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Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble:impact of ocean-atmosphere coupling and increased resolution

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Abstract:

Medicanes are cyclones over the Mediterranean Sea having a tropical-like structure but a rather small size, for which the sea-atmosphere interaction plays a fundamental role, differently from the extra-tropical cyclones where the baroclinic instability mechanism prevails. High resolution and ocean-atmosphere coupled RCM simulations performed in MedCORDEX and EURO-CORDEX projects are used to analyze the ability of RCMs to represent the observed characteristics of medicanes, and the impact of increased resolution and air-sea coupling on their simulation. An observational database based on satellite images combined with high resolution simulations (Miglietta et al. 2013) is used as the reference for evaluating the simulations. The simulated medicanes do not coincide in general on a case-by-case basis with the observed medicanes. The main exception are high-intensity observed medicanes with a relatively long duration of the phase with tropical characteristics, which are better replicated in simulations. Thus, the evaluation should be considered in a statistical sense.

The spatial distribution of medicanes is generally well simulated, while the monthly distribution reveals the difficulty of simulating the first medicanes appearing in September after the summer minimum. Increased resolution has a systematic and generally positive impact on the frequency of simulated medicanes, while the general underestimation of their intensity is not corrected by most increased resolution runs. The better simulation of intensity in a few models suggests that model formulation is more important than reducing the grid spacing alone.

A negative intensity feedback is frequently the result of air-sea interaction for tropical cyclones in other basins. The introduction of air-sea coupling in the present simulations has a limited overall impact on medicane frequency and intensity, but it produces an interesting seasonal shift of the simulated medicanes from autumn to winter. This fact, together with the analysis of two contrasting particular cases, indicates that the negative feedback could be limited or absent in certain situations. We suggest the possibility that the effects of air-sea interaction on medicanes depend on the oceanic mixed layer depth, which would increase the interest of applying ocean-atmosphere coupled RCMs for climate change analysis of this kind of cyclones.

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Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean-atmosphere coupling and increased resolution

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Abstract

Medicanes are cyclones over the Mediterranean Sea having a tropical-like structure but a rather small size, for which the sea-atmosphere interaction plays a fundamental role, differently from the extra-tropical cyclones where the baroclinic instability mechanism prevails. High resolution and ocean-atmosphere coupled RCM simulations performed in MedCORDEX and EURO-CORDEX projects are used to analyze the ability of RCMs to represent the observed characteristics of medicanes, and the impact of increased resolution and air-sea coupling on their simulation. An observational database based on satellite images combined with high resolution simulations (Miglietta et al. 2013) is used as the reference for evaluating the simulations. The simulated medicanes do not coincide in general on a case-by-case basis with the observed medicanes. The main exception are high-intensity observed medicanes with a relatively long duration of the phase with tropical characteristics, which are better replicated in simulations. Thus, the evaluation should be considered in a statistical sense.

The spatial distribution of medicanes is generally well simulated, while the monthly distribution reveals the difficulty of simulating the first medicanes appearing in September after the summer minimum. Increased resolution has a systematic and generally positive impact on the frequency of simulated medicanes, while the general underestimation of their intensity is not corrected by most increased resolution runs. The better simulation of intensity in a few models suggests that model formulation is more important than reducing the grid spacing alone.

A negative intensity feedback is frequently the result of air-sea interaction for tropical cyclones in other basins. The introduction of air-sea coupling in the present simulations has a limited overall impact on medicane frequency and intensity, but it produces an interesting seasonal shift of the simulated medicanes from autumn to winter. This fact, together with the analysis of two contrasting particular cases, indicates that the negative feedback could be limited or absent in certain situations. We suggest the possibility that the effects of air-sea interaction on medicanes depend on the oceanic mixed layer depth, which would increase the interest of applying ocean-atmosphere coupled RCMs for climate change analysis of this kind of cyclones.

1. Introduction

Medicanes (Mediterranean tropical-like cyclones) are a particular kind of cyclones that are observed sporadically over the Mediterranean Sea. Their diameter is rather small, typically less than 300 km and they present a generally symmetrical cloud structure around a cloudless eye (Fita et al. 2007), which points to tropical characteristics like a warm core and a predominant role of air-sea fluxes and convection in their development and maintenance. They form from baroclinic cut-off lows, developing a warm core through tropical transition (Emanuel 2005; Chaboureau et al. 2012). Medicanes can produce large damages due to the combination of intense winds and heavy precipitation. Observed cases of tropical-like cyclones in the Mediterranean region have been analyzed in detail (Pytharoulis et al. 2000; Reale and Atlas 2001; Homar et al. 2003; Moscatello et al. 2008).

Cyclones with partially tropical characteristics occur in other basins of the world. As a few examples, subtropical cyclones have been observed in the Atlantic Ocean (Guishard et al. 2009; Evans and Braun 2012; González-Alemán et al. 2015) or in the Pacific Ocean (Garde et al. 2010). There is no clear-cut separation between tropical and extratropical cyclones. Hart (2003) developed a classification method, the cyclone phase space analysis, in which the different types of cyclone form a continuum, and transitions between extra-tropical and tropical cyclones are integrated in a smooth way. Medicanes can attain fully-tropical characteristics during their lifetime, but this tropical phase is generally rather short (Miglietta et al. 2013).

The small size of medicanes and the sparse data available over the sea, where they develop, complicate the analysis of their climatological characteristics. Reanalysis data are too coarse for detecting and characterizing medicanes adequately. This has led to the use of satellite data as the main way of obtaining databases of medicanes (Tous and Romero 2013). Miglietta et al. (2013) combined satellite data and high resolution limited area meteorological model simulations for describing additional aspects of medicanes like their warm core structure and low level windspeed. A long-term climatology has been derived by Cavicchia et al. (2013) through dynamical downscaling of six decades of reanalysis, applying a regional climate model (RCM) with spectral nudging. The spatial distribution of medicanes is very similar in all climatologies, with two maxima over the Western Mediterranean and the Ionian Sea. This distribution differs clearly from the most frequent extratropical Mediterranean cyclones. The seasonal distribution shows the highest activity in autumn and winter, while very little medicanes are seen during summer, despite the high sea surface temperature (SST) in this season. The frequency of medicanes depends on the selection criteria, ranging from 0.5 to about 1.5 medicanes per year in the three indicated databases.

The future variations of medicane characteristics due to climate change are a matter of concern. To this effect, RCMs have been used to downscale global climate model (GCM) scenarios (Gaertner et al. 2007; Cavicchia et al. 2014; Walsh et al. 2014). Romero and Emanuel (2013) have applied a statistical-deterministic method for increasing the medicane sample size. Tous et al. (2015) have used a high resolution global climate simulation to analyze future medicane changes. A consistent result is a frequency reduction of medicanes under future climate conditions, together with an intensity increase for the most intense medicanes.

Dynamical downscaling with RCMs has advantages, as they can offer high resolution results, which are fundamental for representing medicanes, and include feedbacks that can affect their development. One aim of the present study is to analyze the impact of ocean-atmosphere coupling on the simulation of medicanes. A possible effect of this coupling could be an intensity reduction, at least for the most intense cyclones. Air-sea coupling generates typically a negative feedback on the intensity of tropical cyclones, through vertical mixing of the oceanic column (Emanuel 1999). This can bring deeper cold water to the surface, reducing the sea surface temperature and in consequence the latent and sensible heat fluxes to the atmosphere, which play a key role in the intensification of medicanes.

