



## Tropical cyclones over the Mediterranean Sea in climate change simulations

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[1] Tropical cyclones form only under specific environmental conditions. Anthropogenic climate change might alter the geographical areas where tropical cyclones can develop. Using an ensemble of regional climate models, we find an increase in the extremes of cyclone intensity over the Mediterranean Sea under a climate change scenario. At least for the most sensitive model, the increase in intensity is clearly associated with the formation of tropical cyclones. Previous studies did not find evidence of changes in the projected areas of formation of tropical cyclones (Intergovernmental Panel on Climate Change, 2007; Walsh, 2004; Lionello et al., 2002). Those studies were based either on relatively low-resolution global climate models or on one particular regional climate model. The use of a multi-model ensemble of relatively high-resolution regional climate models has allowed us to detect for the first time a risk of tropical cyclone development over the Mediterranean Sea under future climate change conditions. **Citation:** Gaertner, M. A., D. Jacob, V. Gil, M. Domínguez, E. Padorno, E. Sánchez, and M. Castro (2007), Tropical cyclones over the Mediterranean Sea in climate change simulations, *Geophys. Res. Lett.*, 34, L14711, doi:10.1029/2007GL029977.

### 1. Introduction

[2] Changes in the areas of formation of tropical cyclones are a possible effect of anthropogenic climate change. A direct relationship between an increase in the areal extent of warmer sea surface temperatures (SSTs) (greater than 26°C) and a corresponding increase of areas affected by tropical cyclones cannot be established, as the genesis and development of tropical cyclones also depend on atmospheric conditions like vertical wind shear and atmospheric stability. The IPCC Fourth Assessment Report [Intergovernmental Panel on Climate Change, 2007] and a previous review [Walsh, 2004] haven't indicated changes in the projected areas of tropical cyclone formation.

[3] Two very unusual cyclones that have developed recently over the Atlantic Ocean have provoked questions about this issue. In March 2004, the first documented South Atlantic hurricane, called Catarina, made landfall over the southern coast of Brazil [Pezza and Simmonds, 2005]. Additionally, Hurricane Vince [Franklin, 2006] formed next to Madeira Islands in the Atlantic Ocean and was the first

detected hurricane to develop over this area. It was also the first known tropical cyclone to make landfall in Spain. Both cyclones developed from an initially baroclinic cyclone, and the tropical transition occurred over SSTs lower than 26°C. The mechanisms of tropical transition and the potential impacts of large scale circulation changes on them have been analyzed in recent studies [Davis and Bosart, 2003; Pezza and Simmonds, 2005].

[4] The possible development of tropical cyclones over the Mediterranean Sea has received some attention, as summer SSTs in climate change scenarios are projected to increase above the already high present values. Some observed cyclones over the Mediterranean Sea have already shown partially tropical characteristics [Reale and Atlas, 2001; Homar et al., 2003], after developing initially in a baroclinic environment. A mechanism for the development of Mediterranean tropical cyclones, initiated by upper-level cut-off lows, has been proposed [Emanuel, 2005]. For future climate conditions, a study with a global climate model (GCM) [Lionello et al., 2002] indicated more extreme events in the scenario simulation, though this result was not clearly significant. Higher resolution simulations in the same study looking at a small number of cyclones did not alter this result. Another study applied a regional climate model (RCM) to analyze Mediterranean cyclones and also did not find any clear tendency in the number of intense summer cyclones for future climate conditions [Muskulus and Jacob, 2005].

### 2. Methodology

[5] Here we analyse changes in Mediterranean cyclone characteristics from a climate change experiment with a multi-model ensemble of nine RCMs, taken from PRUDENCE project [Christensen et al., 2002]. Brief descriptions of the models and different analyses about the simulations are given by Jacob et al. [2007] or Déqué et al. [2007]. The domains cover most of Europe, but differ in the location of the southern and eastern boundaries. This is the reason for the differences in the extension of the Mediterranean basin covered by the models. The horizontal resolution is between 50 km and 55 km. Two 30-year time slice simulations have been performed: the control run for 1961–1990 period (CTRL), and a scenario run for 2071–2100 period (SCEN), considering SRES-A2 greenhouse gases evolution [Intergovernmental Panel on Climate Change, 2000]. Lateral boundary conditions were provided by simulations performed with the Hadley Centre atmospheric global climate model (HadAM3H) [Pope et al., 2000].

