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MEDEX: a general overview

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Abstract

The general objective of the international MEDiterranean EXperiment (MEDEX) was the better understanding and forecasting of cyclones that produce high impact weather in the Mediterranean. This paper reviews the motivation and foundation of MEDEX, the gestation, history and organisation of the project, as well as the main products and scientific achievements obtained from it. MEDEX obtained the approval of WMO and can be considered as framed within other WMO actions, such as ALPEX, MCP and, to certain extent, THORPEX and HyMeX. Through two phases (2000–2005 and 2006–2010) MEDEX has produced a specific database, with information about cyclones and high impact weather events, several main reports and a specific field campaign (DTS-MEDEX-2009). The scientific achievements are significant in fields like climatology, dynamical understanding of the physical processes and social impact of cyclones, as well as on aspects related to the location of sensitive zones for individual cases, climatology of sensitivity zones and the improvement of the forecasts through innovative methods like mesoscale ensemble prediction systems.

1 Introduction

The MEDiterranean EXperiment (MEDEX) has been an international project oriented to an improved understanding and better forecasting of cyclones that produce high impact weather in the Mediterranean. The basic motivation of MEDEX is that at least part of the Mediterranean cyclones produce high impact weather. It is well known that deep and intense cyclones produce severe weather, in particular strong winds and/or heavy precipitations anywhere, not only in the Mediterranean. In the Mediterranean several examples of intense cyclones associated to severe weather can be cited (Homar et al., 2002; Hamadache et al., 2003; De Zolt et al., 2006; Genoves et al., 2006; Lagouvardos et al., 1996, 2007, among others).

However, severe or high impact weather in the Mediterranean is not exclusively associated with intense cyclones. In particular there are cases of very heavy precipitation (Rivera and Riosalido, 1986; Riosalido et al., 1988; Senesi et al., 1996; Buzzi et al., 1998; Kotroni et al., 1999; Romero et al., 2000; Nuissier et al., 2008) that are not related to particularly intense cyclones. In most of such cases a large amount of the precipitation appears to be the result of deep moist convection, in particular that produced by Mesoscale Convective Systems (MCS) that may affect the same area for a relatively long time. The complex topography of the Mediterranean area, characterized in many places by steep mountains close to the sea, favours the occurrence of heavy rain and subsequent flash floods. The high population density in the coastal areas, as well as many infrastructures, historical and artistic settlements, make these areas specially vulnerable, easily converting severe weather into socially and economically high impact weather.

When examining in detail the above cases as well as other similar historical events, in many examples there is no evidence of the presence of intense cyclones, still weak or moderate cyclones are very often observed in the vicinity of the affected areas, playing a role in the organisation of the heavy precipitating systems. The underlying idea is that the presence of a weak or moderate cyclone is enough to organise a low level warm and moist inflow towards an area of potential ascending motion and potential convective instability, where the heavy precipitation occurs in response (Jansa, 1997). This inflow contributes to the precipitation feeding and, being warm and moist, tends to increase the convective instability. The indirect role of a cyclone in determining the occurrence of heavy precipitation has been stated in Jansa et al. (1991), Ramis et al. (1994) or Jansa et al. (2000a), among other papers.

From a more systematic point of view, the Western Mediterranean Basin has been explored looking for the simultaneity and possible connection between heavy rain and cyclonic presence (Jansa et al., 2001a). The conclusion is that in more than 80 % of heavy rain cases, a cyclone is found in the vicinity of the affected area, in a proper location for organising a warm and moist inflow of air originally located in the marine

boundary layer over the Mediterranean (Jansa, 1997; Berto et al., 2004). Most of such cyclones exhibit only weak or moderate intensity.

Regarding the Eastern Mediterranean, some studies also relate heavy rain with cyclonic presence (see Kotroni et al., 2005; Ziv et al., 2006; Houssos et al., 2008, among others).

In summary, high impact weather in the Mediterranean is in some cases directly related to intense cyclones and in some events indirectly linked to weak or moderate cyclones. In any case, a distinct cyclonic signature is usually found in connection with the onset of high impact weather. Obviously there are many weak or moderate cyclones or shallow depressions in the Mediterranean that do not produce any high impact weather. But still, an investigation of Mediterranean cyclones properties is required to better understand their potential role in causing severe weather. In this sense, the general objective of MEDEX is meaningful and becomes a significant research topic for the Mediterranean area.

This paper, of which all the co-authors have been members of the MEDEX Science Steering Committee, aims to provide a quick look of what MEDEX has investigated and achieved during its effective time span, namely from 2000 to 2010. The second section provides a succinct history of MEDEX, including aspects of its organisation, and serves to frame this project in the context of the WMO research activities and also reviews the project organisation. The third section highlights and describes the main products of MEDEX. The fourth section is devoted to some specific scientific results of MEDEX. The paper ends with a brief conclusion.

2 MEDEX history and organisation

There is a long history of research devoted to Mediterranean cyclones and their consequences. A review of this history is out of the scope of this paper. We only refer here to some steps that can be considered as important in the genesis and development

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

of MEDEX, particularly in the frame of the World Meteorological Organisation (WMO) research on this topic.

First we can refer to the ALPEX project. ALPEX (the ALPine EXperiment) was the last field experiment of the Global Atmospheric Research Programme (GARP), a main scientific programme under the auspices of WMO and the International Council of Scientific Unions (ICSU). The ALPEX field phase took place in 1982. ALPEX intended to obtain experimental documentation of the influence that a pronounced but limited in horizontal extension mountainous chain like the Alps exerts on the atmospheric flows. The Alpine region was selected mainly due to the important phenomenon of lee cyclogenesis. Alpine lee cyclogenesis is the most prominent type of Mediterranean cyclogenesis, probably explaining the highest world frequency of cyclones (Pettersen, 1956). Moreover, at that time, forecasting of lee cyclogenesis was a challenging problem, due mainly due to the difficulty in adequately representing the effects of orography in numerical models. High interest was also raised about the very important wind systems that are more or less directly related to the Alpine lee cyclogenesis, namely the Mistral-Tramontane wind system and the Adriatic Bora.

Less attention was paid at that time to the heavy rain topic. In general, diabatic/moist processes, which involve scales of motion smaller than those characterising cyclones and cyclogenesis, were the main object of investigation of the MAP field project in 1999 with reference to the Alpine area (see Bougeault et al., 2001).

In the very preliminary volume devoted to ALPEX scientific results (ICSU/WMO, 1982), around half of the contributions were specifically devoted to the Alpine lee cyclogenesis and associated winds. Also, a high percentage of contributions in these topics were presented at the ALPEX Final Conference, in Venice, in 1985 (ICSU/WMO, 1986). Work on ALPEX, and particularly on the Alpine lee cyclogenesis (including theories and analysis of observations) and their consequences, continued during years and many papers were published until about mid nineties.

