Climate change projections of medicanes with a large multi-model ensemble of regional climate models

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Abstract

Cyclones with tropical characteristics, usually called medicanes, occasionally develop over the Mediterranean Sea. Possible future changes of medicanes are a matter of concern due to their large damage potential. Here we analyse a large set of climate change projections with regional climate models (RCMs) from ENSEMBLES project. The aim is to increase our knowledge about the future evolution of medicanes, advancing previous studies along several important lines: use of a large ensemble of RCMs, nested in many different GCMs, and covering a long continuous time period (up to 150 years). The main overall results are a future reduction in the number of medicanes and an increase in the intensity of the strongest medicanes, in agreement with other studies. But the large size of the ensemble reveals some important model-related uncertainties. The frequency decrease is not statistically significant in many of the simulations extending to 2100, with two simulations even showing no frequency decrease at all. Large decadal changes affect the medicane frequency, emphasizing the need for long period simulations. The increase in extreme intensity shows a clear dependence on the GCM driving the simulations. In contrast to the overall results, a few simulations also show changes in the monthly distribution of medicanes, with less winter cases and more autumn and late summer cases. Some environmental variables have been explored in an attempt to offer physical explanations for these results. A plausible reason for the overall decrease of medicane frequency is the projected increase in vertical static stability of the atmosphere. A relevant result is that the general and clear increase in average static stability is unable to avoid that several simulations project higher maximum winds in the future. This could indicate that the increased SST and latent heat fluxes may overcome the limitation of a higher overall static stability, if favourable conditions for medicane genesis indeed occur. This is a worrying possibility, as the strongest damages are associated to the most intense cyclones.

Keywords: Medicanes, Climate Change, Mediterranean cyclones, Regional Climate Models

1.1 Introduction

The Mediterranean Sea is a region with a high density of cyclones (more than 1500 cyclones/year according to Campins et al., 2011), which are responsible for heavy precipitation and strong wind events (Jansá et al., 2001; Bocheva et al., 2007; Trigo et al., 2000; Nissen et al., 2010). Mediterranean cyclones are often responsible for considerable damages mainly in the Mediterranean islands and coastal zones, due to their greater exposure to strong winds and floods. A better understanding and description of these extreme meteorological phenomena in the present climate can be crucial to understand and predict the response of the Mediterranean climate to global climate change during the current XXIst century.

Not all the Mediterranean cyclones have the same characteristics: some recent studies have focused on cyclones with tropical characteristics (axial thermal symmetry and warm core) over the Mediterranean Sea, the so called medicanes (acronym for Mediterranean Hurricanes). The singular situation of the Mediterranean Sea favours the development of such tropical-like cyclones. Gibraltar Strait is the only communication with the Atlantic Ocean so the water exchange is very limited and the Mediterranean water temperature may reach very high values in September. Another special feature of the Mediterranean Sea is the surrounding orography: high mountains like the Alps surround the basin and modify the circulation, favouring the generation of baroclinic cyclones, which later may develop into medicanes.

Different studies have shown that medicanes do not happen in all locations of the Mediterranean Sea with the same probability. In the climatological studies by Tous and Romero (2013) and Cavicchia et al. (2014a), the same two preferred regions of occurrence came out (Ionian Sea and Balearic Islands), although the methodology they used was based in the former case on satellite images and in the latter on numerical simulations. The combined satellite and numerical approach uses in Miglietta et al. (2013) identified fourteen medicanes among the cases described in the literature and in the websites from 1999 to 2012, reproducing a similar geographic distribution.

From a modelling perspective, the use of General Circulation Models (GCMs) to analyse medicanes is not possible due to the typical size of the medicanes and the low resolution of GCMs, as medicanes have typically a diameter of less than 300 km (Walsh et al., 2014). Therefore, the use of higher resolution models, such as Regional Climate Models (RCMs), is necessary. Chapter 14 of the last IPCC report (Christensen et al., 2013) pointed out the important spread among the cyclones detected by different RCMs, which is similar to the changes expected in the future scenarios or to the natural interannual variability. The use of a model ensemble allows to take into account the large spread among different climate models, which represents an added value in comparison with studies using only one RCM (e.g. Walsh et al., 2014; Cavicchia et al., 2014b).

Gaertner et al. (2007) used an ensemble of RCMs from PRUDENCE European project (Christensen and Christensen, 2007), with a grid spacing of 50 km, to analyse projections of future intense cyclones over the Mediterranean Sea. That study detected for the first time a future risk of tropical cyclone development over the Mediterranean Sea, and stressed the need for higher resolution and a more complete ensemble of RCMs (higher number of RCMs, use of different GCMs or different emission scenarios). It is expected that the number of detected cyclones may increase using higher resolution models, as smaller cyclones could be missed if the resolution used is too coarse (Pinto et al., 2005). ENSEMBLES project (Van der Linden and Mitchell, 2009) extended the analysis from PRUDENCE increasing the number of RCMs, the number of GCMs, and reducing the horizontal grid spacing (25 km). The simulated period was also much larger than in PRUDENCE.

The present study aims to analyse climate change projections of medicanes, advancing previous studies along several important lines: use of a large ensemble of RCMs, nested in several different GCMs, and covering a long time period (up to 150 years). These are advantages of ENSEMBLES project compared to PRUDENCE. First, the ERA40 forced simulations for 1961-2000 period are evaluated against the available observational information about medicanes to determine the capability of these RCMs to describe the observed characteristics. Then, both present (1951-2000) and future climate periods (reaching 2050 for all the simulations and 2100 for many of them) are analysed. Several characteristics of the simulated medicanes are studied: frequency, intensity, regional and monthly distribution, as well as their changes under future climate change conditions from a multi-model RCM perspective. Some environmental variables affecting medicanes are analysed, trying to provide physical reasons for the future evolution of medicanes and the spread among different simulations.

1.2 Methodology

Ten RCMs from ENSEMBLES European Project (see Table 1), with a horizontal grid spacing of 25 km, nested in ERA40 (evaluation period) and in six different GCMs (scenarios) have been used. ERA40 driven simulations (1961-2000) are compared with a database of observed medicanes (Miglietta et al., 2013). The GCM driven simulations cover both a present climate period (control run) from 1951 to 2000 and a future climate period (scenario run) from 2001 to 2050 (four simulations) and from 2001 to 2100 (nine simulations). Some RCMs have been nested in more than one GCM (Table 1 shows the different RCM/GCM combinations).

The months selected for the study are from August to January, as most of the medicanes occur during late summer, autumn and early winter (Cavicchia and von Storch, 2012; Miglietta et al., 2013).

		RCM (Institution)									
		RCA3 (C4I)	**ALADIN (CNRM)**	**CLM (ETHZ)**	**HadRM3Q16 (HC)**	**HadRM3Q3 (HC)**	**RACMO (KNMI)**	**HIRHAM (METNO)**	**REMO (MPI)**	**RCA (SMHI)**	**PROMES (UCLM)**
	ERA40	1961-2000	1958-2000	1961-2000	1959-2000	1959-2000	1958-2000	1961-2000	1961-2000	1961-2000	1961-2000
GCM	**ECHAM**	A2 1951-2050					A1B 1950-2100		A1B 1961-2100	A1B 1951-2100	
	ARPEGE		A1B 1951-2100								

	RCM (Institution)									
	RCA3 (C4I)	**ALADIN (CNRM)**	**CLM (ETHZ)**	**HadRM3Q16 (HC)**	**HadRM3Q3 (HC)**	**RACMO (KNMI)**	**HIRHAM (METNO)**	**REMO (MPI)**	**RCA (SMHI)**	**PROMES (UCLM)**
BCM							A1B 1951-2050		A1B 1961-2100	
HCQ0			A1B 1951-2099				A1B 1951-2050			A1B 1951-2050
HCQ16				A1B 1951-2099						
HCQ3					A1B 1951-2099				A1B 1951-2100	

Table 1: Summary of models, institutions, periods and scenarios used in the present study.

