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Meteorological environments associated with medicane development

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ABSTRACT: Medicanes are 'Mediterranean tropical-like cyclones', warm-core cyclones that occasionally put in danger the islands and coastal regions. In spite of large geographical differences between the Mediterranean Sea and the tropical oceans, their genesis mechanisms, based on the thermodynamical disequilibrium between the sea and the atmosphere, are similar.

The special characteristics of the medicanes make their detection difficult: only with high resolution meteorological analysis data and dense maritime observations that task would be possible. An alternative method, using satellite data and restricted criteria about the disturbance symmetry, size and lifespan, has been successfully used to detect 12 medicanes from 1982 to 2003.

To enhance the medicane prediction capability or even to assess the risk potential in future climates, it is necessary to characterize the special conditions of the synoptic-scale meteorological environments that are needed for their development and maintenance. By comparing these environments against the bulk of Mediterranean cyclonic situations, high values of mid-tropospheric relative humidity, significant diabatic contribution to the surface level equivalent potential temperature, and low values of tropospheric wind shear, are revealed as important parameters involved in medicane genesis, as in tropical cyclones. An empirical genesis index previously derived for the tropical cyclones is also tested in the study, and its behaviour is revealed as a possible discriminative parameter of the precursor environments.

In the context of the growing concern about how climate change will affect the number and intensity of hurricanes, a preliminary analysis for medicanes has been done here. By projecting the previous empirical index into three different global climate model (GCM)-simulated climates, spatial distributions of the monthly index values have been evaluated. The monthly mean values and the frequency of extreme values of this index tend to decrease, showing that the number of days with a medicane risk tends to reduce at the end of the 21st century. Copyright © 2012 Royal Meteorological Society

KEY WORDS Mediterranean; Medicanes; Synoptic environments; Climate Change; Extreme events.

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1. Introduction

The Mediterranean basin is recognized as one of the main cyclogenetic areas in the world (Pettersen, 1956; Hoskins and Hodges, 2002; Wernli and Schwierz, 2006), and much of the high impact weather affecting the Mediterranean countries (notably strong winds and heavy precipitations) have been statistically associated with the near presence of a distinct cyclonic signature (e.g. Jansà *et al.*, 2001). Cyclones can range from synoptic to mesoscale in size and from pure baroclinic systems to orographically or diabatically modulated disturbances in type, and their peak occurrences and notorious consequences have been clearly linked to the presence of prominent orographic systems surrounding the Mediterranean Sea (Reiter, 1975; Buzzi and Tibaldi, 1978; Speranza *et al.*, 1985; Genovés and Jansà, 1991; Martín *et al.*, 2007).

In spite of the relatively low latitude of the Mediterranean region, some of the baroclinic developments can be so fast as to reach the category of 'meteorological bombs' (Conte, 1986; Homar *et al.*, 2002). Even without reaching that definition, some cyclones can be intense enough to produce serious wind-driven social impacts, like the 10–12 November 2001 event (Arreola *et al.*, 2003; Romero, 2008). Another kind of violent cyclonic windstorm is the so-called medicane or Mediterranean 'hurricane', a subclass of polar lows according to some authors (Businger and Reed, 1989). These subsynoptic warm-core vortices are very notorious for inducing sudden changes in pressure and wind over the affected areas, although the winds do not normally attain hurricane intensity. Indeed, satellite images (Figure 1) as well as meteorological reports from ships and coastal regions confirm that hurricane-like storms do occasionally develop over the Mediterranean Sea (Ernest and Matson, 1983; Reale and Atlas, 2001; Jansà, 2003). Some of these storms have hit populated areas, leading to hazardous consequences.

The maritime characteristics of these phenomena and the small geographical extent of the Mediterranean, coupled with the quite reduced size and infrequent occurrence of the storms themselves and the absence of aircraft reconnaissance missions of the kind

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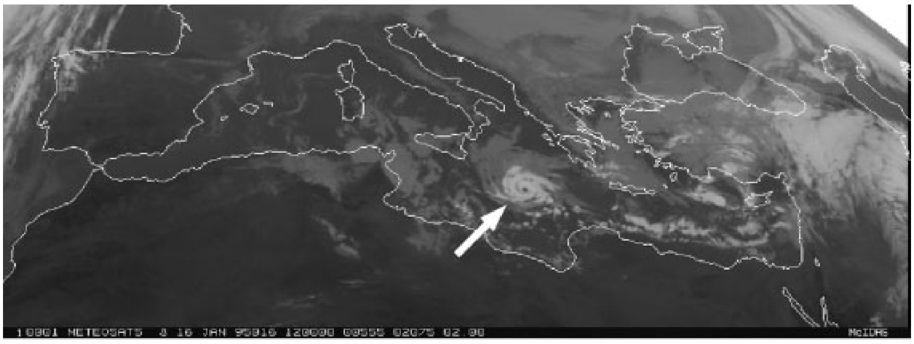
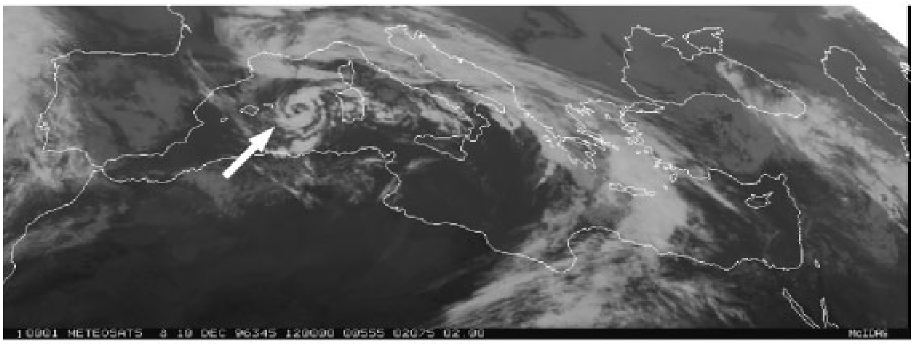
(a) 16-January-1995, 12 UTC



(b) 9-October-1996, 21 UTC

(c) 10-December-1996, 12 UTC



(d) 19-March-1999, 18 UTC

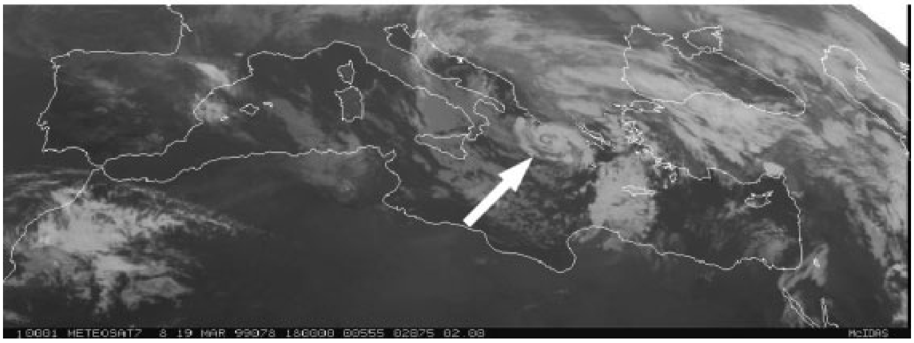


Figure 1. Examples of medicanes as seen in the IR channel of Meteosat satellite (taken from Table I).

undertaken commonly in Atlantic hurricanes, means that the statistical record of medicanes is very sparse. How often do they actually occur and in which meteorological environments? Are there favoured locations within the Mediterranean for their development and maintenance? How could medicanes react to global warming? Answers to these and other relevant questions require a systematic database of events.

