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Cyclones in the Mediterranean region: the present and the doubled CO_2 climate scenarios

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ABSTRACT: This study investigates the variations of the cyclonic activity in the Mediterranean region that would be produced by doubling the CO_2 atmospheric content. The analysis is based on the SLP (sea-level pressure) fields produced by two 30 yr long time slice experiments of the ECHAM-4 model at T106 resolution, carried out by DMI, simulating the present and doubled CO_2 scenarios. The cyclonic activity in the Mediterranean region is similar in the 2 climate scenarios. The present climate is characterized with a slightly, but statistically significant, higher overall number of cyclones. The doubled CO_2 simulation is characterized with more extreme weather events, but the difference between the 2 scenarios is hardly significant. No variation in the regions of formation of the cyclones was clearly identified. An, admittedly small, number of cyclones of both scenarios was simulated using a limited area model (LAM) with 0.25° resolution. These simulations do not suggest that an increased model resolution should add new major findings to the results of this study, but the possibility that a climate change signal is not evident because of the coarse T106 model resolution remains open for further investigations. However, this study does not show a large change in the regime of the cyclones in the Mediterranean region due to the atmospheric CO_2 doubling.

KEY WORDS: Cyclones · Regional scenarios · Climate change · CO_2 doubling · Mediterranean region · Extreme events

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1. INTRODUCTION

The goal of the study is to identify the changes in the frequency, intensity and characteristics of the atmospheric cyclones in the Mediterranean region due to atmospheric CO_2 doubling. An assessment of the variations in the cyclonic activity is obviously important, since the cyclones are a potential source of major damage, because of their association with storm surges, high wind waves, intense precipitation and floods. The effect of the atmospheric CO_2 content doubling on mid-latitude cyclonic activity is not obvious. The larger SST (sea-surface temperature) and the associated larger specific humidity should increase the potential for intense cyclogenesis. In fact, in a warmer climate, the Mediterranean SST could exceed the threshold for the onset of tropical storms and hurricanes. At the same time, the diminished meridional gradient of the SST should reduce the baroclinicity of the atmosphere and the potential for baroclinic instability. The effectiveness of the 2 effects, which act in opposite directions on the frequency and intensity of the cyclones, is difficult to quantify *a priori*. In this study, statistical analysis of the results of the ECHAM atmospheric circulation model is used to determine the overall effect of CO_2 doubling on cyclones in the Mediterranean region.

The frequency and intensity of cyclones in a doubled CO_2 environment have already been investigated at a global scale. The analysis of ensembles of experiments carried out with the Hadley Centre coupled ocean-

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atmosphere general circulation model has shown a decreased total number of storms in the northern hemisphere and a tendency towards deeper low centers (Carnell & Senior 1998). These changes were, however, not generally statistically significant. A different analysis, based on the identification of cyclonic vorticity centers and applied to the results of a different model (the CSIRO9 general circulation model, including a slab ocean with prescribed heat fluxes), has shown a decrease of 10 to 15% in cyclonic activity (Sinclair & Watterson 1999). The changes in the cyclonic activity over the North Atlantic and Europe have been evaluated using a 240 yr long run of the ECHAM/OPYC3 coupled ocean-atmosphere general circulation model with transient greenhouse forcing (Knippertz et al. 2000). The analysis has shown a north-eastward shift of the cyclone activity accompanied by a decrease in the number of cyclones and an increase in deep cyclones. Therefore, these studies agree that there is reduced cyclonic activity in a doubled CO_2 climate. Marginally lower values of the pressure minima in the cyclone centers have also been suggested, but it has been pointed out that this result might be produced by a decreased mean SLP (sea-level pressure) and is not a necessary indication of more intense cyclones (Sinclair & Watterson 1999). All these analysis were carried out with coarse resolution datasets: 2.5° latitude × 3.25° longitude for the Hadley Centre model; 3.2° latitude × 5.6° longitude for the T21 CSIRO9 model; and 2.8° latitude × 2.8° longitude for the T42 ECHAM/OPYC3 model. This study aims to carry out a similar analysis with a higher resolution model, where the development of the cyclones is better simulated and regional details can be identified and analyzed.

This analysis is based on two 30 yr long global simulations (May 1999) carried out with the ECHAM 4 model at the DMI (Danish Meteorological Institute): a CTR (control) experiment which attempts to reproduce the present climate, and a CO_2 experiment which simulates the effect of a doubled atmospheric CO_2 content, based on an updated IS92a scenario, including, besides CO_2, methane, nitrous oxide and several industrial gases. Both experiments were carried out at T106 resolution, corresponding to a 160 × 320 global Gaussian grid, with 19 vertical levels. The ERA-15 data set (ECMWF ReAnalysis carried out at T106 resolution for the period from 1979 to 1993, Gibson et al. 1997) is used for the assessment of the reliability of the CTR climate scenario.

Section 2 describes the procedure used for the identification of the cyclones and shows the resulting cyclonic trajectory over the Mediterranean region. Section 3, which analyses the statistics of the cyclones in the ERA-15, CTR and CO_2 datasets, is divided into 4 subsections. In the first 3 subsections the changes of overall average number, extreme intensity, and geographical distribution of the cyclones are discussed. The fourth subsection discusses the possible implications of the model resolution. The outcomes of the study are summarized in Section 4.

2. METHOD FOR THE IDENTIFICATION OF CYCLONES

An objective procedure has been devised to identify low-pressure systems over the Mediterranean region. The method is based on the search of pressure minima in the T106 SLP fields, available at time intervals of 6 h on a 25 × 46 grid, with a 1.1° step, extending, approximately, from 10° W to 40° E and from 25 to 55° N.

The method carries out the partitioning of the SLP fields in depressions by the identification of sets of steepest descent paths leading to the same SLP minimum. Each grid point is connected to the lowest of the 8 nearest-neighbor grid points. This step is repeated until a pressure minimum, which is, obviously, a point where the SLP value is lower than the SLP at the 8 nearest grid points, is reached. All the points crossed by a path leading to the same minimum are assigned to the same depression. An example is shown in Fig. 1. Fig. 1a shows the original SLP field, and Fig. 1b the results of its partitioning. The small depressions whose central minimum is at a distance less than 4 grid points from the boundary of a different and deeper depression are included in the latter, and the whole map thus contains only a few large depressions (Fig. 1c).

A trajectory obtained by joining the location of the same low pressure center in successive maps was associated with each depression. The low pressure center is, approximately, the location of the pressure minimum, but it is slightly shifted when the low pressure distribution is asymmetric. A box is associated with each center identified in the map. In the meridional direction the box is centered at the location of the center, with a width of $1.4R$, where R is the average distance of the grid points of the depression from its center. In the zonal direction the box is not symmetric, with its western side at a distance of $0.3R$, and its eastern side at a distance of $0.8R$. Moreover, the box is further extended in the direction of the former motion of the center, with an increase equal to the distance covered by it in the previous 6 h. A center in the map $i + 1$ is assumed to be the continuation of the cyclone in the map i if its center is inside such box. When no center is found inside the box, cyclone termination is assumed. The procedure results therefore in a trajectory, an initial and final point, a sequence of pressure minima, and a sequence of areas covered by the cyclone.

