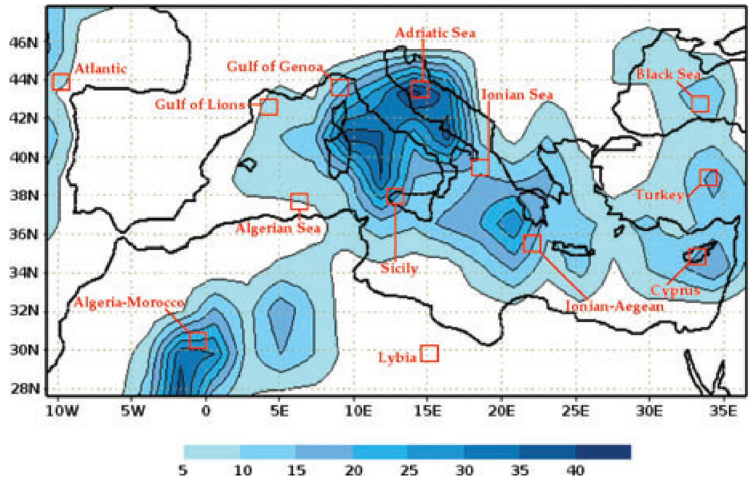

Fig. 1. Number of mature intense cyclones per square of 2.25° × 2.25° over the 45-yr ERA-40 period and the labelled regions used in the classification of intense cyclones (adapted from Homar et al., 2006).

45-yr period covered by the ERA-40 (September 1957 to August 2002) including characteristics such as their size, position, intensity, depth and path. The detection and tracking algorithms as well as the characterization methods are thoroughly described in Campins et al. (2006) and Picornell et al. (2001). Homar et al. (2006) selected 1359 intense cyclones as those members of the database with a maximum circulation exceeding 7×10^7 m^2 s^{-1} and a lifetime of at least 24 h. The intensity was computed as an area integral of the geostrophic vorticity at 1000 hPa over the area around the cyclone's centre with positive geostrophic vorticity. Typical winds associated with these cyclones average at speeds of about 20 m s^{-1}. The mean frequency of intense cyclones detected in the database exceeds 30 intense cyclones per year over the study domain, which gives an indication of the intensity of the population of cyclones under study.

The highest density of intense mature cyclones is found over the Thyrrenian and Adriatic Seas (Fig. 1), which are closely linked to the Gulf of Genoa and south of the Alps, already detected as the most cyclogenetic area in the Mediterranean by Petterssen (1956). Other well-known Mediterranean cyclogenetic areas such as Cyprus, Turkey and the Black Sea are also regions with persistent occurrence of intense cyclonic systems (Fig. 1).

At the basis of the ensemble sensitivity technique of AH07, perturbation fields of a forecast aspect of interest and ensemble initial conditions perturbations are correlated. These perturbed fields are naturally obtained as departures from the mean of an ensemble forecasting system. Because of the wide range of locations of intense cyclones present in the climatology, this study requires a division in more homogeneous classes that allows to define relevant mean fields and render sensible perturbations.

Here, we use the same classification obtained by Jansà and Homar (2006), which is based on fields characterizing the location of the cyclone at the time of maximum intensity as well as selected fields that represent the large-scale pattern preceding that time. To classify the 1359 cyclones into homogeneous groups, the non-hierarchical k-means classification algorithm was used. A collection of prototype intense cyclones was 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. Thus, days with similar loadings on the extracted components were clustered together. Two rounds of classification were necessary. To join together those cyclones that achieved mature stage in the same area, a first partition grouped cyclones based on SLP at the time of maximum cyclonic intensity. This classification grouped events by region but did not guarantee intracluster homogeneity of preceding conditions, which is a desirable property for the classes to derive representative sensitivity fields for each one. Thus, the second round of classification divided each cluster from 1 (no division) to 5 subgroups taking into account the fields of geopotential height at 500 hPa for 24 and 48 h before the time of cyclone maturity (t) and the temperature field at 850 hPa for $t - 24$ h. Definitive subgroups were ultimately chosen subjectively, trying to minimize the final number of classes and maximize the homogeneity of the fields within each cluster. This subjective selection was very useful to remove intractable outliers, such as subclasses with very few members. Finally, 1202 d with intense Mediterranean cyclones were classified into 25 clusters which cover classical regions of intense cyclogenetic activity such as the Gulf of Lyons, Gulf of Genoa, the Ionian Sea or Cyprus (Table 1). Although 25 classes might seem a large number which provides too much detail, note that the ultimate goal is to compute representative sensitivities for each cyclone type. The finer the classification, the more homogeneous the clusters and so the more representative the derived statistical sensitivities will be, at the expense of a reduced sample size.

2.2. *Ensemble sensitivity*

The ensemble sensitivity technique was first formally applied by Hakim and Torn (2008) to an extratropical cyclone. In that

Table 1. Classification of intense cyclones as derived from the two rounds of k-means clustering

Number cluster	Members	Region
1	103	Atlantic
2	85	Algeria–Morocco
3	32	Algerian Sea
4	20	
5	42	
6	25	Gulf of Lions
7	25	
8	32	
9	65	Gulf of Genoa
10	11	
11	15	
12	48	Adriatic Sea
13	40	
14	49	
15	65	Sicily
16	11	
17	35	Lybia
18	23	Ionian Sea
19	52	
20	38	
21	21	Ionian-Aegean
22	111	
23	53	Black Sea
24	40	Turkey
25	131	Cyprus

case, the method confirmed the known linkages between surface cyclones and upper-level disturbances as well as suggested relationships between the cyclone and a surface cold front, a second upper-level short-wave, and a subtropical jet stream. AH07 compared ensemble sensitivity to adjoint sensitivity analysis for a wintertime flow pattern and showed that an ensemble sensitivity field is proportional to the projection of the analysis-error covariance matrix onto the adjoint sensitivity field. In addition, the results of Torn and Hakim (2008) suggest that ensemble sensitivity analysis may also prove useful in the context of targeted observations based on the predicted effect of a hypothetical observation on forecast error variance in case-study episodes.