In this study, an alternative method to detect medicanes has been applied as the best and, possibly, only way to build the database. Using historical infrared (IR) Meteosat satellite data, two lists of medicanes have been created based on different criteria (Section 2). In addition, an identification of the large-scale thermodynamical parameters associated with medicanes development has been attempted (Section 3). For this purpose, meteorological conditions occurring over the genesis areas of medicanes have been compared against the synoptic settings of ordinary Mediterranean cyclones, typically baroclinic disturbances, using the MEDEX (The MEDEX project was endorsed by the World Weather Research Programme (WWRP) and The Observing System Research and Predictability Experiment (THORPEX), global research projects of the World Meteorological Organization (WMO). All the information about MEDEX project, including the used databases, is available at http://medex.aemet.uib.es) database. That is, we have performed a dynamically oriented climatology of Mediterranean cyclones with the aim of isolating thermodynamical descriptors favouring the formation and maintenance of medicanes.

Finally, there is increasing concern that extreme events may be changing in frequency and intensity as a result of human influences on climate [the Intergovernmental Panel on Climate Change (IPCC, 2007)]. In fact, climate change may be perceived most through the impacts of extremes, but the availability of observational data largely restricts the analysis of their occurrences. The rarer the event, the more difficult it is to identify long-term changes, simply because there are fewer cases to evaluate (Frei and Schär, 2001; Klein Tank and Können, 2003). For projecting future changes, global climate models (GCMs) are commonly used. The last part of the study (Section 4) contains a preliminary outlook of the future environments provided by these GCMs at the end of 21st century with regard to the statistical changes in the medicane-prone conditions compared to present. These atmosphere–ocean coupled physical models provide quantitative estimates of future climate change, particularly at continental and large scales. However, the resolution of GCMs (typically in the range 2–3°) makes them inappropriate to deal explicity with extreme phenomena of subsynoptic size, like medicanes.

2. Database of events

There is a large number of cyclone climatologies, for both the northern Hemisphere (Hoskins and Hodges, 2002; Wernli and Schwierz, 2006) and the Mediterranean region ((Alpert *et al*., 1990; Maheras *et al*., 2001). These climatologies usually attempt to characterize the genesis and lysis regions of cyclones, their trajectories, duration, etc. Some climatologies have also studied other characteristics, such as size and intensity of the detected cyclones (Trigo *et al*., 1999; Campins *et al*., 2006; Campins *et al*., 2010).

The small size and the maritime characteristics of medicanes imply that this special type of cyclones can not be captured in the above climatologies: it would be possible only with very high resolution meteorological grid analyses and dense observational data over the Mediterranean. Therefore, a direct visual analysis appears as the best way to detect medicanes. The use of satellite images to track and document tropical cyclones has been a fundamental tool for the issue of advisories (e.g. at the NOAA/National Hurricane Center) and also for the study (Ernest and Matson, 1983; Reale and Atlas, 2001; Jansà, 2003) and the forecast of their Mediterranean analogues. For these reasons, the use of satellite images has been recognized as a useful tool to consistently detect storms and, in this case, medicanes. In satellite images, medicanes tend to exhibit a clear circular eye surrounded by a convective eyewall and a roughly axisymmetric cloud pattern (Mayengon, 1984).

However, the application of fully automatic procedures in the Mediterranean might be problematic, owing to the small size of medicanes and their fuzzy cloud structure. Furthermore, medicanes can be confounded with shallow orographic cyclones (Jansà, 2003). These aspects must be taken into account in the process of generating a database of medicanes, and the use of subjective detection seems necessary.

The full collection of Meteosat satellite images, from 1982 to 2003 at 30-min intervals, is used to detect medicanes in this study. On the basis of the infrared channel, 220 events (MED220) are first screened for having a highly symmetric structure that vaguely resembles that of tropical cyclones. But not all these events are medicanes (most are large baroclinic systems that evolve into symmetrical structures during its occlusion phase, probably under increasing diabatic influences around its core; see an example in Figure 2), so it is necessary to use more restrictive selection criteria. These criteria are based on the detailed structure, the size and the lifetime of the systems, all of them assessed in the IR channel. Medicanes must have a continuous cloud cover and symmetric shape around a clearly visible cyclone eye. The diameter of medicanes must be less than 300 km: due to the size of the Mediterranean Sea, heat fluxes from the sea to the atmosphere (that are one of the main characteristics in tropical cyclones development and, by

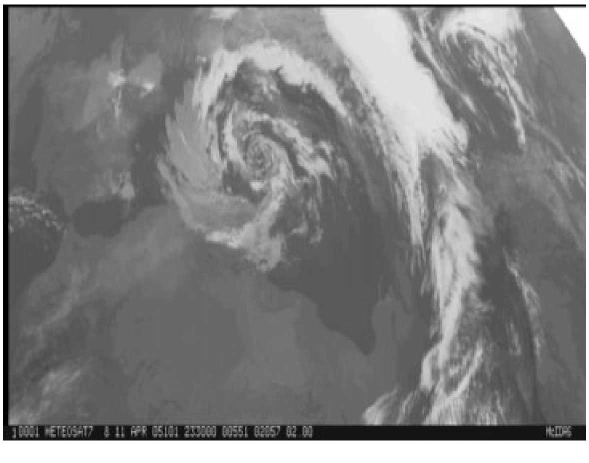


Figure 2. Large and highly symmetric baroclinic cyclone on 11 April 2005 at 2330 UTC (IR image of Meteosat).

Table I. Date, approximate time of the mature phase (00, 06, 12 or 18 UTC); latitude and longitude of the mature cyclone centre; and maximum diameter and lifetime of the 12 detected medicanes.

Date	Time (UTC)	Latitude (°N)	Longitude (°E)	Maximam diameter (km)	Lifetime (h)
29 September 1983	12	41.1	6.8	220	90
7 April 1984	06	36.4	19.2	230	36
29 December 1984	06	35.4	11.6	220	60
14 December 1985	12	35.5	17.6	290	54
5 December 1991	12	36.2	16.7	320	30
15 January 1995	18	36.4	19.1	200	78
12 September 1996	12	39.4	2.8	170	12
6 October 1996	18	37.2	3.9	240	90
10 December 1996	00	40.3	3.7	230	48
26 January 1998	12	36.7	17.9	250	30
19 March 1999	06	38.5	19.6	250	30
27 May 2003	00	40.1	2.8	280	42

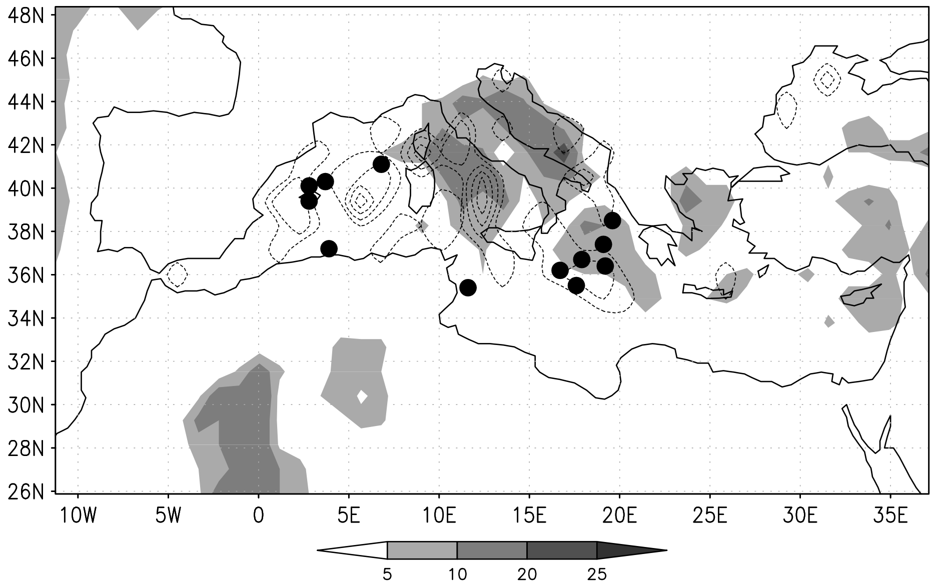


Figure 3. Spatial density distribution of intense cyclones from the MEDEX project (shaded) as number of events in a square of 1.125° lat–lon; density distribution of MED220 cyclones (dashed lines, contour interval is one event/$(1.125°)^2$ starting at value 1); and the 12 detected medicanes (black points).