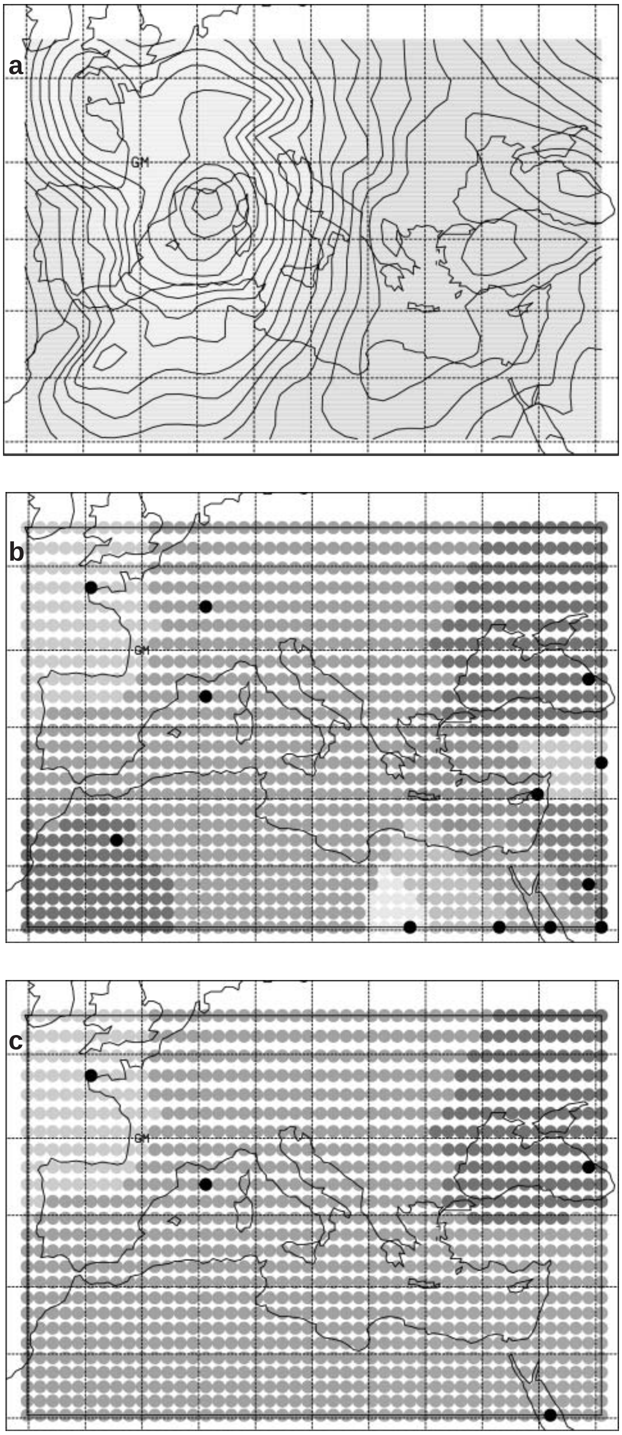

Fig. 1. Example of the procedure for the identification of the cyclones. (a) Original sea-level pressure (SLP) field. (b) Results of the partitioning procedure. Each dot represents a grid point, and the dots with the same gray level belong to the same partition. Black dots show the location of the pressure minimum of each partition. (c) Final set of large depressions that result from the merging of the small depressions whose central minimum is at a distance less than 4 grid points from the boundary of a different and deeper depression

This method is applied to 2 different sets of high-pass filtered fields. The first set (denoted as 3MHPF, 3 Months High-Pass Filtered) was obtained by subtracting the seasonal cycle from the original SLP data. The second set (denoted as 2WHPF, 2 Weeks High-Pass Filtered) was obtained by subtracting a shorter, biweekly, running mean. Both 3MHPF and 2WHPF fields were produced for each scenario (namely ERA-15, CTR and CO_2). The depth of each cyclone is the absolute value of the lowest SLP that is reached in the filtered fields during the whole development of the cyclone. In other words, the cyclone depth is the maximum absolute value of the departure of the original field from the running mean. Therefore, the depth is a positively defined quantity which increases with the intensity of the cyclone. The analysis of the 2WHPF and 3MHPF fields gives different values for the cyclone depth. In fact, since the 3MHP filter eliminates the frequency variability on the seasonal (time scale greater than 3 mo) scale, the estimated depth of each cyclone might be affected by the residual shorter time scale frequency variability. In order to show that the outcomes of this study do not depend on the choice of the filter, the analysis is carried out for both the 3MHPF and the 2WHPF fields.

The analysis selects cyclones whose trajectory (defined by the path of their pressure minimum) passes over the sub-region delimited by the coasts of the Mediterranean and the Alps. This complex procedure results in a list of depressions ordered by intensity. The criterion used for the intensity of the cyclone is the maximum depth of the cyclone during its whole development, i.e. the lowest value of the pressure minimum in the high-pass-filtered fields. The analysis is restricted to cyclones deeper than 15 hPa.

The resulting trajectories for the ERA-15 dataset are shown in Fig. 2. Fig. 2a shows all the trajectories identified in the 2WHPF fields inside the whole squared geographical area searched by the procedure. The white area in Fig. 2b shows the 'Mediterranean region', that is the mask used for the selection of the 'Mediterranean' cyclones. Only cyclones whose trajectories pass over this white area are included in the analysis. The selected trajectories are shown in Fig. 2c. This set includes cyclones that entered the Mediterranean from the Atlantic and from northern Europe. The subset of the trajectories initiated by a cyclogenesis in the Western Mediterranean, Eastern Mediterranean and Northern Africa (the zones labelled WM, EM, NA in Fig. 7) is shown in Fig. 2d.

Fig. 2 confirms the well-known features characterizing the cyclonic activity in the Mediterranean region that have already been investigated in former studies (Alpert et al. 1990, Trigo et al. 1999). They show that most of the cyclones affecting the Mediterranean