The Mediterranean Sea has been divided in three zones (see Figure 1) in order to study the regional distribution of medicanes: Western (longitude less than 10ºE), Central (longitude greater than 10ºE and less than 24ºE) and Eastern (longitude greater than 24ºE). Those subregions are comparable to the ones described in Giorgi and Lionello (2008). Here, the cyclones are assigned to a subregion when they reach their maximum intensity as a medicane.

1.2.1 Cyclone Detection Method

The cyclone detection method described by Picornell et al. (2001) based on sea level pressure (SLP) has been used. August to January daily SLP averages are analysed to identify the pressure minima. A Cressman filter with a radius of 200 km is next used (Sinclair, 1997) to smooth out noisy features appearing in the SLP field. Weaker cyclones are filtered out through a SLP gradient threshold, and a radius of 400 km around every SLP minimum is used for determining the cyclone extension.

The cyclone tracks have been calculated using the horizontal wind at 700 hPa as an auxiliary variable indicating the likely direction of movement of the cyclones. A 10 m wind filter has been applied, dismissing all the cyclones whose daily maximum 10 m wind speed is less than 17.5 $m \cdot s^{-1}$ during their whole lifetime, as that value is the threshold to distinguish between a tropical depression and a tropical storm (or the threshold for gale force in the Beaufort Scale).

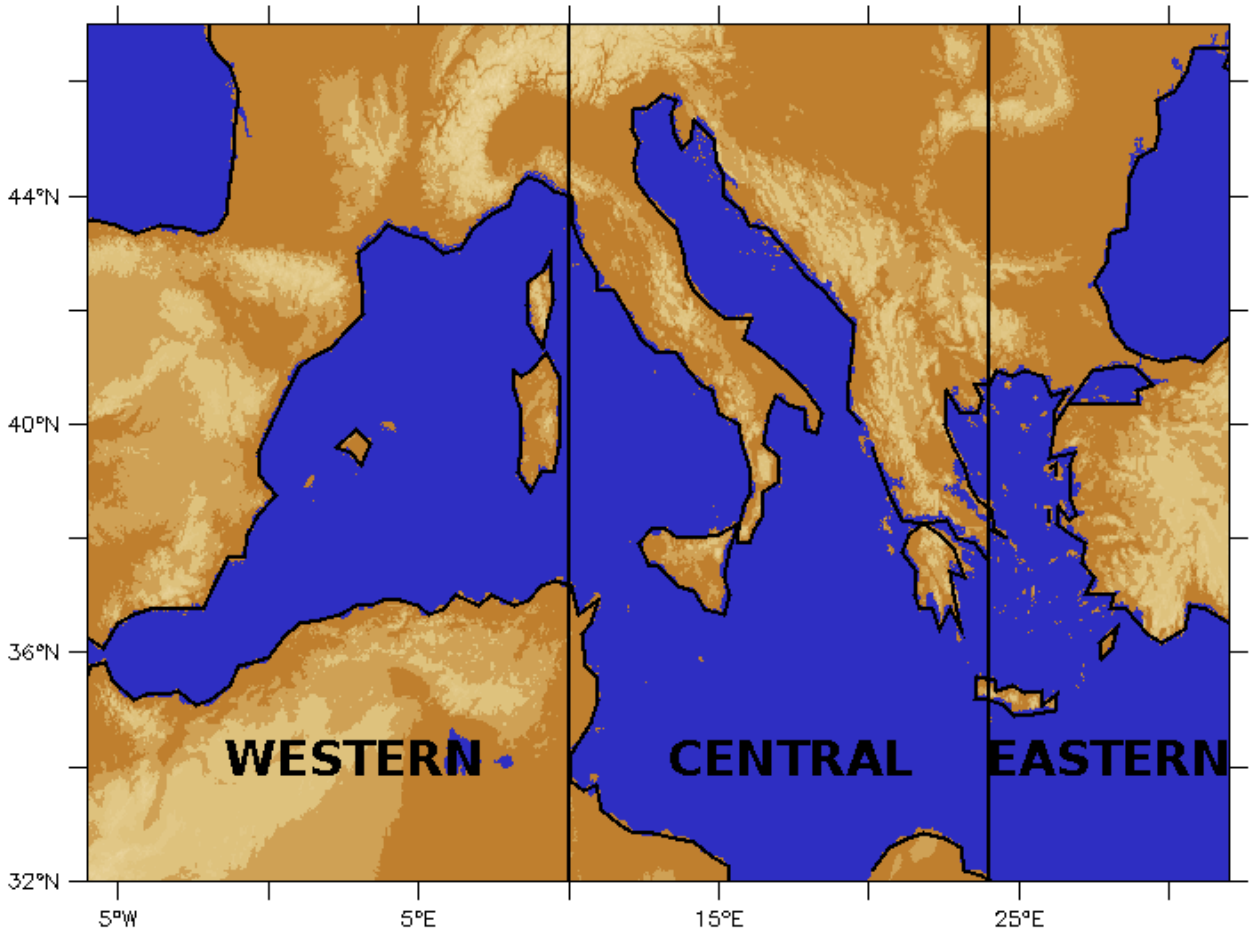

Figure 1: Topography of the studied domain and subregions chosen for the study.

1.2.2 Vertical Structure of the Cyclones (Medicanes classification)

The geopotential fields between 900 and 300 hPa have been used to apply the cyclone phase space method (Hart, 2003) in order to select the medicanes among all the detected cyclones. The Hart method is based on three parameters: B, $-V_T^U$ and $-V_T^L$. The B parameter is a measurement of the symmetry or asymmetry of the cyclone; a value of B near zero indicates that the cyclone is symmetric, with 10 m being a suitable threshold below which symmetric cyclones are identified (following Hart, 2003). $-V_T^L$ (lower troposphere thermal wind) and $-V_T^U$ (upper troposphere thermal wind) parameters determine the existence of a warm or cold core between 900 and 600 hPa ($-V_T^L$) and between 600 and 300 hPa ($-V_T^U$). Tropical cyclones show a full-troposphere warm core, and thus $-V_T^L$ and $-V_T^U$ must both be positive (Hart, 2003).

In this study all the cyclones with $-V_T^L$ above zero and $-V_T^U$ greater than -10 m are selected as medicanes. The latter threshold of -10 m has been chosen to include also some cyclones showing an upper tropospheric warm core during less than one day, as the data used here are daily average values. The parameters have been calculated using a radius of 150 km, chosen as representative of the typical dimension of medicanes. B parameter has been calculated when possible. However, it cannot be calculated with daily values for cyclones with 1 day lifetime, as the direction of movement of the cyclone is needed. Due to this, B has not been used in the selection of medicanes.

1.3 Results

1.3.1 RCM evaluation against available observations

From a purely observational point of view, it is difficult to detect medicanes from surface measurements, as many of them do not touch the coastline and ships try to avoid them. With the use of satellites it has been possible to create a list of observed events but this is limited to the recent past so it is impossible to know the frequency of medicanes further back in time. Some studies have estimated that the frequency of the medicanes is one or two events per year (Romero and Emanuel, 2013; Cavicchia et al., 2014a) or even less than one per year (Walsh et al., 2014; Tous and Romero, 2011).