extension, in medicanes) can not create larger cyclones. The last requirement is a lifetime of at least 6 h. This limit ensures a sufficient tracking of the large-scale meteorological parameters associated with the cyclones using the European Center for Medium-Rante Weather Forecasts (ECMWF) reanalyses ERA-40 (see next section). The application of these criteria has resulted in the detection of six cases. Six additional events studied by some authors (Homar *et al*., 2003), which were also revealed as medicanes, are included in the list although their visual appearance in satellite images do not entirely fulfill the above criteria (e.g. the diameter can be slightly larger than 300 km, or the cloud cover or cyclone shape can not be perfectly continuous and axisymmetrical, respectively). Nevertheless, the eye of the medicane must be visible in all cases, although it may be partially covered by high clouds. At the end, 12 events have been identified as medicanes (Table I; Figure 1). The lifetime of the detected medicanes ranges from 6 to 72 h, and the printed date in the Table I is fixed as the first time when it is possible to infer the mature phase of the medicane, that is when the cyclone eye is clearly observable.

Moreover, it is also known that the Mediterranean area has a high number of cyclones per year (Pettersen, 1956; Hoskins and Hodges, 2002; Wernli and Schwierz, 2006). The spatial distribution of these cyclones is not uniform. There are two preferred regions: Cyprus and the gulf of Genoa (Alpert *et al*., 1990; Campins *et al*., 2010). Shaded areas in Figure 3 represent the spatial density of intense cyclones (that is with a surface geostrophic circulation greater than 7 gcu, where 1 gcu = 10^7 m^2 s^{-1}) using the MEDEX database. This kind of MEDEX cyclone climatologies were built using the ERA-40 data for the period 1957–2002. Although intense cyclones have virtually occurred everywhere in the Mediterranean, there are again two preferred regions of cyclogenesis: Italian maritime areas and Ionian and Aegean Seas. It should be kept in mind that part of the Atlantic ocean is included in the domain of the MEDEX project, so some statistical results using this database can be slightly adulterated by non-Mediterranean cyclones.

The density distribution of the MED220 events at mature state is represented as dashed lines in Figure 3; they are located preferably in the Central and Western basins: the area between the Balearic Islands and Italian peninsula contain most of these cyclones. The 12 detected 'true' medicanes (black points in Figure 3) are situated in the Central and Western regions of the Mediterranean Sea, but in different areas than those described above. Medicanes lie over the Ionian sea and Balearic sea.

With regard to the period of occurrence, medicanes are more frequent in winter [like intense baroclinic Mediterranean cyclones (Campins *et al.*, 2010)] and autumn, but they have also occurred in early spring and late summer (Figure 4). This fact indicates a notable difference with respect to tropical cyclones, which happen only in a few specific months of the year, when the sea surface temperature (SST) is at its highest.

3. Characterization of environments

3.1. Meteorological parameters

Numerical simulations of particular medicane events (Homar *et al.*, 2003; Emanuel, 2005a; Fita *et al.*, 2007) indicate that these storms are distinguished from ordinary Mediterranean cyclonic systems in their development mechanism. While ordinary winter storms are baroclinic in origin (drawing their energy from the available potential energy associated with large-scale horizontal temperature gradients), medicanes operate on the thermodynamic disequilibrium between the Mediterranean Sea and the atmosphere. That is, their energy source is the massive latent heat release occurring in convectively driven cloud systems rooted in a continuously moistened boundary layer. In this respect, as well as in their visual appearance in satellite images, medicanes are much like tropical cyclones. Thus, it seems reasonable to apply the concepts and tools developed for the well known hurricanes to these Mediterranean analogues. An exercise like this has been proven very useful for understanding the mechanics of polar lows (Emanuel and Rotuno, 1989).

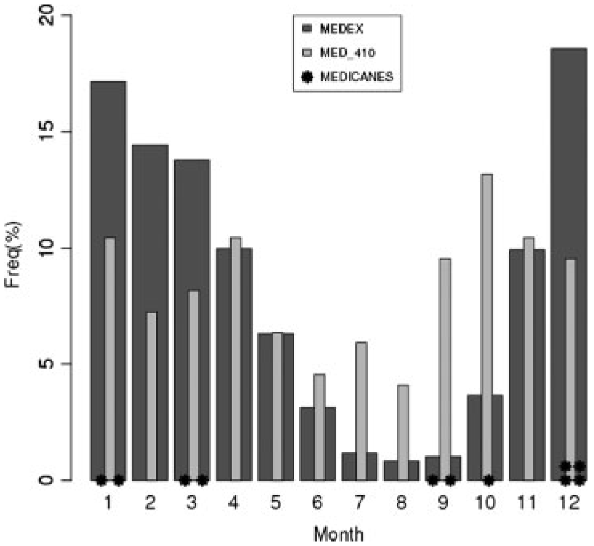


Figure 4. Monthly frequency distribution (%) of intense cyclones of the MEDEX project (dark bars), MED220 events (lighter bars) and detected medicanes (stars).

Some of the large-scale parameters characteristic of hurricane-prone environments will be analysed here: the presence of cyclonic low-tropospheric vorticity (AVOR850, calculated at 850 hPa level), substantial mid-tropospheric relative humidity (RH600, calculated at 600 hPa level), high (relative to air) SST, and low values of tropospheric wind shear (VSHEAR8525, calculated between 850 and 250 hPa levels). Furthermore, also the diabatic contribution to the surface level equivalent potential temperature local tendency (DIAB1000) is strongly related to tropical cyclone development, so it is considered here too. This diabatic term is related with the sea–atmosphere sensible and latent heat fluxes. Owing to the temporal discretization of the available meteorological fields, this parameter is calculated as:

$$DIAB1000 = \left[\frac{\theta_e(t + \mathrm{d}t) - \theta_e(t - \mathrm{d}t)}{2\mathrm{d}t} \right. \\ \left. - Adv\theta_e(t) \right] \tag{1}$$

where the advection term, $Adv\theta_e(t)$, is formulated through finite spatial differences at the time t, and dt indicates the time interval of the used analysis data.

The air–sea interaction theory for tropical cyclones (Emanuel, 1986), presented as an alternative to the previous conditional inestability of the second kind (CISK) mechanism theory introduced by Ooyama (1964) and Charney and Eliassen (1964), shows that the steady-state maintenance of these storms can be idealized as a natural heat engine or Carnot cycle, with the provision that the heat input is largely in the form of the latent heat of vaporization acquired from the sea surface by the inwards airflow (Emanuel, 2003). The mechanical energy available from this thermodynamic cycle balances turbulent dissipation in the storm's atmospheric boundary layer, and after formulating and equating these two terms, the theory allows to determine the potential intensity (MAXWS) of the storm from the environmental conditions (Bister and Emanuel, 1998):

$$MAXWS \approx \sqrt{\frac{C_k}{C_D}\frac{T_S - T_0}{T_0}(k_0^* - k)} \tag{2}$$

where T_S is the SST, T_0 the mean temperature at the top layer of the idealized storm, k the specific enthalpy of the air near the surface, k_0^* the enthalpy of air in contact with the ocean, assumed to be saturated with water vapour at ocean temperature, and C_D and C_k are the dimensionless transfer coefficients of momentum and enthalpy. Details of the calculation may be found in the study of Bister and Emanuel, 2002. A FORTRAN subroutine to calculate the potential intensity is available at http://wind.mit.edu/emanuel/home.html. Real events from the tropical oceans demonstrate that the idealized model correctly predicts the maximum wind speed (or minimum central pressure, according to gradient wind relation) achievable in tropical cyclones (Emanuel, 2000).