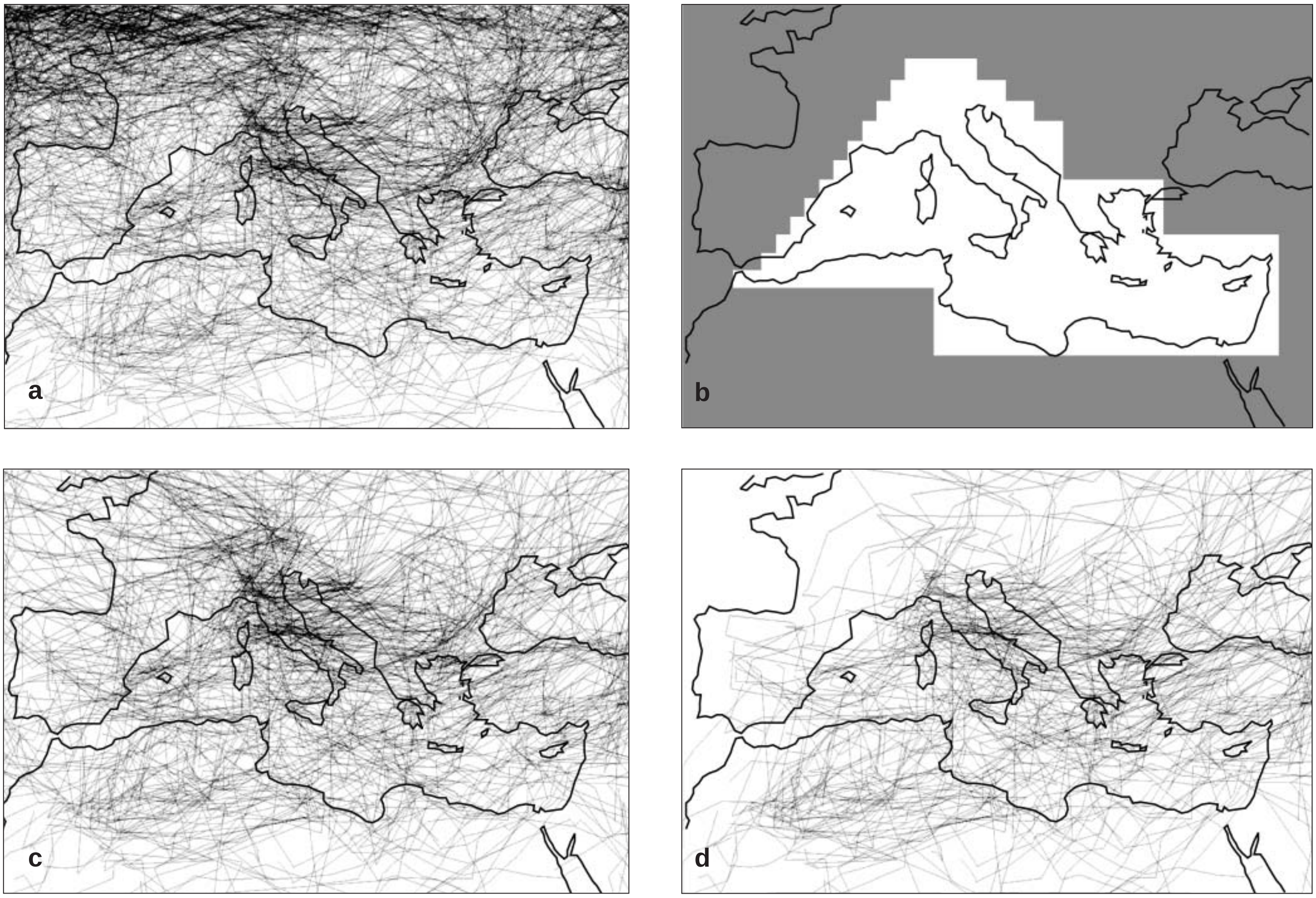

Fig. 2. (a) Cyclonic trajectories identified in bi-weekly filtered fields of the ERA-15 dataset. (b) Mask used for the selection of the Mediterranean cyclones: only the cyclones whose trajectories pass over the white area are included in the analysis. (c) Trajectories selected. (d) Trajectories of the cyclones originated inside subregions WM, EM and NA shown in Fig. 7

region arrive from the Atlantic storm track, whose effect is partially shielded by the mountain ridges at the northern boundaries of the Mediterranean basin. The strongly cyclogenic areas on the southern side of such ridges, namely in the Gulf of Genoa, the Po valley, the Adriatic Sea, the northern Aegean Sea, are evident. Other cyclogenic areas are present over North Africa and between Cyprus and Turkey. Obviously, this average picture hides the intermonthly variability and areas where cyclogenesis occurs during summer, such as Spain, that are not present because of the relatively high threshold (15 hPa) adopted in this study.

3. CHANGES IN THE CLIMATE OF THE CYCLONES

The analysis of the CTR, CO_2 and ERA-15 datasets produces 3 lists of low pressure systems whose intercomparison allows us to deduce systematic differences between the CTR and CO_2 scenarios and to assess the reliability of the model by intercomparing CTR and ERA-15 scenarios. Three main characteristics of the cyclones were analyzed: their overall number, their extreme intensity, and the area where cyclogenesis occurs.

3.1. The average cyclonic activity

The cyclones identified in the 3 different scenarios were ordered according to their intensity, and the yearly average number of cyclones exceeding a given intensity was computed. The result is, for each scenario, a cumulative distribution of cyclones as a function of their intensity; that gives the average number of cyclones per year deeper than a given threshold.

The evaluation of the intensity of the cyclones based on the SLP values is partially problematic. While SLP is a robust, well-simulated and predictable field, the absolute value of the minimum is not a good indicator of the intensity of the circulation associated with it. In fact, the value of the SLP minimum results from the superposition of the cyclone itself and of larger-scale and longer-period patterns. The intensity of the cyclone is more correctly indicated by the depth of the SLP minimum relative to the background field. Such a background field was estimated in this study as the 3 mo running mean or the 2 wk running mean. These 2 different choices of the background field imply quite different depth values of the cyclones. When the seasonal running mean is subtracted from the fields, that is the 3MHPF fields are used, the cyclones obviously become deeper, since a larger amount of low frequency variability remains present in the fields. In spite of the different values, the analysis of the 3MHPF and 2WHPF fields lead to the same conclusions as far as the climate change signal is concerned.

In Fig. 3 the left and the right panels refer to the 3MHPF and 2WHPF fields respectively. Fig. 3a and b show the average number of cyclones per year (*y*-axis) whose depth exceeds a given threshold (*x*-axis) for the range from 15 to 35 hPa. The 3 lines in Fig. 3 show the cumulative distribution for the CTR (dotted line), CO_2 (dashed line), and ERA-15 (solid line) scenarios. The overall number of cyclones, that is the number of cyclones deeper than 15 hPa, is larger in the CTR scenario than in the CO_2 scenario, while CTR and ERA-15 present a similar amount of cyclones. However, as the threshold increases, and the counting is restricted to cyclones of progressively stronger intensity, the CTR scenario tends to overestimate the number of cyclones with respect to ERA-15, and the CO_2 scenario becomes very similar to the ERA-15 scenario.

The statistical significance of the differences between the 3 distributions was evaluated with the standard Student's *t*-test, that is the differences among the average distributions of the 3 scenarios were compared to their interannual variances. Fig. 3 c and d show the values of the Student's *t* function for the CTR versus ERA-15 distribution (solid line) and for CTR versus CO_2 distribution (dashed line). The horizontal thick line marks the threshold value for 2 statistically different distributions with a 95% confidence level. Clearly, the cyclone distribution of CTR and CO_2 are statistically different in the range up to 25 hPa, while the null hypothesis of CTR and ERA-15 being statistically equivalent should only be maintained for cyclones weaker than 17 hPa. These conclusions are strictly valid only if the 2 distributions are Gaussian, which is not guaranteed in this case.

The statistical significance of the difference among the distributions has also been tested using the MW (Mann-Whitney) test. This test is based on assigning a rank to every year of each scenario. Rather than specifying a particular functional form, the MW test requires an identical distribution of the cyclone intensity deviation from its mean value in the 2 data sets. The years of the 2 scenarios compared are ordered according to the number of cyclones above the given threshold that take place during each of them; thus the first position is occupied by the year with most cyclones, and the last one by the year with fewest cyclones. The rank assigned to each year is its position in this ordered list. The sum of the ranks of the years for each scenario is the rank of the scenario itself, so that the scenario with the larger number of cyclones is characterized by the lower rank. The MW test is valid under the assumption that the 2 distributions to be compared are identical, without the requirement of being Gaussian.

The results of the MW test are shown in Fig. 3e,f (comparison between CTR and ERA-15) and Fig. 3g,h (comparison between CTR and CO_2). Note that the ERA-15 scenario has a necessarily lower rank than the CTR scenario because it consists of a smaller number of years. The lines in Fig. 3e,f show the rank of CTR (dotted line) and ERA-15 (solid line). Only if the rank of the CTR and ERA-15 scenarios lie outside the intervals delimited by the 2 respective pairs of horizontal lines are the 2 distributions statistically different at the 95% significance level. The lines in Fig. 3g,h show the rank of CTR (dotted line) and CO_2 (dashed line) and the 95% confidence interval delimited by the solid horizontal lines. Therefore, the MW test confirms the results of the Student's *t*-test.

