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Projected changes in medicanes in the HadGEM3 N512 high-resolution global climate model

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Abstract Medicanes or "Mediterranean hurricanes" represent a rare and physically unique type of Mediterranean mesoscale cyclone. There are similarities with tropical cyclones with regard to their development (based on the thermodynamical disequilibrium between the warm sea and the overlying troposphere) and their kinematic and thermodynamical properties (medicanes are intense vortices with a warm core and even a cloud-free eye). Although medicanes are smaller and their wind speeds are lower than in tropical cyclones, the severity of their winds can cause substantial damage to islands and coastal areas. Concern about how human-induced climate change will affect extreme events is increasing. This includes the future impacts on medicanes due to the warming of the Mediterranean waters and the projected changes in regional atmospheric circulation. However, most global climate models do not have high enough spatial resolution to adequately represent small features such as medicanes. In this study, a cyclone tracking algorithm is applied to high resolution global climate model data with a horizontal grid resolution of approximately 25 km over the Mediterranean region. After a validation of the climatology of general Mediterranean mesoscale cyclones, changes in medicanes are determined using climate model experiments with present and future forcing. The magnitude of the changes in the winds, frequency and location of medicanes is assessed. While no significant changes in the total number of Mediterranean mesoscale cyclones are found, medicanes tend to decrease in number but increase in intensity. The model simulation suggests that medicanes tend to form more frequently in the Gulf of Lion–Genoa and South of Sicily.

Keywords Mediterranean · Medicanes · Climate change · Cyclone climatology · HadGEM3

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1 Introduction

Medicanes are small intense cyclones that develop over the Mediterranean Sea. Medicanes share many characteristics with tropical cyclones (TC), both in their visual appearance on satellite images (e.g. highly concentric convective cloud bands around a central eye, Fig. 1) and in the physical processes associated with their development. Meteorological reports from ships and coastal regions confirm these similarities (Ernest and Matson 1983; Reale and Atlas 2001; Jansà 2003). These cyclones usually form in environments resulting from synoptic-scale Rossby wave breaking over the region and are fed by sensible and latent surface heat fluxes from the relative warm sea surface. The enhanced surface fluxes reflect the thermodynamical disequilibrium between the sea and the atmosphere, as occurs in TC development.

The frequency of medicanes is relatively low. A study of 20 years of infrared channel satellite images (Tous and Romero 2013) found 12 medicane events that fulfill strict criteria in terms of cloud structure, degree of symmetry, size and lifetime. When investigated in high-resolution mesoscale models, medicanes are represented as small, isolated, symmetric, intense cyclones with a warm core (Pytharoulis et al. 1999; Homar et al. 2003; Tous et al. 2013).

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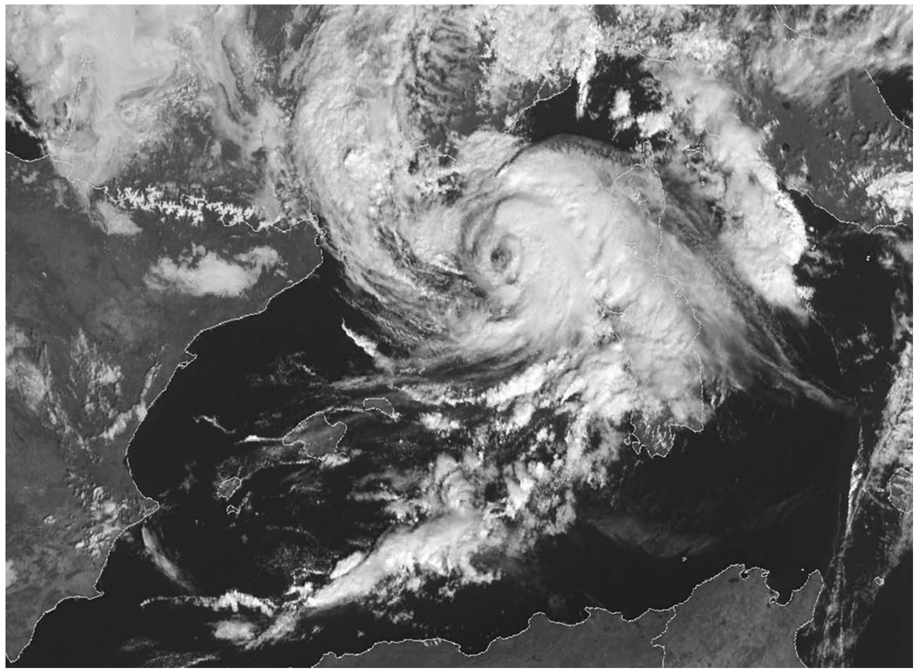

Fig. 1 Satellite image of the medicane of 8 November 2011 at 10 UTC in the western Mediterranean (*source*: EUMETSAT)

The small size of medicanes (typically less than 300 km) and the complex inner core dynamics are two aspects poorly represented in current atmospheric reanalysis (~80 km in resolution) and low-resolution global climate models (GCMs, ~200 km). Applying objective techniques to detect or track medicanes in these datasets is therefore not appropriate. Previous work investigating the potential response of medicanes to climate change have used different downscaling approaches. For example, Cavicchia and Storch (2011) and Walsh et al. (2014) developed a methodology using a high-resolution regional climate model. An alternative was adopted in Romero and Emanuel (2013) which used a statistical-deterministic approach to generate thousands of synthetic events in order to assess in a statistically robust way the change in the medicane risk.

The aim of the present study is to further our understanding of how medicanes might respond to climate change. This is achieved by investigating a recent set of GCM simulations that are integrated at high enough horizontal resolution to resolve medicanes explicity, checking if the tendencies showed by previous studies are consistent with those found in the direct technique of using a high resolution global model. The description of the model characteristics and the tracking details are provided in Sect. 2, followed by a general validation of Mediterranean cyclone climatologies for the present climate scenario in Sect. 3. Section 4 is focused on medicanes. It explains the specific features implemented in the objective tracking algorithm to select the medicane events, and studies medicane spatial-temporal distributions and thermodynamical properties in the detected events. This section has been organized in two parts: the analysis of the present climatology of events (Sect. 4.1) where an assessment of the model's capability to represent medicanes and a comparison against other medicane climatologies are provided; and next, the study using future scenario data (Sect. 4.2), where the projected tendencies of medicanes are evaluated. Finally, Sect. 5 contains a summary of the main conclusions reached in the study.

