Mediterranean Warm-Core Cyclones in a Warmer World

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Abstract

Regional climate model projections over the Mediterranean region are analysed for the presence of intense, warm-core lows that share some of the characteristics of tropical cyclones. The results indicate that the number of such systems decreases in a warmer world, particularly in winter. Comparison of the simulated numbers to changes in relevant climate diagnostics suggests that numbers decrease due to an increasingly hostile environment for storm formation, combined with a general poleward shift in the incidence of wintertime lows over western Europe.

1. Introduction

It has been previously shown that some storms forming and developing in the Mediterranean Sea have some of the structural characteristics of tropical cyclones (e.g. Reale and Atlas 2001; Emanuel 2005). Numerous studies have shown that tropical cyclones differ from baroclinically-forced systems in that they are warm core systems whereas extratropical cyclones usually are cold cored (Haurwitz 1935; Mayengon 1984). More recently, attention has focused on a subset of intense, small Mediterranean warm-core systems, popularly known as “medicanes”, with a number of studies examining their structure and characteristics (Lagouvardos et al. 1999; Pytharoulis et al. 2000; Fita et al. 2007; Tous et al. 2010; Tous and Romero 2011, 2012). Typically, the rate of occurrence of these storms in the Mediterranean basin is less than one per year.

The recent study of Tous and Romero (2012) thoroughly characterizes the synoptic environment of these rare storms. A database of events is compiled using a combination of automated and manual detection techniques and their typical formation conditions are elucidated through the comparison of a number of diagnostics. Medicane formation is associated with high diabatic heating from surface fluxes, sea surface temperatures (SSTs) greater than 15 degrees C and larger than normal values of Maximum Potential Intensity (MPI; Bister and Emanuel 1998), a diagnostic more usually associated with tropical cyclone intensity.

In general, because of the small size of these storms (a diameter of less than 300 km), they have been poorly simulated in climate models. A recent exception is the high-resolution simulations of Cavicchia and von Storch (2012). Using resolutions as fine as 10 km, they were able to simulate successfully the generation of medicane cases described in the literature when the model was initialised two weeks in advance of storm formation. Since this time period is long enough so that the model's simulation of short timescale phenomena such as medicanes was no longer sensitive to initialization, this study demonstrated the potential of this modeling approach to generate medicanes when running in climate mode.

Previous climate model simulations have suggested that deep Mediterranean low pressure systems may become more intense or more numerous in a warmer world. For example, Gaertner et al. (2007) analysed results from the regional climate model (RCM) simulations generated as part of the PRUDENCE project (Christensen et al. 2002). These simulations were performed at a horizontal resolution of 50 km and were forced by a suite of general circulation models (GCMs). The results showed a wide range of responses across RCMs, but in general the frequency of cyclone centres increased in a warmer world, accompanied by increases in the 95th percentile of storm intensity, as measured by the low-level geostrophic vorticity. Gaertner et al. (2007) also investigated the structural characteristics of Mediterranean lows, particularly the limited subset of lows that have clear warm-core characteristics, as deduced from the phase-space diagram of Hart (2003). The changes of these storms in a warmer world were model-dependent, with some models showing increases in storm lifetimes while others did not.

In further work, Gaertner et al. (2011) employed a similar methodology to analyse the results of the ENSEMBLES project (Hewitt and Griggs 2004), a suite of RCM simulations at 25 km resolution. They used the tropical cyclone detection method of Picornell et al. (2001) to detect intense warm core lows over the Mediterranean, of which true medicanes would be a subset. They concluded that for most simulations, the number of storms in the Mediterranean was reduced in a warmer world but their intensity was slightly increased. Lionello et al.

(2008) also analysed changes in the frequency and intensity of cyclones in regional climate change projections with a horizontal resolution of 50 km over the European region and found a predominant decrease of the frequency of storms over the Mediterranean region, but more contrasting results concerning changes in peak storm intensity. Clearly, further work is needed in order to assess more firmly possible changes in frequency and intensity of Mediterranean storms under global warming conditions.