Though the selected cyclones passed over the Mediterranean region, their maximum depth could have been outside it; such a cyclone could thus be not representative of their effect in this region. In fact, the maximum intensity of many cyclones reached over south-eastern Europe after they left the Mediterranean Sea. Fig. 4 shows the same quantities as Fig. 3, but the maximum depth of the cyclones is computed accounting only for the part of their trajectory over the Mediterranean region. With respect to Fig. 3, all distributions have reduced values, but their intercomparison leads to the same conclusions.

Therefore, both the *t*-test and the MW test, the analysis of both the 3MHPF and the 2WHPF fields, and computing the maximum depth both along the whole trajectory and only along the portion over the Mediterranean region all lead to similar conclusions. The total number of cyclones per year (that is, the yearly average number of cyclones with depth exceeding 15 hPa) is significantly reduced in the CO_2 scenario with respect to the CTR scenario. There is no significant difference in the total number between the CTR and ERA-15 scenarios. However, as the intensity of the cyclones increases, the agreement of CTR and ERA-15 becomes worse and the difference between

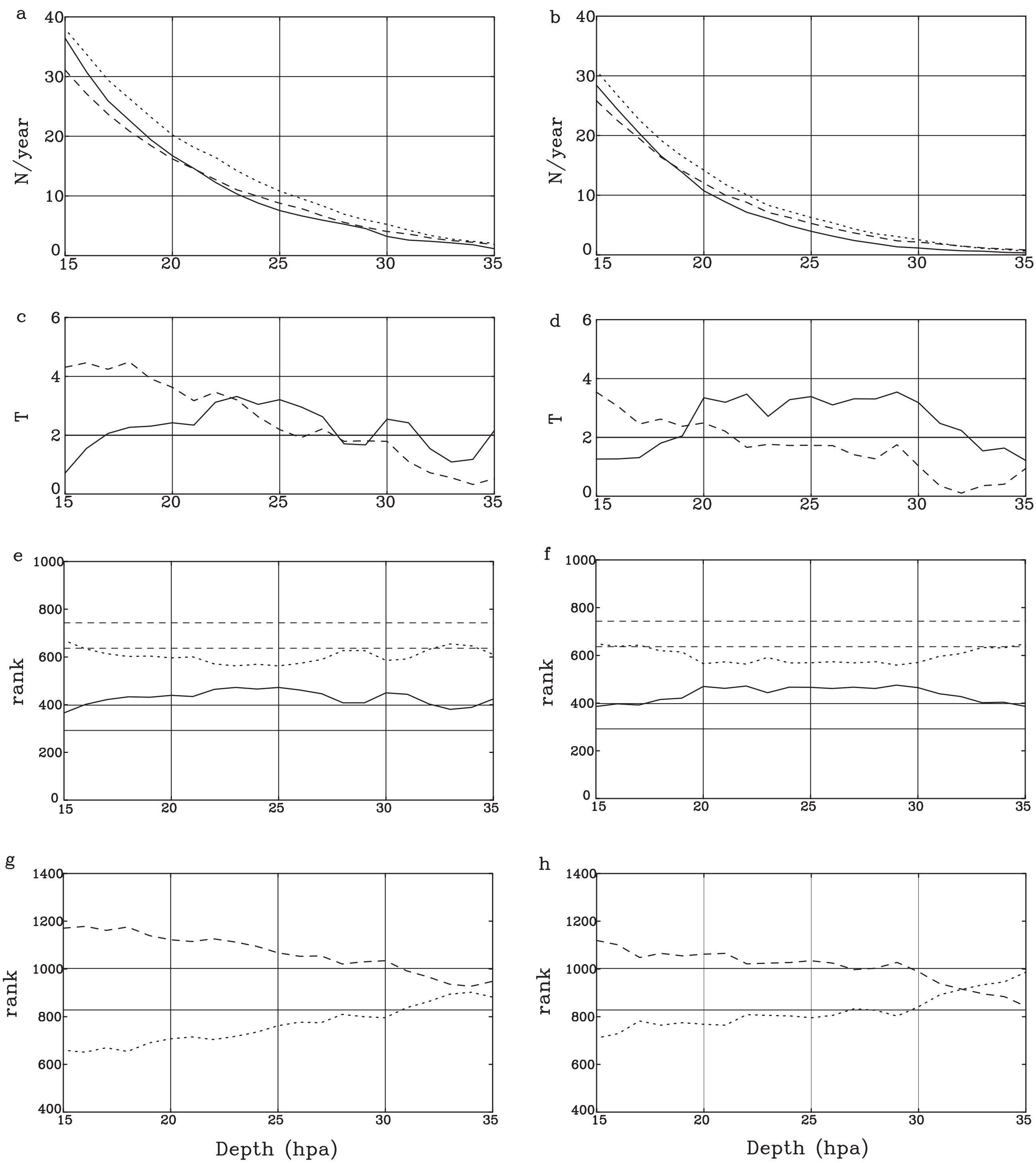

Fig. 3. 3MHPF (left column) and 2WHPF (right column) fields. (a,b) Cumulative distribution, that is the average number of cyclones per year (*y*-axis) exceeding a given threshold (*x*-axis)for the CTR (dotted line), CO_2 (dashed line), and ERA-15 (solid line) scenarios. (c,d) Student's *t*-test for ERA-15 vs CTR (solid line) and CO_2 vs CTR (dashed line). Values above the horizontal thick line indicate that the 2 distributions can be considered different with a 95% confidence level. (e,f) Ranks of the CTR (dotted line) vs ERA-15 (solid line) data. The 2 distributions are different with a 95% confidence level for the depth values where the ranks of CTR and CO_2 lie outside the range between the 2 thin horizontal dashed and solid lines, respectively. (g,h) As in (e,f) but for CTR (dotted line) vs CO_2 (dashed line)

CTR and CO_2 smaller, and no firm conclusion can be derived.

In summary, this analysis suggests a reduction in the number of cyclones affecting the Mediterranean region. This reduction is due to a smaller number of relatively weak cyclones, while there is no indication of an appreciable variation in the number of the strong cyclones.