2 Data and methodology

2.1 The HadGEM3 climate model

The model used in this study is an N512 atmosphere-only configuration of the HadGEM3-GA3 Met Office Unified Model (Walters et al. 2011). The simulations were performed as part of the UPSCALE project (UK on PRACE—weather resolving Simulations of Climate for globAL Environmental risk), a collaborative project between the National Centre for Atmospheric Science-Climate (NCAS) at the University of Reading, and the UK Met Office Hadley Centre (Mizielinski et al. 2014). The N512 HadGEM3-GA3 model has a horizontal grid resolution of approximately 25 km (Fig. 2) and has 85 levels in the vertical. An ensemble of five historical and three future atmosphere-only simulations were performed. Historical simulations were forced with daily observed OSTIA SSTs (Donlon et al. 2012). SSTs and ice for the future simulations were determined by adding to the OSTIA SSTs, the change in SSTs from the RCP8.5 HadGEM2-ES coupled climate simulations performed for IPCC AR5. This study uses 26

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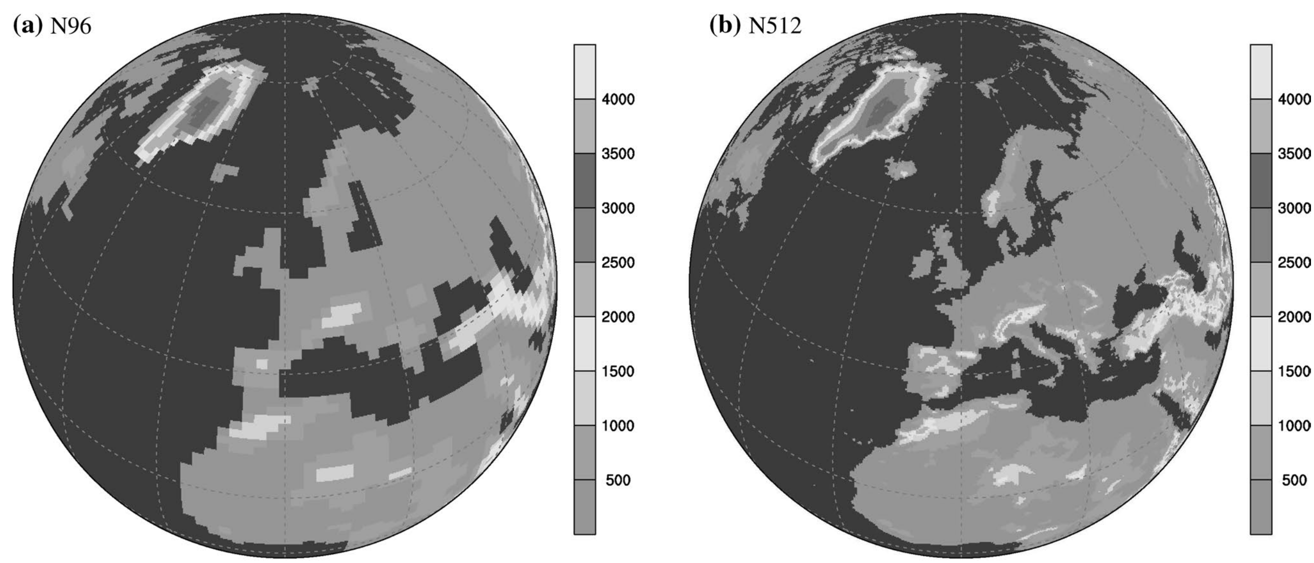

Fig. 2 Illustration of grid resolutions N96 and N512 (approx. 135 and 25 km at mid-latitudes, respectively) showing the topography (height above sea level, in m) and coastline (ocean area for fractional land cover of less than 50 %). (UPSCALE project website: http://proj.badc.rl.ac.uk/upscale)

years of output from one member of the historical ensemble and from one member of the future ensemble (enough to get the objectives of this study). Concentrations of carbon dioxide, methane, nitrous oxide, CFCs, HFCs, ozone and aerosol emissions were set to constant values (i.e. the mean values for 1980–2010 for the historical simulations and mean values of 2080–2110 for the future simulations). Model output is available at 6 h intervals.

The influence of the large scale environment on TC has initally been studied by Strachan et al. (2013) and Bell et al. (2013, 2014) for the HadGEM1 model, then by Roberts et al. (2015) for the HadGEM3 model. More generally, the HadGEM3 TC simulation skill has been tested in a large GCM intercomparison carried out by the CLIVAR Hurricane Working Group (Shaevitz et al. 2014) including the response to natural and forced variability (Walsh et al. 2014; Daloz et al. 2015).

Walters et al. (2011) showed the N96 and N216 models have relatively small biases over the Mediterranean in DJF. However, other relevant biases include there being generally too much precipitation over the NH and a cold surface temperature bias over North Africa. It is not apparent how these biases would impact on Medicanes in the N512 version of HadGEM3, which is why it is important to directly evaluate the representation of medicanes in these simulations.

In addition, previous studies have determined that intense baroclinic Mediterranean cyclones are most frequent in winter (Campins et al. 2011). Medicanes are also more frequent in winter and autumn than in the warm seasons (Tous and Romero 2013). Consequently, the cyclone season studied here has been defined from June to May. Thus, we use data from June 1985 to May 2011 for the historical period, and from June 2085 to May 2111 for the future period.

2.2 Cyclone tracking algorithm

The cyclone tracking is based on the objective feature-algorithm of Hodges (1994, 1995, 1999). The tracking algorithm has been used in previous studies analyzing the dynamics of tropical and extratropical cyclones, including polar lows (Hoskins and Hodges 2002; Strachan et al. 2013; Zappa et al. 2014), the ability of climate models to represent storm tracks (Greeves et al. 2007; Catto et al. 2010; Zappa et al. 2013) and characterising their future response to climate change (Bengtsson et al. 2006; Catto et al. 2011; Roberts et al. 2015).