Here we analyse the ability of RCMs to simulate medicanes, using a large multi-model ensemble of RCM simulations from EURO-CORDEX (Jacob et al. 2014) and Med-CORDEX (Ruti et al. 2015) projects. The use of many different models represents an advance over previous medicane simulation studies, and allows us to consider the uncertainty linked to RCM formulation differences. EURO-CORDEX and Med-CORDEX ensembles are particularly valuable for the analysis of medicanes, as they include high resolution (up to 10 km) and atmosphere-ocean coupled runs. This will allow us to assess the impact of increased resolution and air-sea coupling on the simulation of medicanes in RCMs. The present analysis can also contribute to improve the assessment of the effects of anthropogenic climate change on medicanes, in projections with RCMs.

2. Method and data

We have used a total of 29 simulations from Med-CORDEX and EURO-CORDEX projects, all nested in ERA-Interim reanalysis, with the exception of AWI simulations which have been nested in ERA-40 reanalysis and cover a much bigger domain, including the Atlantic tropical region. The following list indicates the institution acronym, followed by the RCMs used. The most relevant information for the purposes of the paper is included in brackets (coupled or uncoupled RCM; horizontal resolution in km), and the simulation periods are also shown:

- AWI/GERICS: REMO (uncoupled; 50, 25 and 18 km) and ROM (coupled; 50, 25 and 18 km (Sein et al. 2015)). Simulation periods: 1982-2001 (50 km runs), 1978-2001 (25 km runs), 1975-2001 (18 km runs)
- CNRM: ALADIN5.2 (uncoupled; 50 and 12.5 km (Colin et al. 2010; Herrmann et al. 2011)) and RCSM4 (coupled; 50 km (Sevault et al. 2014)). Simulation periods: 1979-2011 (ALADIN5.2 runs), 1980-2011 (RCSM4 run)
- ENEA: REGCM (uncoupled; 25 km (Artale et al. 2010)) and PROTHEUS (coupled; 25 km (Artale et al. 2010)). Simulation period: 1982-2010.
- GERICS: REMO (uncoupled; 50 and 12.5 km(Jacob et al. 2012)). Simulation period: 1989-2008.
- GUF: CCLM 4-8-18 (uncoupled; 50 and 10 km (Rockel et al. 2008; Kothe et al. 2014)). Simulation period: 1989-2008
- IPSL-INERIS: WRF (uncoupled; 50 and 12.5 km (Vautard et al. 2013)). Simulation period: 1989-2008
- IPSL: WRF3.1.1 (uncoupled; 50 km (Skamarock et al. 2008; Flaounas et al. 2013; Stéfanon et al. 2014)) and WRF3.1.1-NEMO (coupled; 50 km (Brossier et al. 2015)). Simulation period: 1989-2008

- KNMI: RACMO22E (uncoupled; 50 and 12.5 km (Meijgaard et al. 2012)). Simulation period: 1989-2008
- MET(Office): HadGEM3 (uncoupled; 50, 25 and 12.5 km (Moufouma-Okia and Jones 2014)). Simulation period: 1990-2010
- SMHI: RCA4 (uncoupled; 50 and 12.5 km (Kupiainen et al. 2011; Samuelsson et al. 2011)). Simulation period: 1980-2010
- UCLM: PROMES (uncoupled; 50, 25 and 12.5 km (Domínguez et al. 2010; Domínguez et al. 2013)). Simulation period: 1989-2008

As the aim of the study is to analyze the impact of high resolution and air-sea coupling on the simulation of medicanes, we have grouped the simulations in pairs of low/high resolution simulations and pairs of uncoupled/coupled simulations with the same atmospheric RCM. Multi-model ensembles of such simulation pairs are finally used for the evaluation of the RCM ability to simulate medicanes. The different simulations are identified combining the acronyms of the institution and the model plus the horizontal resolution in km (e. g., AWI-REMO-50).

The cyclone detection and tracking method of Picornell et al. (2001) is applied for detecting cyclones. This method is designed particularly for mesocyclones, and is therefore especially suited for the detection of medicanes. The detection of lows is based on sea level pressure (SLP), and wind at 700 hPa is used as an auxiliary variable for the tracking. We measure the cyclone intensity by the daily maximum surface wind. Only cyclones exceeding tropical storm intensity (17.5 m/s surface winds) are considered.

As medicanes have tropical characteristics, we use the cyclone phase space (CPS) method of Hart (2003), by which a cyclone is classified as tropical if it's thermally symmetric (it has no frontal structure) and it has a full-tropospheric warm core. These features are measured by 3 parameters: B, $-V_T^L$ and $-V_T^U$, derived from geopotential values between 900 and 300 hPa. B represents the thermal symmetry of the cyclone, with positive values above 10 m indicating an asymmetric (frontal) cyclone, and values below that threshold (around zero) indicating a symmetric (non-frontal) cyclone. The thermal wind parameters for the lower troposphere ($-V_T^L$) and the upper troposphere ($-V_T^U$) describe the warm or cold core structure of the cyclone. Positive values indicate a warm core and negative values a cold core. Due to the small diameters of medicanes, we have applied a radius of only 150 km around the low pressure center for CPS analysis.

Taking into account the huge amount of data to analyse and the highly time-consuming methods applied, we have limited our analysis to the months with higher medicane frequency. Medicanes appear more frequently in autumn and winter, so we have focused our analysis on the months from August to January. For the same reason, and also because of the unavailability of some needed fields with 6-hourly resolution, we use daily average values of the different variables, instead of 6-hourly values. This has the side effect of not allowing the calculation of the B parameter for cyclones lasting only 1 day. A sequence of at least two low centers is needed for calculating B. Due to this, we have not considered the B parameter for selecting tropical cyclones.

The medicane database developed by Miglietta et al. (2013), covering the 1999-2012 period, has been used as reference for evaluating the simulation results. In this database, observed medicane cases selected through satellite images are simulated with a high resolution model. Only those cyclones showing a fully tropical structure for at least 6 h are considered as medicanes. This criterion has been adapted for comparison with the daily data used here. For daily average data, a cyclone is considered to be a medicane if $-V_T^L > 0$ (lower warm core) and $-V_T^U > -10$ (upper warm core or nearly warm core). The latter value is an approximate threshold selected in order to classify as medicanes cyclones that have an upper warm core lasting less than 1 day. In what follows, the location of the medicanes corresponds to the points where the cyclones reach their maximum intensity with tropical-like characteristics.

3. Results and discussion

3.1 Simulation of observed medicanes

The generation mechanism of medicanes (tropical transition) is very complex, as shown for example by Davis and Bosart (2004) or Moscatello et al. (2008). It depends on synoptic features (an upper level cut-off low, vertical wind shear), on local air-sea interactions and on small-scale processes (convection developing around the location of the low and liberating latent-heat) that are parameterized in climate models. This combination of factors make the simulation of tropical transitions a challenging issue. It is not clear that climate-mode simulations can reproduce in a deterministic way the observed medicanes, as no reinitialization of atmospheric fields is done in the domain interior after the beginning of the simulation. Medicanes form well within the model domains, which means that their tropical characteristics are not directly transmitted through the lateral boundary conditions.

In order to analyze the correspondence between simulated and observed medicanes, we have compared their dates and locations. Some margin has been allowed in this comparison, so that simulated medicanes found within 10º of the observed location, or up to two days before or after the observed medicanes (if they form under the same cut-off low) have been considered as corresponding to the same case.

Table 1 shows the set of high-intensity medicanes (maximum surface winds above 25.5 m/s) and Table 2 the set of moderate-intensity medicanes (maximum surface winds between 17.5 and 25.5 m/s) registered in the reference database from Miglietta et al. (2013). The cases in which the models indeed simulate a medicane are indicated in red. There are rather few such matches between the two sets, as can be seen in Tables 1 and 2. This confirms a previous result obtained by Walsh et al. (2014) with one RCM, in which most of the simulated medicanes did not correspond to observed cases. They pointed to the stochastic processes dominating the formation of such small-size cyclones as a reason for this result.