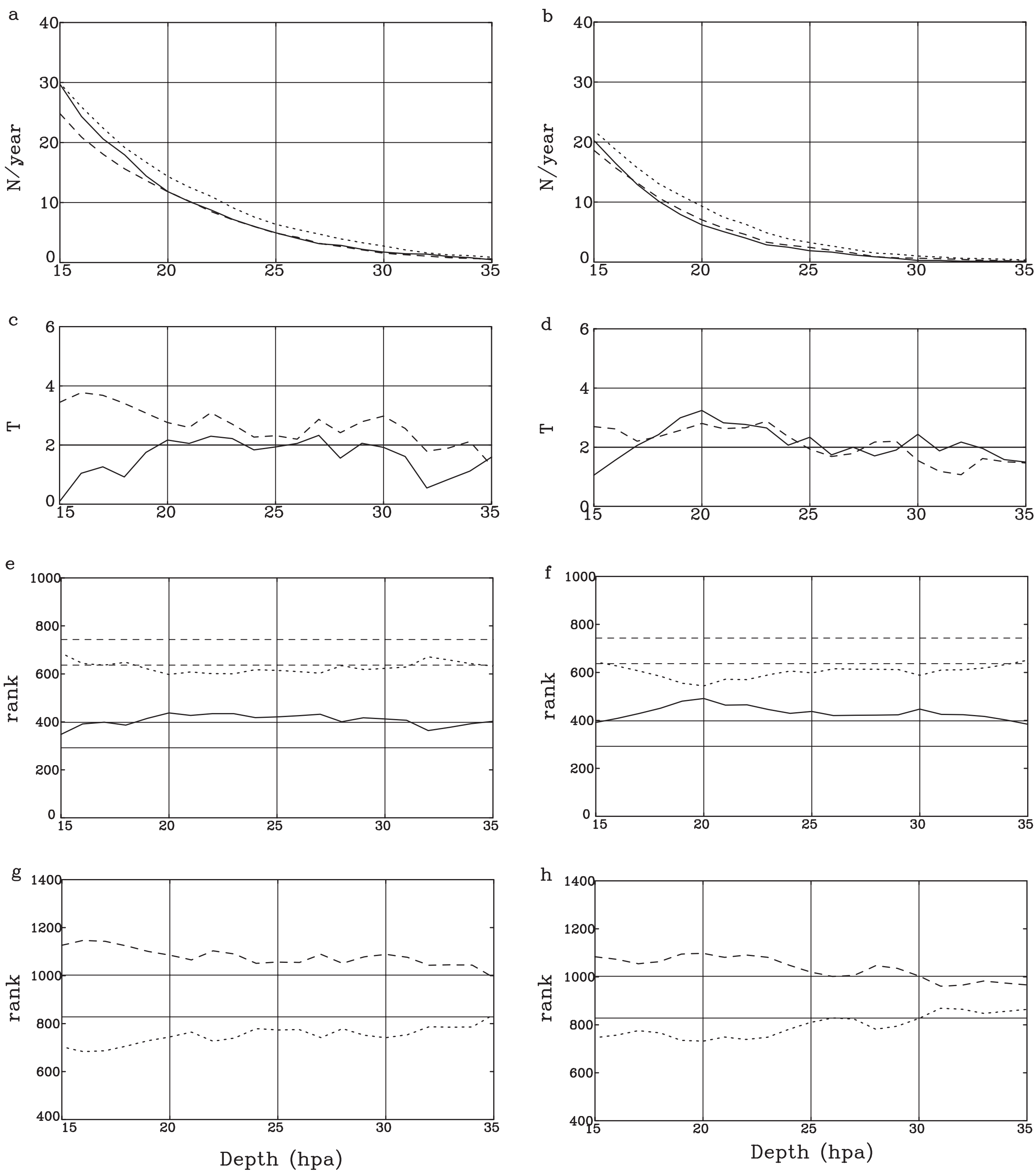

Fig. 4. 3MHPF (left column) and 2WHPF (right column) fields. Same as Fig. 3 but considering only the maximum depth inside the Mediterranean region when evaluating the intensity of the cyclones

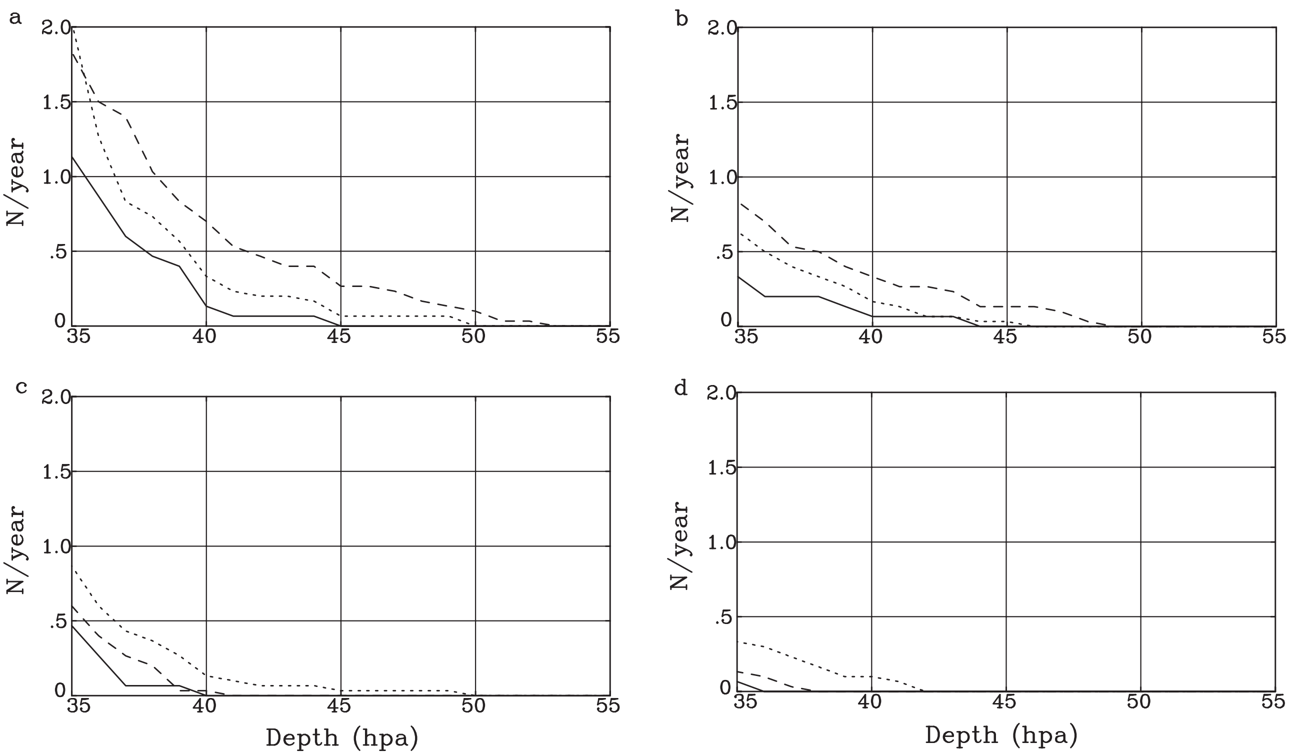

Fig. 5. Tails of the cumulative distributions for the CTR (dotted line), CO_2 (dashed line), and ERA-15 (solid line) scenarios. Only cyclones with depth exceeding 35 hPa are shown. (a,c) 3MHPF fields; (b,d) 2WHPF fields. In (c,d) the intensity of the cyclones was evaluated considering the maximum depth inside the Mediterranean region only

3.2. Extreme events

The increased SST (in the CO_2 scenario the Mediterranean Sea is 4 K warmer than in the CTR one) could trigger extreme cyclones whose growth is strongly reinforced by diabatic processes. Mediterranean lows, whose growth is strongly dependent on latent heat release, have been studied in the present climate (e.g. Pytharoulis et al. 1999), and it is important to identify signals of their intensification in the CO_2 scenario. The analysis described in this paper is not able to investigate the dynamics of the events, but aims simply to analyze the tail of the distribution of the cyclones and to identify changes in the intensity of extreme events.

Fig. 5 shows the tails of the cumulative distributions, that is, the part beyond the 35 hPa, not shown in Figs. 3a,b and 4a,b. If the depth of each cyclones is evaluated accounting for its whole trajectory (Fig. 5a,b), the extreme cyclones are deeper in the CO_2 scenario than in the CTR scenario, while CTR and ERA-15 present almost equivalent extreme values. This aspect of the analysis suggests an increase in extreme cyclonic events in the CO_2 scenario, and it does not depend on the choice between 3MHPF and 2WHPF fields. Note that the depth of the cyclones is clearly larger when evaluated from the 3MHPF fields than from the 2WHPF fields, because of the larger amount of low-frequency variability that remains present in the first case. However, the choice of the 3MHPF or 2WHPF fields does not change the relative levels of the ERA-15, CTR and CO_2 distributions.

If the depth of each cyclone is evaluated accounting only for the portion of its trajectory over the Mediterranean region (Fig. 5c,d), the situation reverses, and the CTR scenario has stronger extreme events than the CO_2 scenario. This aspect of the analysis would suggest a milder climate over the Mediterranean region in the CO_2 scenario. This result is consistent with the decrease in the total number of cyclones and with the northward shift of the storm track observed in the time slice experiment (1999).