Here, we propose to apply the same principle to each cluster derived from the climatology of Mediterranean intense cyclones of Jansà and Homar (2006). Thereupon, the ensembles of perturbations are built from the members of each class, taking the reanalysis fields for each cyclone at the time of maximum intensity as well as the fields valid 24 and 48 h earlier. Therefore, no additional forecasting system is involved in the sensitivity calculations and the linear assumptions are made upon the real atmospheric evolution, or the analysis snapshots of it. The following subsections expound on the methodological details of this technique.

2.2.1. Response function. The definition of the response function, J, is a key point in any sensitivity study. The response function is usually defined as an aspect of the forecast field in which we are interested. In this work, however, J is not determined using forecasts fields but using reanalysis fields at the time of maximum cyclone intensity. A measure of the cyclone's depth is the chosen response function from which the sensitivities will be derived. To facilitate the comparison among sensitivity results from different clusters, the response function is defined with a common criterion. In particular, for a cluster of M members, we define the set of response functions as the average of the SLP at time t over an area of 300 × 300 km (5 × 5 gridpoints) centred over the cyclone centre of the cluster's mean SLP field:

$$J^k = \sum_{p=-2}^{2} \sum_{q=-2}^{2} \frac{\mathrm{SLP}^k_{r+q\ s+p}}{25}, \qquad k = 1, \ldots, M, \tag{1}$$

where r, s denote the coordinates of the cyclone centre of the cluster's mean SLP field. Note that the location of the each individual cyclone belonging to one cluster may differ from the location of the cyclone in the cluster's mean SLP field.

2.2.2. Linear regression. A change in J due to a precursor field perturbation δx_{ij} may be expressed by means of Taylor expansion:

$$\delta J = \sum_{i,j} \left(\frac{\partial J}{\partial x}\right)_{ij} \delta x_{ij} + O\left(\delta x^2\right), \qquad \begin{array}{l} i = 1, \ldots, n \\ j = 1, \ldots, m \end{array} \tag{2}$$

for an initial condition field x_{ij} on a grid of $n \times m$ points. Ensemble sensitivity method proposes to reject terms of order 2 and above, and to exploit the linearity of the remaining relationship using sample statistics. This provides an attractive alternative to the expensive adjoint sensitivity analysis. Ensemble sensitivity proposes to estimate $(\frac{\partial J}{\partial x})_{ij}$ by means of linear regression between $\{J^k\}$ and $\{x^k_{ij}\}$. Here, for a cluster of M members, a linear regression where the independent variable is the precursor conditions to the time of cyclone maturity and the dependent variable is the response function, yields a regression coefficient $\mathcal{S}_{ij}$ defined as

$$\mathcal{S}_{ij} \equiv \left(\frac{\partial J}{\partial x}\right)_{ij} = \frac{\mathrm{cov}(J^k, x^k_{ij})}{\mathrm{var}(x^k_{ij})}, \qquad \begin{array}{l} i = 1, \ldots, n \\ j = 1, \ldots, m \\ k = 1, \ldots, M. \end{array} \tag{3}$$

Therefore, for each precursor field, x_{ij}, we can derive a raw sensitivity field, $\mathcal{S}_{ij} \equiv (\frac{\partial J}{\partial x})_{ij}$, that indicates the change in the response function produced by an unitary perturbation introduced to the precursor condition field.

2.2.3. Correlation coefficient. In the full model, the link between $\{J^k\}$ and $\{x^k_{ij}\}$ is strictly non-linear and the significance of the sensitivity, $\mathcal{S}_{ij}$, derived from linear regression depends on the degree of linearity between these variables, which can be tested by means of the correlation coefficient. Although a $\left(\frac{\partial J}{\partial x}\right)_{ij}$ may be calculated at each location and field using eq. (3), a correction factor should be applied to prevent points with low correlation coefficients to show large (not significant) sensitivity values. Thus, with the aim of filtering out irrelevant values of $\left(\frac{\partial J}{\partial x}\right)_{ij}$ from final sensitivity products, we apply a simple correction factor based on the correlation coefficient as

$$S_{ij} \equiv \left(\frac{\partial J}{\partial x}\right)_{ij} \mathcal{R}_{ij}, \qquad \text{where}$$

$$\mathcal{R}_{ij} = \begin{cases} 1 & r_{ij}^2 \geq c^2 \\ \frac{r_{ij}^2}{c^2} & r_{ij}^2 < c^2 \end{cases} \quad \text{and} \quad r_{ij} = \frac{\mathrm{cov}(J^k, x_{ij}^k)}{\sqrt{\mathrm{var}(x_{ij}^k)}\sqrt{\mathrm{var}(J^k)}}, \tag{4}$$

where r_{ij} is the correlation coefficient and c is the minimum correlation coefficient for which raw linear sensitivities remain unaltered. Those linear trends with correlation coefficients lower than c will be reduced by a factor $\frac{r_{ij}^2}{c^2}$. The definition of c is a crucial point of this technique as it selects the lower limit on the degree of linearity between precursor conditions and response functions that we are willing to accept to obtain relevant sensitivity information. This type of choices are similar to those made with the adjoint model when setting a criterion on the linearity check (Homar and Stensrud, 2004). It is obvious that the response of the atmosphere to slightly different initial states is strictly non-linear but linear sensitivity calculation techniques have proven of great value in various applications (Errico et al., 1993). The distribution of correlation coefficients of all $\{J^k\}$ and $\{x_{ij}^k\}$ considered in this study shows moderately low values of correlation, with slightly more than 20% (20.50% for $t-48$ h and 20.54% for $t-24$ h) indicating linearly uncorrelated couples, that is, with correlation coefficient equal to 0. The chosen lower bound for the squared correlation coefficient is $c^2 = 0.1$ which leaves unaltered those sensitivity estimates with absolute correlation coefficients exceeding 0.32. This threshold represents the 88th percentile of the r_{ij}^2 distribution for all variables and levels considered in this study. Note that, after setting this loose criterion, only 12% of all computed trends remain unmodified, most of them being faded out due to significance concerns. An additional consideration to bear in mind when setting the parameter c is the cluster homogeneity. Uniformity is an important factor to the correlation coefficient and here is restricted by minimum cluster size considerations and total population of cyclones available from the ERA-40 analyses period.