In the present study we complement previous work by focusing on a subset of all Mediterranean lows, those that have high wind speeds and warm cores. Throughout the paper we refer to such storms as “warm core lows”. A further subset of these, consisting of small, intense, symmetric storms, is considered in the present study to have characteristics similar to those of observed medicanes. To complement the work of Gaertner et al. (2011), we also examine changes in the incidence of all intense lows, not just warm core systems, and use relevant diagnostics to examine changes in the physical factors that are related to storm formation. We analyze RCM simulations of present day and future climate conditions under increased greenhouse gas concentrations over the European region to determine the response of simulated warm core lows to anthropogenic climate change, and to examine the geographical variation of this response. We accomplish this goal by using a storm detection and tracking algorithm specifically designed to identify warm core systems. Section 2 of the paper details the methodology, Section 3 gives results and Section 4 provides a discussion and concluding remarks.

2. Methodology

The simulations analysed here are from the regional model RegCM3 (Giorgi et al., 1993a,b; Pal et al. 2007) running at a horizontal grid spacing of 25 km and 18 sigma-p vertical levels.

The model employs the radiative transfer scheme of Kiehl et al. (1996), a non-local planetary boundary parameterization based on Holtslag et al. (1990), the Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al. 1993) for the description of land surface processes, the cumulus convection scheme of Grell (1993) and the resolvable precipitation representation of Pal et al. (2000).

These simulations were performed as part of the ENSEMBLES project (Hewitt and Griggs 2004) and in particular two experiments are considered here. The first uses lateral boundary conditions from the ERA40 reanalysis (Uppala et al. 2005), while the second is driven by output from a scenario simulation conducted with the ECHAM5 general circulation model (Roeckner et al. 2003). The scenario simulation extends from 1951 to 2100 under greenhouse gas forcing from the A1B emission scenario of Nakicenovic and Swart (2000) and we analyze here three time slices: 1981-2000 for current climate and 2041-2060, 2081-2100 for future climate conditions.

The model output is then analyzed to test the model's ability to generate intense low pressure systems in the Mediterranean. Intense Mediterranean lows are detected using the CSIRO tropical cyclone detection scheme of Walsh et al. (2004). The steps used by this detection routine are as follows:

- Points with cyclonic vorticity greater than $1.x10^{-5}$ s^{-1} are first identified; this threshold serves only to eliminate isolated points of weak cyclonic vorticity, thus speeding up the detection routine (the actual intensity threshold is set by the wind speed criterion below);
- A centre of low pressure is then found;

- At the centre of the storm a warm core is found, specified as the sum of the temperature anomalies at the storm centre versus the surrounding environment, with the temperature anomaly at 300 hPa being greater than zero; in addition, the mean wind speed over a specified region at 850 hPa must be greater than that at 300 hPa.
- A minimum 10 m wind speed threshold of 17.5 ms^{-1} is then imposed, such that wind speeds within the storm must exceed this value; this corresponds to the observed defined threshold of tropical storm strength

Detections of very small, intense warm-core lows were also compared with the observed medicane cases of Tous et al. (2011) and Tous and Romero (2012) to determine the ability of the model to generate these rare Mediterranean storms. In order to estimate future changes in storm characteristics, storm statistics in the future time slices of the ECHAM-driven run were compared to the corresponding values in the current climate period.

The detection scheme produces storms tracks, including storm intensity, that are then analysed to produce genesis density and track density plots, in number of storm formations or tracks per 2x2 degree grid square. Like all such schemes, one of its main limitations is the possibility that the tracking may not be entirely consistent between storms, leaving gaps in the tracks along with possible double-counting of storms. This possibility is excluded by manual inspection of the resulting storm tracks. Compared with other widely-used storm tracking schemes (e.g. Murray and Simmonds 1991a,b; Flocas et al. 2010), this scheme has the advantage of simplicity and is well suited to the detection of rare events such as warm-core Mediterranean lows.