At the time of the ALPEX Conference in Venice, another project on Mediterranean cyclones had started under the auspices of WMO, namely the Mediterranean Cy-

clones Study Project (MCP), endorsed in the frame of the WMO Programme on Short- and Medium-Range Weather Prediction Research (PSMP), later grouped into the Programme on Weather Prediction Research (PWPR). MCP was proposed during the Sofia Consultation on Mediterranean Cyclones (WMO/PSMP, 1984), held in 1983, in response to a decision of the IX WMO Congress. The object of MCP was the study of the Mediterranean cyclones in general. MCP was initially conducted by three activity centres (the meteorological services of Bulgaria, Egypt and Italy); the meteorological service of Spain (AEMET, Instituto Nacional de Meteorologia, INM, at that time) was soon added as the fourth activity centre. MCP lasted from 1983 to 1995, when PWPR disappeared due to a change in the research organisation within WMO. The project was first leaded by N. Godev and latter (since 1991) by D. Radinovic, with A. Jansa and P. Alpert as vice-chairmen. The operating mode included periodical specific meetings, with a wider participation than that of the activity centre members, in which scientific achievements were presented and discussed and subsequently published (WMO/PSMP, 1986, 1987, 1989, 1991 and WMO/PWPR, 1994). D. Radinovic produced a start-up document in 1987 (Radinovic, 1987). An important task on cyclone compilation was performed by the Regional Centre of INM in the Balearics (INM, 1992–1995) that in 1994 was declared as the Regional Research Centre on Mediterranean Cyclones.

In the time period between MCP and MEDEX, WMO and INM jointly organised an important "Symposium on Cyclones and Hazardous Weather in the Mediterranean", held in Palma de Mallorca, in April 1997. The Symposium was attended by around two hundred people and 111 contributions were presented (see Bougeault and Jansa, 1997). This symposium can be considered as the starting point of MEDEX, given that in a parallel meeting INM (through A. Jansa) was invited to prepare a proposal of a project on Mediterranean Cyclones (MEDEX) susceptible to be integrated into the new research scheme of WMO.

A first draft of MEDEX was submitted in 1998 to the Science Steering Committee (SSC) of the new WMO World Weather Research Programme (WWRP). SSC/WWRP encouraged the development of MEDEX with the help of an Interim Steering Committee (MISC). MISC was formed by eighteen people from several countries, who produced a renewed "MEDEX Preliminary Research Proposal", submitted to SSC/WWRP in 2000 (Jansa et al., 2000b). In that session SSC/WWRP approved MEDEX as a "Research and Development Project (RDP)" within WMO/WWRP. MISC, once reduced in number of members, became the MEDEX Science Steering Committee (MSSC). It underwent only small variations in composition and number of members during the subsequent entire MEDEX life (see Appendix A), chaired by A. Jansa.

In 2001 a further developed MEDEX proposal (Jansa et al., 2001b) was presented to the SSC/WWRP, with the indication that it comprised the First Phase of the project, planned until 2005. After the approval of this proposal the MEDEX First Phase was formally initiated.

During the First Phase MEDEX was mostly oriented to the improvement of knowledge about the cyclones that produce high impact weather in the Mediterranean. Four specific objectives were defined for this phase:

1. to build a dynamical climatology of cyclones
2. to study the factors involved in their genesis and evolution (including both the physical understanding and numerical simulation of these factors)
3. identification of sensitive areas where more and/or better observational data would produce better forecasts
4. analysis of the societal impacts and benefits (an objective added when the project was already initiated).

Sections 3 and 4 inform about products and achievements of this phase, related to the former specific objectives.

A progressive involvement of institutions and individual scientists in MEDEX occurred during the first years of MEDEX operation. The number of participating institutions

reached a maximum above thirty, from eighteen different countries. The institutions were mostly national and regional meteorological services, universities and other research organisations. A network of about one hundred individual scientists was formed, mostly connected with each other through e-mail and a specific MEDEX web site. The operating mode included meetings of the MSSC, opened to the entire MEDEX community. A summary of the MEDEX meetings (including those held during both the First and Second Phases) is presented in Table 1. Many MEDEX meetings were held in combination with Plinius Conferences on Mediterranean Storms (an European Geosciences Union, EGU, initiative). The convergence of objectives between MEDEX and the Plinius Conferences produced a positive synergy: the Plinius Conferences provided a good forum to the MEDEX community for presenting and discussing the latest scientific results, while the participation of the MEDEX community reinforced the meteorological branch of the Plinius Conferences.

With regard to the specific objective 3, it is noteworthy that a Memorandum of Understanding (MoU) was signed in 2003 between the UK Meteorological Office, representing the EUMETNET/EUCOS Programme (see http://www.eumetnet.eu/composite-observing-system-eucos), the Spanish INM, in representation of MEDEX, and the University of the Balearics Islands (UIB). According to this MoU, UIB became the main executor of studies devoted to the identification of sensitive areas, defined as the geographical zones where an improved deployment of observational platforms would improve most significantly our forescasts of cyclones and high impact weather in the Mediterranean. EUCOS provided funding to UIB for these specific studies.

About the specific objective 4, a key activity was the organization of a Workshop on Social Impact Research in MEDEX, held in Barcelona in 2004. The attendance of R. Pielke Jr. (at that time member of the SSC/WWRP) was very relevant. It is worthy to note that this Workshop promoted the creation of a specific Group of Social Impact Research within MEDEX, led by M. C. Llasat, mainly focused to the creation of a data base and the analysis of societal impacts of heavy rainfalls, floods and windstorms.

During 2005 a working draft for the MEDEX Second Phase was prepared, discussed and informally approved by the MSSC and the MEDEX community (Jansa et al., 2005). The Second Phase of MEDEX was planned for 2006–2010. Five specific objectives were defined for this phase:

1. climatological aspects of cyclones (continuation)
2. physical understanding and numerical simulation of processes (continuation)
3. development and testing of methods related with targeted observations, data assimilation and impacts calculation
4. development and testing of forecasting techniques (EPS, statistical methods, . . .)
5. societal impacts and benefits (continuation).

Note that objectives 1, 2 and 5 express a continuation of the tasks developed in objectives 1, 2 and 4 of the First Phase. Objectives 3 and 4 are different and more application oriented compared to the objective 3 of the First Phase. They reveal that the Second Phase of MEDEX was more concerned with practical questions referred to forecasting improvement than the First Phase.

During the MEDEX Second Phase and in order to support these more applied tasks, a small MEDEX International Core Steering Committee (MICSC) was established in October 2005, chaired by Jean Pailleux (Meteo-France), while the MSSC continued to take care of scientific tasks.