The increase in the extreme intensity of the cyclones in the CO_2 scenario is, therefore, associated with their intensification over south-eastern Europe, after they left the Mediterranean Sea. This intensification remains important for the Mediterranean region because the air flow at the rear of the cyclones can strongly affect this region, even after the low pressure center has left. A tentative explanation for this effect of the CO_2 doubling could be the interaction between mountain ridges and the 'Mediterranean' air which would be more humid and warmer in the CO_2 scenario than in the CTR one.

Table 1. Maximum recorded and expected 100 yr return depth inside the 25 × 46 analysis grid, and inside the Mediterranean region

Scenario	Whole grid Max depth	Whole grid 100 yr return value	Mediterranean region Max depth	Mediterranean region 100 yr return value
3MHPF				
ERA-15	44.6	53.1 ± 3.3	39.0	49.7 ± 3.2
CTR	49.8	57.4 ± 2.5	49.3	54.0 ± 2.3
CO_2	52.1	64.2 ± 3.4	40.1	50.1 ± 2.4
2WHPF				
ERA-15	43.3	50.0 ± 3.5	35.3	40.9 ± 2.7
CTR	45.2	52.0 ± 2.4	41.1	51.4 ± 2.9
CO_2	48.0	56.7 ± 3.0	37.5	45.0 ± 2.2

The results of the extreme value analysis of the depth of the cyclones is summarized in Table 1. For each scenario the maximum recorded depth and the 100 yr return value of the depth are reported for both the 3 MHPF and the 2 WHPF fields, and considering both the whole trajectories and their portion inside the Mediterranean region. The 100 yr return value was computed by assuming a Gumbel distribution for the extreme values (von Storch & Zwiers 1999). The 2 parameters that specify the Gumbel distribution were fitted to a dataset obtained by selecting the 2 most intense cyclones for each simulated year using the maximum likelihood method. The analysis shows no significant difference between the extreme events of the CTR and ERA-15 scenarios. It confirms that the CO_2 doubling produces an intensification of the extreme events, and, at the same time, their attenuation if only the portion of the trajectories inside the Mediterranean region is considered. However, accounting for the errors in the evaluation of the Gumbel distribution, the difference between the intensity of the extreme events in the CO_2 and CTR scenarios, though statistically significant, is small.

3.3. Geographical distribution of the cyclones

Fig. 6 shows the number of Mediterranean cyclone trajectories initiating in each cell of the 25 × 46 grid used for the SLP analysis. This figure refers to the ERA-15 dataset, it is based on the 3MHPF fields, and it considers only cyclones whose maximum intensity is greater than 15 hPa. The gray levels represent the average number of cyclones per year: the areas of frequent cyclogenesis correspond to dark cells, and in the white areas no cyclogenesis has been recorded. The darkest areas, located south of the Alps, in the Po Valley, and over the Gulf of Genua, are the main source of cyclones inside the Mediterranean region. Presumably, the formation of cyclones is due to the well-known mechanism of orographic cyclogenesis. The other regions where there is relatively frequent cyclogenesis are located on the southern side of the Atlas Mountains in Northern Africa and in the Eastern Mediterranean, in the Aegean Sea and between Cyprus and Turkey. The grey cells located along the western boundary of the domain show that many cyclones have entered the Mediterranean from the North Atlantic storm track. All these features are well known and they reproduce realistically the characteristics of the cyclones in the Mediterranean region (Alpers et al. 1990, Trigo et al. 1999). The analysis of the CTR and CO_2 scenarios presents similar distributions. The differences between ERA-15, CTR and CO_2 are not statistically significant because of the high space-time variability of cyclogenesis, and the analysis of the geographical distribution of the cyclones on such a relatively fine grid could not produce convincing conclusions.

In order to reduce the effect of small-scale spatial variability, the cyclones were divided into 5 groups according to the subregions where they formed. The 5 sub-regions (see Fig. 7) were subjectively defined on the basis of the distribution observed in Fig. 6 and based on knowledge of the meteorological phenomenology in the Mediterranean region. The 5 groups are as follows: 'At' cyclones entering the Mediterranean region from the Atlantic Ocean; 'NA' cyclones formed over Northern Africa; 'WM' cyclones formed in the Western Mediterranean, including the Po Valley and Spain; 'EM' cyclones generated in the Eastern Mediterranean; and 'Ot' cyclones that entered from

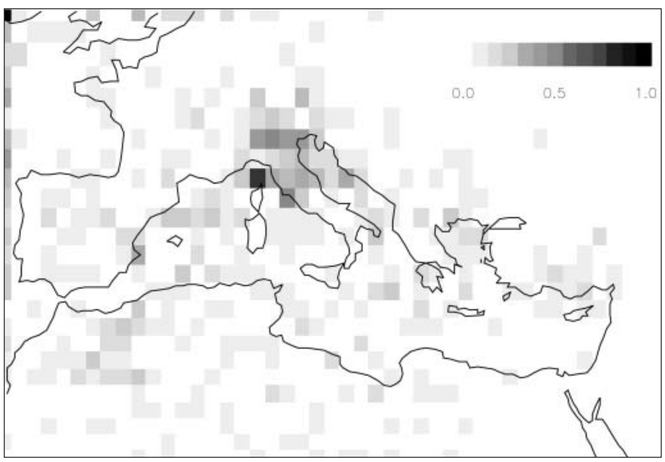

Fig. 6. Number of cyclogenesis events per year in each cell of the grid used for the analysis of the SLP. Results of the analysis of the ERA-15 data are shown. In the solid black cells at least one cyclogenesis event per year was observed

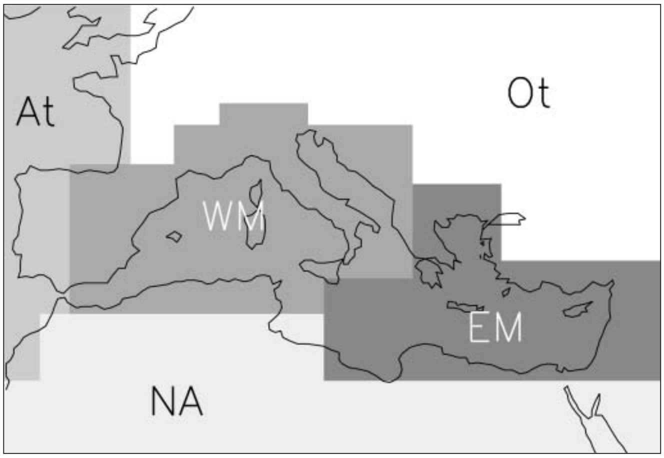

Fig. 7. Geographical sub-regions used for the analysis of the cyclone distribution in the Mediterranean region. At: Atlantic; WM: Western Mediterranean Sea; EM: Eastern Mediterranean Sea; NA: North Africa; Ot: remaining part of the grid

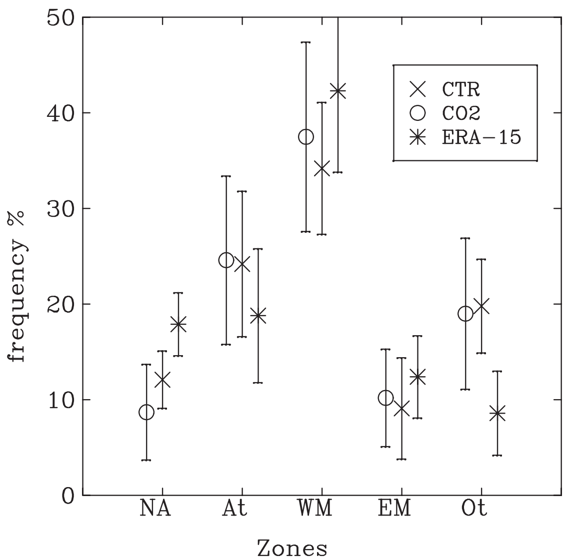

Fig. 8. Percentage of cyclones in the 5 geographical groups for ERA-15 (asterisks), CTR (crosses),CO_2 (circles). The bars show the interannual variance. The percentages have been computed for the 5 geographical groups NA, At, WM, EM, Ot

the northern boundary of the analyzed grid or were generated in the rest of it, mostly over Central Europe.