3. Results

3.1. Simulated storm numbers

Figure 1 shows results for the detection of intense warm-core systems in the simulation nested within the ERA-40 reanalysis, for both the full year and seasonally varying conditions. A storm is detected if it occurs once in the data set (which is archived four times a day) and numbers are summed over 2x2 degree grid squares. Thus one detection corresponds to a single detection in that grid square over the period of simulation, in this case 1981-2000. The plots are then smoothed to reduce random spatial variability between grid squares. Figure 1 shows that these systems are generally infrequent. A strong seasonal variation in the simulation of intense storms is simulated, with considerably more occurring in the winter months than in the summer. Maximum occurrence in the winter season is in the western Mediterranean to the west of Sardinia, but other important regions of occurrence are located over the Adriatic Sea southern Italy and in the Aegean. A number of such storms are also generated in the Black Sea (Efimov et al. 2008). A similar pattern is seen in the climatology of Maheras et al. (2001), derived from NCEP reanalysis (Kistler et al. 2001). Fig. 2 shows the Maheras et al. (2001) winter climatology of intense storms, defined as those with central pressures less than 995 hPa. They showed a similar strong seasonal dependence in their observational analysis to that shown in Fig. 1: essentially no such storms are observed in the summer over the Mediterranean and the Black Sea, while a pronounced winter maximum is seen. Fig. 2 shows that geographical maxima of winter storm occurrence in the observations are located over the Gulf of Genoa, the northern Adriatic, and over southern Greece (Maheras et al. 2001; their Fig. 6f). In the observations of Maheras et al. (2001) there is also a tongue of high observed occurrence running north from the north-central Black Sea region into Ukraine and Russia. This is also simulated by RegCM3, as shown in Fig. 1.

Fig. 1 also shows that a large number of such intense, warm-core storms are also simulated off the west coast of western Europe and over the British Isles. It is possible that such storms are examples of the subset of extratropical systems that evolve in a manner consistent with the warm seclusion mechanism proposed by Shapiro and Keyser (1990), where extratropical storms can possess a warm core during part of their lifecycles. This hypothesis is difficult to confirm without significant additional analysis. In any event, our focus in this study is on the Mediterranean region.

An analysis was also undertaken of these simulated lows to determine whether the simulations were generating the observed lows within the interior of the domain, rather than simply generating a similar statistical distribution of such systems with no day-to-day correspondence between simulated and observed lows. A manual examination of the forcing ERA-40 reanalyses showed that almost all of the detected lows in the ERA-40 RegCM3 simulations shown in Fig. 1 were also observed in the forcing ERA-40 reanalyses, at similar locations. This implies that the model is able to reproduce a representative set of real Mediterranean low pressure systems.

In contrast, very few of the observed medicane cases of Tous et al. (2011) or Tous and Romero (2012) can be seen in the model simulations forced by reanalyses. Clearly, for such small systems, stochastic formation processes must dominate, thus leading to a poor simulation of their observed formation in a model experiment like this one that is run in climate mode without reinitialisation. There is one exception: the medicane of late October 1994 that formed to the southeast of Sicily. This appears to be well simulated by RegCM3 when forced by ERA-40. Fig. 3 shows the simulated mean sea level pressure of this case, while Fig. 4 shows the simulated warm core anomaly, here defined as the sum of the mid-tropospheric temperature anomalies versus the surrounding temperatures at those levels. The storm is small, has a strong warm core and clearly shares a number of the defined characteristics of a medicane. Tous et al. (2011) and Tous and Romero (2012) define these largely from the storm's appearance in satellite images: a diameter less than 300 km, the existence of a definite eye, a symmetric and continuous cloud structure surrounding the eye and a duration longer than 6 hours. The storm shown in Figs. 3 and 4 has a diameter less than 300 km, appears symmetric and lasted for more than 6 hours. It is noted, however, that the October 1994 storm does not appear in the updated medicane list of Tous and Romero (2012) (their Table 1).

In this analysis, we define "medicane-like" in a similar fashion to the work of Tous and Romero (2012), although without their analysis of the cloud structure of the storms. Here we define a simulated storm as "medicane-like" if it satisfies the detection conditions listed in section 2, and in addition has a distance of less than three degrees of latitude from its centre to its last closed isobar, appears symmetrical in shape and is located only over the ocean. Of the simulated warm-core systems in the run driven by ERA-40 reanalyses, a subset of these appear to have the characteristics of medicanes, even though apart from the October 1994 storm mentioned above they did not correspond to specific observed medicanes in the available observations. Overall, sixteen "medicane-like" storms were identified in this 20-year period analysed from this run, a similar formation rate to that observed. Their general geographical pattern of occurrence (not shown) indicates a tendency for formation further south than that of other warm-core cyclones, as shown by Tous and Romero (2012). Their seasonal variation shows a maximum in winter, instead of the autumn maximum shown by Tous and Romero (2012), thus indicating a possible inclusion of other warm core systems in our definition, as these have a clear maximum in winter.