It is worth to mention that during its Second Phase, MEDEX was no longer a RDP directly depending from the WWRP. Since it was considered that the aims of MEDEX were to some extent included among the THORPEX objectives, the SSC/WWRP, in its 8th meeting in Kunming, China (October 2005) decided that “the MEDEX representation in WMO will be done through THORPEX rather than directly to the WWRP”. Since then MEDEX activities were reported to the THORPEX/ICSC.

The planning for the MEDEX Second Phase considered also the implementation of field experiments. Some of these would be “low or moderate” intensity field experiments, while the final one was intended as a “high” intensity experiment. The low-moderate intensity field experiments were accomplished through the participation in the 2008 PREVIEW Campaign and through the organisation and execution of the 2009 MEDEX Campaign (see below). A high intensity experiment was not finally organised in MEDEX, but we could say it was virtually “replaced” by the 2012 and 2013 HyMeX SOPs. In fact, the HyMeX Science Plan (Ducrocq et al., 2010) states that “the idea of a multi-scale large field experiment to finalise THORPEX/MEDEX was collected in the MEDEX second phase proposal (2005)”. The HyMeX field experiment (Ducrocq et al., 2013) can be considered a materialisation of this idea even though HyMeX is much larger than MEDEX in terms of disciplines and scales”. HyMeX is presently a RDP project within WWRP and includes part of the MEDEX objectives within its wider scope.

3 Project results and products

Apart from purely scientific results (see Sect. 4), MEDEX has produced a variety of tangible products. Regarding the MEDEX First Phase a main output was the MEDEX Database, as well as a comprehensive scientific summary (Buzzi et al., 2005) and a report for EUCOS about sensitivity computations (Jansa et al., 2004), besides a number of reports for the SSC/WWRP and for the MEDEX community. During the Second Phase the main product was the performance of the MEDEX-2009-DTS Campaign, as well as a second report for EUCOS (Jansa and Homar, 2006) about the results of sensitivity computations.

3.1 MEDEX database

The MEDEX Database was established to support both climatological and physical process studies (specific objectives 1 and 2 of both MEDEX phases). It was constructed in a progressive way and, although it was never totally completed, most of it was ready for use shortly after the beginning of MEDEX.

The MEDEX Database (open access, available at http://medex.aemet.uib.es) contains three blocks of information: *cyclones database*, *high impact weather calendars* and *list of selected cases*.

In the *cyclones database* there are listings and basic information about any kind of cyclones or depressions detected in the Mediterranean. There are three lists of cyclones, as obtained from three different series of objective analyses (see Table 2). The technique used for cyclone detection and tracking and for the three dimensional description of the disturbances can be found in Picornell et al. (2001) and Campins et al. (2006a). Note that in order to avoid excessive noise in the dynamical description of the cyclones, it was decided that the original fields would need to be smoothed; a Cressman filter (Cressman, 1959) with 200 km of radius was used for that purpose. Correspondingly, all the information that was incorporated into the cyclones database comes from filtered fields. The data for each "detected cyclone" contains almost twenty variables referred to the cyclone as a whole: date, time, code, location, minimum pressure, shift, stability by layers, wind by layers, and almost twenty other variables for every atmospheric layer where the cyclone is still identified (location, minimum geopotential, geostrophic vorticity in the cyclone centre and average in the whole cyclonic domain, geostrophic circulation, area, radius mean and standard deviation, temperature in the cyclone centre, laplacian of temperature, temperature gradient mean and standard deviation, equivalent temperature gradient mean and standard deviation, humidity mean and standard deviation.

The *high impact weather calendars* are in fact calendars of severe or extreme weather. Only heavy rain and strong wind events are considered. To construct the calendars the Mediterranean territory was divided into territorial units, which correspond either to natural regions (for Bulgaria) or to administrative or political regions or communities (for Italy, France and Spain); in Croatia only one territorial unit was considered. An event is defined as a day in which pre-defined thresholds for precipitation

or for maximum sustained wind or gust are exceeded in at least one station of a territorial unit. A datum is referred to a single day, territorial unit and station; therefore several data can be included in the same event if the corresponding threshold was exceeded in different stations of the same territorial unit. The threshold for precipitation is 60 mm day^{-1}. The thresholds for wind depend on the climatological characteristics of the station. The usual thresholds are 18 m s^{-1} for maximum sustained wind (ten minutes average) and 25 m s^{-1} for the maximum daily gust, but for the windiest stations the thresholds are increased to 25 m s^{-1} and 33 m s^{-1} respectively. Unfortunately MEDEX obtained data for only part of the Mediterranean surrounding territories (see Fig. 1). The national meteorological services of Bulgaria, Croatia, France, Italy and Spain and the Catalan Meteorological Service provided these data. Details about data included in the calendars can be seen in Table 2. A significant part of the events include documentation of analysed meteorological fields, direct and derived (since June 1998 to May 2003) and/or satellite pictures (since 2002).

The third part of the MEDEX Database is the *list of selected cases*. The selection of cases was made subjectively by a dozen of the contributing institutions based on a global assessment of the intensity of the phenomena (heavy rain and/or strong wind), the importance of the associated cyclone (if any) as well as the magnitude of the social impact of the event. The period initially considered was 1995–2002, although a few more recent cases were added later. The initial list includes 52 events. Twelve of them were classified as high priority events, thirty as medium priority, and ten as low priority. For every event it was compiled information about date, priority level of the case, affected countries, concise data about heavy rain or strong wind, social impacts, existence of alerts or warnings, quality of model forecasts and formal or informal bibliographical references. In 2003 there were 42 references on the list of selected cases. An outstanding case of the list is the super-storm of 10–11 November 2001 that produced more than 700 casualties in Algeria and some casualties and great damages in the Balearics, where hundreds of thousands of trees were uprooted and roads cuts and telephone and electricity lines interruptions occurred (Hamadache et al., 2003; Genoves and Jansa, 2003, see Fig. 2).

3.2 Scientific summary

By the end of the MEDEX First Phase, Buzzi et al. (2005) produced a review paper that summarises the scientific progress in the physical and dynamical understanding and numerical modelling of the Mediterranean cyclones and their consequences on weather. The document presents and discusses results of the research performed by members of the MEDEX community under the project scope, mainly with regard to the specific objective 2 of the First Phase, but also includes reviews, ideas and achievements on the same matter obtained previously in parallel actions. Buzzi et al. (2005) is available in the MEDEX web site. This valuable document contains 110 references.

3.3 MEDEX reports for EUCOS

In connection with objective 3 of the First Phase of MEDEX and in accomplishment of the EUCOS-MEDEX MoU, two reports were prepared by MEDEX for EUCOS. The first one (Jansa et al., 2004) includes initial studies, made in France and Spain, regarding the sensitivity to the initial conditions (IC) of the prediction of some cases as derived from adjoint models or indirectly through potential vorticity inversion. Other MEDEX studies are also mentioned in this report.