In Miglietta et al. (2013), a combined satellite and modelling method has been used for obtaining a list of the medicanes observed in different zones of the Mediterranean sea between 1999 and 2012, and the difficulty of compiling a medicanes catalogue has been expressed. Note that the results in Miglietta et al. (2013) are based on the analysis of individual case studies and cannot be considered like a true climatological analysis. But the medicane detection method applied there is very similar to the method used here, which makes this list particularly suitable for the RCM evaluation. Table 2 shows the medicanes frequency registered in that study and for the RCMs. Frequency values are given for the whole Mediterranean Sea and for the three different subregions indicated above. In addition to the annual values, monthly frequency from August to January is also shown. The frequency of the medicanes studied by Miglietta et al. (2013) is 0.86 events/year for August-January, agreeing pretty well with the frequencies calculated in the other studies. According to Miglietta et al. (2013) the Central zone (between 10º and 24 º E of longitude) is the region of the Mediterranean Sea with the largest number of detected medicanes, since half of them have been registered there, while the Eastern zone has only 0.14 events/year. Walsh et al. (2014) also pointed out the central zone of the Mediterranean Sea as the zone with a major risk of medicanes development, but Cavicchia et al. (2014a) indicated the western zone of the Mediterranean Sea as the zone with the strongest medicanes activity. According to Miglietta et al. (2013), taking into account the whole year, 85.7 % of the medicanes occurred from September to December, and more than one half occurred during the months of September and October. Nevertheless, Tous and Romero (2011) pointed out a different monthly distribution with the greatest number of medicanes in December. The different periods and methodologies used in the two studies are responsible for such discrepancies.

	Frequency (n/year)	**Distribution by regions (%)**			**Distribution by months (%)**					
	Mediterranean	**West**	**Center**	**East**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**
Miglietta	0.86	33	50	17	0.0	33	33	17	17	0.0
RCA3	0.74	27.6	51.7	20.7	0.0	3.5	13.8	27.6	27.6	27.6
ALADIN	0.88	46	32.4	21.6	0.0	5.4	18.9	21.6	29.7	24.3
CLM	10.21	33.2	43.2	23.6	3.5	8.5	15.6	19.6	24.9	27.9
HadRM3Q16	2.02	19.3	54.2	26.5	2.4	3.6	12.1	26.5	27.7	27.7
HadRM3Q3	2.24	29.3	43.5	27.2	1.1	7.6	10.9	27.2	28.3	25
RACMO	2.48	27.9	51	21.1	3.9	6.7	11.5	26	26.9	25
HIRHAM	1.56	24.6	47.5	27.9	1.6	4.9	11.5	21.3	32.8	27.9

	Frequency (n/year)	Distribution by regions (%)			Distribution by months (%)					
	Mediterranean	**West**	**Center**	**East**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**
REMO	1.67	27.7	44.6	27.7	3.1	0.00	9.2	30.8	23.1	33.8
RCA	0.67	42.3	42.3	15.4	0.00	0.00	19.2	30.8	23.1	26.9
PROMES	2.41	29.8	47.9	22.3	2.1	7.5	16	22.3	27.7	24.5
RCM Mean	2.49	30.4	45.6	24	2.6	6.5	13.9	23.3	26.5	27.2

Table 2: Annual frequency of medicanes for Miglietta et al. (2013) data, every RCM and RCMs mean for ERA40 period (1961-2000): total frequency, regional relative frequency and monthly relative frequency. All data are calculated for August to January.

The period to evaluate the ensemble of the ten ERA40-forced RCMs is from 1961 to 2000. Here we compare the annual frequency from the ensemble with the results obtained in Miglietta et al. (2013). The annual medicane frequency for most of the regional models ranges between 0.67 and 2.41, in good agreement with previous studies (Romero and Emanuel, 2013; Cavicchia et al., 2014a; Walsh et al., 2014; Tous and Romero, 2011). Only CLM presents a clear overestimation, with more than 10 events per year. CLM is the model which simulates the largest number of cyclones in general, and more than 40 % of them are medicanes, which is clearly above the observed percentage. For the rest of the models, the percentage of medicanes is less than 16 % of the total number of cyclones. Regarding the distribution by regions, most of the models follow the observed distribution (with maximum values over the Central part of the Mediterranea Sea), with the exception of ALADIN, which simulates the western zone as the one with the largest number of medicanes, and RCA, with an identical number of events in the western and in the central zone. With respect to the time (monthly) distribution, most of the RCMs follows a similar behaviour, with the highest frequency in November, December and January, showing a distribution closer to Tous and Romero (2011) than to the results in Miglietta et al. (2013). Although the Tous and Romero (2013) and Miglietta et al.

(2013) databases show a decrease of medicanes activity during January, Cavicchia et al. (2014a) detects a peak activity in that month. On the other hand, all models clearly underestimate the relative frequency of medicanes in September. This may point to a common difficulty of the models in representing early autumn medicanes, when the environmental factors favour only marginally their formation.

As explained above (section 1.2.2), the axial symmetry (B parameter) of the cyclones has not been used to select the medicanes. But for the cases where B could be calculated, almost all of the selected medicanes satisfy the axial symmetry criterion: eight of the ten RCMs simulate more than 93% of the medicanes with axial symmetry. CLM is the model with the least percentage of symmetric medicanes (79,40%) followed by RCA3 (86,21%). The fact that the B parameter has not been considered may partially explain the overestimation in the number of medicanes simulated by CLM.

1.3.2 Climate Change Projections (up to 2050 or 2100)

In order to analyse the intensity extremes of the simulated medicanes, Figure 2 shows the 95th percentile (p95, represented by colour bars) and the maximum value (represented by squares) of the daily maximum wind speed near the centre of the medicanes for every RCM and every period (1951-2000, 2001-2050 and 2051-2100; the latter period is not available for all models). The figure shows a large variability among simulations, not only in the values of p95, but also in the tendency in the future climate. This variability makes it difficult to find patterns common to different simulations, but some interesting patterns can be identified. Looking at p95, six of the nine simulations reaching 2100 show an extreme intensity increase from present climate to the second half of XXIst century. This shows up clearly in the ensemble mean. Though the mean values represented Figure 2 include all the simulations (thirteen for the first two periods), a very similar increase is obtained including only the nine simulations covering also the third period, with p95 mean values of 26.06, 26.39 and 27.52 $m \cdot s^{-1}$ for the respective periods. Previous studies, using one only RCM, also concluded that the intensity extremes of the medicanes (Cavicchia et al., 2014a, 2014b) or of all Mediterranean cyclones (Lionello et al., 2002) will increase at the end of the century.

If we group the simulations by the driving GCM, some noteworthy results are obtained. Simulations nested in ECHAM (M1, M6, M9 and M11) show low to intermediate p95 values. These simulations show no clear tendency in intensity. In contrast to this, simulations nested in HCQ3 (M5, M12) show the clearest increasing tendency in intensity. Also two of the three simulations nested in HCQ0 present this upward tendency. The influence of the GCM can also be seen in the set of simulations with RCA, driven by different GCMs (M10-M12), with rather different p95 values and time dependence. Therefore, the GCM exerts a visible influence on the intensity values and tendency.