Some further analysis was performed to determine whether the formulation of the detection routine was causing simulated medicanes not to be detected, through the imposition of unnecessarily strict detection criteria. Another detection run was performed, this time turning off the requirement for a warm core, and a similar search for medicane-like storms was made. The results (not shown) did not represent a substantial improvement in the simulation of the observed Tous and Romero (2012) medicane cases, suggesting that initialization issues are critical in generating these small storms in the correct locations.

We have examined the changes in medicane numbers in the ECHAM5-driven simulations in the current and future climates. A total of 19 medicane cases were identified in the current-climate simulation, while this number decreased to 8 in the 2081-2100 simulations. Thus there is a clear decrease in medicane-like storm numbers. We also examined any changes in the intensity distribution of these storms in a warmer world, but since numbers are low, it was difficult to draw any conclusions. Since the number of true medicane cases appears to be small, both in the observations and the simulations, and their identification in the simulations has a subjective component, we instead focus on the larger group of warm-core cyclones for subsequent analysis.

The comparison of Fig. 1 to the regional model simulation nested with the current-climate output from the ECHAM5 model is instructive. Figs. 5 and 6 show that the patterns of occurrence when the regional model is nested within the reanalysis and the GCM are similar, but the number of storms generated by the GCM nesting is somewhat larger. Figure 6 shows that the ECHAM5 run has more pronounced maxima over the Black Sea, the Italian peninsula and the Bay of Biscay, and to a lesser extent over the Aegean, in regions corresponding to maximum cyclone occurrence in both runs. Examination of the surface temperature fields in the ERA40 and ECHAM5 runs shows that the surface temperature in the ECHAM5 run is slightly colder over the Mediterranean and the meridional temperature low-level gradient is slightly greater over the northern Mediterranean in the ECHAM5 run. This suggests a relationship between this increased gradient and the larger number of storms in this run.

The climate change simulation of the ECHAM5-nested runs was next examined. Fig. 7 shows the differences in numbers of lows from the current climate simulation for the period 2041-2060 and 2081-2100. The patterns of differences in the two time periods are remarkably similar: in January-March, for both time periods there are decreases in numbers in the region near Sardinia and increases over the Gulf of Genoa and northern Italy. Both time periods also show decreases over southern Greece and the central Black Sea region, as well as the Bay of Biscay. The consistency of this response across two separate time periods suggests that it is systematic and not a result of multidecadal variability. Due to the similarity of the response in the two time periods, we will focus on results for the later period of 2081-2100.

Total numbers of intense storms over the Mediterranean region decrease in a warmer world, however. Figure 8 shows intensity distributions of storm maximum wind speeds over the Mediterranean region bounded by 5-40E, 30-45N. As the climate is projected forward in time, the total numbers of storms drop but the maximum wind speed reached in each time period increases. Few storms exceed hurricane intensity (33 ms^{-1}), however.

3.2 Climate diagnostics

Maximum potential intensity

A useful diagnostic for understanding the intensification of tropical cyclones is the Maximum Potential Intensity (MPI; Bister and Emanuel 1998). Since we are examining here the small subset of intense Mediterranean cyclones that have significant warm cores, it is of interest to determine whether the MPI diagnostic can give insight into the simulated changes in cyclone characteristics. We focus on the JFM season as this is the season with the most cyclones and we show maximum low level wind speed (Vmax) calculated from the MPI theory. Comparing Figures 9(a) and Figure 8(a), we see that Vmax is in generally agreement with the maximum intensity of the simulated storms, with highest intensities between 25 and 30 ms^{-1}. By 2081-2100, Figure 9(b) gives decreases in Vmax over the Mediterranean mostly between 2 and 5 ms^{-1}. In contrast, Figure 8(b) shows that the maximum intensity of the strongest storms increases, although there are a only few storms that exceed 30 ms^{-1} in intensity. The total number of intense storms decreases in the warmer world simulations, and this may be a more accurate reflection of the impact of decreasing Vmax.