In our study, there are additional possible reasons for the absence of correspondence between simulations and observations. The duration of the phase with tropical characteristics in the observed cases is generally limited to a few hours, which is below the time resolution available in the simulation outputs considered here. In this respect, it is noteworthy that medicanes with a longer persistence of tropical features are more frequently reproduced in the simulations. The medicane in December 2005 (reproduced as a warm-core cyclone by five simulations) had a tropical structure during 33 h, and reached maximum 10 m winds of 33 m/s, while the medicane in November 2011 had a tropical phase of 63h, and maximum 10 m winds of 32 m/s. This latter case is reproduced by all three available simulations (CNRM) as a medicane. Even the two lower resolution simulations with CNRM models are able to detect a fully tropical structure for 2 days. The November 2011 medicane shows a really remarkable reproducibility, compared to the other ones. No other simulation reached year 2011, so this case cannot be analyzed for other models.

A clear factor affecting the simulation of medicanes is their intensity. Lower-intensity medicanes (Table 2) are not replicated by most models. More coincidences between simulated and observed medicanes are found for higher-intensity medicanes (Table 1). Davis and Bosart (2004) distinguish two types of tropical transition, depending on the amplitude of the precursor disturbance: in transitions originated by strong extratropical cyclones, wind-induced surface heat exchange (WISHE; Emanuel (1987)) is the key process, while in cases where the precursor is a weak extratropical cyclone, this extra-tropical disturbance is an organizing factor for the convection, which must then experience self-organization to generate a self-amplifying cyclone. This could explain in part the different degree of reproducibility of some medicanes: the two cases cited above, that are better reproduced by the models, correspond to strong and large upper-level cut-off lows. In contrast, the medicane in September 2006 formed under a comparatively weak disturbance, and is not reproduced in most simulations. The coincident cases show no preference for a particular model configuration or resolution.

There are several possibilities for the absence of a simulated medicane. The simulated tropical transition could be only partial, resulting in a hybrid cyclone with warm and cold core parts. The simulated cyclone could maintain its original cold-core structure, or the simulated cyclone might not reach the threshold of 17.5 m/s (maximum surface wind) used in our detection method. We have examined these possibilities. Simulated cyclones with a hybrid structure are shown in grey, and simulated cyclones with a cold-core are marked in blue in Tables 1 and 2. An empty cell indicates that no cyclone with intensity above 17.5 m/s has been simulated.

Hybrid and cold-core cyclones are simulated much more frequently in cases of high-intensity observed medicanes than of moderate-intensity observed medicanes. It is clearly more likely that models simulate a cyclone corresponding to an actually observed medicane if the latter is intense. The case of IPSL-WRF311, which employs spectral nudging, is revealing in this aspect. All high-intensity medicanes are replicated by this model as cold-core, hybrid or warm-core cyclones; but only one out of five less intense medicanes are captured by it. The same happens with MET-HadGEM3-12 simulation. This behaviour is likely associated to the general underestimation of intensity in the simulations. Observed medicanes with intensity above 25.5 m/s are generally simulated as cyclones with intensities below this threshold, and observed medicanes with intensity between 17.5 and 25.5 m/s do not reach the 17.5 m/s threshold in many simulations. Another factor contributing to this could be the smaller size of the less intense observed medicanes, which limits the ability of the models to capture them. But the lack of clear differences between low and high resolution simulations in Tables 1 and 2, suggests that this is not a major factor.

The ability of models to simulate at least partially tropical characteristics also seems to depend on the intensity of observed medicanes. In Table 1 there are more hybrid and warm-core cyclones than cold-core cyclones in the simulations. The opposite is seen for the less intense medicanes, as a large majority of the simulated cyclones in Table 2 show a cold core.

The simulation domain is another factor affecting the reproduction of observed medicanes. The set of AWI/GERICS simulations stands out from the rest, as very few of the observed medicanes are detected in them. This is likely related to the domain used in that runs, which is much bigger than in other simulations and covers the whole Atlantic tropical area. The differences with the other REMO simulation are also likely due to the domain differences, as GERICS-REMO uses the (much smaller) EURO-CORDEX domain.

On the other hand, the models simulate medicanes that do not coincide in date with the observed ones, but occur in favorable environments for their development. A visual examination of the synoptic setting for several simulated intense medicanes indicates that they appear typically under observed cut-off lows. The different models also simulate different cases. These facts indicate that medicanes have a clear stochastic component, and the evaluation of their simulation in climate models should be made in a statistical sense. We analyze now several statistical measures for them.

3.2 Impact of increased resolution:

In order to adequately consider the effect of resolution on the simulation of medicanes, the most simple effect of resolution on cyclones intensity has to be removed first. As we are dealing with tropical-like cyclones, we will use the criteria presented by Walsh et al. (2007) for obtaining a resolution-dependent threshold for tropical storms, which have maximum surface winds above 17.5 m/s. Winds in tropical cyclones reach a maximum at a relatively small radius with respect to the cyclone center, decreasing rapidly with increasing distance from the center. Therefore, if we sample the winds using a larger grid spacing (less resolution), a smaller wind maximum will be seen. Following that paper, for the resolutions used in the present study, the threshold values for tropical storm intensity are 16.5 m/s (50 km grid spacing) and 17.5 m/s (12.5 km grid spacing). The application of the same method for hurricane intensity (33.5 m/s, corresponding to 65 knots) yields the curve of Fig. 1. The threshold values for this intensity are 31 m/s (50 km) and 33.5 m/s (12.5 km). Therefore, intensities of 16.5 m/s and 31 m/s in the low resolution simulations are respectively equivalent to intensities of 17.5 m/s and 33.5 m/s in high-resolution runs. Equivalent values for other intensities are obtained through a linear interpolation between those values.

Fig. 2 (upper panel) shows the yearly frequency of medicanes for the different low/high resolution pairs (most of them have 50/12.5 km grid spacings). There is a clear frequency increase with resolution, which is systematic (all models show it) and generally strong (in six out of ten models, the frequency increases nearly two times or more). Whereas most of the low resolution simulations underestimate the observed frequency of about 1 medicane/year found in our reference database (and even more the value of 1.5 medicanes/year in Cavicchia et al. (2013)), the high resolution simulations show an improvement, with values generally nearer to the observed value. There is a large spread among models, with appreciable overestimations and underestimations of the observed frequencies.

Regarding the effect of resolution on intensity, we have clustered the distribution in two groups (moderate intensity: 17.5-25.5 m/s, and high intensity: above 25.5 m/s). The small number of medicanes in many simulations hinders the use of percentiles, obtained directly from the simulated values, for analysing intensity changes. Fig. 2 (lower panel) shows the number of high-intensity medicanes per year for each pair of low/high resolution runs. The reference database gives a value of about 0.5 high intensity medicanes per year. The strong underestimation of high intensity medicanes in the 50 km simulation (with values between 0 and 0.2 medicanes per year) is not corrected by many of the high resolution simulations. Only three high-resolution simulations show a strong increase of high-intensity medicanes. The average simulated intensity (not shown) confirms the difficulties of most models in reproducing high values of intensity: the negative intensity bias found in low resolution simulations (the observed value is of about 27 m/s, while the simulated values lie between 19 and 22 m/s) is not appreciably improved by many of the increased resolution models. Intensity changes seem to be strongly model-dependent, and increased resolution alone does not improve this aspect of the simulated medicanes.

The spatial distribution of medicanes is shown in Table 3. In the reference database, the highest number of medicanes are found in the central area (around Italy and to the south of it), followed by the western area. The lowest number of medicanes are detected over the eastern Mediterranean. Other observed databases like the one of Tous and Romero (2013) show similar spatial locations. The RCMs reproduce well the eastern minimum, and on average the high resolution runs improve the distribution between western and central Mediterranean area. The north-south distribution is well captured by both low and high resolution simulations. An important aspect of observed medicanes is that their distribution is clearly displaced to the south when compared to the spatial distribution of all Mediterranean cyclones, which has a strong maximum around the Gulf of Genoa. Simulated medicanes also reproduce well this displacement to the south with respect to the typical baroclinic cyclones.