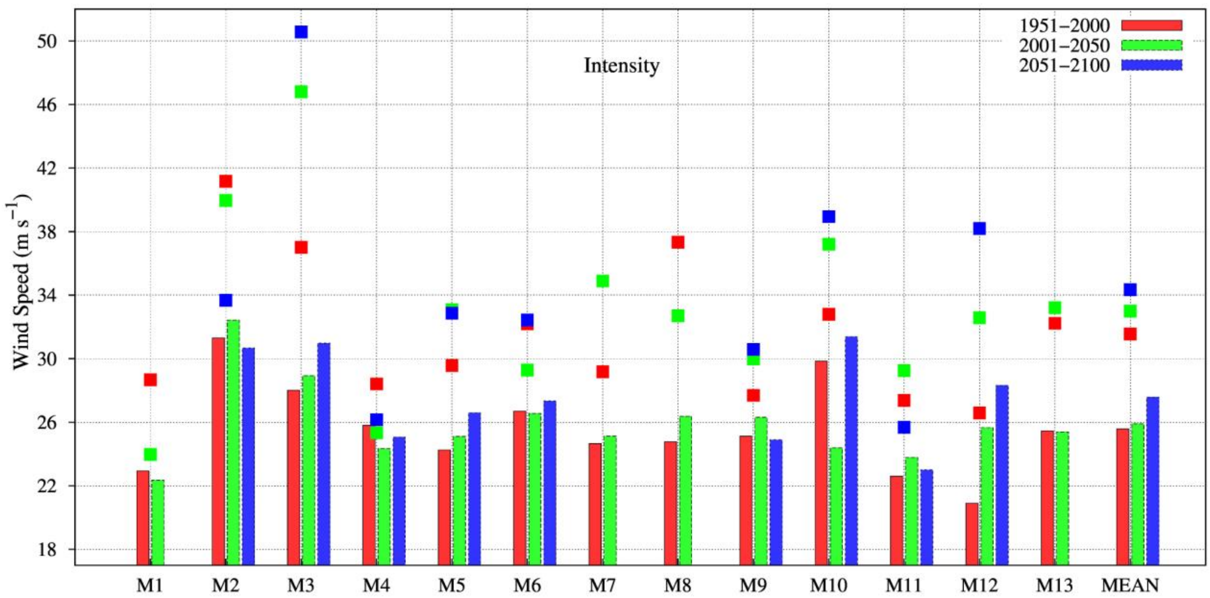

Figure 2: Wind Speed p95 ($m \cdot s^{-1}$) for all the RCMs and RCMs mean (MEAN) for the periods 1951-2000 (red bar), 2001-2050 (green bar) and 2051-2100 (blue bar). Squares represent maximum wind speed for each model and period. Note that some RCMs simulations are available until 2050 so there is no blue bar neither blue square. In the figure M1=RCA3-ECHAM, M2=ALADIN-ARPEGE, M3=CLM-HCQ0, M4=HadRM3Q16-HCQ16, M5=HadRM3Q3-HCQ3, M6=RACMO-ECHAM, M7=HIRHAM-BCM, M8=HIRHAM-HCQ0, M9=REMO-ECHAM, M10=RCA-BCM, M11=RCA-ECHAM, M12=RCA-HCQ3 and M13=PROMES-HCQ0.

Maximum wind speed has also been depicted in Figure 2 (represented by colour squares) for each simulation and period. Again, simulations nested in ECHAM (M1, M6, M9 and M11) give smaller maximum wind values than the most of the other models. On the other hand, CLM-HCQ0 (M3) stands out with the greatest maximum wind speed. The maximum wind speed shows a wider range of values than p95. An increase in medicane intensity in future climate can also be drawn from this variable, as summarised in the corresponding ensemble mean.

The increase in the medicane intensity extremes could be related to the projected increase in sea surface temperature (SST). Once a medicane is formed, its intensity will depend on the available energy which it can extract from the ocean through the Wind-Induced Surface Heat Exchange (WISHE) mechanism (Rotunno and Emanuel, 1987), which strongly depends on enthalpy fluxes, i.e. sensible and latent heat fluxes, and therefore on sea surface temperatures. Tous et al. (2013) showed that air-sea interaction plays an important role for medicane development since cyclone pressure minima and central pressure gradients were found to be undoubtedly influenced by surface heat fluxes. Figure 3 shows how SST tends to rise in all simulations (note that for 3 simulations there this variable was not available). Linked to this SST increase, the total surface heat flux (not shown) also experiments an increase in ten of the thirteen models, driven by the increase in latent heat flux. This should provide more available energy for the medicane intensification than in present times.

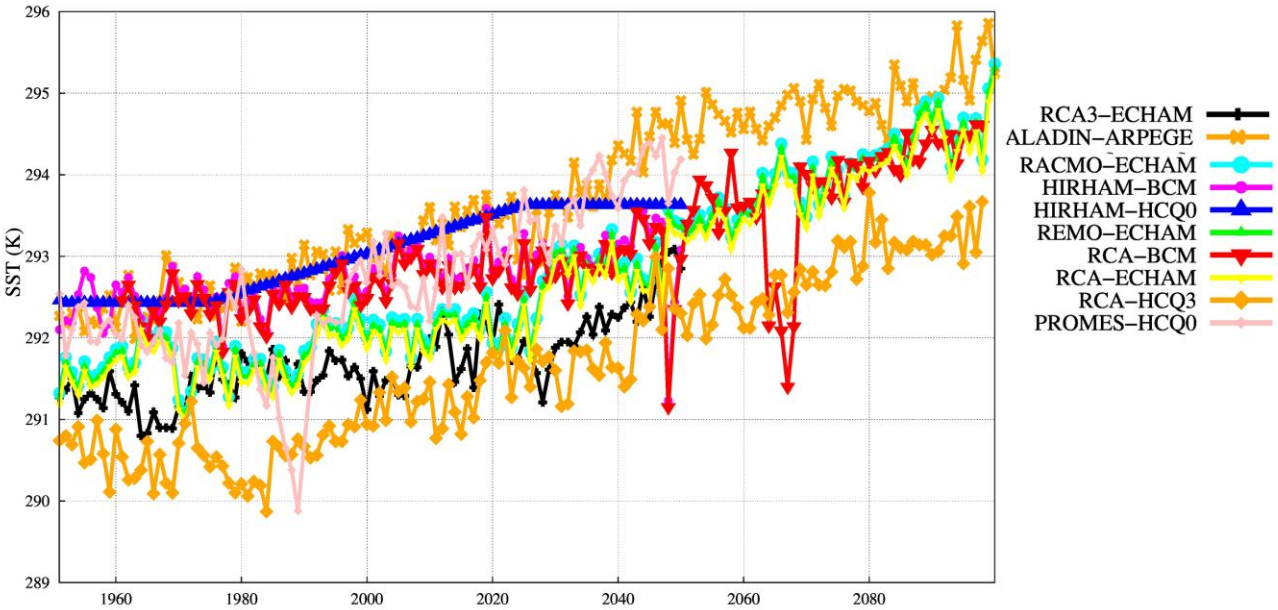

Figure 3: Evolution of sea surface temperature (SST) for each of the simulations where it is available. As indicated before, some simulations end in 2050.

With respect to the projected changes in frequency, Figure 4 (top-left panel) shows the annual frequency of the medicanes from 1951 to 2100 for every simulation, averaged over each decade. Although the figure reflects an important decadal variability in the changes in the number of medicanes with time, there is an overall tendency to a decrease in the number of such events during the XXIst century. Eleven of the thirteen simulations have a negative slope, which is statistically significant for eight simulations at 95% confidence level, using a linear regression. Nevertheless, the result is less clear if we look only at the runs reaching 2100: less than half (four out of nine) show a statistically significant decrease. All three simulations with RCA regional model show no statistically significant change, with one of them showing no change and another one even an increase in medicane frequency. On the contrary, three of the four ECHAM-driven simulations show a statistically significant decrease. This points to a clear model dependency of the frequency decrease, and reinforces the need of considering simulation ensembles when these processes are studied.