Vertical wind shear

Warm-core systems, both tropical and subtropical cyclones, can be disrupted or prevented from forming by vertical wind shear, the magnitude of the vector difference between winds in the upper and lower troposphere (e.g. Briegel and Frank 1987). Vertical wind shear V_z is defined here as where the zonal and meridional velocities are evaluated at 300 and 850 hPa. Figure 10 shows the change in vertical winds shear for JFM. Climatological wind shear is significantly greater in the warmer world simulation, with a substantial area of the Mediterranean having average wind shears more than 4 ms^{-1} greater. This climatological average difference is large enough to affect the generation rate of tropical cyclones (e.g. Shapiro 1987) and may have some relevance in possibly inhibiting the future formation of cyclones in our scenario simulation.

Eady growth rate

The Mediterranean is located in a region subject to baroclinic processes. A standard measure of the intensity of baroclinicity is the Eady growth rate (EGR; Eady 1949; Vallis 2006):

where N is the Brunt-Väisälä frequency, *f* is the Coriolis parameter and *U* is the zonal wind. Here we diagnose this quantity for current and future climate conditions from mean climate fields. It has been noted by previous authors (e.g. Simmonds and Lim 2009) that it is more accurate to derive the EGR from instantaneous fields and then average to create a climatology. Thus the present, time-mean average diagnostic is intended only as an estimate of whether changes in EGR are consistent in sign with the simulated storm response. Figure 11 shows the difference in EGR for JFM between the current and future climate time periods, for both 600 hPa and 850 hPa heights. Both are given as it is not yet established which of these is most suitable for the assessment of baroclinic conditions (Simmonds and Lim 2009). Simulated 600 hPa EGR (Fig. 11a) in the current climate over the Mediterranean generally increases from west to east, reaching maximum values of between 0.6 and 0.8 day^{-1} over the eastern Mediterranean, similar to observed values for this region derived from reanalyses by Paciorek et al. (2002). Changes in EGR in a warmer world at both levels are generally small (Figs. 11b and d), with slight increases at 850 hPa in the eastern Mediterranean and slight decreases in the west, while there are more uniform but generally small increases at 600 hPa. Since the total number of intense warm-core lows decreases substantially in a warmer world, the small changes in the EGR indicate that baroclinic processes are not a strong contributing factor to the processes driving that change.

Comparison between warm core storms and all intense storms

The present study focuses on a subset of all Mediterranean cyclones, those with maximum wind speeds comparable to tropical cyclones and with accompanying warm cores. These storms are infrequent, so it is useful to compare the results for this set of storms to a similar set of intense storms with same wind-speed threshold but that do not satisfy the warm-core criterion (Fig. 12a). Comparing Fig. 12a to the observations (Fig. 2), the patterns of formation are quite similar, with largest values over the Italian peninsula and declining towards the east. Comparing Fig. 12a to Fig. 5, we see that the patterns are similar, although the regions of maximum occurrence of the warm core systems appear to be further out into the Mediterranean Sea than those for all intense storms. The difference pattern between current and future climate for all intense storms (Fig. 12b) is similar to that for warm core storms (Fig. 7b), but the differences for the warm-core storms appear more pronounced over the sea than over land. In addition, Fig. 12b appears to show a poleward movement in the incidence of such storms, with increasing numbers over continental regions north of the Mediterranean.

4. Discussion and conclusions

In common with previous work, the results here show that the numbers of Mediterranean cyclones are likely to decrease in a warmer world, for both warm-core and other lows, particularly in winter. A wintertime decrease in numbers of Mediterranean lows is consistent with predictions of a poleward movement of the mid-latitude storm track (e.g. Ulbrich and Christoph 1999; Lionello et al. 2008; Giorgi and Coppola, 2007).