The algorithm locates vorticity centers at 850hPa calculated from instantaneous wind fields. The vorticity fields used in this study have been filtered by a T40-T100 spectral filter (about 200–500 km in the equator). The choice of T40–T100 was based upon work by Zappa et al. (2014) and Xia et al. (2012), which filters out the high frequency noise and the large-scale synoptic flow to allow the objective tracking algorithm to identify mesoscale features. This filtering seems appropriate given the results of Picornell et al. (2001), where most of the cyclones found in the Western Mediterranean have a radius between 150 and 350 km, with mean radius of 236 km. Moreover, the radius of medicanes have not been observed to be greater than this mean value.

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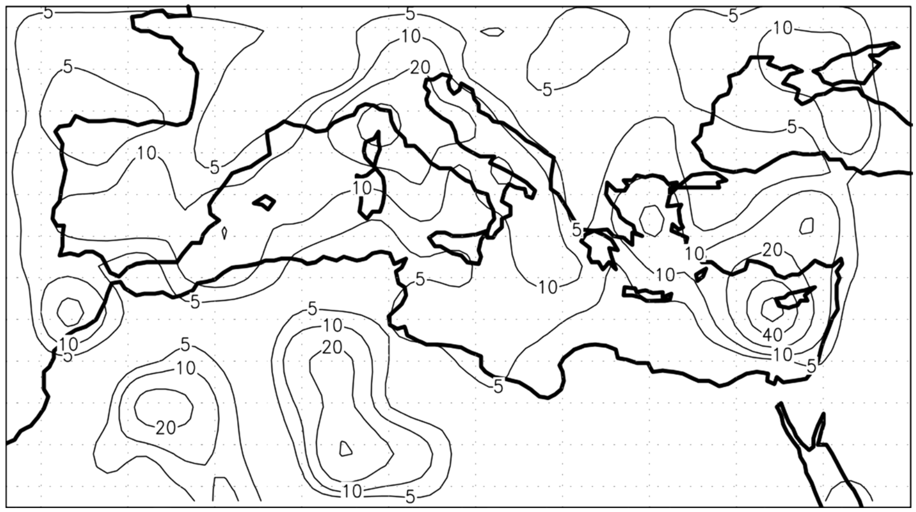

Fig. 3 Mean number of cyclone centres in 2.25° ×2.25° *latitude–longitude boxes*. *Contour intervals*: 5, 10, 20, 40 and 60 centres/year. (From Campins et al. 2011)

Cyclone centers are identified as relative maxima in these vorticity fields exceeding an intensity of $2 \times 10^{-5}\,\mathrm{s}^{-1}$. The tracks of the cyclones are determined by minimizing a cost function in the track smoothness (Hodges 1999). Further conditions include: (1) restricting the search region to the Mediterranean Sea plus the nearest sector of the Atlantic ocean (lat: 25N–50N; lon: 20W–50E); (2) including only cyclones with a minimum lifetime of 12 h and (3) cyclones require a minimum in mean sea level pressure (MSLP) closely located (≤200 km) to the relative maximum of vorticity. The location of the MSLP minimum is where the detected cyclone center is positioned. For the medicane risk assessment in present and future climate conditions (Sect. 4), some additional specific criteria will be used in the cyclone identification and tracking algorithm.

3 Climatology of mesoscale cyclones in the Mediterranean

In this section, the Mediterranean mesoscale cyclone climatology from the N512 HadGEM3 historical simulation is qualitatively evaluated using the MEDEX cyclone climatology. The MEDEX climatology is based on ERA-40 reanalysis (September 1957 to August 2002, at 6 h intervals) and describes the climatology of surface cyclones and their three-dimensional structure. The methodology is detailed in Picornell et al. (2001) (hereafter, P2001) and the main results are contained in Campins et al. (2011) (hereafter, C2011). In the P2001 and C2011 climatologies, the method used for cyclone tracking has three main steps: first, surface cyclones are detected from MSLP fields; next, the vertical extension of a surface cyclone is explored by means of the geopotential height at different isobaric levels; and finally, each cyclone centre is tracked in time. In C2011, 81762 cyclonic centers were detected (i.e. an average of 1817 centers/year). These centers tend to be preferentially located near Cyprus and the gulf of Genoa (Fig. 3), apart of other maxima over the African continent associated to thermal lows.

Figure 4 shows the annual mean spatial distribution of mesoscale cyclone feature density in the N512 HadGEM3 historical simulation. The main centre of cyclonic activity is found in the gulf of Genoa, with an average frequency of 40–50 cyclone centers per year, which is comparable to the 37.4 cyclones per year found in C2011. There is another maximum situated south of the Pyrenees, which is similar to P2001. Finally, the other notable maximum found over Cyprus in C2011 is not apparent in the HadGEM3 model. One explanation for this omission could be that cyclones detected in C2011 in this area are usually shallow (Alpert et al. 2004, C2011) and thus may not be reflected as a significant vorticity maxima at 850 hPa applying our methodology. Nevertheless, a small maximum of cyclonic activity appears over the Turkish Southern coast, which is located further south than the Aegean Sea maximum in C2011. African maxima represent a high frequency of thermal lows during the warm season. In summary, the spatial distribution of mesoscale cyclones is qualitatively similar to that seen in the MEDEX climatology.

4 Simulated medicane climatology

4.1 Present climate

Medicanes are identified from the full set of mesoscale cyclone tracks by applying further criteria on the lifetime, thermal structure and humidity associated to the tracks. In particular, the lifetime of the track is required to be 12 h or longer, corresponding to at least 2 intervals of