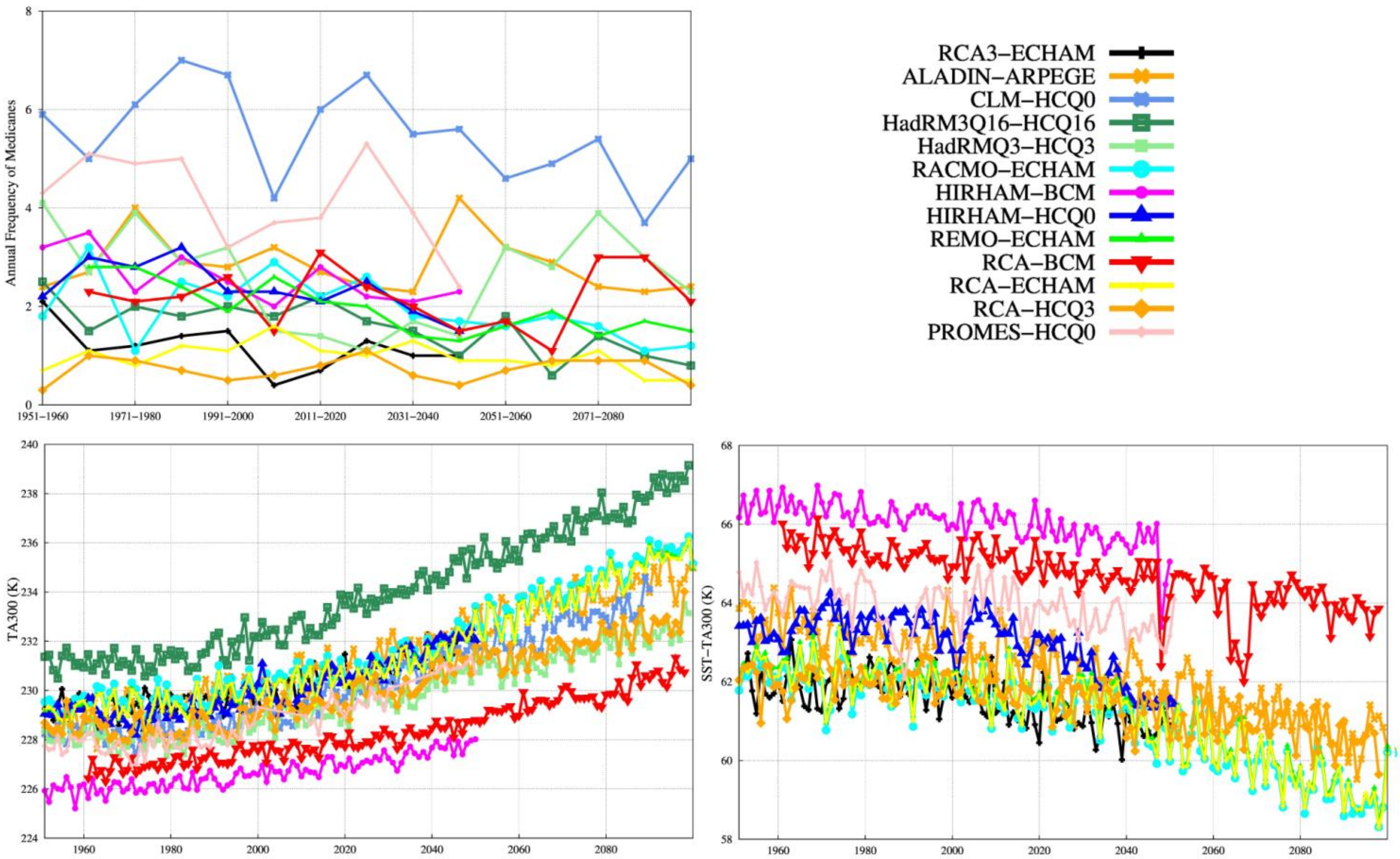

Figure 4: Evolution of medicanes decadal frequency (top-left), 300 hPa temperature (TA300) (bottom-left) and the difference between sea surface temperature (SST) and TA300 (bottom-right) for each model for the whole simulated period (1951-2100). Note that for some models simulations end in 2050.

The overall frequency decrease of medicanes and increase in their extreme intensity (Figure 2) under climate change conditions is consistent with the results from Walsh et al. (2014), Cavicchia et al. (2014a) and Romero and Emanuel (2013), although their methodology was different, as they used a single model or statistically based methods. Searching for a physical meaning, these changes could be related to differences in the evolution in the atmospheric and oceanic environment. As stated by Tous and Romero (2013), a necessary condition for a medicane development is the presence of a cut-off low in the upper-troposphere. Therefore, it is reasonable to hypothesize that a decrease in the number of medicanes will be linked to a decrease in the number of upper cut-off lows affecting the Mediterranean Basin.

Temperature at 300 hPa level (TA300) has been selected as proxy for the arrival of these cut-offs since they are associated with a drop in the temperature in the upper troposphere. Figure 4 (bottom-left panel) shows that, in all models, there is a positive trend in TA300, statistically significant in nine of the thirteen runs. This suggests that a decrease in the number of cut-offs affecting the Mediterranean Sea could be expected in the future, and is consistent with projections of a poleward movement of the mid-latitude storm track (Ulbrich and Christoph, 1999; Lionello et al., 2008; Giorgi and Coppola, 2007). The lower frequency of cut-off lows reaching the Mediterranean Sea would lead to changes in the vertical temperature difference between the surface and the upper troposphere (a measure of static atmospheric stability), as is shown in Figure 4 (bottom-right panel). All the simulations show indeed a positive trend for static stability, except for PROMES-HCQ0 (this simulation only reaches 2050). Note that lower values of the represented temperature difference (SST-T300) indicate more stability. This average stability increase would cause atmospheric environmental conditions to be worse for medicane development.

The highest values of static stability and the highest increase in it are found for ECHAM-driven simulations. The same simulations show relatively low values of medicane frequency, as well as the largest decrease in medicane frequency among the simulations running until 2100. This suggests a relationship between average static stability and medicane frequency. The only partial exception to this behaviour, among the four ECHAM-driven simulations, is the run with RCA in which the frequency decreases only slightly and non-significantly. But this RCM shows the lowest frequency values both in the scenario simulations and in the evaluation runs, and the low frequency values for present climate obviously put a limit to the future decrease. It is also noteworthy that simulations nested in ECHAM show relatively low intensity values, as shown before in Figure 2, which points also to a relationship of this variable to static stability. Interestingly, the strong static stability decrease for this GCM does not induce a decrease in extreme intensity in the future. On the other hand, the lowest values of static stability are seen in BCM-driven simulations. The spread in static stability between simulations increases from about 4 K in 1950 to about 5 K in 2100. This higher spread is mainly due to the nearly constant value of static stability that RCA-BCM run reaches during the last decades of the present century, which reflects in a clear pick-up of medicane frequency in this run.

The monthly distribution of medicanes frequency (Figure 5) indicates that the spread among models could decrease at the end of the century, although an important variability among runs remains. As summarised by the ensemble mean (dashed line in the figures), no appreciable variations are simulated in general under climate change conditions. An exception to this are RCA-BCM results, as the monthly distribution in this simulation shifts from a December maximum in 1951-2000 to a clear October maximum in 2051-2100. A marked future reduction in winter medicanes is seen in this simulation, which also shows an appreciable increase in August medicanes. Similar changes are also simulated by ALADIN-ARPEGE, which as a result shows an August maximum in 2051-2100.