2.2.4. Standard deviation. The magnitude S_{ij}, as defined in eq. (4), is an estimate of the change in the response function induced by an unitary variation of a precursor field x at the ij gridpoint. The calculation of $(\frac{\partial J}{\partial x})_{ij}$, as in eq. (3), is inversely proportional to the variance of $\{x_{ij}^k\}$ so that larger regression coefficients, S_{ij}, are obtained from lower-variance than from higher-variance gridpoints. The inversely proportional dependence of the regression coefficient with the variance of $\{x_{ij}^k\}$ results in generally larger values of linear ensemble sensitivity to the south of the domain due to climatologically lower variances at lower than at higher latitudes. Although this is a correct and meaningful characteristic of the S_{ij} fields, it produces a misleading notion when is interpreted as a climatological sensitivity field. Information about the climatological variance of the analysed fields should also be used to get an undistorted picture of the influence of preceding fields on the response function. Therefore, with the aim of accounting for the spatial variability of the variance of $\{x_{ij}^k\}$ with k, an additional factor is used to derive the final sensitivity fields:

$$\mathbb{S}_{ij} \equiv \left(\frac{\partial J}{\partial x}\right)_{ij} \cdot \mathcal{R}_{ij}\sigma_{ij}, \qquad \text{where} \quad \sigma_{ij} = \sqrt{\mathrm{var}(x_{ij}^k)}, \tag{5}$$

where σ_{ij} is the standard deviation of $\{x_{ij}^k\}$. Note that, by introducing this factor, the raw sensitivity (S_{ij}) is transformed into a response function perturbation (δJ) given, not by an unitary perturbation but a perturbation of typical amplitude σ_{ij} at each location x_{ij}. An additional benefit of this standardization is that $\mathbb{S}_{ij}$ allows for comparison among different precursor condition fields. Indeed, its units are those of J ([mb]).

Thus, the raw sensitivity, $\left(\frac{\partial J}{\partial x}\right)_{ij}$, corrected by r_{ij}^2 and normalized by σ_{ij} is a standard product, hereafter referred to as 'sensitivity'. High values of 'sensitivity', $\mathbb{S}_{ij}$, highlight areas where typical initial conditions perturbations produce significant changes to the central sea level pressure of the intense cyclones.

3. Results

For each of the 25 clusters listed in Table 1, the sensitivity field is computed for the following preceding conditions: temperature (250, 500 and 850 hPa), wind speed (250, 500 and 850 hPa) and geopotential height (250, 500, 850 and 1000 hPa) at 24 and 48 h prior to the time of maximum cyclone intensity. Eventually, a huge amount of sensitivity information is derived. For the sake of brevity, average fields are calculated to reduce the number of products to a tractable synthetic summary. However, sensitivity results for all considered precursor conditions fields for one cyclone class are described in detail to illustrate the collection of available results. Also, taking advantage from the fact that the final sensitivity fields are described in terms of δJ, with units of mb, some global results are calculated. Finally, these results are contrasted with analogue adjoint sensitivity fields obtained by Jansà and Homar (2006).

3.1. Illustrative example: Algerian Sea cyclones

The 'Algerian Sea' cyclone classes encompass those systems originated over North Africa that reach maximum intensity over the Algerian Sea (Fig. 2). Homar et al. (2002) proposed a conceptual model for this type of cyclone: their genesis is driven by baroclinic instability over the North African plateau when a

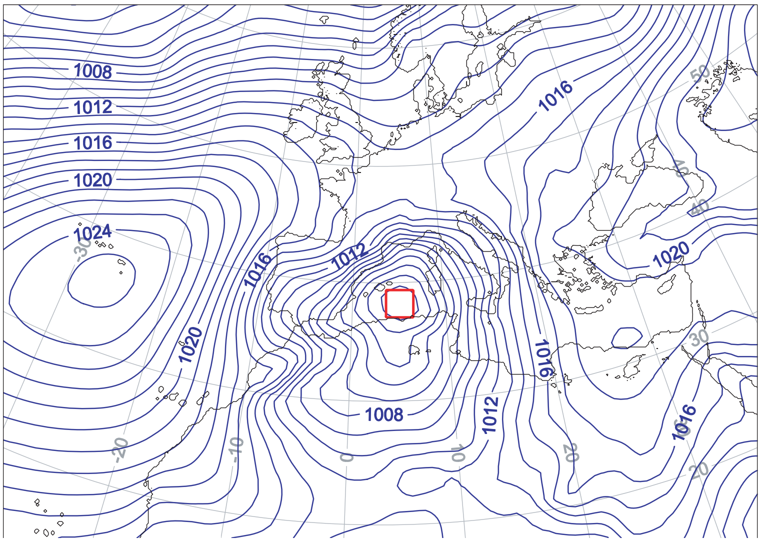

Fig. 2. Mean sea level pressure field for cluster 5 (mb, solid lines). The area used to define the response function is indicated with a square.

cold Atlantic intrusion progresses southeasterly towards warmer air at low levels, and a deep tropopause fold is present at high levels. The surface low shifts to the north, steered by the upper-level trough, and quickly deepens as it reaches the Mediterranean Sea. Some cyclones can be intense enough to produce hazardous weather such as strong windstorms or heavy rains, like the 10–12 November 2001 event (Tripoli et al., 2005). As a result of this event, seven hundred people died in Algiers because of severe floods, and four people died in the Balearic Islands where sustained winds of 30 m s^{-1} and 24 h accumulated precipitation exceeding 200 mm were recorded.

The sensitivity fields derived for cluster 5, with 42 intense Algerian Sea cyclones, are discussed hereafter. The smoother and more spatially consistent sensitivity fields are obtained from the geopotential height (Fig. 3). The cluster's mean field 48 h before the time of maximum intensity reveals a wide positively tilted trough extending along Western Europe throughout the troposphere up to 250 hPa. The southeastern quadrant of the trough is persistently pointed out by high values of sensitivity. These sensitivity structures may be interpreted by means of the vorticity advection term of the quasi-geostrophic equation of tendency that links vorticity advection to surface pressure change (e.g. Holton, 2004). As the trough progresses and intensifies, the sensitivity pattern moves along and also intensifies (right-hand column of Fig. 3). These sensitivity structures show spatial and temporal continuity with the maximum values obtained at 850 hPa, 24 h before the time of maximum cyclone intensity. This is attributable to the strong sensitivity of a baroclinically driven process on the dynamic characteristics of the air parcels directly involved in the cyclone intensification and the eventual central SLP values (e.g. J).