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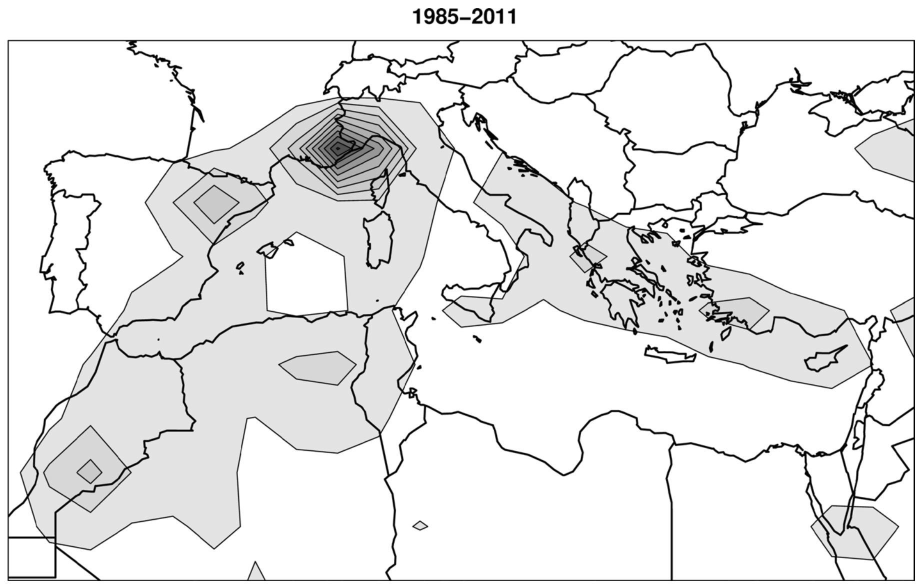

Fig. 4 Feature density of mesocyclone centres per year in the N512 HadGEM3 historical simulation. Contours at every 5 minimum pressure centers per year, calculated in 2.25° ×2.25° *lat–lon boxes*

the N512 HadGEM3 output. To capture the warm core of medicanes, the area averaged temperature within a 50 km radius centred on the MSLP minimum is required to be 1.5 K warmer than the mean temperature in a larger 200 km radius area average. The choice of the 1.5 K threshold follows the observation of 1.5–3.5 K warm core anomalies at mid-tropospheric levels seen in several simulated medicane events (Tous et al. 2013). Furthermore, as medicanes are associated with very moist or saturated environments, the area averaged relative humidity within 100 km radius from the MSLP minimum is requested to be greater than 70 % at both 600 and 850 hPa. Both the warm core and relative humidity conditions need to be satisfied for at least one time step. We find that 65 mesoscale cyclone tracks satisfy the above criteria for medicane identification in the 26 years of the historical climate simulation. A visual inspection of these cases qualitatively confirms that the identified tracks show medicane-like features, and two of them are examined here in more detail in Figs. 5 and 6.

A number of medicanes have been visually inspected to assess the extent to which HadGEM3 can capture the observed structure. The first considered event (labeled MED1) forms in the Balearic Islands region between the end of October and the beginning of November. The MSLP spatial map (see Fig. 5) shows that the medicane is characterized by an isolated pressure minimum, with a high degree of rotational symmetry and a warm core. In particular, the 850 hPa temperature at the cyclone centre is found to be more than 3° warmer than that of the surrounding environment. The near surface (at 10 m height) wind speeds in the vicinity (within a radius of 300 km) of the low pressure reach $24.6\,\mathrm{m\,s^{-1}}$ (which is close to force 10 in the Beaufort scale). The temporal evolution of the MSLP minimum (Fig. 6) shows a remarkably large and sudden MSLP drop (21.7 hPa in 6 h) which is also associated with a 30 % increase of the maximum surface wind speed (the parameter we adopt to characterize cyclone dynamical intensity). This is a manifestation of the rapid growth rate expected in this kind of storm, although we do not have evidence of such large values in the few documented medicanes.

The second event (MED2) occurs to the South of Sicily in the month of February. Although it does not look as isolated from its parent cyclonic disturbance as MED1, it evolves independently from the general circulation. Symmetry and warm core attributes are also clear in MED2. MSLP minimum drops 18.7 hPa in 5 timesteps (30 h) and the associated winds reach $24.7\,\mathrm{m\,s^{-1}}$, which are a clear indication of the severity of the event. Growth rates of this magnitude are typically found in simulations of case studies, like in Tous et al. (2013).

Previous studies (Cavicchia et al. 2014a; Romero and Emanuel 2013) have determined a frequency of 1.5–2 medicane events per year, although not all of them exhibit a clearly visible tropical cyclone like structure in the infrared channel in the satellite images (Tous and Romero 2013). Therefore, 65 medicanes in 26 years is only slightly higher than the expected frequency of occurrence of medicanes. This seems reasonable considering that we are examining a domain which marginally extends over the Atlantic ocean and it is slightly larger than in previous studies (Fig. 9).

Observational studies have found that medicanes tend to primarily form during the cold seasons (winter and autumn) because this is when cold air intrusions, in comparison with a warm Mediterranean, tend to occur. These temperature contrasts are associated with large surface heat fluxes out of the seas which help to sustain medicane development (Tous et al. 2013). Figure 7 shows the monthly frequency distribution of the 65 identified medicanes (represented by