Fig. 8 shows, for each scenario, the percentage of the cyclones deeper than 15 hPa that have been generated over the 5 sub-regions. The bars associated with each value show the respective interannual variability. Figs. 8 & 9 are based on the 3MHPF fields. However, the analysis based on the 2WHPF fields produces equivalent results, if a smaller threshold (approximately 12 hPa) is adopted. With respect to the ERA-15

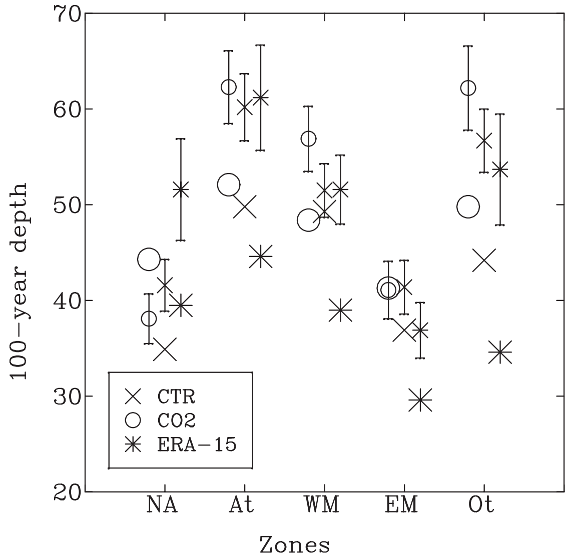

Fig. 9. 100-year return depth and maximum depth reached by the cyclones in the analysed datasets. The values have been computed for the 5 geographical groups NA, At, WM, EM, Ot.The smaller symbols show the 100 yr return and, the larger symbols the maximum depth recorded in the ERA-15 (asterisks), CTR (crosses),CO_2 (circles) datasets. The bars associated with the smaller symbols show the errors of the estimated 100 yr return values

data, the CTR scenario (crosses) overestimates the percentage of cyclones entering the Mediterranean region from northern Europe, while it underestimates the percentage of cyclones formed over Northern Africa. The geographical distributions of cyclones in the CTR and CO_2 (circles) scenarios are very similar, and this shows that the reduction of the cyclonic activity is generalized over the whole Mediterranean region. In general, the differences between the CTR and ERA-15 (asterisks) scenarios are larger than the differences between CTR and CO_2.

Fig. 9 shows the results of the extreme value analysis carried out, separately, for the At, NA, WM, EM, and Ot groups. The results confirm the tendency of the CO_2 scenario to increase the intensity of the extreme cyclones. In fact, in every group, the 100 yr return depth is larger in the CO_2 than in the CTR scenario (Table 2). There is only 1 exception: the extreme intensity of the cyclones generated over North Africa, which is reduced in the CO_2 scenario. This reduction is not very reliable because of the relatively large discrepancy between CTR and ERA-15 for this group. However, the differences between the estimated 100 yr return values in the CTR and CO_2 scenarios are not statistically significant when compared with the errors.

Fig. 9 also shows the maximum depth reached within each group. Since the duration covered by the datasets is much shorter than 100 yr, the maximum depth is

Table 2. Maximum recorded and 100 yr return cyclone depth by region of origin, based on the 3MHPF fields

Scenario	Whole grid		Mediterranean region	
	Max depth	100-year return value	Max depth	100-year return value
Atlantic				
ERA-15	44.6	61.2 ± 5.5	29.7	41.7 ± 4.1
CTR	49.8	60.2 ± 3.5	41.1	50.6 ± 3.2
CO_2	52.1	62.3 ± 3.8	37.5	46.6 ± 3.0
North Africa				
ERA-15	39.5	51.6 ± 5.2	34.3	35.1 ± 3.1
CTR	34.9	41.6 ± 2.7	29.1	32.1 ± 2.3
CO_2	44.3	38.1 ± 2.6	25.7	27.4 ± 2.1
West Mediterranean				
ERA-15	39.0	51.6 ± 3.6	35.3	39.3 ± 2.8
CTR	49.3	51.5 ± 2.8	41.1	42.4 ± 2.4
CO_2	48.4	56.9 ± 3.4	34.1	42.7 ± 2.6
East Mediterranean				
ERA-15	29.6	36.9 ± 2.9	24.7	27.2 ± 2.4
CTR	36.9	41.4 ± 2.8	28.6	30.7 ± 2.0
CO_2	41.3	41.1 ± 3.0	27.2	29.8 ± 1.8
Other				
ERA-15	34.6	53.7 ± 5.8	29.6	31.3 ± 3.2
CTR	44.2	56.7 ± 3.3	40.5	46.2 ± 3.2
CO_2	49.8	62.2 ± 4.4	35.7	37.4 ± 2.5

generally lower than the 100 yr return value, except for the NA group in the CO_2 scenario, where the recorded maximum exceeds the 100 yr return value. This maximum (44.3 hPa) is clearly exceptional, being close to the 500 yr return value. However, if the extreme value analysis is carried out without accounting for it, the 100 yr return value of the NA grouping in the CO_2 scenario is only slightly reduced (from 38.1 to 36.7 hPa) without affecting the conclusions of the analysis.

3.4. Dependence of the results on the model resolution

It is well known that the coarse resolution (T106) used for this simulation with the ECHAM model is not fully capable of reproducing the real intensity of the cyclones in the Mediterranean region. The results of the time slice experiments are, therefore, expected to systematically underestimate the maximum depth of the cyclones. There is the possibility that very extreme meteorological events, with a very fast deepening of the low pressure system, are absent (or greatly underestimated) in this analysis because of the coarse resolution used. This point is particularly important in the CO_2 scenario, because the increase in SST (approximately 4 K) implies that the threshold for the formation of hurricane and tropical storm has been reached in the Mediterranean Sea.

A limited set of high resolution (0.25°) simulations has been performed to investigate these issues. A set of 21 cyclones (11 extracted from the CTR time-slice experiment and 10 from the CO_2 one), which includes the most intense cyclones of both scenarios, has been identified. The simulations, carried out with BOLAM (Bologna Limited Area Model, Buzzi et al. 1994), do not present any dramatic change in the behavior of the analyzed cyclones, though there is a clear positive bias in their maximum depth when the high resolution model is used (see Fig. 10). Anyway, there is no evidence of a larger deepening in the CO_2 scenario, though the largest increase in depth (more than 20 hPa) is actually observed in the CO_2 scenario. This analysis does not give any strong indication that the use of a high-resolution model would imply a different interpretation of the differences between CO_2 and CTR, but it shows that the differences due to the model resolution are not fully negligible and a larger number of events should be analyzed in order to confirm the analysis carried out in this study.