Signals of significant sensitivity point towards the strong region of westerly flow, in the north western corner of the domain, associated with the Atlantic high-pressure system. These patterns are likely highlighting the relevant effect of the evolution of the Atlantic ridge on the deepening of the European trough, and consequently on the intense cyclogenesis process. The method does also reproduce notable sensitivity structures downstream of the main trough, in the eastern region of the domain, which poses a serious interpretation challenge. These signals could highlight dynamical structures that influence the evolution of the main trough, similar to a blocking effect, but might also be consequence of spurious linear correlations obtained from the limited number of cases that constitute this cluster.

The sensitivity of the response function, J, with respect to temperature (Fig. 4) at 250 hPa focuses on the western edge of a cold air mass sitting over east Europe, where the westerly warm advection associated with the main trough is intensifying the temperature gradients between a narrow warm band and the European cold air mass (Fig. 4, lower-left panel). For $t - 24$ h and 500 hPa, there is a sensitivity dipole located southwest and southeast of the thermal trough, where maximum thermal advection occurs. At 850 hPa, the main sensitivity area is located over the thermal front associated with the low-pressure area over the African Atlas, consistent with the sensitivities identified on the geopotential height field. This confirms that the evolution of the cyclone up to the time of maximum intensity and the resulting central SLP values are sensitive to this thermal front. The sensitivity temperature fields also show downstream highlighted areas and its dynamic interpretation is not direct.

Regarding to wind speed field (Fig. 5), there are two main sensitive regions, one associated with the cold Atlantic air intrusion to the northwestern African coast, and another linked to the cyclonic circulation over the North African plateau. This region is identifiable at 500 hPa for $t - 48$ and $t - 24$ h, but achieves maximum intensity at 850 hPa for $t - 24$ h when the cyclonic circulation is more intense. This reflects the importance of the cyclonic vorticity in the cyclone evolution towards its mature stage.

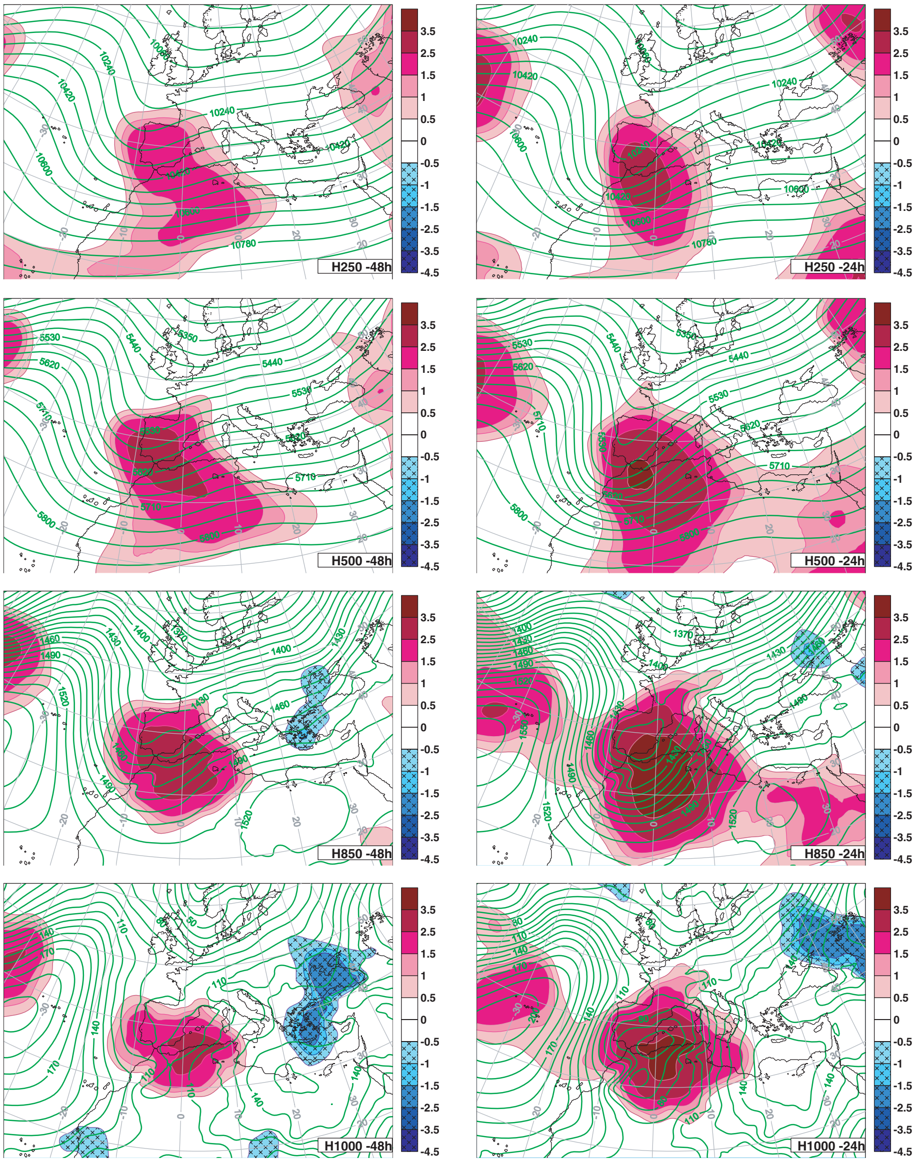

Fig. 3. Sensitivity of the response function (mb, shaded) with respect to geopotential height (cluster's mean field: gpm, solid lines) at $t - 48$ h (left-hand side column) and $t - 24$ h (right-hand column) for cluster 5.

To summarize the extensive information from all sensitivity fields, and taking into account that sensitivity is expressed in terms of δJ for all precursor fields, the mean of the absolute value of the sensitivity of all considered fields and levels is computed for $t - 24$ and $t - 48$ h (Fig. 6). These mean fields show a general outline of the sensitive regions for the SLP central values at the time of maximum cyclone intensity for 'Algerian Sea' cyclones and provide guidance to support decisions regarding important areas to be considered for observational strategies, willing to account for western Mediterranean HIW episodes. Both mean sensitivity fields highlight upstream and downstream areas but the main sensitive region is located over the same region as the maximum cyclonic circulation identified on the wind speed field for $t - 24$ h. At $t - 48$ h, this sensitivity pattern is slightly shifted towards the northwest with two relative maxima, one over the North African plateau and another over southwestern Spain, which is linked to the cold air intrusion towards to the northwestern African coast that characterizes these Algerian cyclones.