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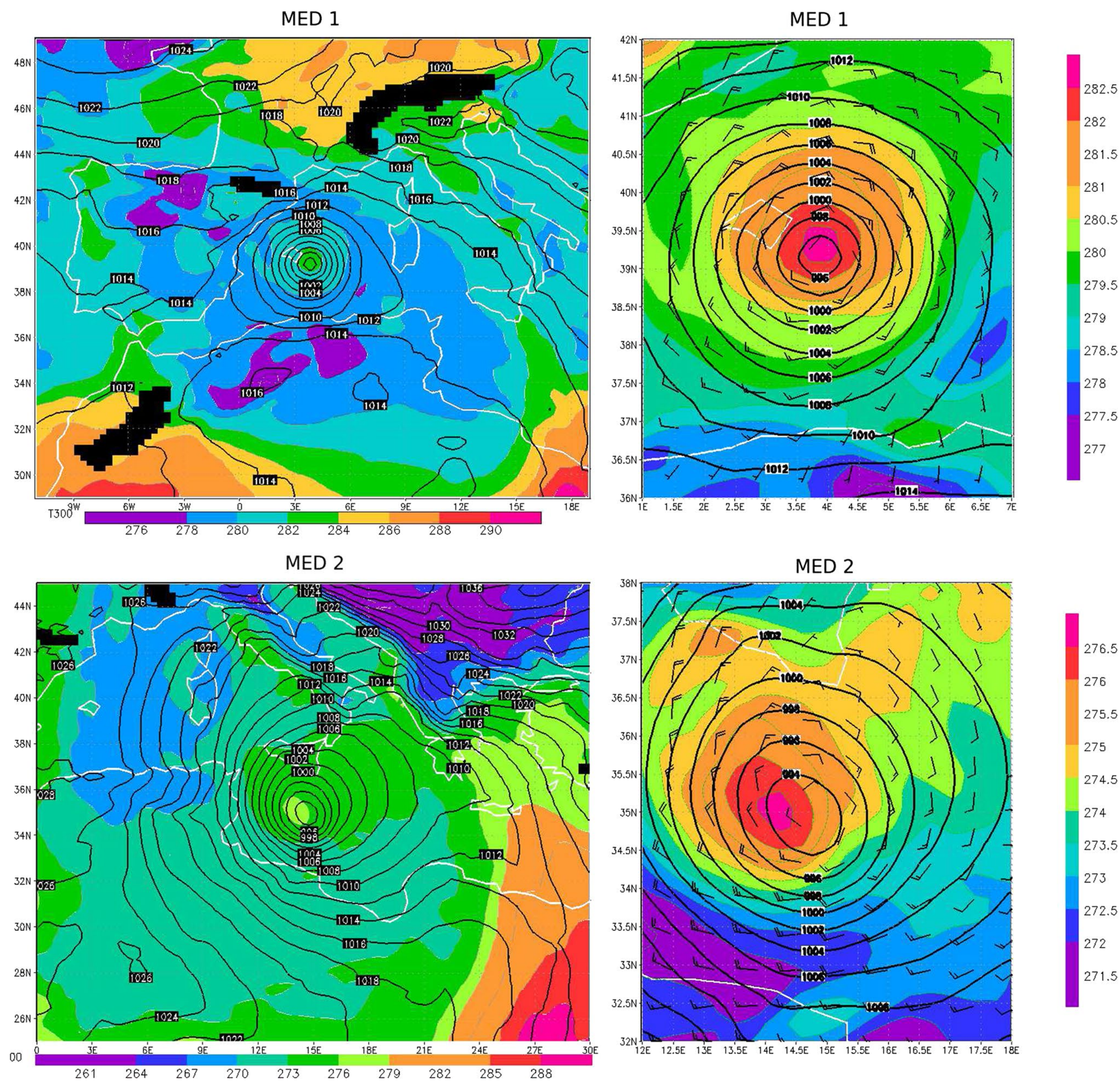

Fig. 5 Spatial structure of two medicanes (*top* MED1, *bottom* MED2) identified in the N512 HadGEM3 historical simulation. The figures on the *left* (*color contours* represent temperature at 850 hPa level in K, and continuous contours, MSLP in hPa) provide a description of the medicane positions in the Mediterranean basin, and those on the *right* (adding also winds at 10 m) provide a more detailed analysis of their structure

light gray bars) in the N512 HadGEM3 historical simulation. Consistent with observations, medicanes are primarily identified in the cold season. No events are detected by the identification and tracking algorithm in the summer months, and only a few are identified in late spring. Note that the strong seasonality in medicanes formation is not found in the total set of mesoscale cyclone tracks (dark bars in Fig. 7) which are almost constant in number throughout the annual cycle.

The spatial distribution of the identified medicanes in the N512 HadGEM3 historical simulation (Fig. 7) shows that a larger number of medicanes is detected south of the Gulf of Lion-Genoa and south of Sicily. This result is qualitatively consistent with the spatial distribution of observed medicanes found in previous studies (Cavicchia et al. 2014a; Tous and Romero 2013; Walsh et al. 2014). In the N512 HadGEM3 historical simulation, medicane-like cyclones are also identified in the Black Sea. Although medicanes

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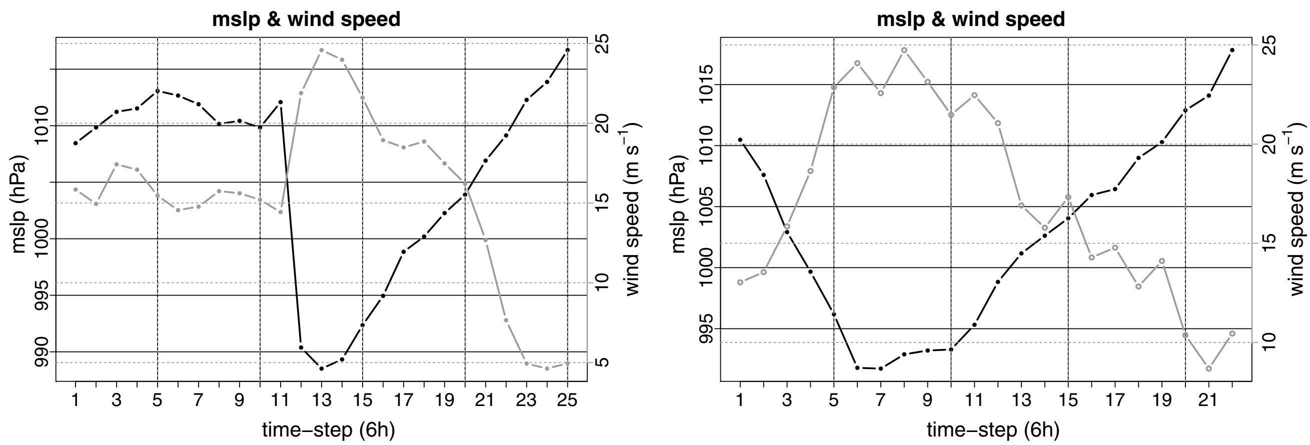

Fig. 6 Lifecycle of the minimum MSLP (*black line*, hPa) and maximum surface wind speed (*gray line* m s^{-1}) for two identified medicanes in the present day climate (*left* MED1; *right* MED2)

are even less frequent in this area, some cases have been occasionally reported. For example, Efimov et al. (2008) describes the formation of a tropical-like cyclone in the Black Sea region in September 2005. Medicanes identified in the Gulf of Biscay are also included among the objective tracks even though they are not conventional medicanes because they are not formed over the Mediterranean sea. Track points over North Africa are also of interest, showing that medicane precursor low pressure centres can be initiated over the continent.