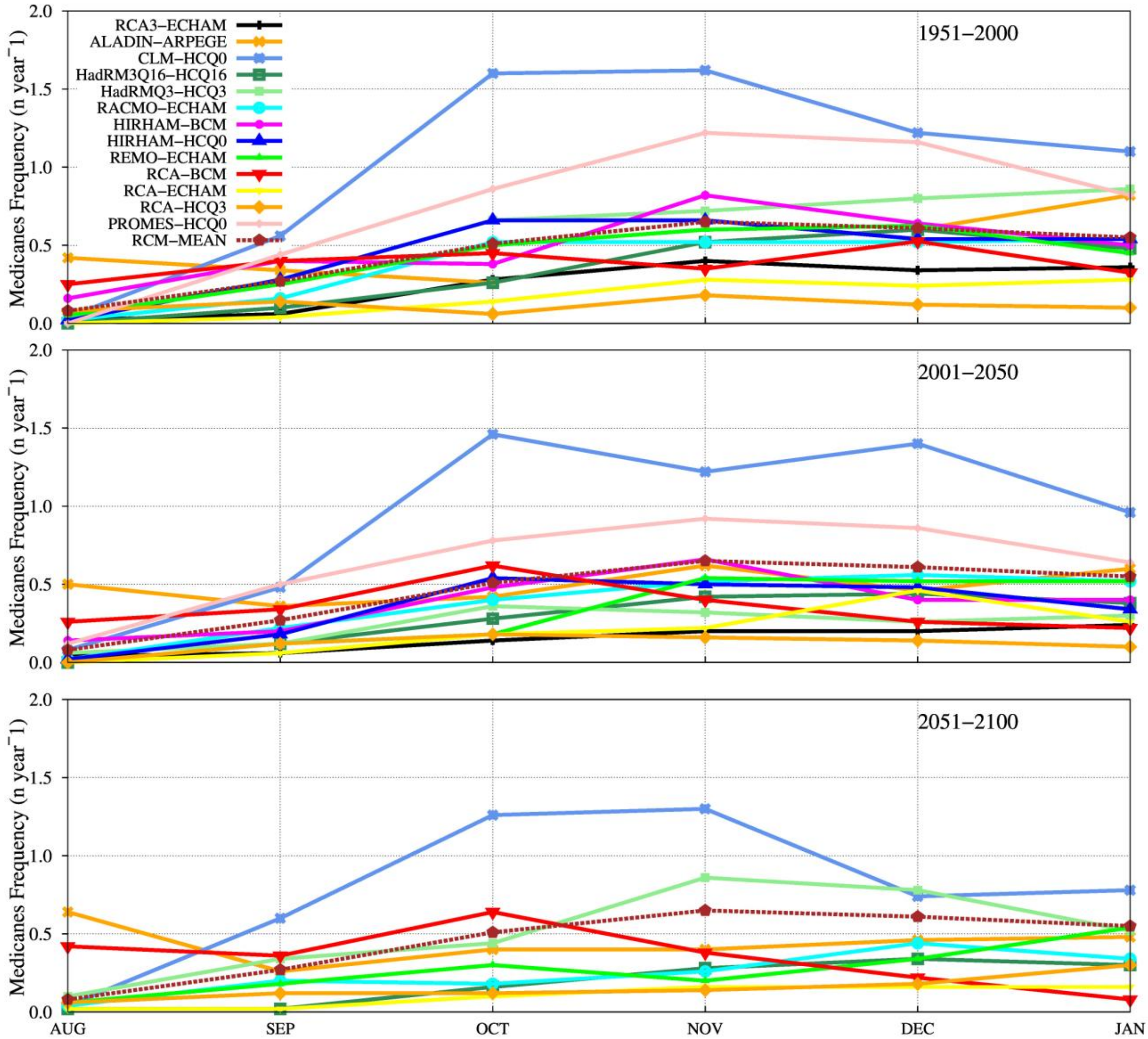

Figure 5: Monthly distribution of medicane frequency for every RCM, and RCM mean (dashed line), for every period: 1951-2000 (top), 2001-2050 (middle) and 2051-2100 (bottom).

The total number of medicanes, divided by the number of available RCMs (thirteen up to 2050 and nine up to 2100), is represented in Figure 6, showing the regional distribution for each period. We assign each medicane to the region where it reaches its maximum 10 m wind speed. The left panel shows the distribution following the regions defined in Figure 1. A decrease in the number of medicanes at the end of the century is clearly identified over the whole Mediterranean Sea, independently of the region. As Miglietta et al. (2013) have pointed out, the central region of the Mediterranean Sea is the region which presents the largest number of medicanes, and this result persists under climate change conditions. But this central region will suffer a larger decrease than the other areas in future climate.

The right panel of figure 6 shows a different regional distribution, dividing the Mediterranean Sea in two zones, north and south of 36ºN. The greater number of medicanes appear in the north of Mediterranean Sea, but the number of events is projected to decrease there under climate change conditions. In contrast, the southern part of the Mediterranean Sea is the only place where the number of medicanes should not experience any change in the future. According to Figure 6 (left and right panels) the regions with a larger number of medicanes in the first period will suffer a more pronounced decrease in the future so the number of medicanes will be distributed in a more uniform way along the Mediterranean Sea at the end of the century.

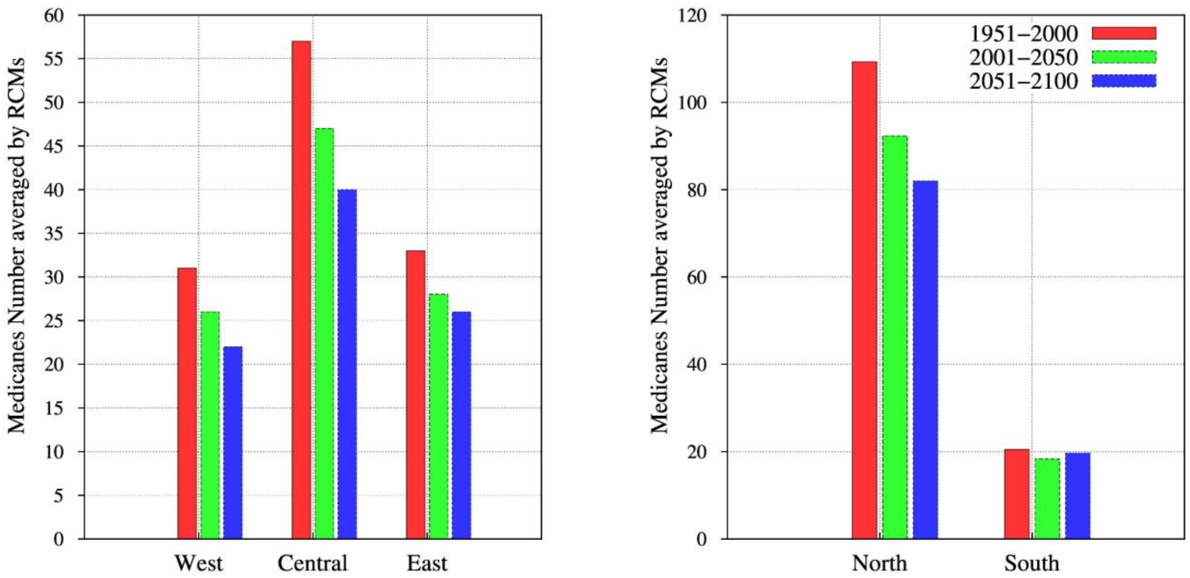

Figure 6: Regional distribution of total number of medicanes, divided by the 13 RCMs available up to 2050 and by 9 RCMs available up to 2100, for each region (left: west, central and east according to Figure 1; right: north, for latitude greater than 36ºN, and south, for latitude less than 36ºN) and for each period: 1951-2000 (red), 2001-2050 (green) and 2051-2100 (blue).

In figure 7 all the detected medicanes, no matter from which RCM simulation they come from, with maximum surface wind speed above 25 $m \cdot s^{-1}$ during their lifetime (threshold between strong gale force and storm force in Beaufort Scale) are represented. The green colour indicates maximum surface wind speed between 25 and 33 $m \cdot s^{-1}$ (minimum threshold of Saffir-Simpson Hurricane Wind Scale) while red colour represents the most intense medicanes (maximum wind speed higher than 33 $m \cdot s^{-1}$, i.e. hurricane strength). The zones with the highest number of medicanes are Ligurian Sea (North of Corsica), Tyrrhenian Sea, Adriatic Sea, the Balearic Sea, the Ionian Sea and Aegean Sea in the first (1951-2000) and second (2001-2050) modelled periods. But in the far future climate (2051-2100) the medicanes seem to be distributed all over the Mediterranean Sea in a more homogeneous way. As previously discussed with respect to Figure 2, the intensity of the strongest medicanes should increase in future climate (more red points in the last period). Figure 7 shows that an important fraction of the most intense medicanes could form in the southern and eastern parts of the Mediterranean Sea, in the regions where the number of events is more scarce in general. The maximum SSTs in the Mediterranean Sea are found precisely over these parts, which points to a important role of the projected SST increase in the increased extreme intensity of medicanes.