On the other hand, no facet of the study of tropical cyclones has proven more vexing that understanding and predicting their genesis (Emanuel, 2003). Nevertheless, the same author has formulated an empirical genesis index (GENPDF) that combines the previous potential wind speed value (Equation (1)) with the low-tropospheric vorticity (AVOR850), mid-tropospheric relative humidity (RH600) and deep-layer wind shear (VSHEAR8525):

$$GENPDF = |10^5 AVOR850|^{3/2} \left(\frac{RH600}{50}\right)^3 \left(\frac{MAXWS}{70}\right)^3 (1 + 0.1VSHEAR8525)^{-2} \quad (3)$$

This index has been successfully tested against the true space-time probability of tropical cyclone genesis. Preliminary analysis for the Mediterranean (Romero and Emanuel, 2006) concluded that it is a suitable diagnostic indicator of the potential of synoptic environments for medicane development. Hence, GENPDF appears to be a good candidate in our objective of describing and identifying as best as possible the meteorological environments conducive to medicanes. In its original formulation, this index was adjusted as number of events per decade in a square of 2.5 × 2.5°. In the case of medicanes, this adjustment is not consistent with the rare occurrence of events, but the units are not used and only a qualitative analysis is provided here.

A summary of the large-scale meteorological parameters calculated in this study is presented in Table II. All these parameters are calculated from the ERA-40 reanalyses corresponding to cyclone maturity time and have been averaged in a square of 600×600 km^2 around the cyclone detection point. In fact, for these calculations, the satellite-observed maturity time is shifted to the closest analysis time among 00, 06, 12 or 18 UTC, and the cyclone centre is also replaced according to the ERA-40 resolution (≈120 km). Since the ERA-40 dataset ends in 2002, the medicane of May 2003 will not be considered in this analysis. GENPDF has an additional variety also: GENPDFmax, which is the maximum value of the GENPDF index found in the averaging square.

For the sake of brevity, displayed results in next section are for DIAB1000, SST and GENPDF only. Except for a slight tendency towards low values of tropospheric wind shear and high values of potential intensity, the other explored parameters (AVOR850, RH600, VSHEAR8525 and MAXWS) turned to be less discriminant of the medicane-prone environments individually, but remember that they are combined in the definition of GENPDF (Equation (2)).

3.2. Comparison against MEDEX intense cyclones

The Mediterranean Sea and overlying atmosphere are only exceptionally conducive to medicane development and maintenance: the potential energy needed for tropical-like cyclones is not ordinarily large, and the atmosphere above a thin boundary layer is usually far too dry to allow genesis. Synoptic analyses of a few well known cases (Pytharoulis *et al*., 2000; Homar *et al*., 2003) indicate that medicanes are not fully isolated structures of the atmospheric circulation; they require a large-scale baroclinic disturbance evolving over the Mediterranean and only during the mature or late stages of this primary cyclonic storm, a medicane might develop. They almost always develop under deep, cut-off, cold core cyclones present in the upper and middle troposphere, usually formed as a result of the 'breaking' of a synoptic-scale Rossby wave. The synoptic analyses of the 12 detected medicanes tend to confirm this hypothesis (Figure 5). As such, a system approaches the Mediterranean, or develops *in situ*, the air through a deep layer of the troposphere is lifted through large vertical displacements, cooling it and increasing the relative humidity. Then, the atmosphere is susceptible to tropical cyclone-like development, for several reasons. At first, thermodynamic potential for tropical cyclones is large according to Equation (1), owing to the anomalously large air–sea thermodynamic disequilibrium. The air through a deep column is very humid, inhibiting the formation of convective downdrafts that often prevent

Table II. Summary of the large-scale meteorological parameters considered in this study, their definition and the used physical units.

Parameter	Definition	Units
AVOR850	Low-tropospheric (850 hPa) vorticity	10^{-5} s^{-1}
DIAB1000	Diabatic contribution to surface level (1000 hPa) equivalent potential temperature local tendency	°C (12 h)$^{-1}$
RH600	Mid-tropospheric (600 hPa) relative humidity	%
SST	Sea surface temperature	°C
VSHEAR8525	Tropospheric wind difference between 850 and 250 hPa	m s^{-1}
MAXWS	Idealized maximum surface wind speed, or Potential intensity	m s^{-1}
GENPDF	Empirical genesis index described by Emanuel (2005a)	–

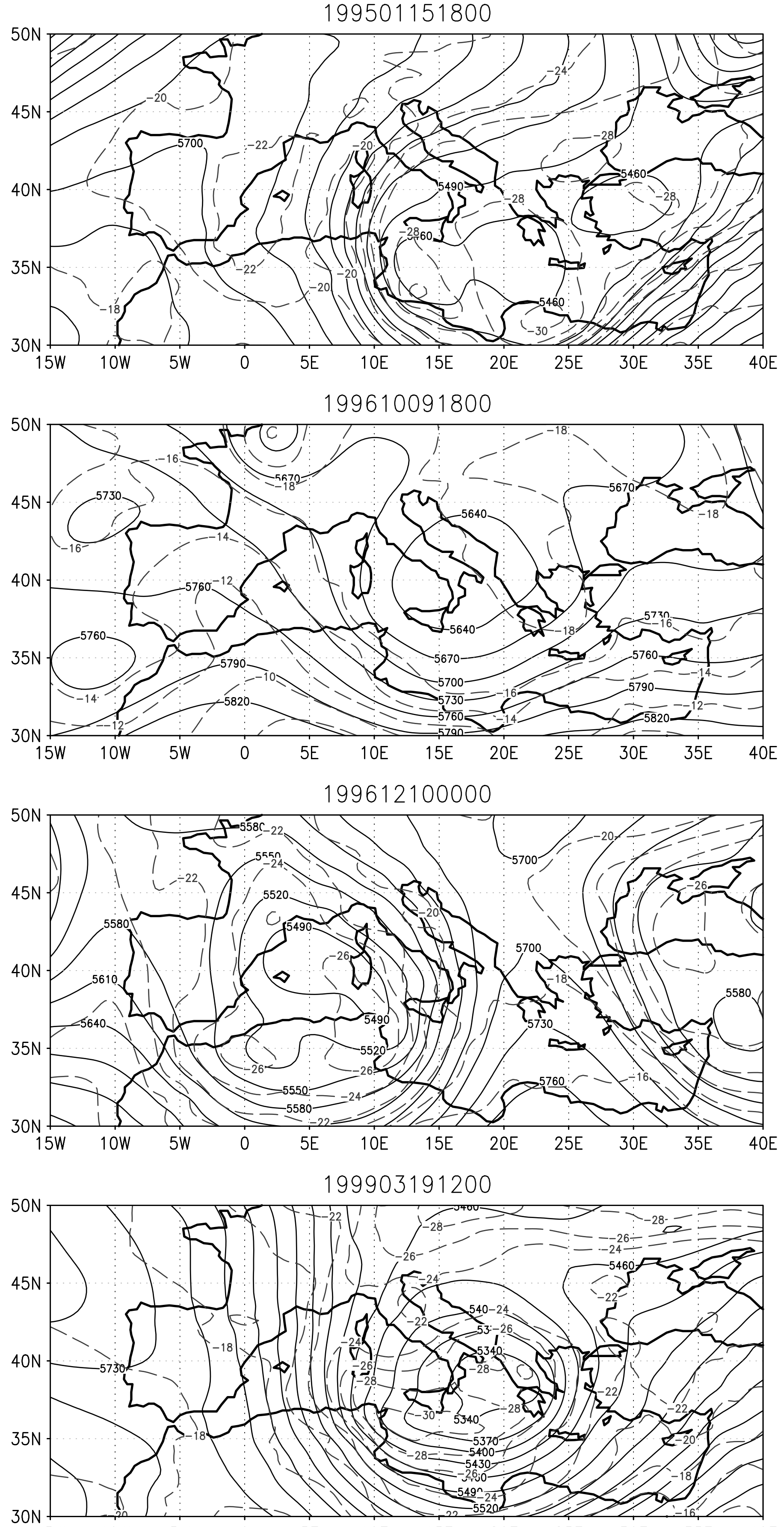


Figure 5. Geopotential height (gpm, continuous lines) and temperature (°C, dashed lines) at 500 hPa for some medicane events listed in Table I (also shown in Figure 1).