Table 3 also shows the monthly distribution of medicanes. The reference database shows a clear autumn maximum (September and October). The percentage of winter medicanes is here smaller than in other observed climatologies like Tous and Romero (2013) or Cavicchia et al. (2013), which cover earlier periods than our reference database. Among the medicanes observed in January is the well known case of January 1995 (Pytharoulis et al. 2000). As our simulations include the 90's and some also the 80's, the appearance of January medicanes should be considered as positive. An increase in the relative percentage of winter medicanes is found with higher resolution.

On the contrary, the high observed percentage of September medicanes is not well captured by the models. No improvement can be seen for September medicanes in high resolution runs. Model formulation seems to be more important than resolution for the representation of these medicanes, as a few models are able to simulate them better. A likely reason for the difficulties of models in the representation of September medicanes is their intensity, as they are generally among the less intense medicanes (as can be seen from the division in Tables 1 and 2). The intensity of the baroclinic disturbance originating them is also frequently weaker than in other autumn or winter months, which could complicate their simulation.

3.3 Impact of ocean-atmosphere coupling:

The frequency of medicanes for the pairs of coupled/uncoupled runs is presented in Fig. 3 (upper panel). No clear frequency change is found between uncoupled and coupled runs. The changes are generally small and of differing signs. The effect of coupling on the number of high-intensity medicanes can be seen in the lower panel of Fig. 3. Some tendency towards a lower number of intense medicanes is found in coupled simulations, but changes are rather small.

The hypothesis that air-sea interaction in the coupled runs can produce a negative feedback is not clearly confirmed. The low resolution of several models could be a reason for the lack of clear changes. A different study by Akhtar et al. (2014) found that coupled runs improved the simulation of medicanes in the case of high resolution (about 10 km), but not for lower resolutions. The general underestimation of intensity in simulated medicanes can also limit the effect of coupling, as its effect should be stronger with higher intensities of cyclones.

Aggregate values like the frequency and intensity statistics presented before might be hiding the underlying mechanisms. Interesting results are found if we separate the medicanes spatially and temporally. Fig. 4 shows the number of medicanes per year north and south of 38N. The changes in the northern part of the Mediterranean Sea depend on the model. But the variations in the southern part of the Mediterranean Sea are more systematic: five of the six simulations simulate less medicanes in this area in the coupled runs. The only exception is ENEA coupled simulation, in which a strong increase of medicanes is simulated in the southern part. Relative values shown for the ensemble mean in Table 3 indicate also an overall reduction of medicanes in the southern part in the coupled simulations.

Table 3 shows another remarkable result: the relative monthly distribution of medicanes shows a distinct reduction of autumn medicanes and a corresponding increase of winter medicanes in the coupled runs. The strongest change occurs for January medicanes, with an increase from 24% in the uncoupled runs to 33% in the coupled runs. There is even a rise in the absolute number of January medicanes for ENEA-PROTHEUS and AWI-ROM coupled models. On the other hand, the absence of September medicanes is not corrected by the use of coupling.

The opposite changes in autumn and winter medicanes in the coupled runs might be related to the oceanic mixed layer depth. As shown by D'Ortenzio (2005), the Mediterranean mixed layer is very shallow in summer, and reaches the maximum depth in winter. Mixed layer depth can control the intensity of the negative intensity feedback due to air-sea coupling. If the oceanic mixed layer is shallow, cold waters from below the mixed layer will be lifted to the surface due to air-sea interaction, reducing the SST. But if the mixed layer is deep, the emerging deeper water will maintain basically the same SST, limiting or canceling the negative feedback. There are even cases where the air-sea feedback can be positive (Shay et al. 2000). Significantly, medicanes are not observed in summer, despite the higher SST values. They appear fundamentally in autumn, when SSTs are decreasing but the mixed layer depth is increasing, or in winter, when SSTs are low but mixed layer depth is at its maximum.

In order to clarify the impact of coupling and the possible influence of oceanic mixed layer depth, we have looked in more detail at two individual simulated cyclones that show an opposite behaviour with respect to intensity. The simulated cyclones are taken from CNRM-ALADIN52/RCSM4 pair of simulations. The first case is a cyclone simulated in December 1996: the uncoupled run generates a rather intense cyclone (23 m/s of maximum surface wind) with a full-tropospheric warm core, while the coupled run reduces strongly the intensity of the cyclone. This can be perfectly seen in the mean sea level pressure maps for 9/12/1996 (coupled run in the upper left panel, uncoupled run in the lower left panel) of Fig. 5. The corresponding SST maps show interesting differences. In the uncoupled run, there is a north-south temperature gradient, with the lowest SSTs at the northern Mediterranean coast. The simulated SSTs in the coupled run show a more complex mesoscale structure. Particularly, the lowest SSTs are not found right at the northern coast, but further south, precisely under the track of the simulated cyclone in the coupled run. The intensity differences can be explained well by the SST differences, as the cyclone in the uncoupled run moves over warmer waters. Mixed layer depth for the coupled run is shown in the upper right panel. The values are relatively low, if we compare them to January values (see Fig. 6).

The second case corresponds to January 1980. A medicane appears in the coupled simulation, but not in the uncoupled run as the warm core criteria are not met there. The intensity is higher in the coupled run (25.4 m/s of maximum surface wind) than in the uncoupled run (21.8 m/s). The location of the cyclone is similar in both runs, as shown in Fig. 6, but there are important differences in the SSTs. There is a tongue of comparatively warm water north of Algeria, at a longitude of about 6W, precisely under the initial part of the track of the cyclone (see Fig. 7 for the initial location of the cyclone). Mixed layer depth values are clearly higher than for the first case, and they show an interesting overlap with SST features. The relatively high SST tongue north of Algeria coincides with an area of relatively deep mixed layer, and a similar coincidence can be seen in the central part of the Mediterranean Sea, between Libya and Sicily. The two opposite cases indicate that the coupling can act differently depending on the distribution of SST, and that mixed layer depth might have some effect on mesoscale SST features.

4. Concluding remarks

We have analyzed multi-model ensembles of RCM simulations with respect to their ability to simulate medicanes (Mediterranean tropical-like cyclones). Medicanes are generated through tropical transition, which is a complex process including factors with a wide range of scales, from synoptic-scale upper level cut-off lows to small-scale convection. This complexity raises the following issue: can observed medicanes be reproduced in climate-mode simulations on a case-by-case basis? We have examined if the RCMs replicate the observed medicane cases through comparison with an observational-numerical database. Results indicate that in most cases, models generate medicanes at dates that are not coincident with actual medicanes. There are some exceptions to this, suggesting that the likelihood that the ability of an RCM to replicate an actual medicane is higher when the observed medicane has a long tropical phase and is intense. In agreement with the existence of two different types of tropical transition, suggested by Davis and Bosart (2004), the intensity of the precursor baroclinic disturbance also seems to be important for the reproduction of observed medicanes. This may explain in part the difficulties of RCMs for simulating September medicanes, as these medicanes originate typically from relatively weak cut-off lows.