Note that, in general, we obtain higher values of $\mathbb{S}_{ij}$ at $t - 24$ h than at $t - 48$ h, which is not consistent with average exponential growth of perturbations. This is attributable to two main causes: the method of classification of the Mediterranean cyclones and the correction factor based on the linear correlation (eq. 4). On the one hand, the cyclones were classified using the geopotential height at 500 hPa for $t - 48$ and $t - 24$ h and the

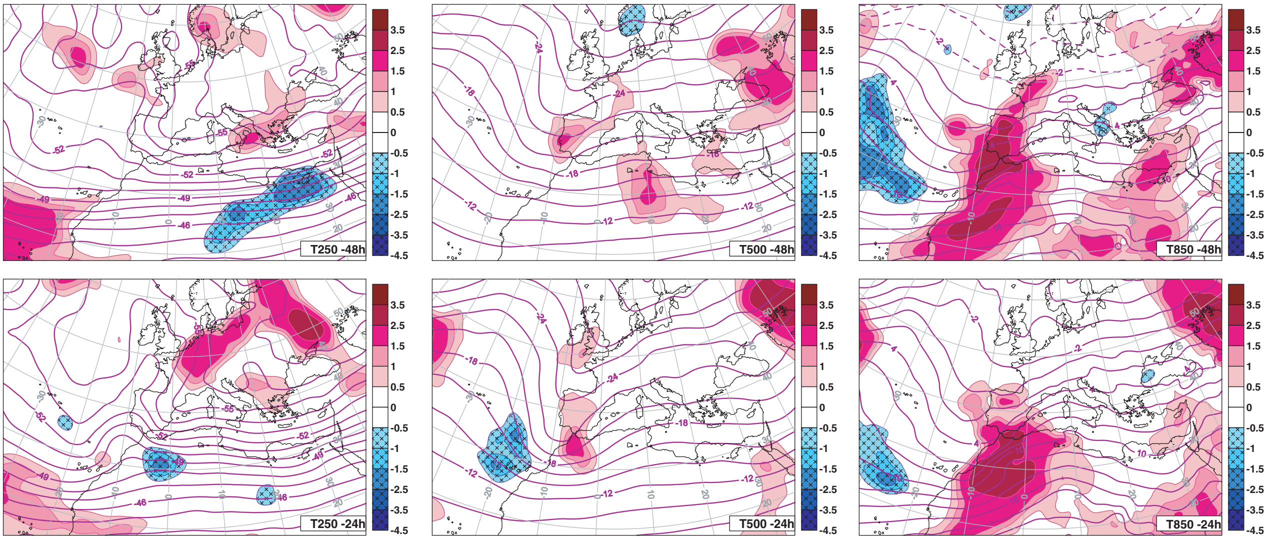

Fig. 4. Sensitivity of the response function (mb, shaded) with respect to temperature (cluster's mean field: °C, solid lines denote positive values and dashed lines denote negative values) at $t - 48$ h (upper panels) and $t - 24$ h (lower panels) for cluster 5.

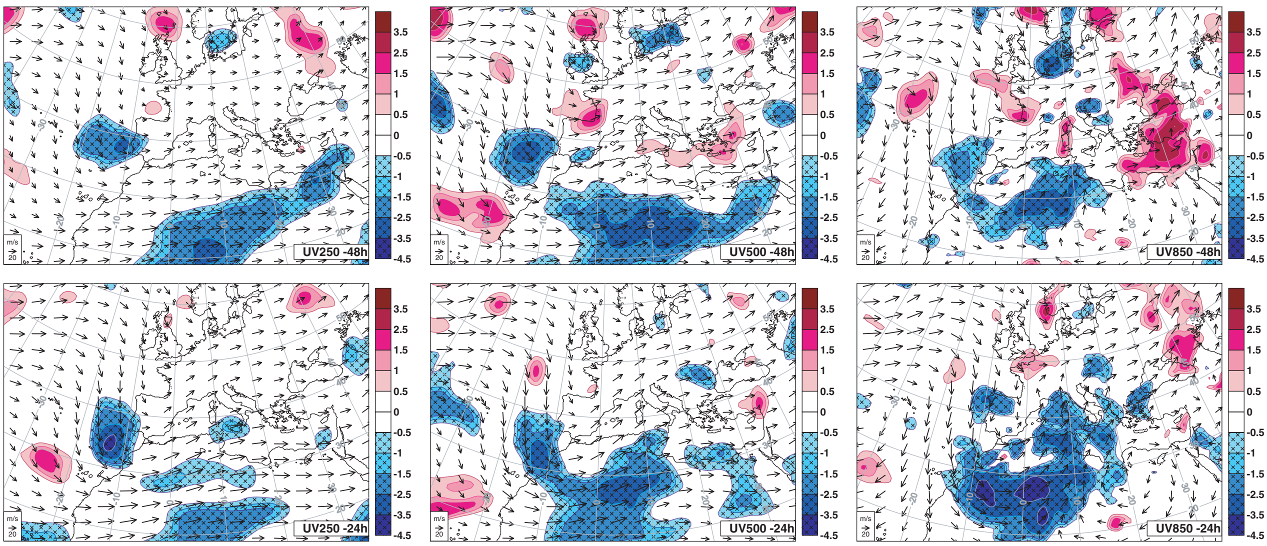

Fig. 5. Sensitivity of the response function (mb, shaded) with respect to wind speed (cluster's mean field: ms^{-1}, vectorial field) at $t - 48$ h (upper panels) and $t - 24$ h (lower panels) for cluster 5.

temperature field at 850 hPa for $t - 24$ h. That is, two precursor conditions fields at $t - 24$ h for one at $t - 48$ h. This tends to render more homogeneous clusters at $t - 24$ h and, therefore, the correlation coefficients are larger (Fig. 7), and also the derived sensitivities. On the other hand, due to the gradual decrease in linear correlation between causes and effects as the timespan over which sensitivities are computed increases, the correlation-based correction factor is increasingly important and the final sensitivity product is notably weakened.