Table III. Summary of compared meteorological parameters (according to units described in Table II) between three lists of events: intense cyclones of MEDEX database, MED220 cases and medicane list. MEDEX and MED220 described through 5 and 95 percentile values, and MEDICANES through minimum and maximum values among the 11 cases.

	MEDEX		MED220		Medicanes	
	5%	95%	5%	95%	Minimum	Maximum
AVOR850	10.2	18.8	9.5	16.8	9.6	17.7
DIAB1000	−5.9	6.4	−2.9	5.8	0.2	7.7
RH600	30.8	89.9	44.8	80.9	49.2	80.9
SST	7.9	19.0	13.1	24.0	15.0	23.2
VSHEAR8525	7.3	42.3	6.2	24.1	4.7	29.0
MAXWS	0.3	49.1	13.3	55.2	31.6	49.5
GENPDF	0.0	16.8	0.2	32.7	0.9	36.6
GENPDFmax	0.0	61.5	0.7	120.9	3.8	329.5

tropical cyclogenesis. Finally, the vertical wind shear under this synoptic scenario is not large. Note that all these ingredients favour high values of GENPDF according to Equation (2). Numerical experiments performed by Emanuel, 2005a, using an axisymmetric, cloud-resolving non-hydrostatic model, show that deep cut-off cold lows (Figure 5) are indeed ideal incubators for surface flux-driven, small-scale, warm-core cyclones.

However, the occurrence of cold upper lows over the Mediterranean is not uncommon, whereas medicanes are rare phenomena, suggesting that very special meteorological conditions are necessary for medicanes to occur. The use of the kind of dynamically oriented climatologies (The framework of the MEDEX project developed a very complete climatology of Mediterranean cyclones, which also involves the three-dimensional characterization of the disturbances in terms of dynamical, thermal and humidity environmental variables: vertical depth, vorticity, circulation, steering wind speed, temperature laplacian, temperature gradient, equivalent temperature gradient and relative humidity (Campins *et al*., 2006).) designed in MEDEX has been applied to attempt a statistical discrimination between precursor and non-precursor cyclonic environments. The large-scale nature of the precursor cyclones (Figure 5) allows for identifying and three-dimensionally characterizing, in currently available analyses, the environments in which medicanes develop. We hypothesize that a comparison of these medicane environments against the generality of intense cyclonic situations should reveal useful discrimination variables among the set of thermodynamical descriptors listed in Table II. A summary of the results is contained in Table III.

DIAB1000 ingredient is linked to sea–atmosphere sensible and latent heat fluxes, and positive values would indicate a flux of enthalpy directed from the sea to the atmosphere. Typical Mediterranean cyclones (including intense cyclones of MEDEX project) do not reach high values of this flux or a preferential direction, so its distribution is basically symmetrical and concentrated at low values. MED220 events show a tendency for positive values of the parameter. For medicane cases, none of the 11 events presents negative DIAB1000 and in some cases values are very high, evidencing the important role of the sea–atmosphere enthalpy flux on medicane development (Figure 6(a)).

Warm SSTs, especially if there is cold air at upper levels, promote high thermodynamic contrasts with height and convective or latent instabilities in the troposphere. While most intense cyclones have a SST around 15 °C, this temperature seems to be a lower bound for the medicane events, because the SST in these cases was never colder than that value (Figure 6(b)). However, SST values from Mediterranean cyclones and medicanes show a significant difference with the results of tropical cyclone studies. It is well known that the minimum SST to produce a hurricane is 26 °C (Trenberth, 2005). This value is never attained for Mediterranean cyclones, since an SST exceeding 26 °C is only reached in the southernmost sectors of the Mediterranean Sea, during the summer months. Clearly, the sea–atmosphere thermodynamical disequilibrium driving this kind of storms can operate at the much lower sea temperatures of the Mediterranean thanks to the prominent cold air intrusions that affect its latitude, while in the warmer tropics, free of the baroclinic influences, elevated SSTs become necessary.

Finally, the empirical index GENPDF exhibits a high spread of values in medicane events, ranging from 0.9 to 36.6, whereas most intense MEDEX cyclones have very low values of this index (Table III and Figure 6(c)). This difference is even more evident when calculating GENPDFmax (Figure 6(d)). In this case, values are around 50, some of them are greater than 100, even surpassing 300 (out of the figure) in the case of September 1996.

As expected, the highly symmetrical MED220 cyclones tend to occur in environments with intermediate values of GENPDF and GENPDFmax. An improved description of medicane environments is possible if, instead of analysing a single moment, the entire lifetime of the medicane is considered (Figure 7). This figure synthesizes the evolution of GENPDFmax parameter for our medicanes, following the satellite-inferred cyclone centre since its inception, through its mature phase until its complete dissipation. Typically, the medicane environments present an increase of GENPDFmax during the incipient phase of the system, attaining the maximum values

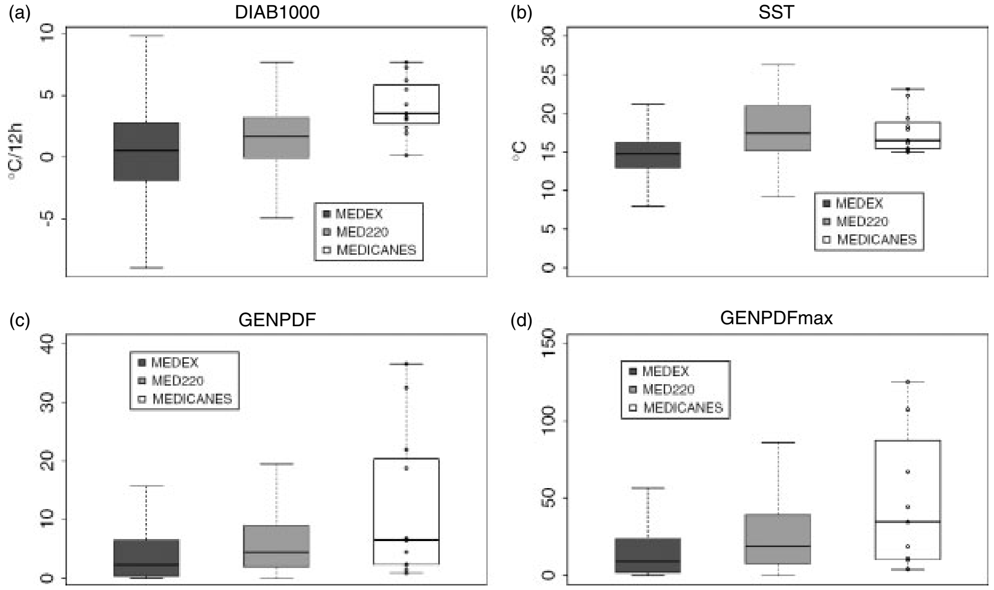


Figure 6. Boxplot diagrams of the indices (a) DIAB1000, (b) SST, (c) GENPDF and (d) GENPDFmax for intense cyclones of MEDEX database (dark grey), MED220 cases (light grey) and medicane events (white).