[6] Observed SSTs (1961–1990) are used for present climate, and future climate SSTs are calculated by adding

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**Table 1.** Frequency of Cyclone Centres<sup>a</sup>

Model	CTRL	A2 SCEN
CHRM (41.5°N)	49	39 (−20%)
HIRHAM (40.5°N)	44	41 (−7%)
RACMO(40.5°N)	66	67 (+2%)
RCAO (39.5°N)	94	105 (+12%)
HadRM3H (36.5°N)	97	94 (−3%)
CLM (35.5°N)	149	209 (+40%)
PROMES (35.5°N)	293	350 (+19%)
REMO (33.5°N)	149	233 (+56%)
RegCM (32.5°N)	330	495 (+50%)

<sup>a</sup>Total number of cyclone centres (during a 30 year period) over the Mediterranean Sea for the month of September. The southern limit of the cyclone detection area is indicated in brackets after the model name. In the third column, the percentage variation from CTRL to SCEN run is indicated in brackets.

a constant increment and a positive trend to the monthly values used in the control simulation. This increment is the 30-year monthly mean difference between the two periods in corresponding runs performed with the ocean-atmosphere coupled model HadCM3 [Johns *et al.*, 2003], and the trend has been taken from the same simulation.

[7] The analysis is performed for the month of September. This month has been selected in order to focus on the possible development of cyclones with tropical characteristics, as the SSTs are near their highest annual value and the summer subsidence over the Mediterranean Sea is also weakening. September SSTs reach values of up to 30°C (averaged over the Mediterranean Sea) at the end of the scenario simulation.

## 2.1. Cyclone Detection Method

[8] An objective cyclone detection method [Picornell *et al.*, 2001] based on sea level pressure (SLP) fields is used. The September SLP output over the Mediterranean Sea from the models has been smoothed with a Cressman filter with a radius of 200 km in order to filter out smaller scale noisy features that appear usually in SLP fields. SLP minima are detected in the filtered fields. Weak cyclones are removed by applying an SLP gradient threshold within a radius of 400 km around the SLP minima. This radius is the reason why the so called cyclone detection area is smaller than the respective RCM domain. For the present study, the geostrophic vorticity at cyclone centre has been used for measuring cyclone intensity.

[9] The cyclone detection method also allows to calculate cyclone tracks, but it uses the horizontal wind at 700 hPa for this purpose. This field is not available for the analysed RCMs. Due to this, a subjective method has been applied in order to assign cyclone duration and track for the most intense cyclones of each simulation.

## 2.2. Vertical Structure of the Cyclones

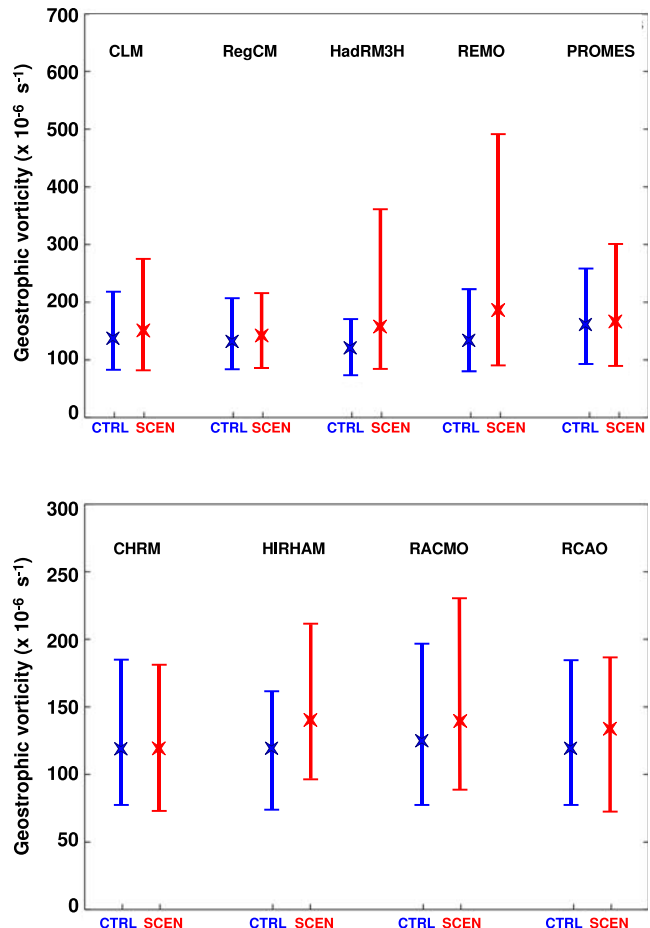
[10] The objective analysis of the vertical structure of the cyclones for determining if the cyclones have tropical or extratropical characteristics has been applied following the published description of the cyclone phase space method [Hart, 2003], based on the geopotential fields between 900 and 300 hPa.