3.1.1. Comparison with adjoint sensitivities. For each of the classes listed in Table 1, Jansà and Homar (2006) computed the sensitivities with respect to initial conditions (48 h before the time of maximum intensity of the cyclone) using the MM5 adjoint modelling system (Zou et al., 1997). The sets of initial and boundary conditions for the simulations were computed by averaging, over all the individual members of the cluster, the fields from the ERA-40 archive necessary to run a single numerical simulation representative of the whole cluster. In this study, the response function was defined for each cluster as the sum of pressure perturbation over a rectangle that bounds the forecast cyclonic area in the three lowest model levels over each cluster's mean SLP field. Then, the raw sensitivity obtained from this procedure was normalized by the number of gridpoints that were used to compute the response function. Finally, to

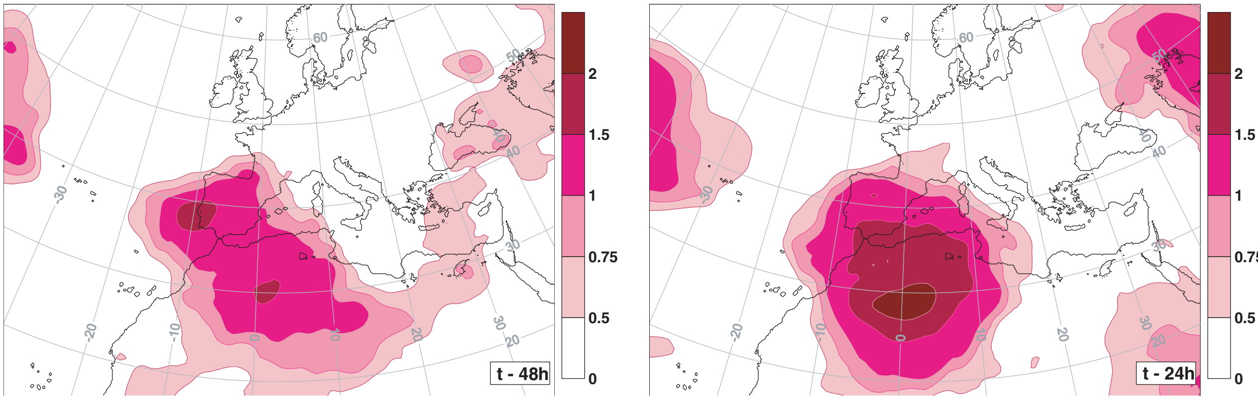

Fig. 6. Mean sensitivity field over all considered precursor conditions fields and levels (mb, shaded) for $t-48$ h (left-hand panel) and $t-24$ h (right-hand panel) for cluster 5.

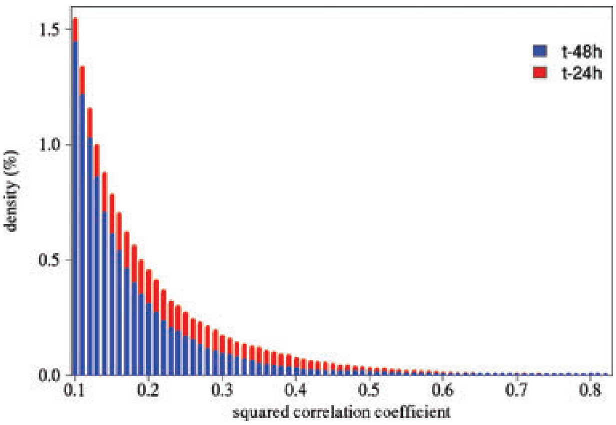

Fig. 7. Distribution of squared correlation coefficients corresponding to all $\mathcal{S}_{ij}$ considered in this study for $t-48$ and $t-24$ h.

summarize the results, the average over all fields and vertical levels was computed, providing a good description of the most sensitive regions. Note that their mean sensitivity is a standardized index without physical units ([Pressure units]/[mixed IC units]).

For cluster 5, the mean sensitivity obtained from the adjoint model (Fig. 8) highlights the Iberian Peninsula and Morocco areas, extending also towards the Atlantic and the Eastern African coasts, aligned with the mid-levels main trough and the low-levels Atlantic cold and North African warm fronts. The $t-24$ h ensemble sensitivities are smoother but consistently shifted to the southeast, where significant baroclinic development is occurring at that time. The $t-48$ h ensemble field is weaker than the $t-24$ h, due to the aforementioned effects, but tends to focus also over the Iberian Peninsula and North African lands.

Differences in the scale and intensity of ensemble and adjoint sensitivities are discussed for a particular case of observation targeting by AH07. Here, the comparison among them can only be qualitative because of methodological differences but the corrections due to non-linearities on the $t-48$ h ensemble fields hamper the direct comparison against similar available adjoint results. However, the temporal consistency of the $t-48$ h adjoint fields with the more significant $t-24$ h ensemble fields is notable.

3.2. *Global results*

To summarize the information obtained for all clusters, a mean sensitivity field over the 25 cyclone types is computed over all considered precursor conditions and levels for $t-48$ h and $t-24$ h (Fig. 9). To take into account the population of each cluster and the significance of the linear trends, this synthetic summary is calculated by means of an average of the linear trends times the standard deviation and weighted by the relative frequency of each cluster and the squared correlation coefficient in the database. For $t-48$ h, the sensitivity regions are mainly located upstream of the westerlies and over northwestern Africa. A more spatially consistent sensitivity structure is obtained for precursor conditions at $t-24$ h. This pattern is similar to the mean sensitivity field obtained by the adjoint model (Fig. 10), although ensemble sensitivites are not focused as much over mountain ranges as the sensitivities derived from the adjoint model. The adjoint results emphasize a region extending along two preferred axes: a north-south axis that indicates the troughs that produce intense Mediterranean cyclones; west-east axis that shows the trajectory followed by Atlantic depressions that reach the Mediterranean region. The ensemble sensitivities also show the north-south axis and a direction of expansion towards the North Atlantic, however, ensemble sensitivities do not extend along the Italian peninsula towards the Aegean Sea. This is attributed to the fact that clusters belonging to Eastern Mediterranean have lower correlation coefficients than the western ones, resulting in larger areas with strong weakening of the raw sensitivity.

Besides the geographical distribution of the sensitivity fields, we can also gain a measure of the predictability of the each intense cyclone class and conduct a comparison among them.