There are several reasons why an actual medicane is not replicated by RCMs: a hybrid cyclone with a partially tropical structure is sometimes simulated, or the simulation maintains the cold core structure of the initial cyclone. In some cases, the simulated cyclones do not reach the minimum intensity (17.5 m/s) required for their detection. There is a general underestimation of medicane intensity, which is well illustrated by the case of a model applying spectral nudging: all high-intensity observed medicanes (with a maximum surface wind above 25 m/s) are reproduced by it as a cyclone above 17.5 m/s, but most lower-intensity cases are not detected in these simulations. The absence of coincidence (on a case-by-case basis) between climate simulations and observations can be expected due to the complicated genesis and structure of medicanes and their small size, and has been observed in previous studies (Walsh et al. 2014). As a consequence, the evaluation of medicanes in long climate simulations (without reinitialisation of the atmospheric fields) should be done in a statistical sense.

Pairs of low and high resolution runs and pairs of uncoupled and coupled runs have been compared to analyze the impact of resolution and coupling on the simulation of medicanes. The use of increased resolution shows a systematic and generally strong impact on the frequency of medicanes. The higher simulated frequency when the grid spacing is reduced represents an improvement in most cases. But unexpectedly, the negative bias in the intensity of medicanes is not corrected by most higher-resolution runs. The intensity seems to depend more on the model formulation than on resolution alone.

For tropical cyclones in other basins, air-sea interaction frequently produces a negative feedback on the intensity of cyclones, as the enhanced vertical mixing in the ocean under strong winds transports colder deep water to the surface. But if the oceanic mixed layer below the cyclone is deep, the negative feedback is inhibited. The lack of a clear overall effect of coupling on frequency or intensity of the simulated medicanes might be due to the appearance of such contradicting cases. A hint in this direction is provided by the analysis of two particular simulated cyclones, and the distinct seasonal shift of medicanes in the coupled simulations from autumn to winter supports this explanation. The limited number of simulated September medicanes could be also a reason for the limited effect of coupling. The oceanic mixed layer is very shallow in September, and the hypothesized negative intensity feedback should be clearer in this case.

The possible influence of oceanic mixed layer depth on the interaction between medicanes and the sea should be analysed in a detailed way in future studies. But in case it is confirmed, it could open interesting possibilities for the future evolution of medicanes, as projections of the Mediterranean mixed layer depth show important future changes which depend on the emissions scenario (Adloff et al. 2015). This would increase the interest of applying ocean-atmosphere coupled RCMs for climate change studies.

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TABLES:

	17-18/10 2003	3-6/11 2004	13-15/12 2005	26/9 2006	26/10 2007	4/12 2008	6-8/11 2011
AWI/GERICS-REMO-18							X
AWI/GERICS-ROM-18							X
AWI/GERICS-REMO-25							X
AWI/GERICS-ROM-25							X
AWI/GERICS-REMO-50							X
AWI/GERICS-ROM-50							X
CNRM-ALADIN52-12	blue		grey			blue	red
CNRM-ALADIN52-50	blue		grey			blue	red
CNRM-RCSM4-50	blue		grey			blue	red
ENEA-REGCM			grey				X
ENEA-PROTHEUS	blue		red				X
GERICS-REMO-12			red			blue	X
GERICS-REMO-50			blue		red	blue	X
GUF-CCLM4-10	blue	red	blue			blue	X
GUF-CCLM4-50						blue	X
INERIS-WRF-12			blue				X
INERIS-WRF-50			grey			grey	X
IPSL-WRF311	grey	blue	red	grey	blue	grey	X
IPSL-WRF311-NEMO	grey	blue	red	grey	blue	grey	X
KNMI-RACMO22E-12	grey	blue	grey			blue	X
KNMI-RACMO22E-50	blue		grey			blue	X
MET-HadGEM3-12	grey	grey	grey	blue	blue	blue	X
MET-HadGEM3-25		grey	grey		blue	blue	X
MET-HadGEM3-50		grey	grey		blue		X
SMHI-RCA4-12			grey				X
SMHI-RCA4-50							X
UCLM-PROMES-12	red		grey	grey			X
UCLM-PROMES-25	blue	grey	red			grey	X
UCLM-PROMES-50	blue		grey	grey		blue	X

Table 1: Coincidences between simulated cyclones and observed high-intensity medicanes (maximum winds > 25.5 m/s). Colors indicate the type of simulated cyclone: red indicates a warm-core, grey a hybrid and blue a cold-core cyclone. The dates are taken from Miglietta et al. (2013). The “X” indicates that year 2011 was not included in the simulation period of the corresponding models.

	13/09 1999	10-11/09 2000	9/10 2000	21/09 2004	17/10 2007
AWI/GERICS-REMO-18					
AWI/GERICS-ROM-18					
AWI/GERICS-REMO-25					
AWI/GERICS-ROM-25					
AWI/GERICS-REMO-50					
AWI/GERICS-ROM-50					
CNRM-ALADIN52-12					
CNRM-ALADIN52-50					
CNRM-RCSM4-50					
ENEA-REGCM					
ENEA-PROTHEUS					
GERICS-REMO-12					
GERICS-REMO-50					
GUF-CCLM4-10					
GUF-CCLM4-50					
INERIS-WRF-12					
INERIS-WRF-50					
IPSL-WRF311					
IPSL-WRF311-NEMO					
KNMI-RACMO22E-12					
KNMI-RACMO22E-50					
MET-HadGEM3-12					
MET-HadGEM3-25					
MET-HadGEM3-50					
SMHI-RCA4-12					
SMHI-RCA4-50					
UCLM-PROMES-12					
UCLM-PROMES-25					
UCLM-PROMES-50					

Table 2: As in Table 1, but for moderate-intensity observed medicanes (maximum winds between 17.5 and 25.5 m/s).

	Spatial distribution (%)					Monthly distribution (%)					
	West	Center	East	North	South	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.
Reference database	***33***	***50***	***17***	***67***	***33***	***0***	***33***	***33***	***17***	***17***	***0***
Low-resolution ensemble mean	52	33	15	67	33	1	4	25	33	19	18
High-resolution ensemble mean	42	45	13	64	36	1	5	17	34	22	21
Uncoupled ensemble mean	39	47	14	59	41	1	1	17	34	23	24
Coupled ensemble mean	47	41	12	65	35	1	2	10	26	28	33

Table 3: Relative spatial distribution of medicanes (percentage of total medicanes). Zonal division in 3 zones: Western Mediterranean (lon < 10E), Central Mediterranean (10E < lon < 24E) and Eastern Mediterranean (lon > 24E). Meridional division in 2 zones: North (lat > 38N) and South (lat < 38N). Monthly distribution of medicanes (percentage of total medicanes) from August to January. The results are shown for the ensemble means, for low/high resolution runs and uncoupled/coupled runs.

FIGURES:

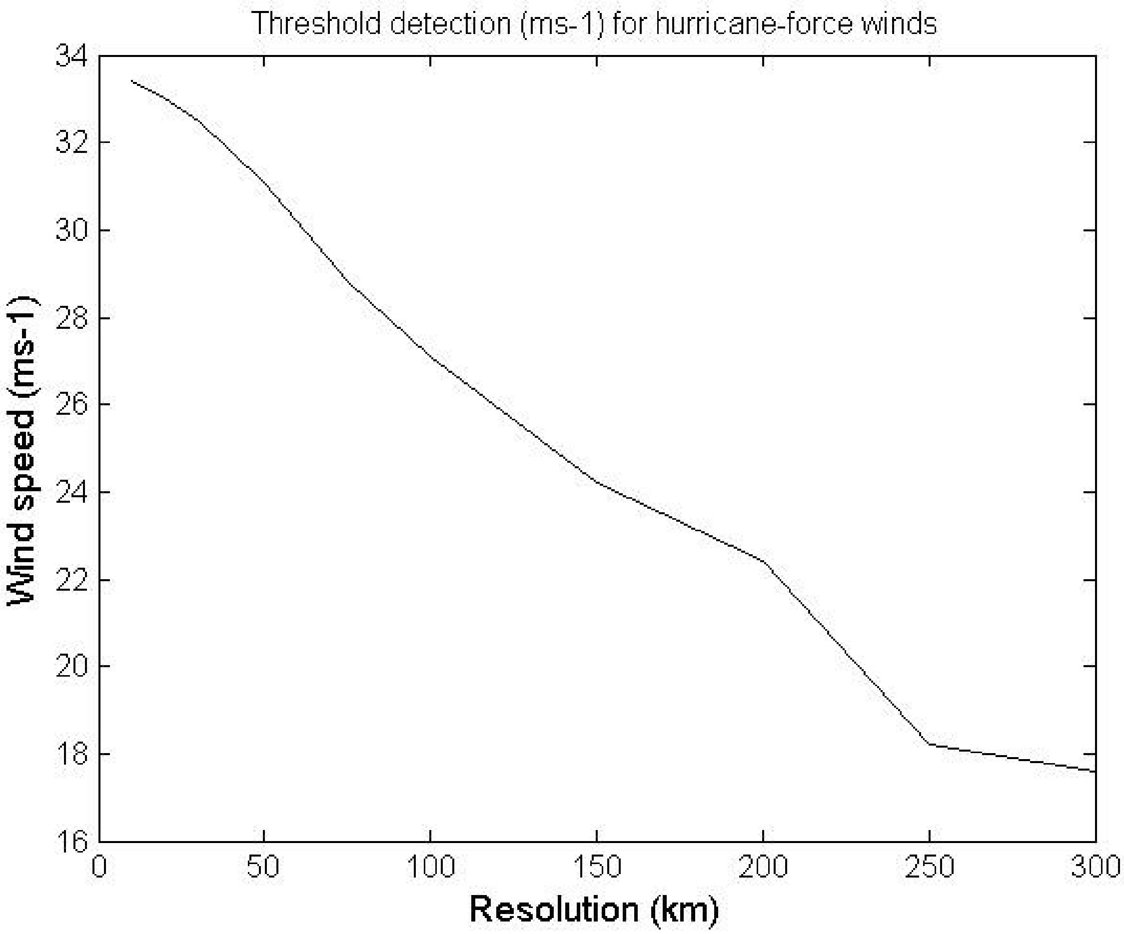

Figure 1: Windspeed threshold (m/s) for hurricane-force wind detection as a function of model resolution (km).

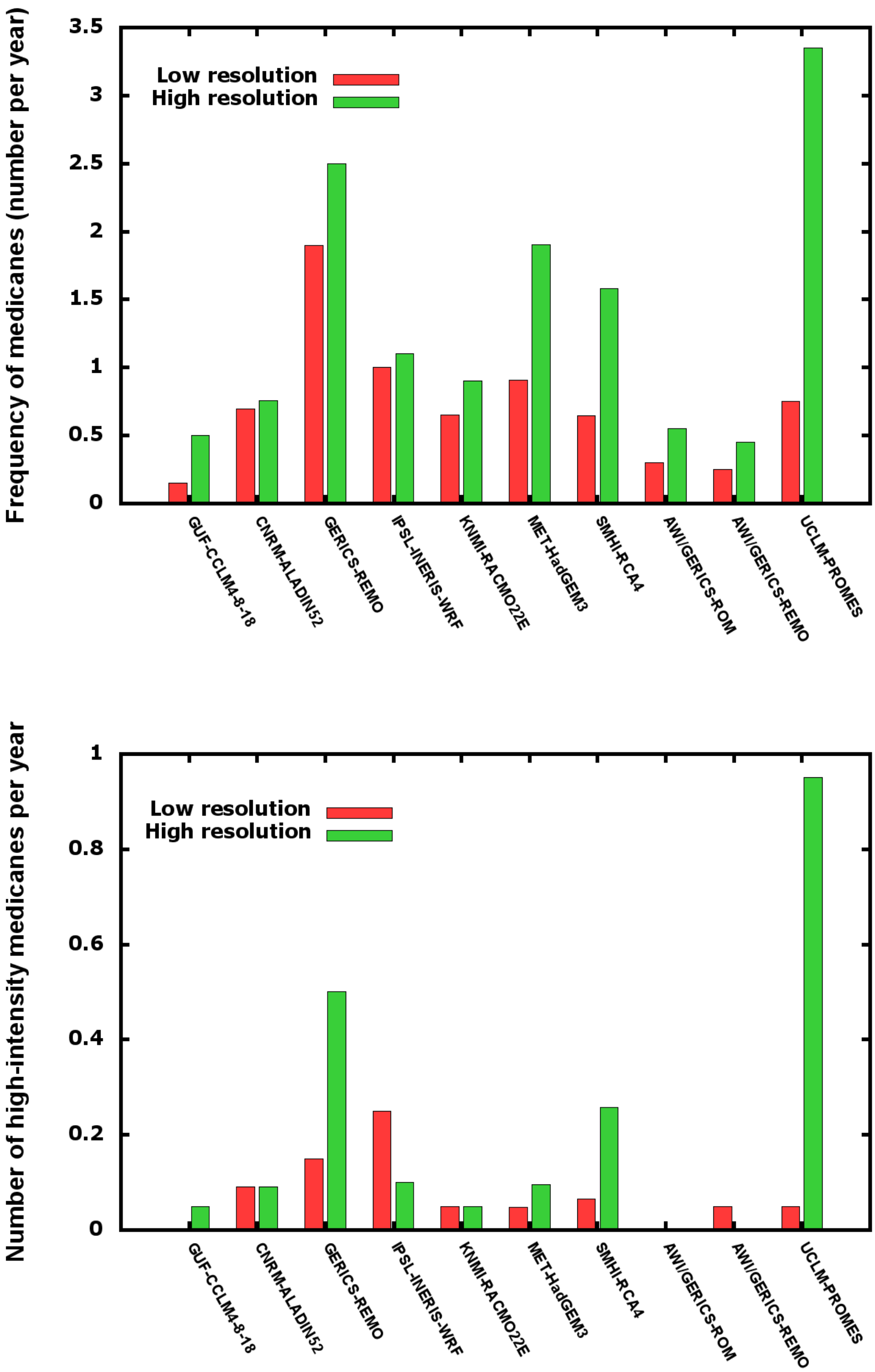

Figure 2: Upper panel: frequency of medicanes (cyclones per year) for pairs of lower resolution (red bars) and higher resolution simulations (green bars). Lower panel: number of high-intensity medicanes (above 25.5 m/s) per year.