## 3. Results

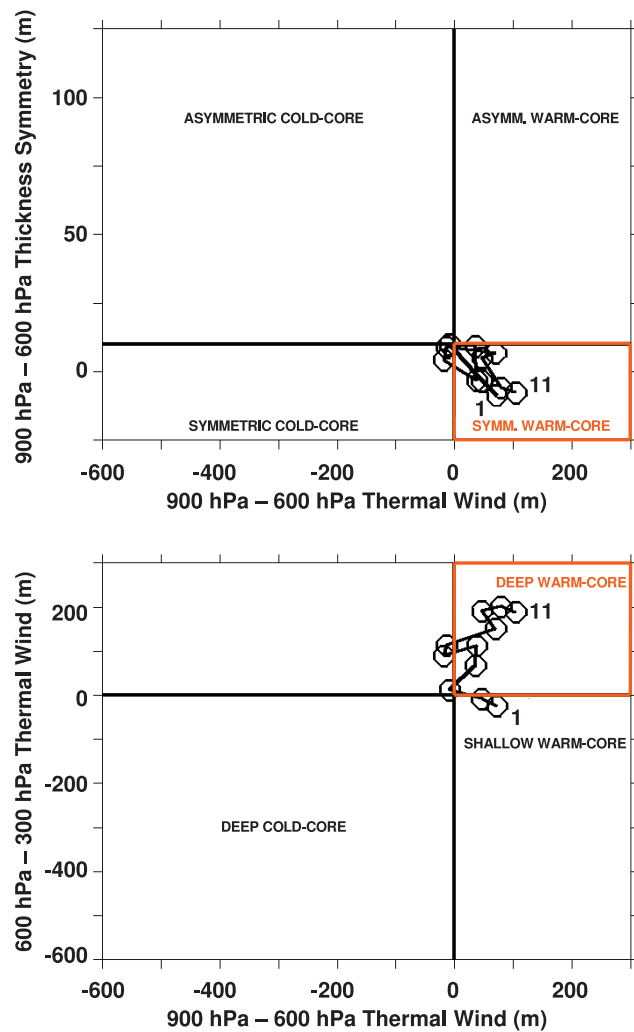
[11] Table 1 shows the total frequency of cyclone centres for the nine models. The domain of the nine models was not

the same, with some models covering a smaller part of the Mediterranean Sea than others. The detection area (indicated in the table by its southern limit in degrees N) is smaller than the model domains since the detection method requires a minimum distance from the low centres to the boundaries. The four models with a cyclone detection area extending farthest to the south simulate an increase (between 19% and 56%) in frequency of cyclone centres in the SCEN simulation relative to the CTRL simulation. The remaining models show no defined changes (ranging from a 20% decrease to a 12% increase).

[12] The geostrophic vorticity at cyclone centre has been used for analysing the intensity of the cyclones. Figure 1 displays the mean value, the 5th and 95th percentile of cyclone intensity for the different RCMs. The 95th percentile has been taken to represent extreme intensities. Among the five models extending further to the south (Figure 1, top), two simulate a strong increase (from CTRL to SCEN) of the 95th percentile (122% and 114%), two a moderate increase (27% and 17%) and the remaining model a slight



**Figure 1.** (top) Intensity statistics for the RCMs extending over a large part of the Mediterranean. The limits of the bars indicate respectively 5th and 95th percentile, and the cross indicates the mean value of geostrophic vorticity ( $\times 10^{-6} \text{ s}^{-1}$ ) at cyclone centre. (bottom) RCMs extending only over the northern part of the Mediterranean. Note that the scale is different compared with the upper frame, reflecting the smaller intensity change for these models.