The second report (Jansa and Homar, 2006) pursues a climatology of forecast sensitivities to IC for a subset of cyclones that produced high impact weather in the Mediterranean. This subset is composed of the intense cyclones included within the MEDEX Database. It was easier to centre the analysis on the population of intense cyclones than on the large variety of high impact weather cases related to weak or moderate cyclones, even at the risk of loosing many interesting events. Several references about more general climatological studies on Mediterranean cyclones are included in this report.

3.4 DTS campaigns and MEDEX

Objective 3 of the MEDEX Second Phase (Jansa et al., 2005) proposes the "development and testing of observational targeting and adaptive strategies (...), oriented to the improvement of the forecasting of the cyclones that produce high impact weather in the Mediterranean" and includes the assessment of forecasting impact of the eventually added observations. The goal was to apply the data targeting (DT) approach to the prediction of high impact weather in the Mediterranean, taking into account that the DT approach seeks the identification of sensitive areas where an improvement (in type or number) of the observations is likely to reduce the forecasting error.

This objective was reached through the agreed participation of MEDEX, as a particular voice, during the autumn of 2008 in Eurorisk-PREVIEW campaign. This project used the DTS (Data Targeting System) facilities, developed by ECMWF in partnership with the UK Met Office for the campaign (Prates et al., 2009). Several cases of particular Mediterranean interest were selected for targeted observations.

The main action of MEDEX in this line was the specific DTS-MEDEX-2009 Campaign (see Jansa et al., 2011). This campaign was sponsored by EUCOS, which also provided organisation and facilities. The ECMWF/UK DTS software formerly developed was used in this campaign. As in Eurorisk-PREVIEW, only operational radiosonde stations and commercial aircraft data (AMDAR) provided additional observations. In addition to AMDARs, DTS-MEDEX-2009 involved 50 radio sounding stations of 16 meteorological services and 484 extra-soundings were performed. The campaign lasted from 30 September to 20 December 2009. All the additional observations have circulated in the WMO-GTS and are available for observational and assimilation experiments, including impact studies or sensitivity verifications.

The experience accumulated during DTS-MEDEX-2009 has been fully used in the preparation and execution of the SOP1 of HyMeX, the first field phase of this more recent Mediterranean project.

4 Scientific achievements

A thorough evaluation of the scientific production in MEDEX is not an easy task, because not all the scientific papers that appeared since the beginning of MEDEX and that were related to the objectives of the project can be considered part of the MEDEX production. Part of this work was performed by groups external to MEDEX and even part of the research performed by people belonging or connected to the MEDEX community could have been done even if MEDEX had not existed. On the contrary, the contributions directly presented to some of the MEDEX meetings (see Table 1) can be considered strict MEDEX production, although preliminary or informal; the same holds for many contributions to the Plinius Conferences on Mediterranean Storms (Table 1), as already mentioned in Sect. 2. Part of both sets of informal scientific contributions became later formal literature. In the following sections, some clear and significant MEDEX scientific achievements will be mentioned, grouped according to the specific objectives of the two phases of MEDEX.

4.1 Climatological aspects

The MEDEX Database, in particular the databases of cyclones and the calendars of high impact weather have made possible or at least have inspired most of the climatological work done in the framework of MEDEX. Apart from an initial effort devoted to the development of methods for the detection, tracking and description of cyclones, some work has dealt with the analysis of the frequency, distribution and characteristics of Mediterranean cyclones. A preliminary work in this sense is that of Campins et al. (2000), but Picornell et al. (2001) is allegedly the first climatological MEDEX paper in that line. Note that the tracking procedure is based on the Alpert et al. (1990) method and that part of the ideas about the detection and description of the cyclones are inspired by Radinovic (1997). In Picornell et al. (2001) the analysis method was applied without any filtering. Gil et al. (2003) used analyses from the operational ECMWF model, and compared results about cyclones between the West-

ern and Eastern Mediterranean, with and without filtering the used fields of departure. Apart from some unpublished work, comparing Mediterranean and Atlantic cyclones, Campins et al. (2006a) represents an important step in this line of research, providing a careful three-dimensional description of Western Mediterranean cyclones. The most complete and ambitious paper about frequency, distribution and description of cyclones for the whole Mediterranean is that of Campins et al. (2011). From all the above papers, several interesting conclusions can be extracted. It can be stressed that some areas are characterised by a high concentration of cyclones; some of these areas are active throughout the year, but some tend to present a very marked seasonal behaviour. The seasonality and the genesis location determine the characteristics of the cyclones, such as their thermal structure or their vertical depth. For instance, most of the summery cyclones are warm and shallow depressions, while most of the winter time disturbances are deep cyclones. Most of the Genoa or Tyrrhenian Sea cyclones are deep lows, while most of the disturbances in Cyprus, Saharan areas, interior of the Iberian Peninsula or Algerian Sea are warm and shallow depressions.

Particular aspects like a special attention to intense cyclones are considered in other studies (Genoves et al., 2006) or are included in other papers (like Homar et al., 2007). Figure 3 shows the geographical distribution of intense Mediterranean cyclones, defined as having a total geostrophic circulation greater than $7 \times 10^7\ m^2\ s^{-1}$ (Homar et al., 2007).

An independent effort on this subject was conducted in France, based on the tracking algorithm of cyclones developed by Ayrault and Joly (2000). Some unpublished presentations and summaries have been prepared along this line by Bruno Joly and Alain Joly. More recently, a climatology of cyclones based on the 850 hPa vorticity maxima tracks shares common features with the aforementioned works (see Fig. 4). Moreover it has been shown that the largest impact regarding strong winds is found over specific areas affected by local winds such as Mistral or Tramontane, rather than being directly tied to the vorticity centres as observed for the Atlantic mid-latitude cyclones.

In Croatia, operational analyses of the ECMWF were used to evaluate the cyclonic activity over the Adriatic Sea (Horvath et al., 2008). These analyses identified four types of cyclogenesis over the Adriatic. These cyclones produce a chain of weather phenomena in the Adriatic coast, where Jugo winds and mountain-induced precipitation precede strong Bora winds.

In MEDEX some attention was paid to the question of time evolution of the frequency and characteristics of the Mediterranean cyclones in connection with climatic change (Guijarro et al., 2006).