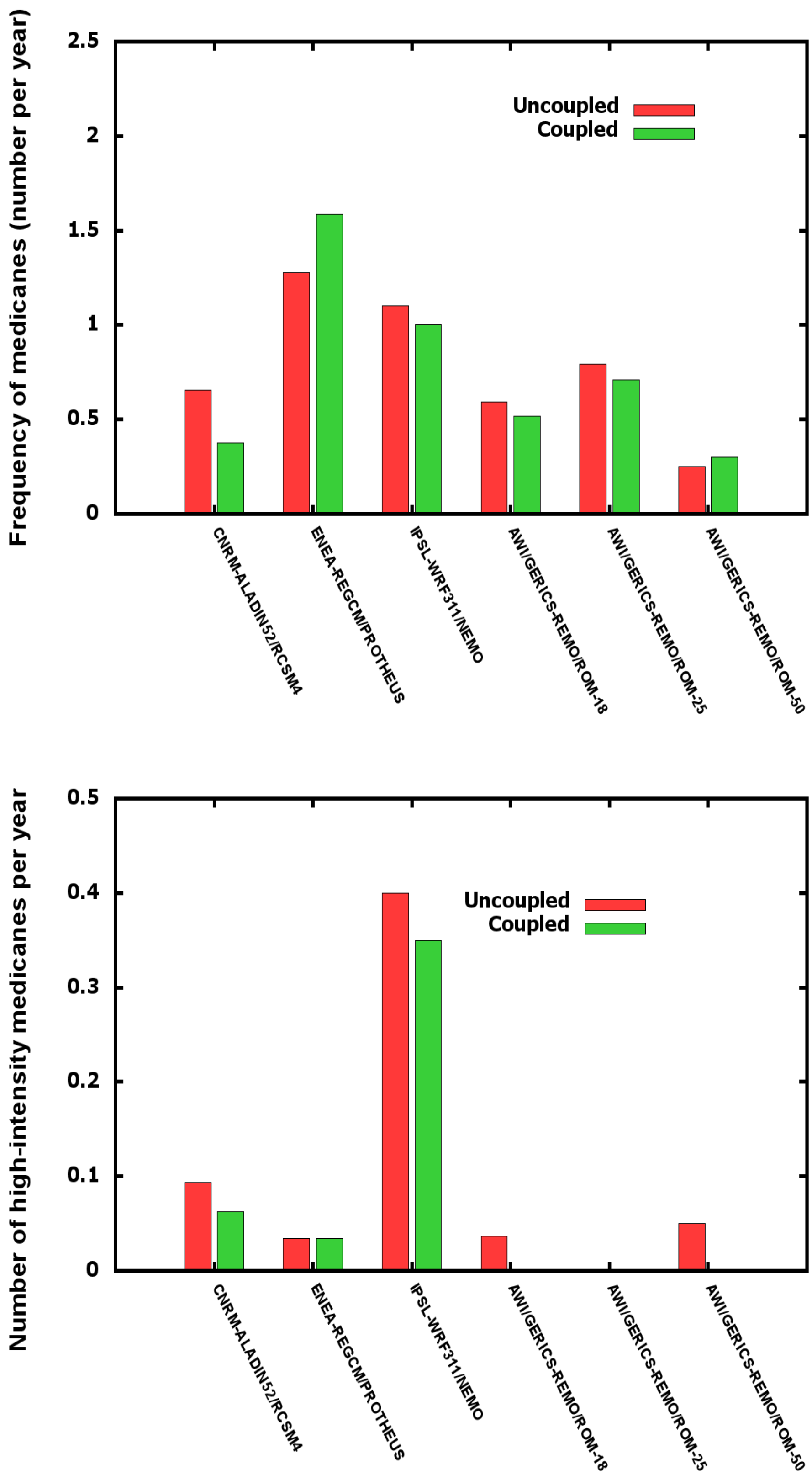

Figure 3: As in figure 2, but for pairs of uncoupled (red bars) and coupled (green bars) simulations.

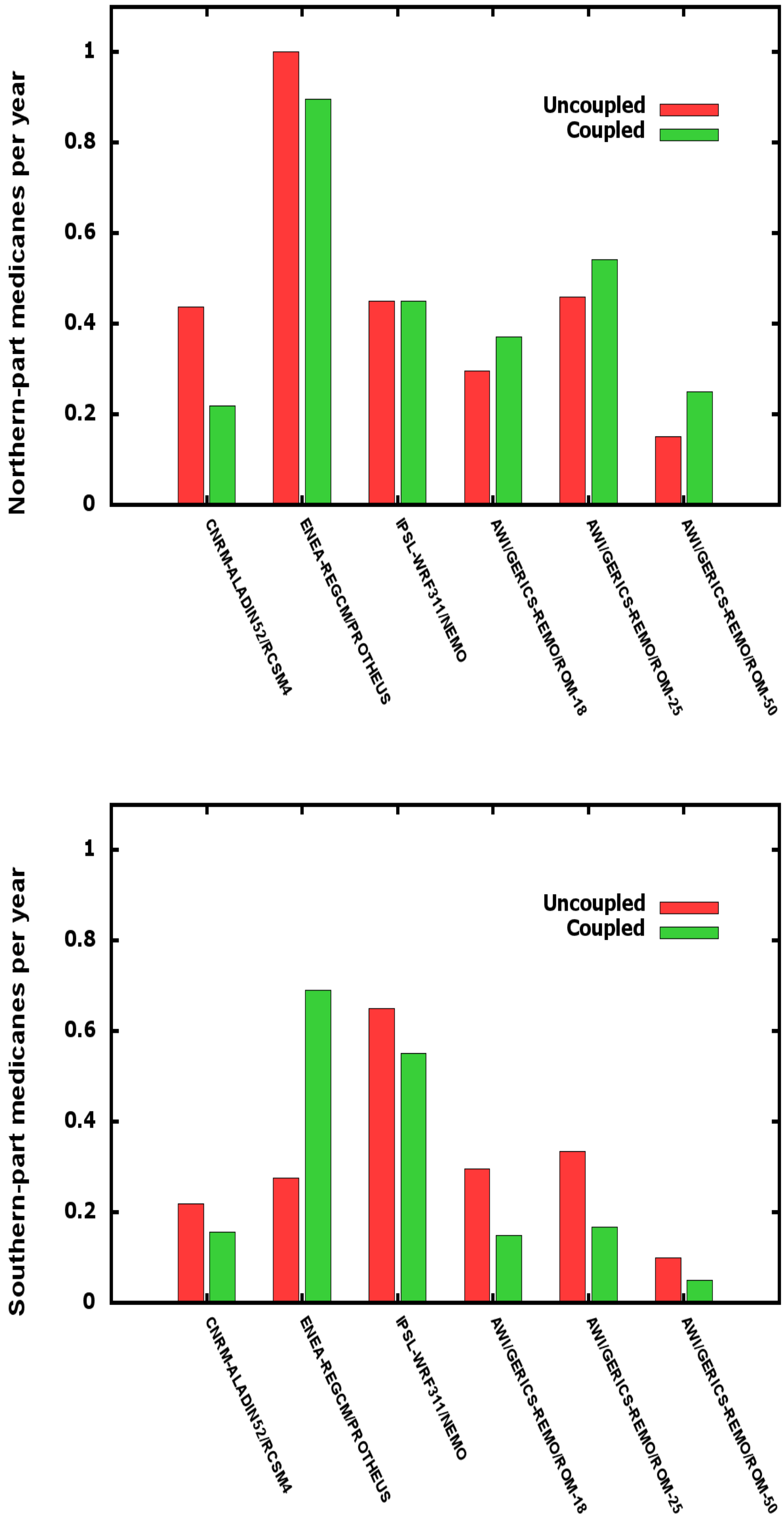

Figure 4: Number of medicanes per year, north of 38N (upper panel) and south of 38N (lower panel), for pairs of uncoupled and coupled simulations.