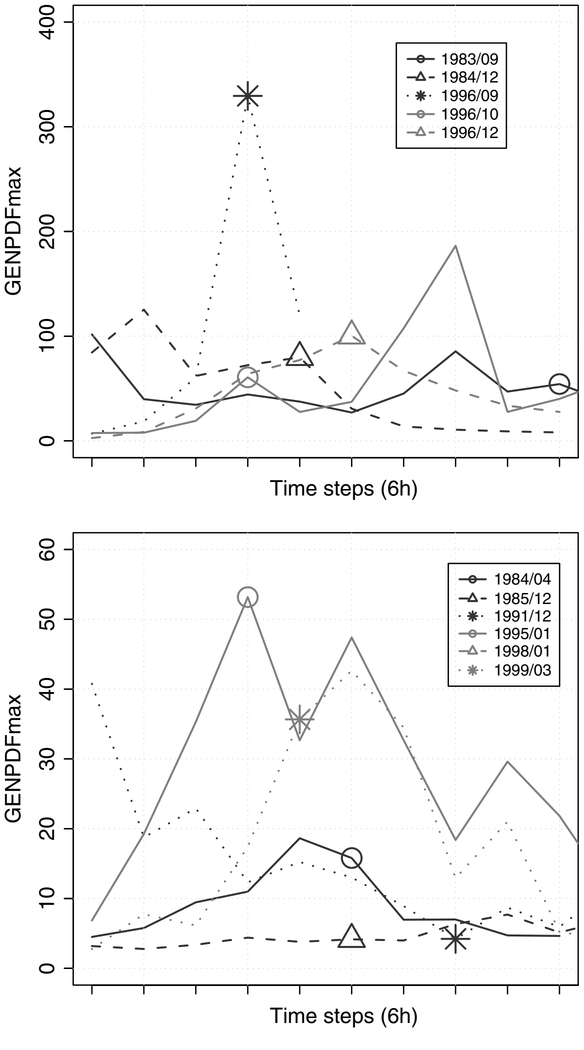


Figure 7. Evolution of GENPDFmax parameter during the lifetime of each medicane (lines), with the symbol indicating the cyclone maturity time. Two figures with different vertical scale to improve clarity.

close to the mature phase. This temporal pattern could be useful for the identification of potential medicane situations, although it is clear that the discrimination power of GENPDF index is only relative. First, there is a significant fraction of cyclonic environments showing high and sustained values of the index but not producing distinguishable medicanes, presumably as consequence of the relatively small size of the Mediterranean Sea and the ubiquitous baroclinic and orographic effects that disrupt the proto-cyclone. Second, high values of the index should be considered, at most, a necessary but not sufficient ingredient for medicane development, very much the same role that high amounts of convective available potential energy (CAPE) in a certain environment would play in severe convection development.

4. Climatologies

According to Equation (1), global warming can theoretically influence the maximum potential intensity of tropical cyclones through alterations on the surface energy flux and/or the upper-level cold exhaust (Emanuel, 1987; Lighthill *et al*., 1994; Henderson-Sellers *et al*., 1998). Observations of tropical and subtropical SST have shown an overall increase of about 0.2 °C over the past 50 years. Emanuel (2005b) reports a very substantial upward trend in potential destructiveness or total power dissipation (i.e. the sum over the lifetime of the storm of the maximum wind speed cubed) in the well-sampled North Atlantic and Western North Pacific, with a near doubling over that period (Webster *et al*., 2005). The further increase of potential intensity associated with global warming as predicted by GCMs (Emanuel, 1987) is consistent with the increase in modelled storm intensities in a warmer climate (Knutson and Toleya, 2004). In the Mediterranean, SST has increased around 0.6 °C in the western and 1 °C in the eastern basins in the last 20 years (Nykjaer, 2009). GCMs used in climate change research do not have yet sufficient spatial resolution to allow resolve explicitly depressions with the size of medicanes, but their outputs can be useful in monitoring expected changes of the large-scale environments. Here we provide a first climatology of the GENPDF parameter.

Among the available GCM runs from the last IPCC report (IPCC 2007), the resolution of the model was especially taken into account. For this reason, CSIRO-MK3.0 (Gordon *et al.*, 2002); with an atmospheric resolution of 1.8° lat–lon), ECHAM5/MPI-OM (Roeckner *et al.*, 2003); 1.8° lat–lon) and GFDL-CM2.1 (Delworth *et al.*, 2006); 2° lat, 2.5 lon) are the selected models for this study. We analyse the outputs obtained for 1981–2000 and 2081–2100 as representative of the current and future climates (hereafter referred to as 20C and 21C, respectively) under the 'high' special report on emissions scenarios (SRES) A2 scenario (Nakicenovic, 2000). The calculated climatologies from 20C are first compared against the climatology of GENPDF derived from ERA-40 for the same period and then the changes across the century are analysed. As mentioned previously, high values of this index would represent higher probability of having environmental conditions favourable for medicane development. For this reason, the next analyses are focused on the exceedance of an extreme value of the index, in this case the 95 percentile as calculated for the whole Mediterranean and the whole 20C period from ERA-40 database (q95ERA40 = 3.6). In addition, the Mediterranean has been divided into three sectors: the Western, Central and Eastern regions, for a better summary of the results. These regions extend from Gibraltar Strait to Sicily, from this island to Greece, and east of Greece, respectively.

Figure 8 compares the four climatologies for the current climate. All models show that high values of GENPDF are more frequent in autumn and winter than in spring and summer. The GCM models reproduce reasonably well the 'observed' annual cycle of GENPDF in the three Mediterranean regions. Taking into account the high nonlinearity of its formulation (Equation (2)) the above result implies that the combination of the AVOR850, RH600, VSHEAR8525 and MAXWS ingredients is also well represented. ECHAM5 and GFDL are more similar to ERA-40 than CSIRO, which tends to underestimate the extreme values of this parameter. The lower exceedance of extreme values in Eastern Mediterranean appears to be consistent with the observed fact that medicanes tend to occur in the Western and Central regions.

Figure 9 represents the change in the frequency of extreme values of GENPDF (higher than q95ERA40) between the 20C and 21C periods for each model, in principle with greater confidence in ECHAM5 and GFDL according to the previous results. Thus, ECHAM5 reveals that the frequency of extremes values of GENPDF tends to be lower in future than in present climate. In warm seasons, this change is not appreciable because the already low exceedance values remain low, but in cold seasons, when medicanes are most frequent, the monthly frequency decays up to 5%. The GFDL model, which tends to be similar to ERA-40 in the Central and Eastern regions, shows a slight frequency increase in September in Central region and a decrease in winter in both regions. In the Western part, there is a high increase in late summer and early autumn and an equally important decrease in winter. However, it is important to remember that in this region, the 20C analysis (Figure 8) showed a frequency about 5% lower than ERA-40 results. Finally, CSIRO model showed too low frequency values in 20C, and in future projection these values do not change significantly.

December was chosen for the spatial distributions (Additional statistical products and all the monthly maps can be found in http://medicanes.uib.es.) illustrated in Figure 10 because it is the month with greatest number of medicanes (Figure 4). A first comparison between the 20C and 21C climatologies using ECHAM5 reveals that GENPDF monthly means (as the frequency of extreme values) decrease in winter. This is in spite of the SST increases as high as 3 °C in the ECHAM5 simulations, that might suggest an increase in GENPDF according to Equation 1 and 2. But the complexity of the GENPDF formulation makes it evolve in the opposite way and the result is a general decrease in the probability of cold season medicane genesis. Similar deductions can be made using CSIRO and GFDL models (not shown). These results are in agreement with projected scenarios by the IPCC and other regional studies that show a lower frequency of cold low intrusions from high latitudes to the Mediterranean area (Sumner *et al.*, 2003) and, consequently, lower frequency of favourable meteorological conditions for medicanes development.