Another group of papers focuses on the link between cyclones and high impact weather. A point of departure for the concepts used in some of these papers is Jansa et al. (2001a), while Campins et al. (2006b) and Campins et al. (2007) present examples for specific regions. Other approaches to the same idea are found in Speranza and Tartaglione (2006) and Tartaglione et al. (2006)

Another way to face the high impact weather form the climatological point of view is the identification, through statistical methods like principal component and cluster analysis, of the atmospheric patterns that are associated with this kind of weather. In Météo-France some unpublished work in this sense was made by Bruno Joly and other researchers. Later, already in the process of transition from MEDEX to HyMeX, the work by Nuissier et al. (2011) can be mentioned. Tartaglione et al. (2009) deals with similar aspects, but with reference to Italy. Analogous research lines were explored in Spain with papers referred to atmospheric patterns related to heavy rain in the Balearics (Lana et al., 2007) and for the whole Spanish and French Mediterranean area (Martinez et al., 2008). For Bulgaria, the work by Tsonevsky et al. (2010) can be cited.

4.2 Dynamical and physical mechanisms – numerical modelling

A variety of studies have been performed in this field with regard to the cyclones that produce high impact weather in the Mediterranean. Many of these can be considered as genuinely belonging to the MEDEX orbit and some (cited also in this section) were

included in the analysis by Buzzi et al. (2005). But before and after 2005 there is also significant work on the analysis of dynamical and physical mechanisms of Mediterranean cyclones that produce high impact weather and on numerical modelling.

In fact, studies done before 2000 encouraged and inspired some strategies to face the second specific objective of MEDEX. By applying the factor separation method of Stein and Alpert (1993), an analysis of four different factors on an ALPEX cyclone development, illustrating the significant role of double-, triple-, and quadruple synergies, was performed by Alpert et al. (1996). Romero et al. (1997) studied quantitatively the influence of the orography and evaporation factors and their synergy on a heavy precipitation case of northeastern Spain and demonstrated the leading role of the interaction between both factors.

Later, the consideration for other cases of a dynamic variable such as potential vorticity (PV) as another factor in play in the separation method (by applying PV inversion) permitted to isolate the role of mid-upper tropospheric dynamics on the cyclone formation and on the convective triggering (Tsidulko and Alpert, 2001; Homar et al., 2002a). In Tsidulko and Alpert (2001) PV and orography are the factors considered in an Alpine lee cyclogenesis. In Homar et al. (2002a), the modification via PV inversion of the initial and boundary conditions of mesoscale numerical simulations, by incorporating slightly smoothed upper-level PV anomalies, allowed to identify the importance of the high-level disturbance in the development of a quasi-stationary Low Level Jet (LLJ) that provided a continuous moisture supply towards the Spanish coast. Figure 5 displays the difference between the low level flow in a simulation nested in the unperturbed ECMWF analyses and the simulation initialized with the inverted fields obtained from the slightly smoothed PV field.

The roles of boundary factors (e.g. orography and sea surface evaporation) and physical factors (e.g. latent heat release in the cloud systems) were found to be even more critical when the heavy precipitation episode in the Spanish Mediterranean coast was governed by shallow and/or small size cyclones. For instance, the numerical simulations of two different Mesoscale Convective Systems (MCS) in Romero et al. (2000)

showed that the extreme stationarity and efficiency of both systems can be attributed to the leading role of both kinds of factors within a dynamically-weak meteorological setting.

Also with regard to the prediction of a quasi-stationary MCS, Davolio et al. (2007) used high resolution modeling to study the influence of the initial conditions, the assimilation of surface data and the orographic factor.

Romero et al. (2005), Martin et al. (2006) and Argence et al. (2006, 2008, 2009) studied the influence of uncertainties associated with the location and intensity of the upper-level trough in cases of heavy rain in the Western Mediterranean area. Both PV values and specific shape and position of the disturbance, appear to be critical in determining the amount of precipitation, the location of the maximum rainfall and the strength and position of the responsible low levels cyclones. They also found that too deep disturbances at high levels are not excessively favourable to the development of shallow cyclones and heavy rains since they greatly reduce the stationarity of the weather pattern.

In Horvath et al. (2006) the roles of orography, surface sensible heat flux and upper level potential vorticity anomaly are isolated using the factor separation method for the analysis of an intense cyclone that produced extremely strong Bora wind. This cyclone was generated in the lee of the Atlas Mountains and fully developed over the Central Mediterranean. The orography blocking is responsible for the generation of a low-level shallow vortex in the first phase of the lee development, while an upper-level potential vorticity anomaly is the principal ingredient of this event, responsible for a dominant deepening effect in the later stage of lee formation.

Romero (2008) further exploited the capabilities of the PV inversion approach and the factor separation method in a diagnostic system that implements the concepts of “PV thinking” (Hoskins et al., 1985) of cyclones quantitatively. By switching on and off the PV anomalies of interest, the corresponding solutions to the system of equations can be algebraically combined to isolate the magnitude of both the individual and the synergistic effects of the PV anomalies on the spatial pattern of geopotential-height

tendency (and vertical motion) around the cyclone. The potential of the method to elucidate the relative importance of physically-meaningful PV anomalies associated with the undulating tropopause, the low-level thermal field and the latent-heat release, was illustrated for a prototypical intense Mediterranean cyclone: the upper-level PV anomalies contributed very significantly during its whole life cycle; surface thermal anomalies were fundamental during the development period and for the movement of the system during the later stages; the interaction between the two types of anomalies became the dominant effect during the mature stage of the cyclone; and all other contributions, including the individual and synergistic effects of diabatically-generated PV, were generally most relevant during the mature phase of the cyclone.

The presence of small thermal lows has proved to be decisive in the development of convection that tends to produce hail in the northeastern Iberian Peninsula in summer. Tudurí et al. (2003) showed, through numerical simulations, that the action of the thermal low developed around the Ebro Valley is to inflow moist air from the Mediterranean and then promote severe convection. Sánchez et al. (2003) numerically investigated the same subject with similar results. Analogously, convergence produced by Mediterranean cyclones over the maritime areas can lead to organized convective developments like squall lines, often linked to severe weather (Ramis et al., 2009). Non-hydrostatic numerical models have proven their ability to reproduce quite accurately the spatial and temporal distribution of convection and associated strong winds (Cohuet et al., 2011). In this respect, an analysis and model reconstruction of the historical event of high impact weather cyclone that hit Italy in November 1966 was tackled by Malguzzi et al. (2006), using a full chain of numerical tools, from a global model to a high resolution, convection permitting non hydrostatic model.

The relative influence of latent heat release and other diabatic factors on the genesis and intensification of cyclones in the Mediterranean as compared to the baroclinic mechanism has been also analyzed through numerical simulations. Note that this influence has been shown to be very important for the rapid development of both synoptic-scale cyclones (Homar et al., 2002b; Genoves and Jansa, 2003) and smaller mesoscale cyclones (diameter of about 300 km) known as medicanes or "Mediterranean hurricanes" (Lagouvardos et al., 1999; Homar et al., 2003; Chaboureau et al., 2012). Numerical simulations have also demonstrated how sensible and latent heat surface fluxes become influential in medicane deepening and trajectory (Tous et al., 2013; Davolio et al., 2009).