**Figure 2.** Cyclone phase space diagrams for the most intense SCEN cyclone simulated by REMO model: (top) 900 hPa–600 hPa storm-relative thickness symmetry (m) versus scaled 900 hPa–600 hPa thermal wind (m), and (bottom) scaled 900 hPa–600 hPa thermal wind (m) versus scaled 600 hPa–300 hPa thermal wind (m). The phase space area corresponding to tropical cyclones is emphasized.

increase (4%). The four models covering only the northern part of the Mediterranean (Figure 1, bottom) show a less clear climate change response ranging from almost no difference to an intensity increase of 31%. Due to the rather small cyclone detection area of these last four models, the following analysis is restricted to the other models, which cover at least part of the warmer southern Mediterranean Sea between Italy and Libya.

[13] Tropical cyclones are lows with a symmetric, full-tropospheric warm core structure. In order to detect the presence of tropical cyclone characteristics in the simulated lows, an objective method for characterizing cyclones [Hart, 2003] has been applied. It is based on 3 parameters. The first parameter determines whether the cyclone structure is asymmetric/frontal (typical of extratropical cyclones) or symmetric/nonfrontal (typical of tropical or occluded cyclones). The other two are aimed to distinguish between a cold core and a warm core structure in the lower and upper

troposphere, respectively. Among the models that show an important intensity increase, two have been selected for this analysis: the RCM with the strongest response (REMO [Jacob, 2001]) and the one with the weakest response to climate change (PROMES [Sánchez *et al.*, 2004]). The objective method has been applied respectively to the four most intense cyclones for both the CTRL and SCEN runs.

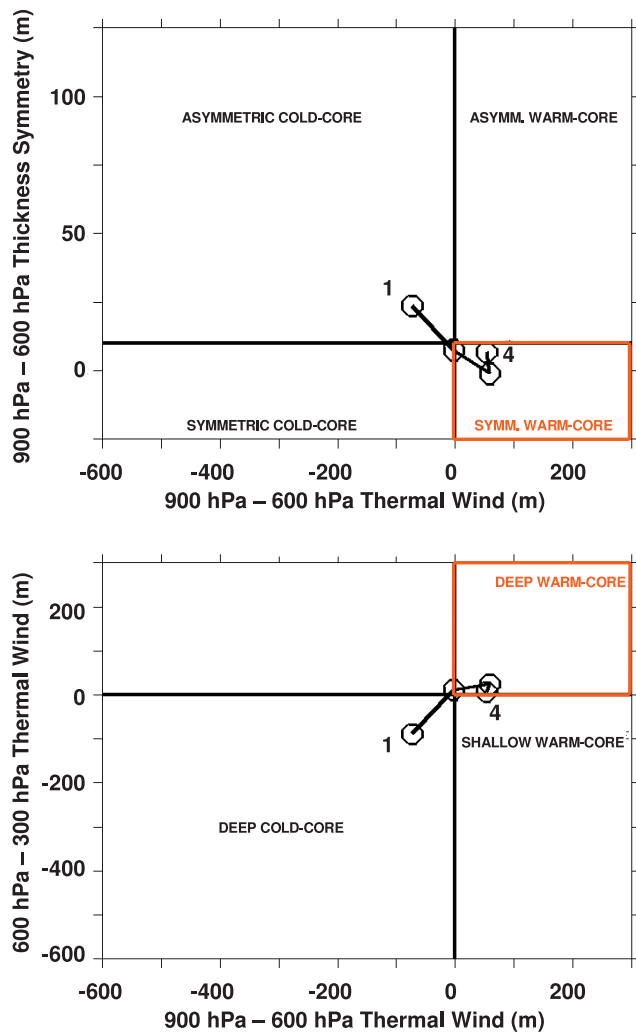
[14] Figure 2 shows the evolution of the most intense cyclone found in the SCEN simulations with REMO (called REMO-SCEN hereafter): the cyclone shows a full-tropospheric warm core during 6 days along with a high thermal symmetry. The parameters reach values comparable to those of a strong hurricane [Hart, 2003]. The next three most intense REMO-SCEN cyclones have a warm core structure during several days (5, 8 and 8 respectively), and simultaneously have low values of the thermal asymmetry parameter. These parameter values show very clearly that these simulated lows are tropical cyclones during part of their lifetime. The cyclones are able to maintain a warm core structure for several consecutive days (up to 8), which is an additional indication that the feedback between latent-heat fluxes and winds at the sea surface is operating as in fully developed tropical cyclones. In contrast, only a total of 3 days with full-tropospheric warm cores are found in the most intense REMO-CTRL cyclones. The maximum values of the warm core parameters are clearly smaller than in REMO-SCEN. Figure 3 depicts the evolution of the REMO-CTRL cyclone that exhibits the most persistent warm core structure (2 days).