5. Conclusions and further work

The lack of meteorological observations over the Mediterranean Sea has motivated the need to build a database of medicane events from alternative methods. The list of medicanes presented in this paper, derived basically using satellite images and restricted criteria, provides a necessary base to grow learning about these rare but violent windstorms. In this way, 12 events have been subjectively detected during the period from 1982 to 2003, with all of them centred in the Central and Western Mediterranean regions and being more frequent in winter and autumn.

Reported similarities between tropical cyclones and medicanes suggest an analysis for the Mediterranean of the large-scale meteorological ingredients that are known to be associated with tropical cyclones. To better identify the very special conditions that medicanes require for their development, these large-scale meteorological parameters in medicane events have been compared against the bulk of intense Mediterranean cyclones, typically baroclinic storms: the diabatic contribution to surface level equivalent potential temperature, the SST and an empirical index of genesis of tropical cyclones have shown a modest performance. High positive values of this diabatic contribution and a SST greater than

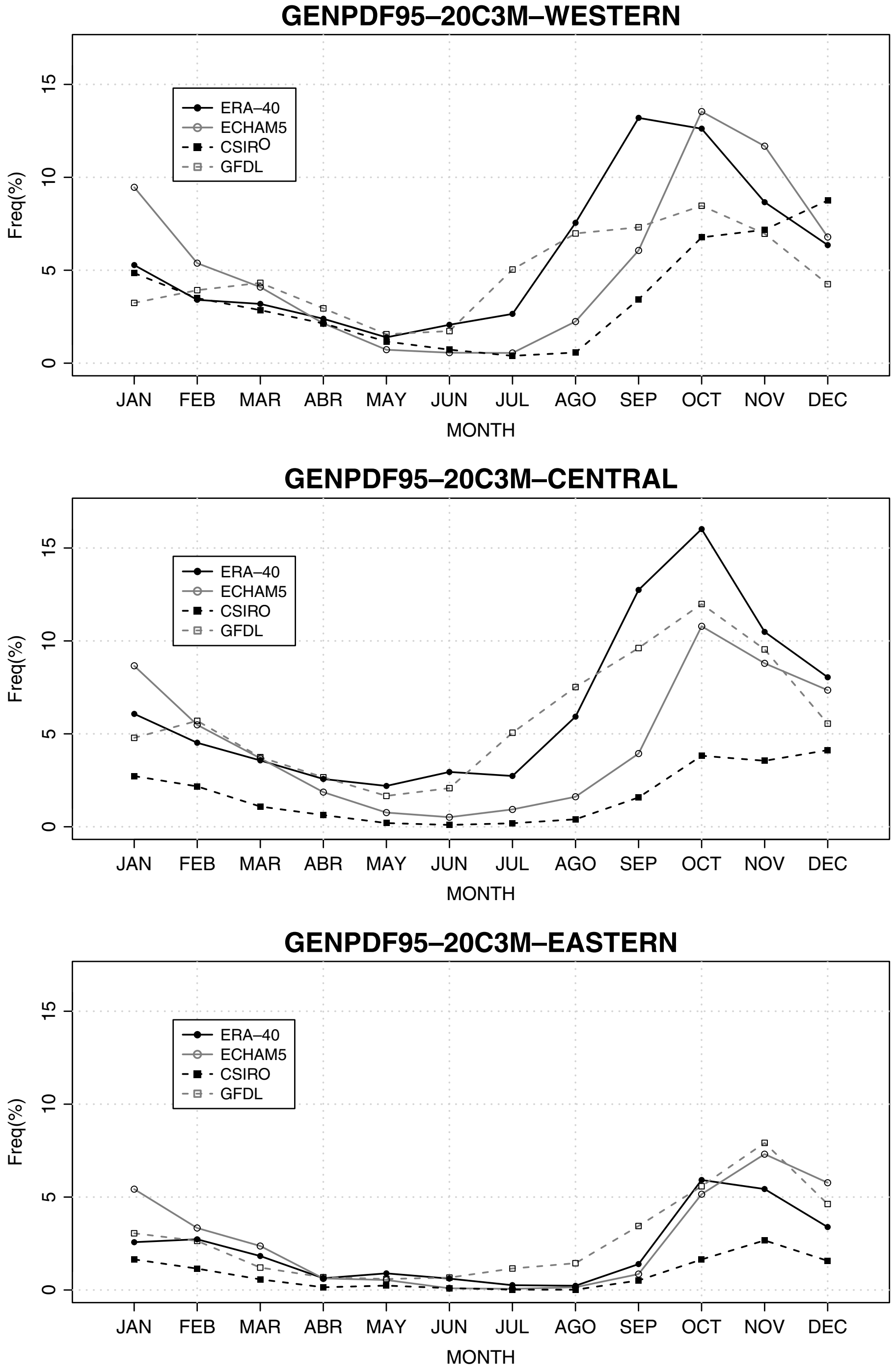


Figure 8. Monthly mean frequency of days where GENPDF is higher than q95ERA40 in 20C period according to ERA-40 (solid black line), ECHAM5 (solid grey line), CSIRO (dotted black line) and GFDL (dotted grey line), in Western (top), Central (middle) and Eastern (bottom) regions.

15 °C seem to be necessary for medicane development. Although it was not possible to establish a lower bound for the empirical index and it cannot be used with the same interpretation than for tropical cyclones, the occurrence of medicane storms is related with high values of the index. This index is going to be useful to discriminate genesis-prone environments of medicanes in future climate conditions.

A first look at the late 21st century climate conditions, using the SRES A2 scenario, has been also taken here. Spatial maps of the empirical index monthly average and extremes exceedance show a general decrease in medicane risk during winter according to the most reliable GCM models, but one of the models indicates a significant increase in autumn. The issue of global warming and its connection to medicane phenomena clearly needs further investigation and a careful analysis of the different sources of uncertainty.

Numerical simulations of the detected medicanes and analogue synoptic scenarios have been planned during a