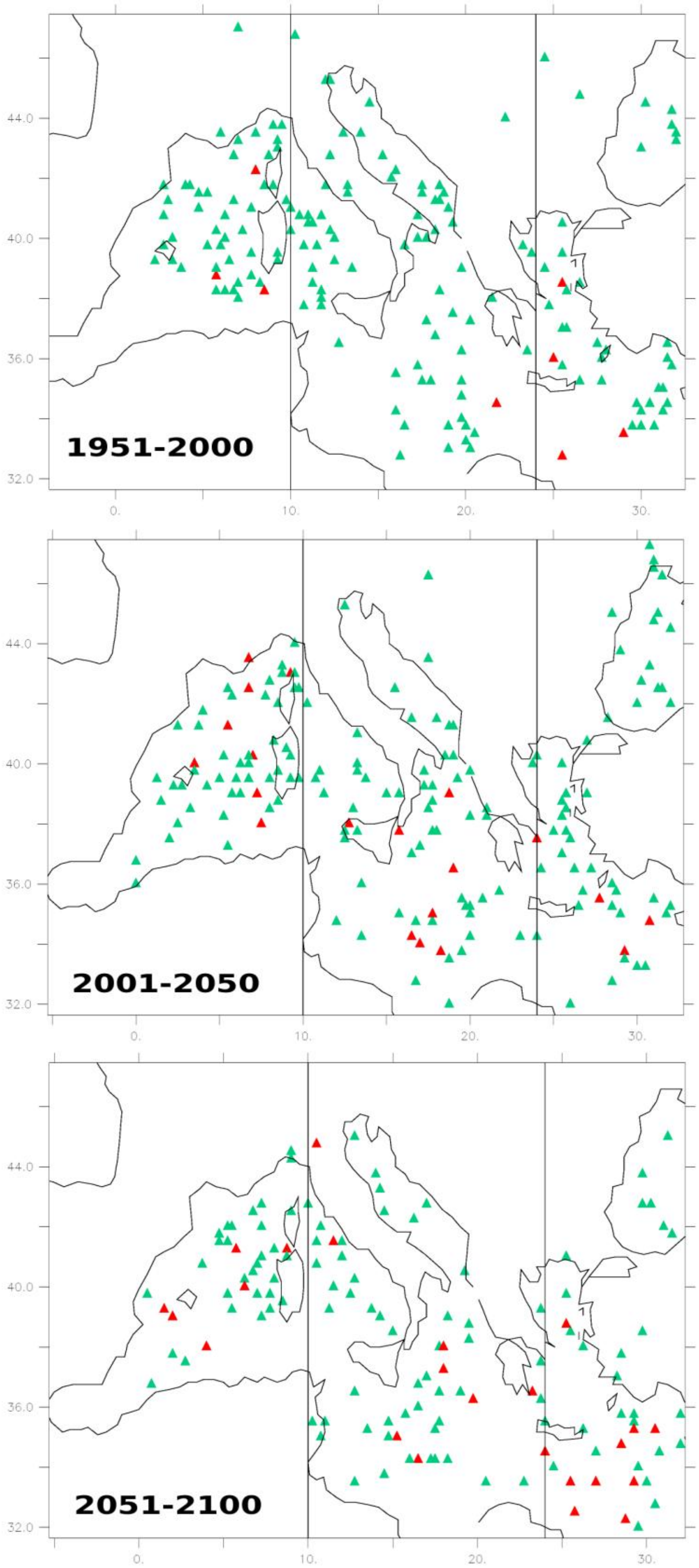

Figure 7: Scatter plot of the medicanes occurrence for 1951-2000 (top), 2001-2050 (middle) and 2051-2100 (bottom). The colours represent the maximum value of surface wind speed along the whole life of the medicane: green points represent wind speed between 25 and 33 m·s^{-1} and red points represent wind speed greater than 33 m·s^{-1}. Medicanes with smaller values of maximum daily wind speed have not been represented.

The total number of medicanes simulated in each run for the three analysed periods is listed in Table

3, where the medicanes are classified in three groups according to their maximum intensity: between 17 and 25 m·s^{-1}, between 25 and 33 m·s^{-1} (intense) and greater than 33 m·s^{-1} (very intense). All runs simulate a decrease in the number of medicanes with intensity between 17 and 25 m·s^{-1} with the only exception of RCA-BCM, in agreement with previously shown results for the overall medicane number tendency. For the intense and very intense medicanes there is no common tendency, as the variability among the simulations is very important. The strong influence of the GCM on the results can be seen in the ECHAM-driven simulations, which do not generate any very intense medicanes, and in the three simulations with RCA regional model nested in different GCMs, which show very different evolutions of the three types of medicanes. It is noteworthy that two of the three runs that generate hurricane-force medicanes in the second half of present century (RCA-BCM and ALADIN-ARPEGE) show an appreciable increase in August medicanes (see Figure 5), which suggests a possible relationship to the yearly SST maximum in that month. A summary of the ensemble results is shown in the last row of Table 3, where the mean number of medicanes for all the simulations reveals a decrease in the number of medicanes with maximum wind speed between 17 and 25 m·s^{-1} and an increase in the number of both intense and very intense events under future climate change conditions.

	1951-2000			**2001-2050**			**2051-2100**		
Maximum daily Wind Speed (m·s^{-1})	**17-25**	**25-33**	**>33**	**17-25**	**25-33**	**>33**	**17-25**	**25-33**	**>33**
RCA3-ECHAM	70	3	0	44	0	0	-	-	-
ALADIN-ARPEGE	93	0	0	59	24	5	51	14	3
CLM-HCQ0	258	45	4	223	48	9	178	47	11
HadRM3Q16-HCQ16	89	9	0	80	2	0	52	4	0
HadRM3Q3-HCQ3	161	7	0	66	4	1	139	13	0

RACMO-ECHAM	104	10	0	100	12	0	65	8	0
HIRHAM-BCM	139	6	0	107	6	1	-	-	-
HIRHAM-HCQ0	128	6	1	96	7	0	-	-	-
REMO-ECHAM	92	7	0	80	14	0	76	5	0
RCA-BCM	50	6	0	71	4	1	70	7	5
RCA-ECHAM	31	1	0	37	2	0	18	2	0
RCA-HCQ3	161	7	0	66	4	1	139	13	0
PROMES-HCQ0	211	14	0	177	13	1	-	-	-
RCM MEAN	122,1	9,3	0,4	92,8	10,8	1,5	87,6	12,6	2,1

Table 3: Total number of medicanes for every RCM and RCM mean (rows) and period (columns). The number of medicanes are classified according to their maximum daily value of surface wind speed: between 17 and 25 $m \cdot s^{-1}$, between 25 and 33 $m \cdot s^{-1}$ and greater than 33 $m \cdot s^{-1}$.

1.4 Conclusions

Several previous studies have dealt with the analysis of medicanes in the present and future climate using single climate model simulations. In order to overcome the limitations of such a single model approach, here an ensemble of ten RCMs from ENSEMBLES project is used to study the occurrence of medicanes (tropical-like cyclones) over the Mediterranean Sea in the present climate and the changes of this kind of events in future climate conditions for the whole XXIst century. The aim is to advance previous studies along several important lines: use of a large ensemble of RCMs, nested in many different GCMs, and covering a continuous long time period (up to 150 years). An objective method, using a cyclone tracking method (Picornell et al., 2001) and studying the vertical structure of the cyclones through the cyclone phase space method of Hart (2003), has been employed to identify and define each medicane event.

First, the ERA40-forced evaluation runs (1961-2000) have been compared with a list of observed medicanes (Miglietta et al., 2013) in order to evaluate the capability of the RCMs to simulate several observed characteristics of medicanes. Almost all RCMs obtain frequency values between 0.7 and 2.5 medicanes per year, which compares well with the available information from several observational datasets. The important variability among the RCMs is comparable to the spread among available observational datasets. Other characteristics of observed medicanes are reasonably well reproduced by the RCMs.