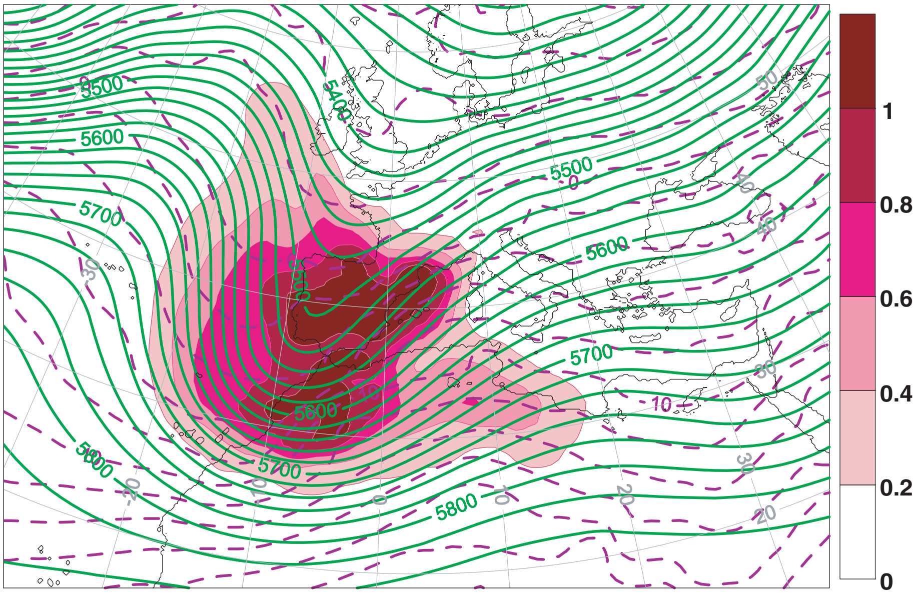

Fig. 8. Vertically averaged adjoint-computed sensitivity fields (darker shaded colours show larger sensitivities) for cluster 5 at $t - 48$ h. Geopotential height field at 500 hPa (gpm, solid lines) and temperature field at 850 hPa (°C, dashed lines) averaged over all cluster's members (adapted from Jansà and Homar, 2006).

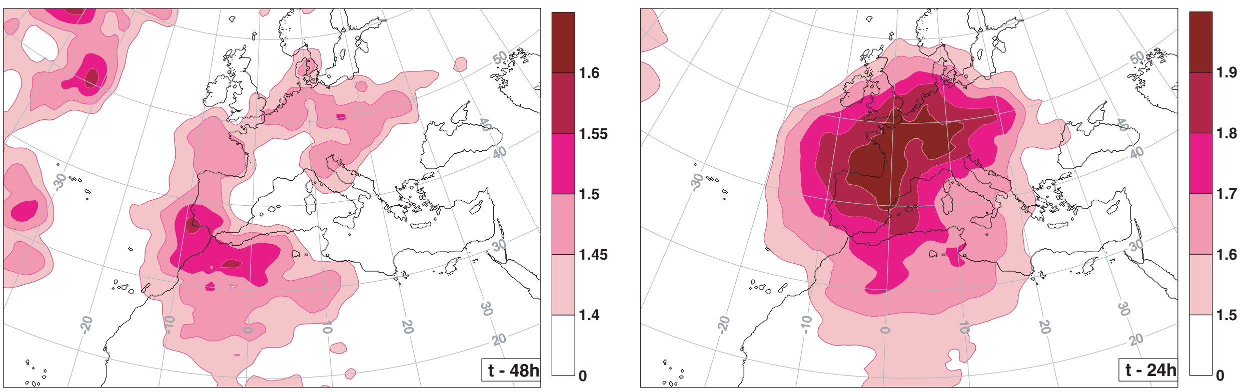

Fig. 9. Mean sensitivity field for all 25 cyclone types computed over all considered precursor conditions and levels (mb, shaded) for $t - 48$ h (left-hand panel) and $t - 24$ h (right-hand panel). Note the scale change between figures.

The mean of the significant sensitivities of a cyclone cluster, that is, averaged sensitivity over gridpoints and fields with $r_{ij}^2 \geq 0.1$, provides a linear estimate of the cyclone's central pressure predictability. Degraded sensitivity values due to the local lack of significance might mislead the linear predictability estimate, therefore, they are not considered in the mean. Since a common criterion to define the response function is used for all cyclone classes, the resulting predictability estimates are consistent and the comparison among them is relevant. With everything else being equal, a cyclone class showing large significant sensitivity mean indicates that the response function of those cyclones will change in a larger extent, on average, than another class showing less significant sensitivity mean under typical perturbations in the precursor conditions. Therefore, the larger significant sensitivity mean, the lower the predictability.

The results show that five out of the six least predictable (highest mean significant sensitivity) clusters represent Western Mediterranean cyclones. On the other hand, Algeria–Morocco, Lybia and Turkey cyclones arise as the most predictable intense cyclones of the data set (Fig. 11).

4. Conclusions

This paper reports on a new sensitivity calculation method based on the ensemble sensitivity technique originally proposed by Hakim and Torn (2008). This new method allows us to

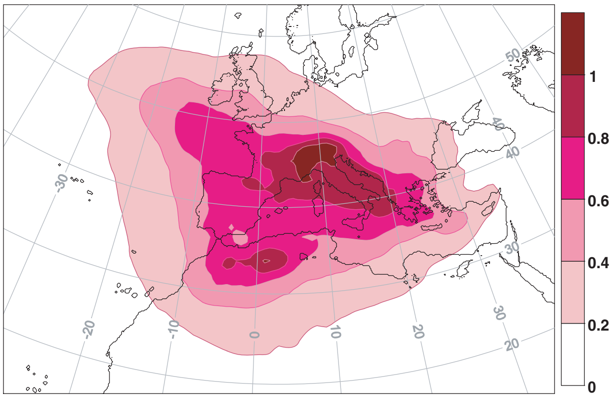

Fig. 10. Mean adjoint sensitivity field to central cyclone pressure at $t - 48$ h weighted by the intense cyclone frequency within the database (darker colours indicate higher sensitivities; adapted from Jansà and Homar, 2006).

investigate the predictability of atmospheric phenomena from a climatological perspective, providing an estimate of its sensitivity to any set of observed causes at a very low computational cost. A key fundamental point of the method proposed here is the lack of dependence on any ad hoc forecasting system, producing results derived directly from observations and analysis fields. In essence, the technique linearly correlates differences in the outcome of many observations of a particular feature of interest with the diversity of corresponding precursor conditions. The technique, explored in detail by AH07, is shown to be competitive with adjoint model products when studying single cases. However, the advantages over adjoint techniques are clear when climatological results are seeked. The cost of running adjoint models for a large number of events is extremely high and additional approximations, such as running the adjoint on individual representative episodes of a certain phenomenon of interest (Homar et al., 2007), produce a number of caveats on the results besides the everpresent tangent-linear assumption.