4.3 Location of sensitive zones and climatology of the sensitivity

Some initial work within MEDEX identified the most sensitive areas, i. e. where additional observations would produce the most beneficial impact on the forecasts by using adjoint models or by means of IC perturbations based on PV inversion. As proxy of the heavy rain, these methods used the water vapour content within an atmospheric box (work by P. Lopez, A. Mezdov, B. Joly and P. Arbogastt; partially included in Jansa et al., 2004). After some parallel work with adjoint models (Homar and Stensrud, 2004), the MM5 adjoint model was the first way adopted to face the work agreed between MEDEX and EUCOS with regard to the systenmatic identification of sensitive zones for generic cases of Mediterranean high impact weather. Owing to the difficulty in identifying proper response functions (that is, specific aspects tracked by the adjoint sensitivities) for a variety of Mediterranean high impact weather associated to cyclones, a proxy was used as a first approach: the study was focused on intense cyclones, the response function being the pressure around the central area of the cyclone. These studies are based on the assumption that intense cyclones are almost always associated with high impact weather. In order to manage a large amount of cases, the intense cyclones were classified by principal components (PC) and cluster analysis in groups (clusters) and the methodology was applied to the cluster centroid, applying later weight coefficients to construct the total climatology. The starting point for the PC and cluster analysis was the MEDEX project cyclone climatology, particularly the intense cyclone climatology (Jansa and Homar, 2006; Homar et al., 2007).

Other methods for sensitivity computation were tested, such as adjoint methods taking into account analysis uncertainties (called KFS, Doerenbecher and Bergot, 2001) or

the method of ensemble sensitivity (Garcies and Homar, 2009, 2010). The ensemble sensitivity was used to construct the climatology of sensitivities for intense Mediterranean cyclones prediction (Garcies and Homar, 2009, 2010).

An indirect approach to the climatology of the sensitivity is through the DTS-MEDEX-2009 campaign (Jansa et al., 2011): the "lead user" had to issue a consensus using the sensitivities objectively computed for the campaign, taking into account the feasibility of additional observations. The distribution of this combined sensitivity defined an approximation to the most sensitive zones for the set of selected cases in the campaign, which not only were intense cyclones, but also heavy rain or strong wind events.

Another aspect that has been studied is the verification of the sensitive information as computed by different methods (adjoint model, ensemble sensitivity or even subjective estimation, Garcies and Homar, 2011).

4.4 Targeted observation and impact of additional observations

The targeted (or adaptive) observations (for cases of Mediterranean cyclones and/or high impact weather in the region) were tested in the Eurorisk-Preview campaign (2008) and in the DTS-MEDEX-2009 campaign, as already mentioned in Sect. 3.4. By using the ECMWF/UK DTS software (Prates et al., 2009), the most sensitive zones, where additional observations had to be deployed, were identified by means of several methods, mostly the ECMWF Singular Vector method, with the help of other methods and the subjective modulation (see Jansa et al., 2011).

Concerning targeting observations, the main scientific objective was rather to verify the correctness and usefulness of the sensitivity computations and of the additional deployed observations.

A way to verify the derived sensitivity information is the introduction of artificial perturbations in the estimated most sensitive zones and studying their evolution throughout the numerical prediction (Garcies and Homar, 2013).

Another way is to analyse the direct impact in the forecast of the additional observations or even of the additional assimilation of some available and non used data, like high density satellite data (Campins et al., 2013). The results obtained until now are not conclusive, but indicate partial usefulness of some additional data. It should be stressed that the impact of the targeted observations was here found to be not negligible with respect to the first experiment of that kind called TREC2003 (for Thorpex Regional Campaign, Fourrie et al., 2006).

4.5 Forecasting methods: testing ensemble prediction systems (EPS)

It is now recognised by many meteorological services that application of high resolution ensemble prediction systems (EPS) is valuable in the frame of high impact weather forecast, even at the small scale (Bouttier et al., 2012).

In parallel to MEDEX, several institutions have been working on EPSs or statistical forecasting methods. The multimodel-multiboundary ensemble system developed at AEMET (AEMET-SREPS, Garcia-Moya et al., 2011) has been presented to the MEDEX community (in different MEDEX meetings) and discussed. AEMET-SREPS has been tested in cases of Mediterranean high impact weather (Callado et al., 2011).

More specifically connected to MEDEX is the work done on EPS at the University of the Balearic Islands. They took practical advantage of the body of knowledge acquired during the course of the project with regard to the roles of dynamical and physical factors on Mediterranean cyclones and heavy rain by designing and testing for MEDEX events three different short-range ensemble prediction systems (EPS) (Vich et al., 2011a, b): a multiphysics EPS that uses different sets of model physical parameterizations; an ensemble based on perturbing the three-dimensional PV features of the input analyses that exhibit intense values and gradients (PV-gradient); and an analogous system whose perturbation zones are guided by the model adjoint-derived sensitivity zones (PV-adjoint). A thorough verification of the results showed that even though all EPSs are skilful and advantageous over a deterministic approach, both PV-perturbed systems beat a multiphysics approach, the PV-gradient being the best. Vich et al. (2012) introduced a novel concept consisting of building the ensemble members

with the previous approach plus subjectively defined perturbations, drawn by a forecaster or an expert.

It was also shown that the hydrological response of medium-size catchments tend to filter to a certain extent the meteorological errors (Amengual et al., 2007) while these errors – and thus the value of an ensemble approach – may become critical in small basins (Amengual et al., 2008).

4.6 Social impact studies

Although most of the papers about case studies usually introduce briefly the main impacts produced by the respective event, the Societal Impact Research Group (SIR) of MEDEX focused its work (presented every year since its birth in the Plinius Conferences), in three main research lines. The first one was the compilation of socioeconomic data on impacts produced by the events included in the database already mentioned in Sect. 4.1, and the completion of it for the period 1990–2006. As a result of this work and in collaboration with the European FLASH project, Llasat et al. (2010) published a preliminary cartography and temporal analysis of flood events that have affected the Mediterranean countries. Fruit of this initiative has been the FLOODHYMEX data base (Llasat et al., 2013) attending that the SIR group was followed by the Working Group on Societal Impacts (WG5) of HYMEX project. Based on the experience gained and following the pioneering initiatives of MEDEX, a database (that is continuously updated) containing all the major events with important socio-economic impacts that occurred since 2000 in Greece has been recently constructed (Papagiannaki et al., 2013).