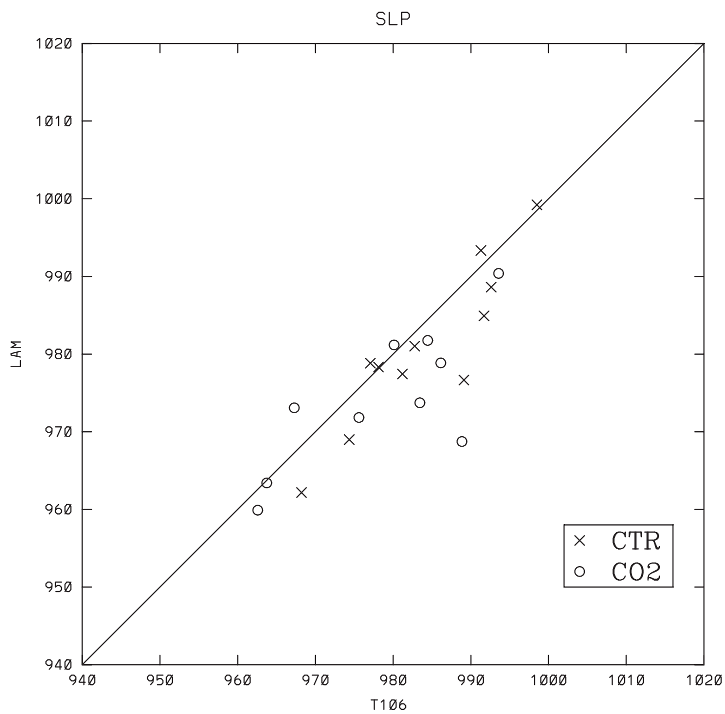

Fig. 10. Minimum central pressure value of 21 selected cyclones in the time slice experiment (*x*-axis) vs LAM simulations (*y*-axis). Data points represented by crosses and circles were extracted from the CTR and CO_2 scenarios, respectively

4. CONCLUSIONS

This study aimed at evaluating the effect of CO_2 concentration doubling on the cyclonic activity in the Mediterranean region. The analysis is based on the 15 yr long ERA-15 data and 2 time-slice experiments, CTR and CO_2, which simulated the atmospheric circulation in the present and the doubled-CO_2 climate scenarios. The cyclones that enter the Mediterranean region in these 3 simulations were identified, ordered according to their maximum depth and sorted according to the geographical sub-region where they were generated. The intercomparison among these 3 sets of data was used to evaluate the effect of the CO_2 doubling.

This study suggests a statistically significant reduction in the overall number of cyclones in the doubled CO_2 climate scenario with respect to the present one. In fact, the overall number of cyclones in the CO_2 experiment is significantly lower than in the CTR experiment, and, at the same time, the difference between the ERA-15 data and the CTR experiment is not statistically significant. Anyway, the interannual variability in the intensity of the cyclonic activity remains comparable to the difference between the 2 scenarios, so that a mild year in the present scenario and a stormy year in the doubled CO_2 scenario have an equivalent number of cyclones. Moreover, the climate change signal is comparable to, though clearly larger than, the error, that is, the difference between CTR and ERA. In other terms, there is no evidence of a large change.

The reduction of the cyclonic activity does not remain valid as the threshold depth of the considered cyclones increases. When progressively stronger cyclones are considered, their number in the ERA data becomes closer to the CO_2 scenario than to the CTR one, and no climate change signal can be clearly identified in these simulations.

The extreme intensity of the cyclones is significantly higher in the CO_2 scenario than in the CTR one when the evaluation of the intensity is based on the maximum depth during the whole duration of each cyclone. However, when the maximum depth within the Mediterranean region is used, the extreme intensity of the cyclones is lower in the CO_2 scenario than in the CTR one. It appears that some extreme cyclones of the CO_2 scenario experience large growth over Eastern Europe, downwind of the Mediterranean Sea. How much this strong growth would affect the Mediterranean region is not clear. Both these opposite climatic change signals, though not large, are statistically significant. Moreover, the change in the extreme values, though it is not dramatic, is larger than the error of the scenario, meant to be the difference between the extreme values in the ERA-15 and CTR simulations. It is important to remark that this extreme value analysis is likely to identify a climatic change signal only if such change is large (Frei & Shär 2001). Therefore, unfortunately, this analysis cannot rule out, with a high confidence level, that the return time for a given cyclone intensity is a factor of from 0.5 to 2 different in the CO_2 scenario.

The cyclones were grouped according to their geographical origin, and the analysis of the distribution and of the extreme values was repeated separately for each group. This analysis reaches uncertain conclusions because of the large variability of the cyclones behavior and the inaccuracies of the CTR scenario, which shows relevant discrepancies for the NA and Ot cyclones with respect to the ERA-15 data. The indication is that in CO_2 scenario the reduction of the number of cyclones and the increase in their extreme intensity is homogeneous over the whole Mediterranean region. The only exception are the cyclones originated over Northern Africa which, in the CO_2 scenario, show a diminished extreme intensity as well as a particularly large reduction in number.

A small subset of 21 cyclones was simulated with a LAM at 0.25° resolution, and the resulting pressure minima were compared to the corresponding scenario values at T106 resolution. The comparison shows that the LAM produces deeper cyclones, but there is no evidence that the increased resolution produces a systematically different effect in the CO_2 and CTR scenarios. Moreover, the results of this study, based on simulations carried out at T106 resolution, are consistent with previous studies that were based on coarser resolution models (Carnell & Senior 1998, Sinclair & Watterson 1999, Knippertz et al. 2000). Therefore, there are no indications that very different conclusions on the variation of the cyclonic activity should be reached using a higher resolution model. Anyway, the issue of the effect of model resolution in these analyses is an important aspect of this research, and it should be more extensively investigated in future.

The outcomes of this study are consistent with the generalized reduction of the cyclone frequency shown in former studies carried out at coarser resolution (Carnell & Senior 1998, Sinclair & Watterson 1999, Knippertz et al. 2000). Moreover, our analysis is consistent with a diminished cyclonic activity over the whole Southern Europe due to the northward shift of the storm track, confirmed by the global analysis of the time-slice experiments (May 1999). The overevaluation of the cyclonic activity in the CTR scenario can be explained by an eastward instead of a north-eastern route for the mean atmospheric circulation at the exit of the Atlantic storm-track incorrectly predicted in the CTR experiment (May 1999). It is interesting to observe that the doubled CO_2 scenario presents a limited, and not convincingly significant, increase in the intensity of extreme storms which could be related to the SST increase. However, there is no evidence for the formation of hurricane-like systems over the Mediterranean Sea, in spite of the high SST, which is approximately 4 K warmer in the doubled CO_2 scenario than in the present one and leads to a tropical SST condition in this region. This is consistent with previous studies, where, in a double CO_2 scenario, there was no appreciable increase in the area affected by tropical cyclones in spite of a substantial increase in the area where the SST was higher than 26°C (Haarsma et al. 1992). In fact, the formation of tropical cyclones is a not fully understood process, whose frequency is not related in a simple way to a SST threshold. There is evidence that a necessary condition is the existence of a wide pillar of very humid air that extends through the whole extent of the atmosphere (Emanuel 1987). It is very likely that this condition is absent in the dry Mediterranean environment. Moreover, the absence of these intense phenomena could be due to the coarse resolution of the GCM used in the scenario simulations. Though a T106 resolution model might be capable of simulating the evolution of a hurricane, it is not adequate for the description of its formation which occurs on scales as small as 50 km.

In summary, the climate variations identified in this study are not large, and the only clear effect of CO_2 doubling on the cyclonic activity in the Mediterranean is the diminished overall cyclonic activity.

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