[15] The duration of the most intense cyclones in REMO simulations shows striking differences between CTRL and SCEN runs: the four REMO-SCEN cyclones have very long lifetimes (between 11 and 15 days), whereas the four CTRL cyclones have much shorter lifetimes (between 2 and 5 days). Observed Mediterranean cyclones are relatively short-lived [Trigo *et al.*, 1999]. Another important difference is the westward movement direction of two of the REMO-SCEN cyclones. One of them shows a particularly noteworthy track: it originates over the eastern Mediterranean, and travels westward until it dissipates near the coasts of southern France, covering a rather long distance. This track direction resembles the westward movement of many tropical cyclones, and is very different to the most frequent tracks of Mediterranean cyclones.

[16] An analysis of the vertical structure of cyclones from PROMES model shows less clear differences between SCEN and CTRL cyclone centres, in good correspondence with the smaller intensity differences. Three of the most intense PROMES-CTRL cyclones develop a warm core during 1 day. In PROMES-SCEN simulations, warm cores appear in two cyclones, but for more days (2 and 3). Another difference with REMO-SCEN results is that the PROMES-SCEN cyclones do not achieve a clear and sustained thermally symmetric structure.

[17] Among the other models showing an important intensity increase for climate change conditions, a particularly noteworthy cyclone is the most intense simulated in the SCEN run of CLM model. This cyclone deepens strongly while diminishing in size, a typical behaviour of tropical cyclones. The spatial distribution of the modelled precipitation field is compact and rather symmetrical around the cyclone centre, showing no evidence of fronts. Another





**Figure 3.** As in Figure 2, but for the CTRL cyclone with most warm-core days simulated by REMO model.

interesting change is that of the maximum cyclone duration (evaluated among the 10 most intense cyclones of each model and simulation). This duration approximately doubles from the CTRL to the SCEN runs for CLM and HadRM3H models, reaching respectively 17 and 12 days. In contrast, RegCM model, which shows almost no intensity change, simulates a decrease in maximum cyclone duration.

[18] It is important to note that the REMO model is not extreme in its results for present climate. Precipitation extremes of REMO-CTRL simulation have been compared to observed data over an area centered on the Alps, including part of the northern Mediterranean [Frei *et al.*, 2006]. The REMO results were in the middle of the RCM ensemble range, showing extreme precipitation index values that are lower than observed. The mean climate of REMO over the whole Mediterranean area has also been compared to observations [Paeth and Hense, 2005], showing good results.

[19] An analysis of Mediterranean cyclones for a REMO simulation corresponding to B2 scenario conditions (a scenario with less projected emissions and less global temperature increase) yielded no significant change in

cyclone tracks and associated precipitation, and no clear tendency in the number of intense summer cyclones [Muskulus and Jacob, 2005]. Apart from the different emissions scenario, the simulation was performed with a domain displaced to the north (the southern boundary was much nearer to the Mediterranean Sea than the southern boundary used in the present study) and was nested in a different GCM.

[20] That last study illustrates the effect of other sources of uncertainty, like the use of different scenarios and GCMs. The particular GCM-scenario combination used here is not an extreme one: the A2 scenario simulation of HadAM3H gives a global mean surface temperature increase of 3.18°C between the CTRL and SCEN runs [Frei *et al.*, 2006], which is at the middle of the range projected by IPCC [Intergovernmental Panel on Climate Change, 2007]. An increase in model horizontal resolution may also give different results, as tropical cyclones are not fully resolved at 50 km resolution.

#### 4. Conclusions

[21] The use of an ensemble of RCMs with a relatively high resolution has allowed us to detect for the first time a risk of tropical cyclone development over the Mediterranean Sea, based on anthropogenic climate change simulations. The spread among the models is large, reflecting the uncertainty linked to model formulation. Several other sources of uncertainty (like different emission scenarios, other GCMs and horizontal resolution) have to be assessed before drawing clear conclusions. Despite the need for further studies, the large implications of the possible development of tropical cyclones over the Mediterranean Sea give much relevance to the present results. The methodology itself (use of an RCM ensemble and of cyclone phase space as a diagnostic tool) could contribute to improve our knowledge of the effects of climate change on tropical cyclones over other regions of the world.

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