The second research line was centred on the analysis of requests received by Meteorological Services as a consequence of the impacts of heavy rains and windstorms, and was developed in collaboration with the Regional Centre of AEMET in the Balearic Islands and the Meteorological Service of Catalonia (Amaro et al., 2010). The idea, followed by other communications presented in different Plinius Conferences, was to take

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benefit of the hard work developed regularly by meteorological services, as source of data serve as inidcators of societal impact.

In the third one, Llasat et al. (2008) introduced the influence of the changing vulnerability and the perception of population in the evaluation of the high impact weather risk as well as in the observed trends. This task was systematically improved with the creation of a data base containing press news relative to floods, heavy rainfalls and severe weather that were published in a newspaper during the period 1982–2007 (Llasat et al., 2009).

MEDEX has been the birthplace of the current group of HyMeX dedicated to the analysis of the social impact caused by meteorological and hydrometeorological hazards. It was one of the first bets for interdisciplinary work between social sciences and natural sciences for assessing impacts.

Finally we can mention some MEDEX research on forecast verification, which is a horizontal topic, with connections with the social impact research and with the research on forecast methods and numerical modelling. A particular objective in this sense was the development of a tool to measure the quality of the cyclone forecast (Picornell et al., 2003, 2011).

5 Conclusions

This paper has reviewed the main results of the international project MEDEX. These results can be grouped in two categories, the tangible products and the scientific findings.

The tangible products comprise: (i) the MEDEX Database, with a rich and useful content about cyclones and severe weather in the Mediterranean, (ii) three main written reports, on scientific achievements during the First Phase of MEDEX, on sensitivity computations and on sensitivity climatology, and (iii) the stored sensitivity computations and the additional observations obtained during the DTS-MEDEX-2009 campaign and in association with the Eurorisk-PREVIEW campaign (2008). Additionally, the reports

about the project submitted to WMO (SSC/WWRP or ICSC/THORPEX) can also be considered as tangible MEDEX production.

With regard to scientific achievements, plentiful literature has emerged from MEDEX, concerning several aspects, in particular (i) climatological aspects (like characterisation of Mediterranean cyclones, atmospheric patterns associated to high impact weather or the relationship between cyclones and high impact weather), (ii) aspects related to the knowledge about the processes involved in the formation and evolution of the cyclones that produce high impact weather and in the high impact weather itself (with regard to factors involved, including dynamical and diabatic forcing, or numerical modelling capabilities). (iii) The location of high sensitivity areas for the prediction of cyclones that produce high impact weather, as well as the climatology of these sensitivities, have been the objects of another series of papers. Some other are relative to the verification of the sensitivity and to the impact of additional observations in the forecasting. (iv) There is also MEDEX literature on prediction methods, particularly about the use or the improvement of ensemble prediction systems. (v) Finally, a group of MEDEX papers deals with the social impact of the Mediterranean cyclones and associated weather and with the forecasting verification.

The documents associated with MEDEX meetings (such as presentations or minutes) can also be considered as MEDEX production. In this sense, the Workshop on Social Impact Research in MEDEX (Barcelona, 2004) was an outstanding event, with interdisciplinary contributions coming from different kind of individuals and organisations. Nineteen papers were presented there.

MEDEX has also contributed to the Mediterranean meteorology by keeping alive during a decade the research spirit on the topic in the region, with particular attention to the Mediterranean cyclones and the associated high impact weather.

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Islands, has constructed and maintained the MEDEX Database. The work associated with this activity has been mostly undertaken by Ana Genoves, Joan Campins and Maria Angeles Picornell (AEMET), all of them authors or co-authors of scientific MEDEX literature and very active participants in the MEDEX campaigns.

The organisational, technical and financial support given by EUMETNET/EUCOS to MEDEX has been very important, particularly for sensitivity studies and for running the MEDEX campaigns. From the management of EUCOS, James Caughey, Bruce Scott and Stefan Klink have provided special help to MEDEX. Most of the work on sensitivity studies has been undertaken or directed by Victor Homar, from the University of the Balearic Islands. Victor Homar has also contributed to this paper through a collaborative reading and improvement of the manuscript.

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Table 1. MEDEX Meetings and associated scientific presentations (P = number of participants; MP = specific MEDEX presentations).

Meeting	Place	P	MP	Other presentations
2001	Palma (Mallorca, Spain)	23	10	
2002A	Athens (Greece)	17	–	
2002B	Alcudia (Mallorca, Spain)	26	–	Combined with Plinius 4
2003	Ajaccio (Corsica, France)	20	6	Combined with Plinius 5
2004	Barcelona (Spain)	39	19	
Workshop on Social Impact Research in MEDEX				
2004A	Barcelona (Spain)	15	–	Combined with Workshop
2004B	Dubrovnik (Croatia)	23	8	
2005A	Madrid (Spain)	28	12	
2005B	Crete (Greece)	21	–	Combined with Plinius 7
2007A	Madrid (Spain)	18	5	
2007B	Varenna (Italy)	10	–	Combined with Plinius 9
2008	Nicosia (Cyprus)	10	–	Combined with Plinius 10
2009	Barcelona (Spain)	21	–	Combined with Plinius 11
2010	Corfu (Greece)	10	–	Combined with Plinius 12

Table 2. MEDEX databases of cyclones. 4 analyses per day.

Analysis model	Resolution	Period	Area	Number of cyclone detections
HIRLAM-INM	0.5° × 0.5° lat-lon	1 Jun 1995 to 31 May 2004	Western Mediterranean	15 733
ECMWF operational	0.5° × 0.5° lat-lon	1 Jun 1998 to 31 May 2004	Whole Mediterranean	19 200
ERA-40	1.125° × 1.125° lat-lon	1 Sep 1957 to 31 Aug 2002	Whole Mediterranean	81 762

Table 3. Data in the calendars of high impact weather events (MEDEX database).

Country	Number of stations	Period (yymm)	Number of events	Number of data
Bulgaria	310	9501–0412	203	432
Croatia	44	9501–0312	119	171
France	1030	9701–0412	468	11 052
Italy	113	9501–0412	333	503
Spain	5898	9501–0412	1012	10 780
Total	7395		1577	22 938

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Table A1. Members of the MEDEX Science Steering Committee (at least part of the time during the MEDEX life).