Needless to say that the relationship between a precursor cause and the feature of interest in the atmosphere is strictly non-linear. While the initial evolution of small-amplitude perturbations in atmospheric models is well approximated by a linear regime, non-linear effects eventually dominate their evolution. The significance of the linear trends, that can be computed for any set of pairs and any time difference between them, is accounted for by means of the correlation coefficient. The linear trends with low significance are smoothed out from the final results. However, this beneficial characteristic produces a fading-out of the resulting sensitivity fields as these are computed earlier and earlier from the feature of interest. This makes the comparison of ensemble sensitivity fields computed for different lead-times difficult and even misleading, as the earlier times will have larger corrections due to weaker linear correlations. In fact, the synthetic sensitivity fields obtained in this paper show larger sensitivities for $t - 24$ h than for $t - 48$ h, which is inconsistent with the well-known average growth of perturbations in atmospheric flows. In this regard, a detailed analysis of the subset of gridpoints with large correlation coefficients ($r \geq 0.5$) shows that the corresponding linear trends are indeed significantly larger for $t - 48$ h than for $t - 24$ h (not shown). This reveals the important effect of the correction factor introduced to the linear trends to account for their significance and clearly reveals the migration from the initial quasi-linear regime towards the eventually non-linear regime. Finally, the proposed method takes advantage of the climatological character of the study, by expressing the sensitivity results in terms of the average impact on the intense cyclones under study produced by typical perturbations on the precursor fields evaluated.

The application of the proposed technique to derive climatologically sensitive regions for intense Mediterranean cyclones shows that the evolution of these high-impact systems 24 h before the time of maturity depends on structures located over Western Europe, the Northern African lands and parts of east North Atlantic. The $t - 24$ h results obtained with the ensemble sensitivities overlap substantially with the $t - 48$ h results obtained with an adjoint model by Jansà and Homar (2006) over Western Europe and North Africa. However, 24 h ensemble fields do not highlight the Eastern Mediterranean as much as the adjoint does. The reduced significance obtained for Eastern Mediterranean cyclones causes this weakened sensitivity signal on the 24 h ensemble results. Similarly, due to the lack of significance, the ensemble sensitivities for $t - 48$ h do not show

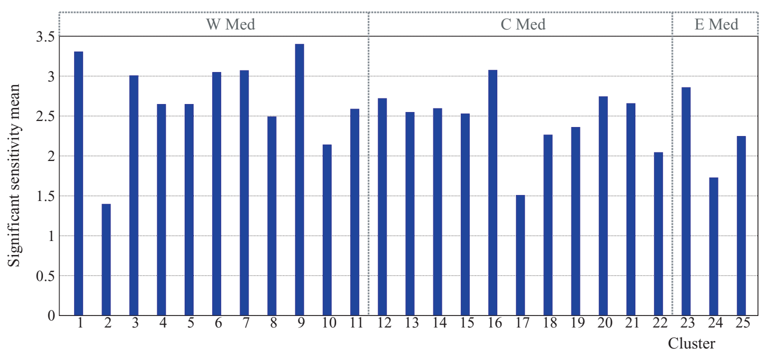

Fig. 11. The mean of significant sensitivities (with $r_{ij}^2 \geq 0.1$) for each intense cyclone cluster at $t - 24$ h. This gives a linear estimate of the cyclone's central sea level pressure predictability.

spatially coherent structures that would be expected from a general, climatological average over 25 cyclone classes. Jansà and Homar (2006) do not provide any test or verification measure for their adjoint results, so no fair comparison can rigorously be performed. However, ensemble sensitivity results show smoother synoptic-scale patterns as opposed to the smaller-scale structures produced by the adjoint, as also pointed out by AH07. Here, in spite of the crucial role of subsynoptic scales in driving the processes that typically produce the highest impact from the Mediterranean cyclones, there are three basic limitations that hamper ensemble sensitivities to produce reliable information about mesoscale structures: the ERA-40 analysis resolution; the underlying linear hypothesis and the reduced homogeneity in cyclone classes at subsynoptic scales.

After an initial exploratory analysis of the suitability of this method to produce climatological fields of sensitivity, much further research is needed to extend the analysis to a wider set of weather episodes and precursor fields and levels. For instance, an analogous climatology of sensitivities could be derived for episodes of heavy rain in the Mediterranean using raw raingauge data or more elaborated rainfall climatologies (Romero et al., 1999). Taking advantage of the simplicity of the method, other climatologies such as severe weather climatological studies focusing on tornadoes, hail and strong winds can be attempted, which would hardly be feasible otherwise. These would make use of descriptive climatological works such as by Tous and Romero (2006). Some methodological aspects need further research as the accuracy of the resulting fields is hampered mainly by two factors: the timespan of the linear correlations and the homogeneity and size of the ensembles (clusters). The 24 h sensitivity fields derived here for intense Mediterranean cyclones are easily interpretable both in amplitude and distribution but 48 h results are mostly faded out. The analysis of the full 6 h-update analysis fields could provide a better description of the transition from the quasi-linear to the non-linear evolution of perturbations for each cyclone case considered. Regarding the homogeneity and size of the clusters, the first is controlled by the initial clustering steps, and could be improved by either increasing the number of clusters or removing a larger number of outliers, though both come at the expense of cluster size. The size determines largely the significance of linear correlations and an insufficient number of elements in a cluster produces spurious distant correlations that degrade the sensitivity results.

Another remaining task regards the verification of the climatological results which is an ever-challenging task for sensitivities. Either expensive long-term routine observation-network experimental modifications or 'Observing System Simulation Experiments' should be endeavoured to rigorously assess the accuracy of any climatological sensitivity products. Much remains to be investigated before robust findings can unequivocally guide policy-makers on plans to redefine routine observational strategies that account for the entire spectrum of weather phenomena affecting Europe.

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