In summary, the identification and tracking algorithm applied to the 6 hourly N512 HadGEM3 historical simulation identified a set of Mediterranean mesoscale cyclones which share a number of similarities with the observed medicanes. In particular, the identified mesoscale cyclones tend to have a similar frequency of occurrence, seasonality, spatial distribution and mesoscale structure relative to observed medicanes. Due to the insufficient resolution of the atmospheric reanalyses, it is not possible to quantitatively evaluate the biases of the model in the representation of medicanes by directly applying the identification and tracking algorithm to the reanalysis output. However, this qualitative assessment of the basic properties of medicanes gives us confidence that the 25 km resolution N512 HadGEM3 historical simulation is capable of generating medicane-like cyclones. In the next section, we will use this methodology to assess the impact of climate change on medicane frequency and intensity.

4.2 Future climate

In this section, the projected response of medicanes to climate change in the N512 HadGEM3 model is investigated by comparing the present day with the future climate simulations. The total number of mesoscale cyclone tracks and medicanes identified by the tracking algorithm are summarised in Table 1.

The total number of mesoscale cyclone tracks is similar in the present and future scenarios, but the number of those satisfying the objective medicane criteria is reduced from 65 to 44 events, both in 26 years.

To assess the significance of the reduction in the number of identified medicanes, we model the frequency of medicanes as a Poisson distributed process. This is motivated by the low count number per year and the expectation that medicanes are dynamically independent, i.e. the formation of a medicane does not affect the probability of another medicane occurring at a later time. Using this approach, we find that the reduction in the number of medicanes is significant at the 6 % level according to a two-tailed test on the Poisson mean. This reduction in the total number of medicanes (−30 %) is consistent with previous studies. For example, Cavicchia et al. (2014b) found a reduction of about 20–60 % depending on the emission scenario, by applying dynamical downscaling to a global climate model while Romero and Emanuel (2013) estimated a reduction of 10–40% depending on the GCM used. Projected changes in medicane frequency for individual seasons are presented in Fig. 8. The largest reductions occur in Autumn (September-November) and Spring (March-May), while small changes are found in Winter (December-February). Although the significance of the changes in individual seasons is low (the p values are 0.12 in Autumn and 0.18 in Spring), it suggests that the active medicane season will tend to be become more limited in winter, which is consistent with findings of Cavicchia et al. (2014b).

Chang (2014) suggests that MSLP might be a very poor way of looking at the changes in cyclone intensity as mean changes in MSLP project onto changes in the extremes, so the wind speed changes are the most important variable to

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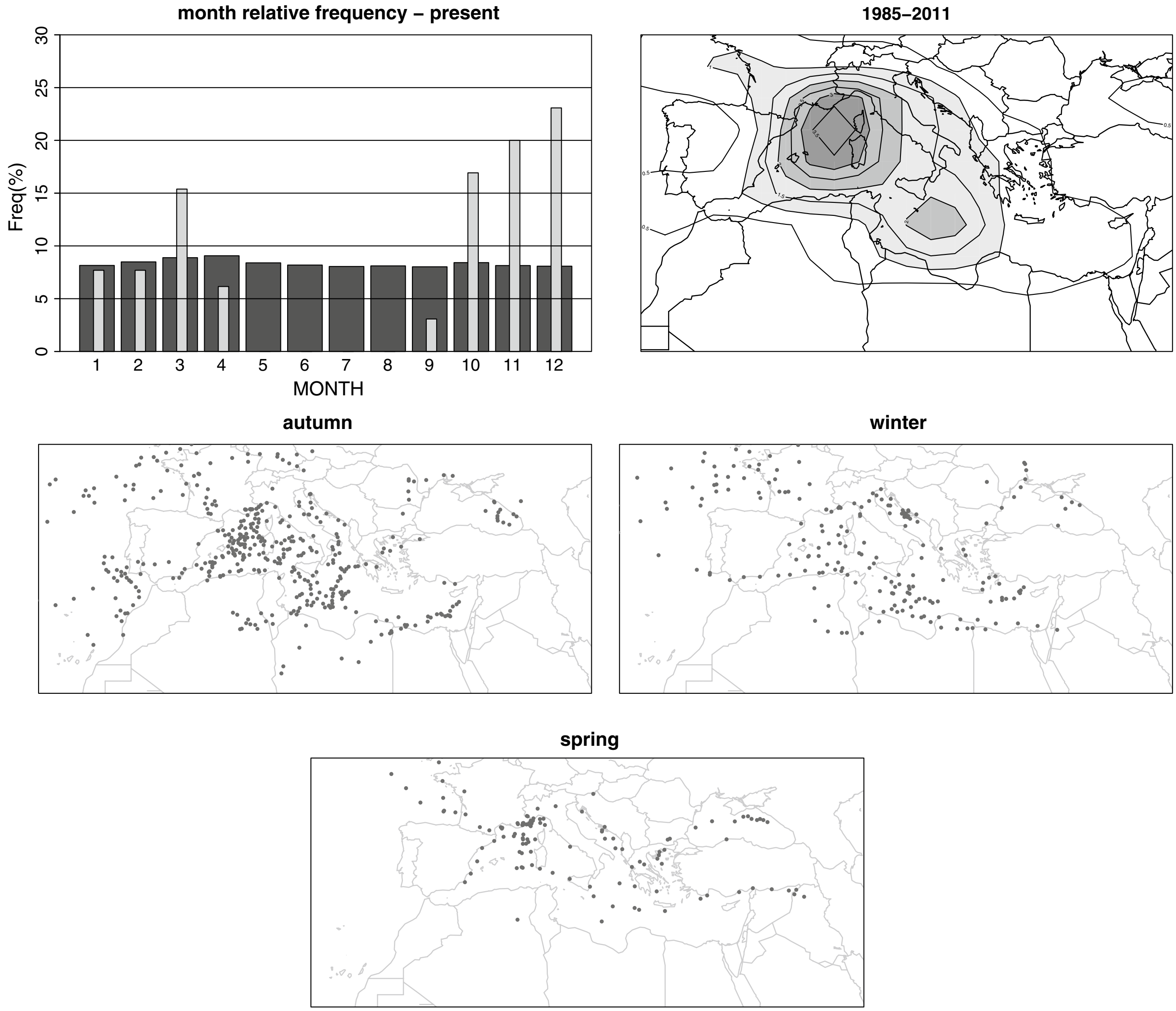