Pinhas Alpert	Israel
Philippe Arbogast	France
Andrea Buzzi	Italy
James Doyle	USA
Klaus Hoinka	Germany
Branka Invancan-Picek	Croatia
Agusti Jansa (chairman)	Spain
Vassiliki Kotroni	Greece
Maria Carmen Llasat	Spain
Abdalah Mokssit	Morocco
Jean Pailleux	France
Climent Ramis	Spain
Romualdo Romero	Spain
Evelyne Richard	France
Antonio Speranza	Italy

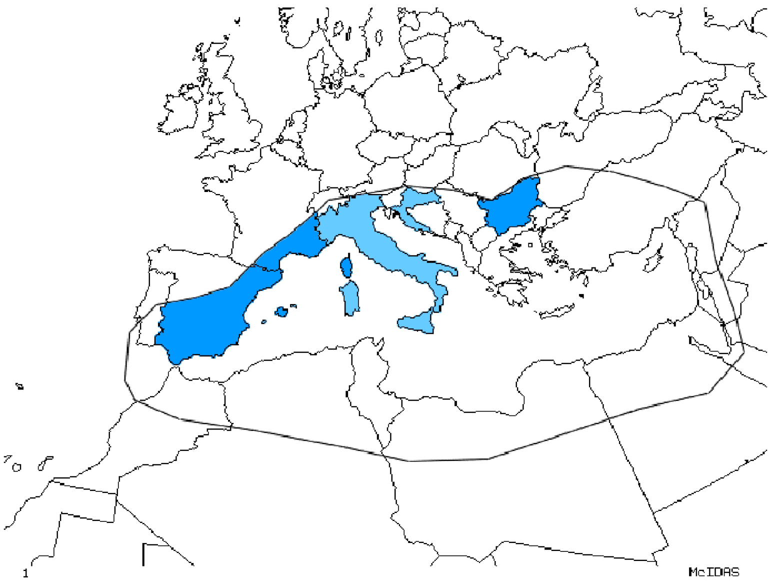

Fig. 1. Zones with data in the calendar of high impact weather events included in the MEDEX database. Dark blue corresponds to zones with high density of stations and light blue, to zones with low density of stations.

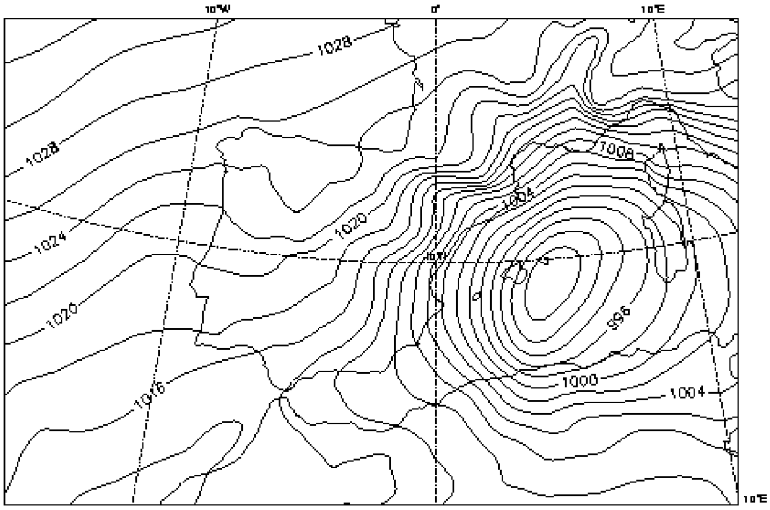

Fig. 2. MSP HIRLAM-INM analysis, 11 November 2001 at 06:00 UTC.

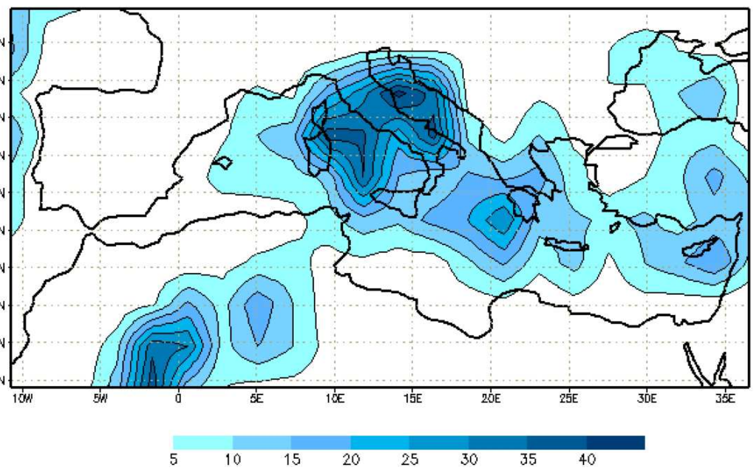

Fig. 3. Geographical distribution of the intense cyclones, that is, with geostrophic circulation larger than $7 \times 10^7\ m^2\ s^{-1}$ (Homar et al., 2007; courtesy of Joan Campins, AEMET).

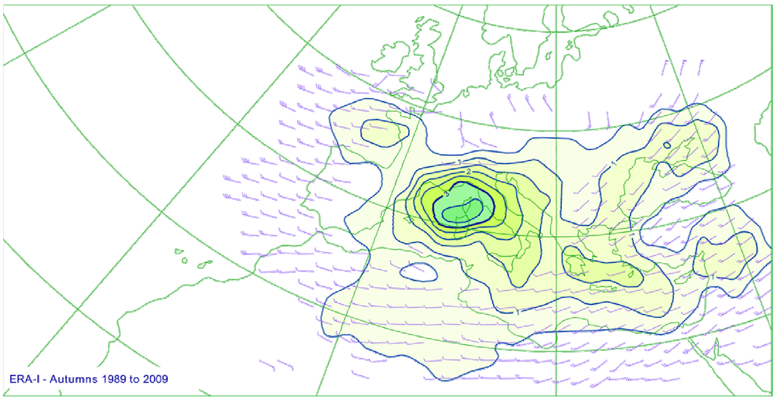

Fig. 4. Density of cyclone tracks over the whole ERA-Interim data set. A cyclone location is defined by the 850 hPa vorticity maximum (courtesy of Bruno Joly, MeteoFrance).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

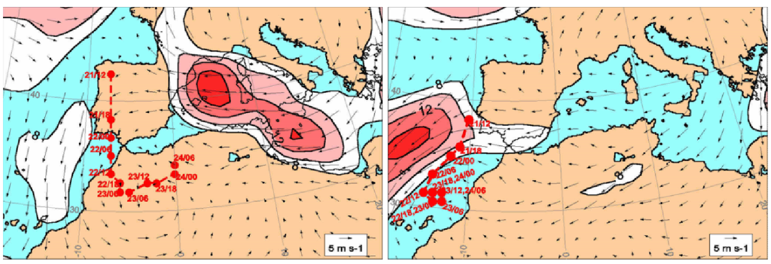

Fig. 5. (left) Position of the cutoff low center at 300 hPa (circled), from 12:00, 21:00 to 06:00 UTC 24 October 2000 as simulated in the control run. Vector field and shaded contours show the 48 h averaged wind and wind speed ($m\,s^{-1}$) greater than 8 $m\,s^{-1}$ at 1000 hPa from 00:00, 22:00 to 00:00 UTC 24 October 2000. (right) The same but for the weakened cutoff low experiment (from Homar et al., 2002a).