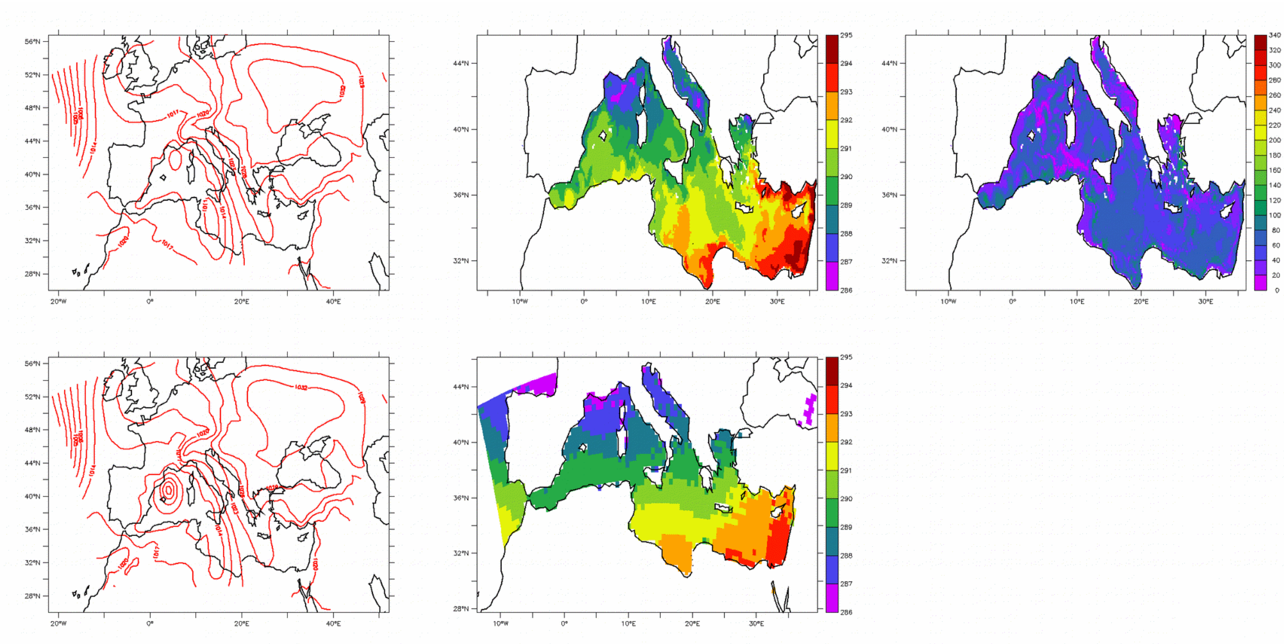

Figure 5: Simulated cyclone of 9/12/1996. Mean sea level pressure (hPa) for coupled run (CNRM-RCSM4; upper-left panel) and for uncoupled run (CNRM-ALADIN52-50; lower-left panel). Sea surface temperature (K) for coupled run (upper-middle panel) and for uncoupled run (lower-middle panel). Oceanic mixed layer depth (m) for coupled run (upper-right panel).

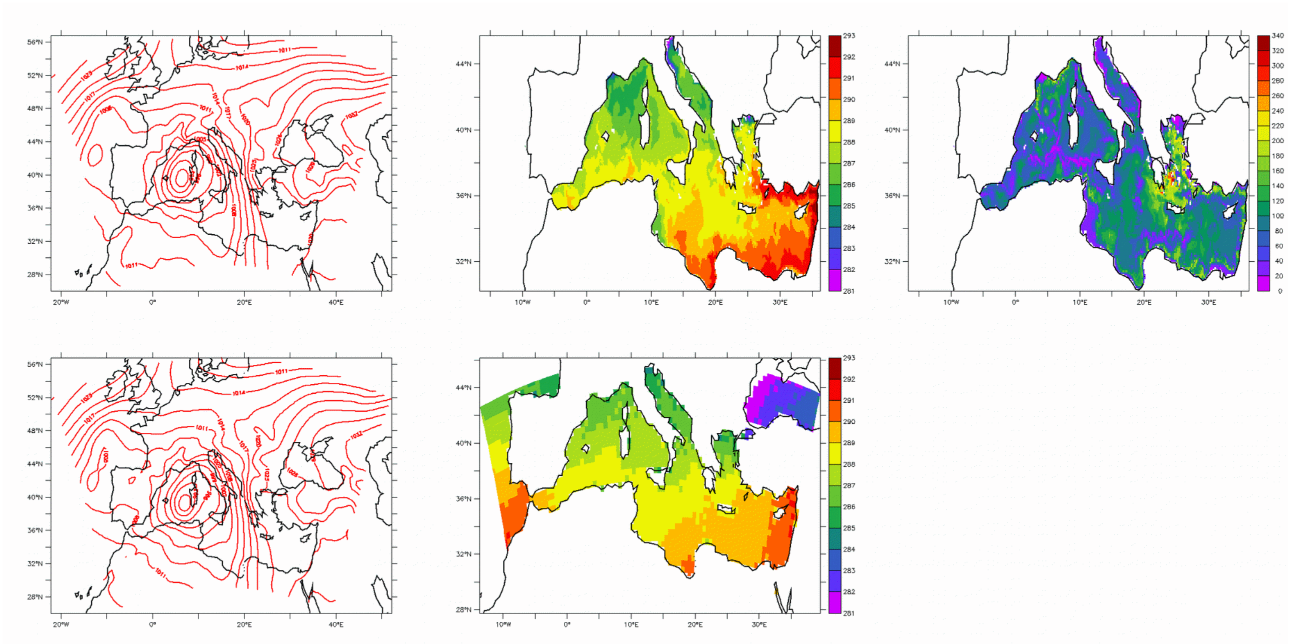

Figure 6: As in figure 5, but for the simulated cyclone of 15/01/1980.

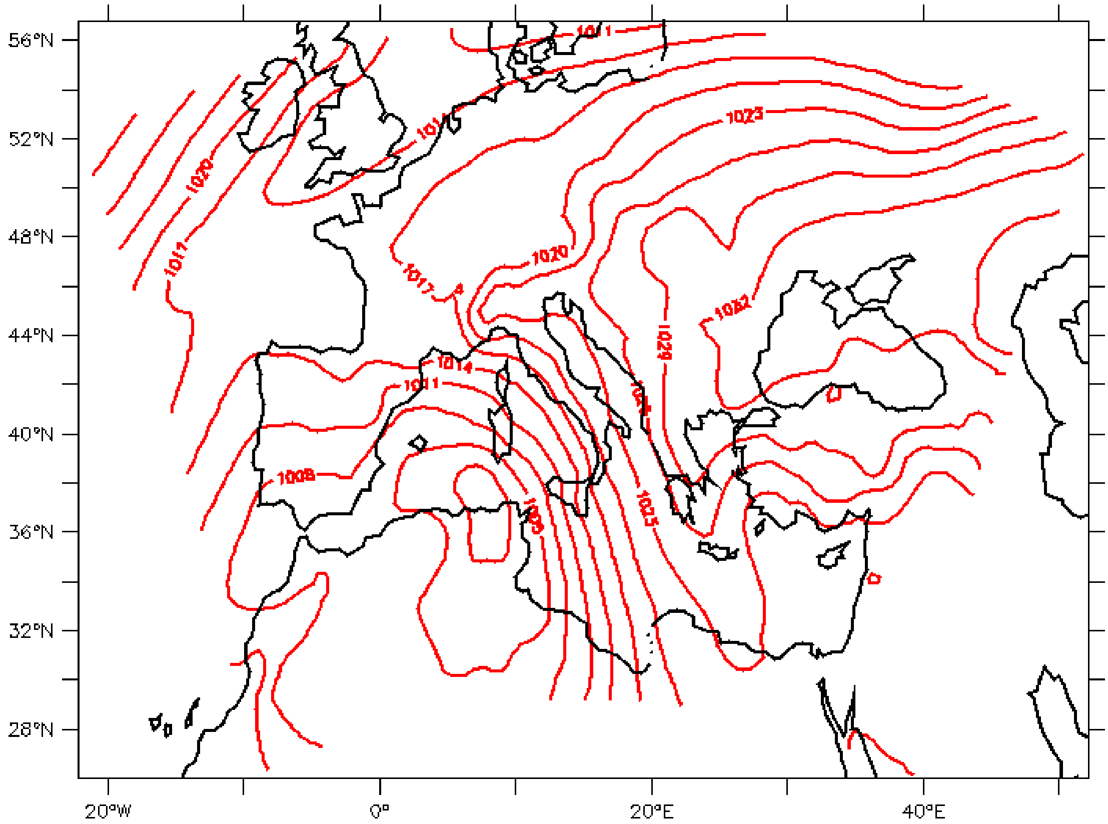

Figure 7: Mean sea level pressure (hPa) for the initial phase of the cyclone of figure 6 (14/01/1980), for the coupled run.