Fig. 7 Monthly distribution and geographical feature density of the minimum pressure centers associated -in all or part of their lifetimes- to medicanes for the N512 HadGEM3 historical simulation. In the histogram, *dark bars* represent all the minimum pressure centers and *light bars* those associated to medicanes. In the geographical total distribution, contours every 0.5 events per *box* of 2.25° ×2.25°, starting at 0.5

Table 1 Total number of events counted by the objective tracking algorithm

	Minumum pressure centers	Number of cyclones	Medicane cyclone centers	Number of medicanes
1985–2011	147,441	45,013	826	65
2085–2111	145,275	44,291	716	44

"Minimum pressure centers": number of MSLP minima accompanying the detected vorticity centers; "Number of cyclones": number of different cyclone tracks in which the mslp minima are grouped; "Medicane cyclone centers" and "Number of medicanes": the subset of the events presenting a medicane phase.

analyse in the vicinity of the track. By inspecting the maximum near surface wind speed associated with medicanes (its cyclone dynamical intensity), we find a slight tendency towards an intensification of medicanes under future climate conditions. For each medicane, the wind speed intensity is evaluated by considering the mean of the three maximum values of surface wind speed associated with the track. Using this approach, the mean wind speed intensity of medicanes is found to be $20.4\,\mathrm{m\,s^{-1}}$ in the present climate and $21.3\,\mathrm{m\,s^{-1}}$ in the future scenarios (see Table 2). The significance of the difference according to the Welch t test (Welch 1947) is low (p value 0.16), but it is consistent

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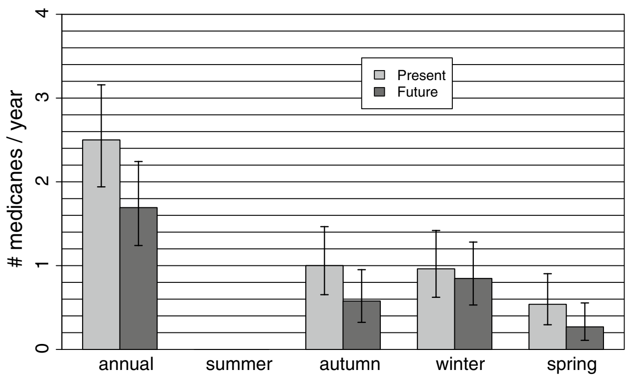

Fig. 8 Annual and seasonal distribution of medicane events for the N512 HadGEM3 historical (*light bars*) and future climate (*dark bars*) simulations, showing Poisson distribution confidence intervals. Summer intervals are omitted because no medicanes are detected

with findings from previous studies (Cavicchia et al. 2014b; Romero and Emanuel 2013). Furthermore, the lifetime of the medicane tracks tends to increase in the future scenario from an average of 16–20 timesteps (see Table 3), and the number of time steps associated with intense surface wind speeds (Bft $\geq$ 8) also increases from 5.4 to 7.2 time steps (significant at the 10 % level according to the Welch *t* test).

Figure 9 shows the spatial distribution of all the tracks associated with medicane events under the present and future climate simulations. Each dot represents a track point and its color the maximum surface windspeed associated with the track at that point. To analyse the medicane risk due to high wind speed, the contours represent the density distribution of the track points associated with strong wind speeds (Bft > 8). Although the total number of medicanes is projected to decrease in the future climate, the frequency of medicanes associated with intense wind speed becomes more frequent in the corridor between the Gulf of Genoa and south of Sicily. For example, in the Gulf of Genoa, the maximum density of medicanes in the historical simulation is about 34 cyclone centers per century per grid box of $2° \times 2°$, while in the future this maximum density increases to about 51 cyclone centers per century. The other maximum located to the south of Sicily increases from 10 to 28 cyclones/(century, $2° \times 2°$ grid box). This suggests a possible future enhanced medicane risk in these areas.

5 Conclusions

Medicanes are rare but extreme mesoscale cyclones with tropical characteristics which develop over the Mediterranean Sea. A new medicane risk assessment taking into account the effects of climate change has been obtained in this work using a 25 km high resolution version of the Met Office HadGEM3 global climate model performed as part of the UPSCALE project. The high horizontal resolution allows medicane-like features to be represented. An objective tracking algorithm is applied to the model output, so that future changes in medicane frequency and intensity can be investigated. This study complements previous results based on regional downscaling of "low" resolution GCMs, like Cavicchia et al. (2014b) and Romero and Emanuel (2013).

The N512 HadGEM3 historical simulation has an adequate representation of general Mediterranean mesoscale cyclones. The number of identified mesoscale cyclones is similar to that found in two previous regional climatologies from the MEDEX project. The mesoscale cyclone spatial

Table 2 Statistical results (1Q: first quartile; mean: mean value; and 3Q: third quartile) for the three most intense timesteps during the medicane phase: minimum mslp (hPa), maximum vorticity (10^{-5} s^{-1}) and maximum wind speed (m s^{-1})

	MSLP (hPa)			Vorticity (10^{-5} s^{-1})			Wind speed (m s^{-1})		
	1Q	Mean	3Q	1Q	Mean	3Q	1Q	Mean	3Q
Present	985.1	**992.7**	1001.0	7.8	**9.6**	11.3	18.1	**20.4**	23.3
Future	993.4	**998.0**	1004.0	7.6	**9.9**	12.2	19.2	**21.3**	23.6
p value (pres; fut)		<0.01*			**0.61**			**0.16**	

Mean values are highlighted in bold

Table 3 Statistical results (1Q: first quartile; mean: mean value; and 3Q: third quartile) for lifetimes steps (every 6 h) for cyclones presenting a medicane phase, and the duration of their strong wind speeds (Bft $\geq$ 8)

	Cyclone lifetime steps ($\times$6 h)			Cyclone lifetime steps (Bft $\geqslant$ 8; $\times$6 h)		
	1Q	Mean	3Q	1Q	Mean	3Q
Present	11.0	**16.2**	21.0	2.0	**5.4**	8.0
Future	10.0	**20.0**	23.2	3.8	**7.2**	9.2
p value (pres; fut)		**0.13**			**0.08**	