As some RCMs have been nested in different GCMs, an ensemble of thirteen simulations (four covering the period 1950-2050 and nine extending to 2100) has been used to study the projected changes in medicanes under future climate change conditions. The two main results are a decrease in the number of medicanes per year and an increase in the extreme intensity of such events during the XXIst century. These results are consistent with those emerging in recent studies using one model (e.g., Cavicchia et al., 2014a, 2014b; Walsh et al., 2014) or a statistically based method (Romero and Emanuel, 2013). Nevertheless, our approach reveals interesting uncertainties in these results. The frequency decrease is less clear if we take into account only the runs reaching 2100: less than half (four out of nine) show a statistically significant decrease. There is a clear dependency on the model formulation in this decrease. Regarding the projected intensity changes, some systematic patterns are also apparent: ECHAM-driven runs simulate less intense medicanes in general, while the simulations nested in HCQ3 GCM show the clearest increasing tendency in intensity.

No clear future changes are found in the monthly distribution of medicanes, but again a few noticeable exceptions are seen, as in two simulations a shift towards an earlier monthly maximum is obtained, together with an increase in August medicanes. On the other hand, the projected decrease in medicanes shows some dependence on the spatial distribution. The central zone of the Mediterranean Sea, which presently is the subregion with a larger number of events, will experience a larger decrease than the western and eastern zones. Remarkably, when the Mediterranean Sea is divided into northern and southern subregions, no future medicane decrease is identified in the southern part, in clear contrast to the northern part. At the same time, the extreme intensity of medicanes is projected to increase more clearly in the southern part.

In order to find physical explanations for the projected tendencies and the differences among simulations, some environmental variables have been explored. A general increase with time of the vertical static stability of the atmosphere seems a plausible reason for the overall decrease of medicane frequency. Some differences among models seem to be linked to static stability, as ECHAM-driven simulations show the highest overall values of static stability and the highest future increase in it. As the same simulations show relatively low values of medicane frequency, as well as the largest projected decrease in it, a link between medicane frequency and average static stability is suggested. A rather large spread is found for this environmental variable. This could explain partly the differences among simulations. It is noteworthy that the clear increase in average static stability projected for the end of present century is not enough to avoid that the most intense medicanes show higher maximum winds in many of the projections. It is likely that the increased SST and latent heat fluxes can overcome this limitation in the atmospheric situations where favourable conditions for medicane genesis indeed occur. This is a matter of concern, as the strongest negative impacts are associated to the most intense cyclones.

As more regional dynamical simulations are becoming available in ongoing projects, this methodology and analysis is expected to be tested for higher resolution and even coupled atmosphere-ocean regional simulations, to see if these results can be confirmed and the characteristics of these important extreme cyclones over the Mediterranean can be further understood and analysed by means of RCMs.

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1.6 References

Bocheva L, Georgiev CG, Simeonov P (2007) A climatic study of severe storms over Bulgaria produced by Mediterranean cyclones in 1990-2001 period. Atmos Res, 83: 284-293, doi:10.1016/j.atmosres.2005.10.018

Campins J, Genovés A, Picornell MA, Jansà A (2011) Climatoloty of Mediterranean cyclones using the ERA-40 dataset. Int J Climatol, 31: 1596-1614, doi: 10.1002/joc.2183

Christensen JH, Christensen OB (2007) A Summary of the PRUDENCE Model Projections of Changes in European Climate by the end of this century. Climatic Change, 81, 1: 7-30, doi: 10.1007/s10584-006-9210-7

Cavicchia L, von Storch H (2012) The simulation of medicanes in a high-resolution regional climate model. Clim Dyn, 39: 2273-2290, doi: 10.1007/s00382-011-1220-0

Cavicchia L, von Storch H, Gualdi S (2014a) A long-term climatology of medicanes. Clim Dyn, 43: 1183-1195, doi: 10.1007/s00382-013-1893-7

Cavicchia L, von Storch H, Gualdi S (2014b) Mediterranean tropical-like cyclones in present and future climate. J Climate, 27: 7493-7501, doi: 10.1175/JCLI-D-14-00339.1

Christensen JH, Kumar KK, Aldrian E, An S-I, Cavalcanti IFA, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau N-C, Renwick J, Stephenson DB, Xie S-P, Zhou T (2013). Climate Phenomena and their Relevance for Future Regional Climate Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Gaertner MA, Jacob D, Gil V, Domínguez M, Padorno E, Sánchez E, Castro M (2007) Tropical cyclones over the Mediterranean Sea in climate change simulations. Geophys Res Lett, 34(14):

L14711, doi: 10.1029/2007GL029977

Giorgi F, Coppola E (2007) European climate-change oscillation (ECO). Geophys Res Lett, 34: L21703

Giorgi F, Lionello P (2008) Climate change projections for the Mediterranean region. Global Planet Change, 63(2): 90-104

Hart R (2003) A cyclone phase space derived from thermal wind and thermal assymmetry. Mon. Wea. Rev, 131: 585-616

Jansà A, Genovés A, Picornell MA, Campins J, Riosalido R, Carretero O (2001) Western Mediterranean cyclones and heavy-rain. Par 2: Statistical approach. Meteorol Appl, 8(1): 43-56

Lionello P, Dalan F, Elvini E (2002) Cyclones in the Mediterranean region: the present and the doubled CO_2 climate scenarios. Clim Res, 22: 147-159

Lionello P, Boldrin U, Giorgi F (2008a) Future changes in cyclone climatology over Europe as inferred from a regional climate simulation. Clim Dyn 30: 657-671. Doi: 10.1007/s00382-007-0315-0

Miglietta MM, Laviola S, Malvaldi A, Conte D, Levizzani V, Price C (2013) Analysis of tropical- like cyclones over the Mediterranean Sea through a combined modeling and satellite approach. Geophys Res Lett, 40(10): 2400-2405, doi: 10.1002/grl.50432

Nissen KM, Leckebusch GC, Pinto JG, Renggli D, Ulbrich S, Ulbrich U (2010) Cyclones causing wind storms in the Mediterranan: characteristics, trends and links to large-scale patterns. Nat Hazards Earth Syst Sci, 10: 1379-1391, doi:10.5194/nhess-10-1379-2010

Picornell MA, Jansà A, Genovés A, Campins J (2001) Automated database of mesocyclones from the HIRLAM-0.5 analyses in the western Mediterranean. Int J Climatol, 21: 335-354

Pinto JG, Spangehl T, Ulbrich U, Speth P (2005). Sensitivities of a cyclone detection and tracking algorithm: individual tracks and climatology. *Meteorologische Zeitschrift*, *14*(6), 823-838.

Romero R, Emanuel K (2013) Medicane risk in a changing climate. J Geophys Res-Atmos, 118: 5992-6001, doi: 10.1002/jgrd.50475

Rotunno R, Emanual K (1987) An air-sea interaction theory for tropical cyclones. Part II: Evolutionary study using a nonhydrostatic axisymmetric numerical model. J Atmos Scie, 44: 542-561

Sinclair M (1997) Objective identification of cyclones and their circulation intensity, and climatology. Weather Forecast, 12: 595-612

Trigo IF, Davies TD, Bigg GR (2000) Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones. Geophys Res Lett, 27: 2913-1916

Tous M, Romero R (2011) Medicanes: cataloguing criteria and exploration of meteorological environments. Tethys, 8: 53-61. doi: 10.3369/tethys.2011.8.06

Tous M, Romero R (2013) Meteorological environments associated with medicane development. Int J Climatol, 33: 1-14

Tous M, Romero R, Ramis C (2013) Surface heat fluxes influence on medicane trajectories and intensitication. Atmos Res, 123: 400-411

Ulbrich U, Christoph M (1999) A shift in the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas. Clim Dyn, 15: 551-559

Van der Linden P, Mitchell JFB (2009) ENSEMBLES: Climate Change and its Impacts: Summary of Research and Results from the ENSEMBLES Project. Mediterranean.... Vol 160 http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf\nhttp://onlinelibrary.wiley.com/doi/10.1002/9781119941156.ch9/summary.

Walsh K, Giorgi F, Coppola E (2014) Mediterranean warm-core cyclones in a warmer world. Clim Dyn, 42: 1053-1066. doi: 10.1007/s00382-013-1723-y