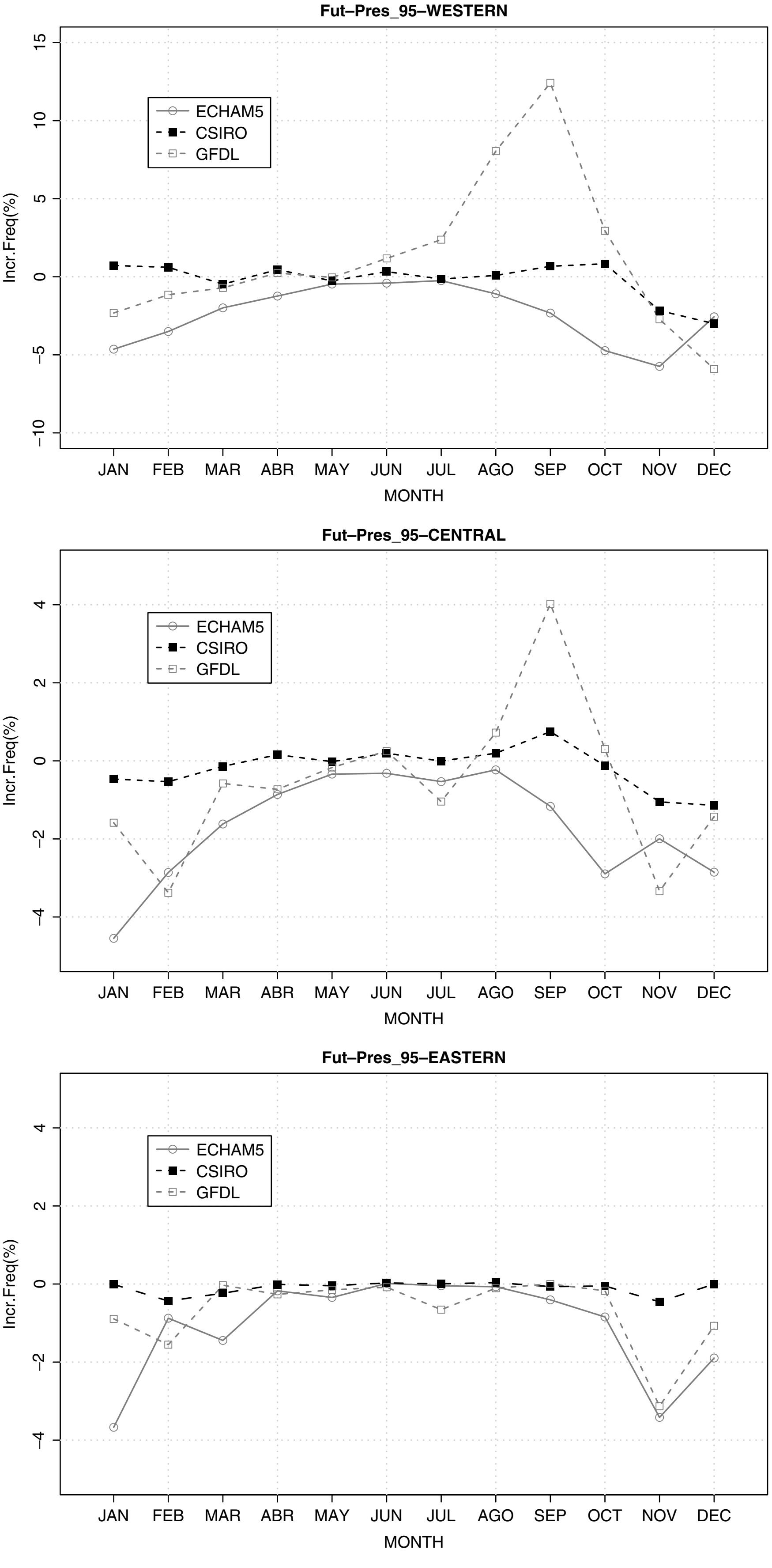


Figure 9. Change in the monthly mean frequency of days where GENPDF is higher than q95ERA40 between the 20C and 21C periods according to ECHAM5 (solid grey line), CSIRO (dotted black line) and GFDL (dotted grey line), in Western (top), Central (middle) and Eastern (bottom) regions. Figures with different vertical scale to improve clarity.

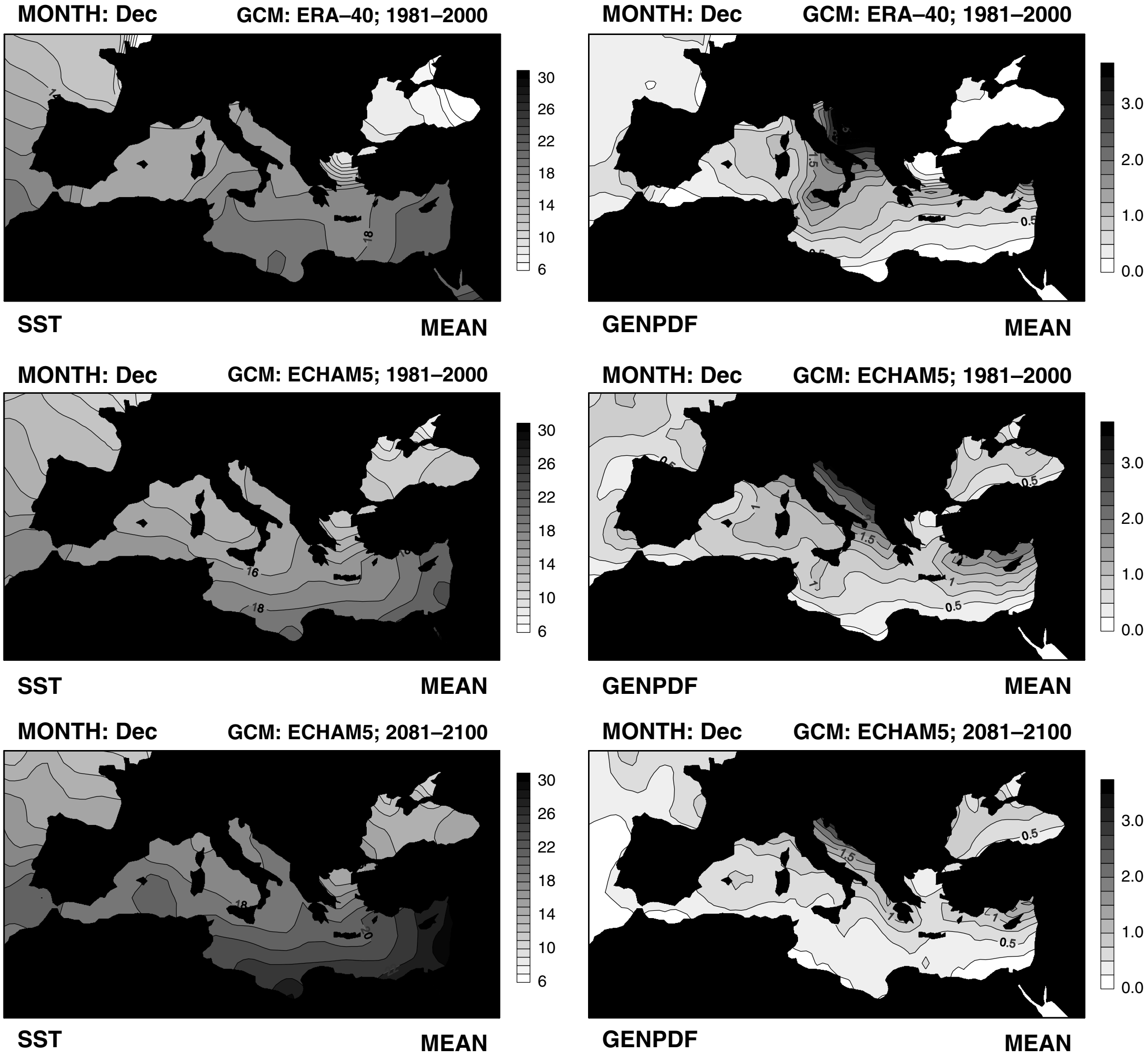


Figure 10. Spatial distribution of mean value of SST (left) and GENPDF (right) for December in the 20C using ERA-40 (top), 20C using ECHAM-5 (middle) and 21C using ECHAM-5 (bottom).

second step of the study. Since the spatial resolution of climate models is not enough to explicitly resolve medicanes, it will be necessary to test and adapt a mesoscale model (MM5) for this purpose. Ensemble simulations will be judged against the 'observed' climatology, helping to evaluate the expected false alarm rate and probability of detection of our strategy. This tool is expected to help us to assess the numerical range of dynamical and thermodynamical parameters that are really associated with medicane development at the mesoscale. This task will also produce probabilistic risk maps for the present climate of diverse medicane attributes (genesis, trajectories, strike probability for land areas, wind and precipitation maxima, etc.). Finally, medicane-favourable days extracted from GCM-scenarios will be simulated and similar probabilistic risk maps for the future climate will be produced as function of the emission scenario and time slice into the future. These maps will be statistically compared against the 'present' climatologies in order to project expected changes in medicane risk imposed by global warming.

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