Mean values are highlighted in bold

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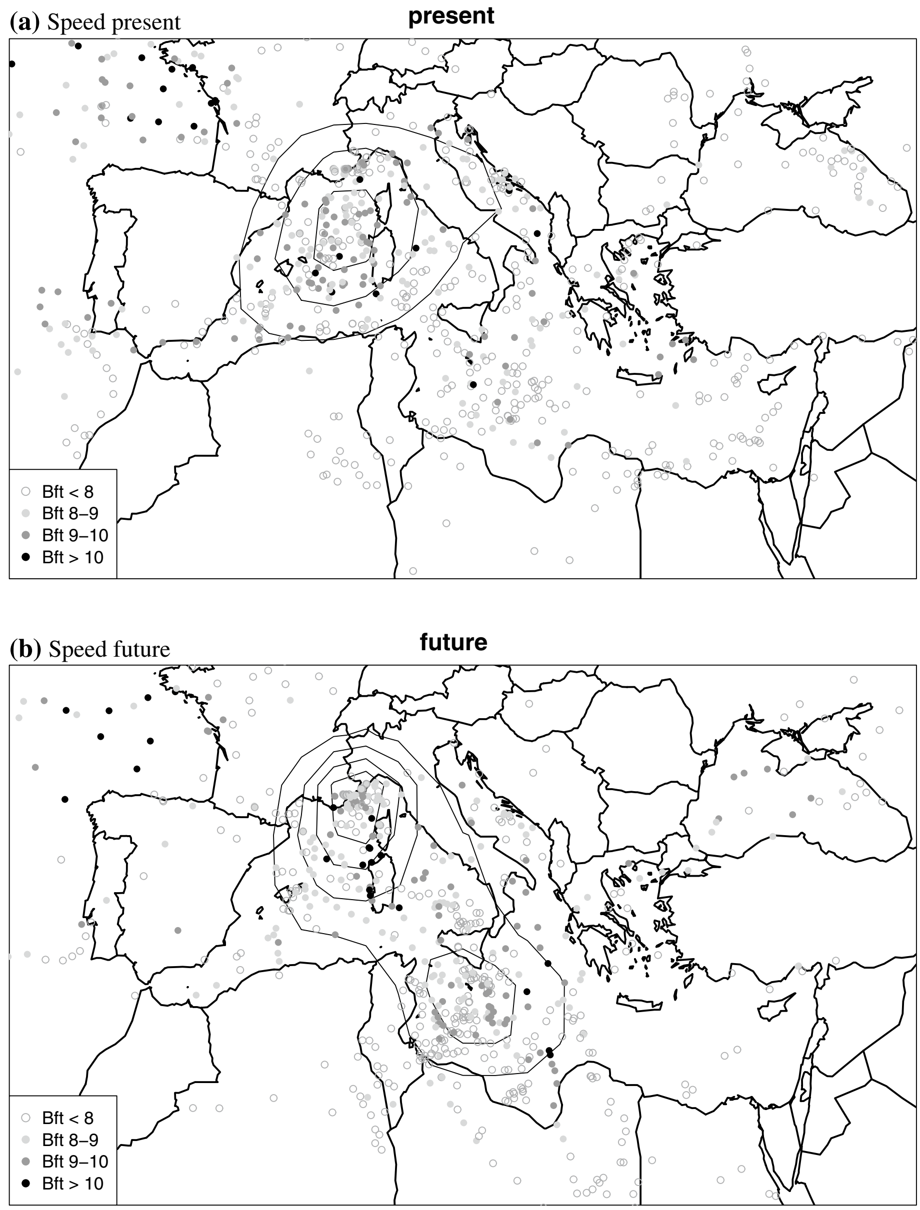

Fig. 9 Spatial distribution of medicanes in the N512 HadGEM3 historical and future climate simulations as function of maximum surface wind speed (Beaufort scale). Contours every 10 intense medicane cyclone centers (with Bft $\geq$ 8) per century in an area of 2° $\times$ 2°. Note some degree of overlap between different medicane positions (*dots*) **a** speed present, **b** speed future

distribution is also qualitatively consistent with these climatologies, although some discrepancies in the Eastern Mediterranean basin are identified. However, this is not a known active area for medicanes.

The climatology of medicanes identified in the present day climate simulations reveals that the N512 HadGEM3 model is able to represent very intense cyclones with a warm core (the main features of medicanes). The temporal frequency and spatial distributions are also consistent with previous climatologies derived using different methods and data. Rapid intensification and strong surface wind speeds are evident for selected examples.

Future changes in the intensity and frequency of medicanes were assessed by applying the tracking method to a future N512 HadGEM3 simulation forced by the RCP8.5 emission scenario. The N512 HadGEM3 model projects that the number of medicanes will decrease in number (about −30%) but increase in lifetime and, possibly, wind speed under future climate conditions. Overall, this may lead areas such as the Gulf of Genoa and south of Sicily to be more at risk of the high windspeed generated by medicanes under future climate conditions. The general trend towards fewer medicanes but an enhanced risk of extreme winds is a common result in the existing literature on medicanes and climate change. This tendency would be a consequence of the projected increase of anticyclonic conditions over the Mediterranean region (e.g. Lionello et al. 2008). Although less frequent in the future, mid-tropospheric cold air intrusions associated with mid-latitude troughs would result in more effective environments for medicane

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intensification owing to the significantly warmer Mediterranean waters.

Finally, future research includes looking at other runs of the N512 HadGEM3 and a multi-model response using a very large ensemble of high resolution GCM outputs (e.g. those available from the new project "PRIMAVERA") to confirm the results found in this study, which used a limited set of simulations. In addition, it is worth investigating alternative methods to analyse the tropical characteristics of Mediterranean lows, as the cyclone phase diagram technique (Hart 2003). This method evaluates if a cyclone is symmetric and has a warm core, two of the main characteristics of TCs and medicanes. However, this approach has not been sufficiently tuned for the medicane events. There are no consensual criteria, for instance, on which isobaric levels should be evaluated for medicanes and also on the threshold value of the so-called B parameter used to assess the symmetry of the cyclone.

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