The new, finer-resolution simulations presented here provide an opportunity to examine the issue of how smaller, intense storms respond to a changed climate. These wintertime decreases are accompanied by a general increase in vertical wind shear over the Basin, some decreases in theoretical tropical cyclone potential intensity, and little change in baroclinic growth rates. An increase in vertical wind shear is well known to affect both tropical and subtropical storm formation rates (e.g. Pezza and Simmonds 2005). Tous and Romero (2012) showed that observed intense cyclones and medicanes in general will not form in very high shear environments, so an increase in climatological shear such as that simulated here would be likely to cause more hostile environmental conditions for these storms.

Tous and Romero (2012) also showed that intense Mediterranean lows and medicanes require reasonably high values of MPI to form. The decrease in the climatological value of MPI simulated here would be likely to make it more difficult to form such storms in a warmer world. This is an additional factor that may be related to the simulated future decline in intense warm-core storm numbers shown here.

A limitation of the analysis shown here is whether the detection routine is identifying the appropriate subset of intense storms in this region. The detection routine was designed to detect tropical cyclones and has been applied to these simulations without modification. While a number of candidate storms have been detected, it may be that a modification of the warm-core criterion could lead to a better discrimination between storms that are primarily baroclinically-driven and those that derive substantial energy from the sea surface through low-level diabatic heating (Tous and Romero 2012). In addition, even though these simulations have been performed at the highest resolution used to date to simulate the climate of the entire Mediterranean basin, the 25 km resolution used here may still not capture highest intensities of the warm-core mid-latitude storms analysed here, and may not be high enough to effectively capture true medicanes (Cavicchia and von Storch 2012). Since these storms are at least partially convectively-driven, this makes the use of finer horizontal and vertical resolution preferable to best represent these processes. Also, comparison with other simulations would be useful to determine whether these results are robust between models. Fig. 8 shows that while the total number of intense storms decreases, there is a tendency for an increase in the storm maximum intensity. The number of very intense storms with wind speeds greater than 30 ms^{-1} in the future climate run is very small, however.

Other limitations of this study are related to the use of a regional climate model and issues of domain specification. A number of studies have shown that the ability of an RCM to simulate a particular atmospheric phenomenon may depend on the exact specification of the domain. For instance, Landman et al. (2005) showed that it was necessary to position the eastern boundary of their domain far enough east so that sufficient tropical disturbances could enter the domain and thus provide a good simulation of tropical cyclone formation. Thus in the regions surrounding the Mediterranean, smaller-scale phenomena that provide initiating mechanisms for some Mediterranean storm systems may not be well represented. Existing larger-scale teleconnection patterns may also be less reliably simulated due to this issue. Phenomena that may be less well represented as a result include interactions between the Red

Sea trough and autumn cyclogenesis in the eastern Mediterranean (Ziv et al. 2005) and interactions between tropical African systems and cyclone formation in this region (e.g. Lavaysse et al. 2010, Schepanski and Knippertz 2011). While this issue has not been examined in this study, it is possible that the effects of a warmer climate on tropical systems may have an impact on Mediterranean cyclone formation that could be less well captured in this modeling system.

A further limitation of this study is associated with the horizontal resolution of the models runs shown here. Cavicchia and von Storch (2012) found that while runs with a horizontal resolution of 25 km gave a good representation of medicane occurrence, maximum wind speeds at such a resolution gave an underestimate of observed wind speeds by 10-30%. A resolution of 10 km was required to best simulate these storms. This restriction would be less of an issue for the larger, warm-core cyclones that we have focused on in this study, however.

An overarching issue is how well the model simulates the details of the mechanisms of formation of observed cyclones. As Campins et al. (2010) note, the most important formation mechanisms of Mediterranean cyclones of various types are orography, baroclinicity, sensible heat fluxes, latent heat release and upper-level precursor troughs. The limitations of the horizontal and vertical resolution of the model used here will affect each of these mechanisms. For instance, the model may not have sufficient vertical resolution to resolve the upper-level jet instability processes that have been proposed as a genesis mechanism for tropical-cyclone like vortices in this region (Reale and Atlas 2001).

In summary, it is found that future projections of intense low pressure systems over the Mediterranean region indicate decreases in the numbers of such systems, particularly in winter. These decreases may be related to a general worsening of the environmental conditions associated with such storms, coupled with a general poleward movement of the typical incidence of such storms.

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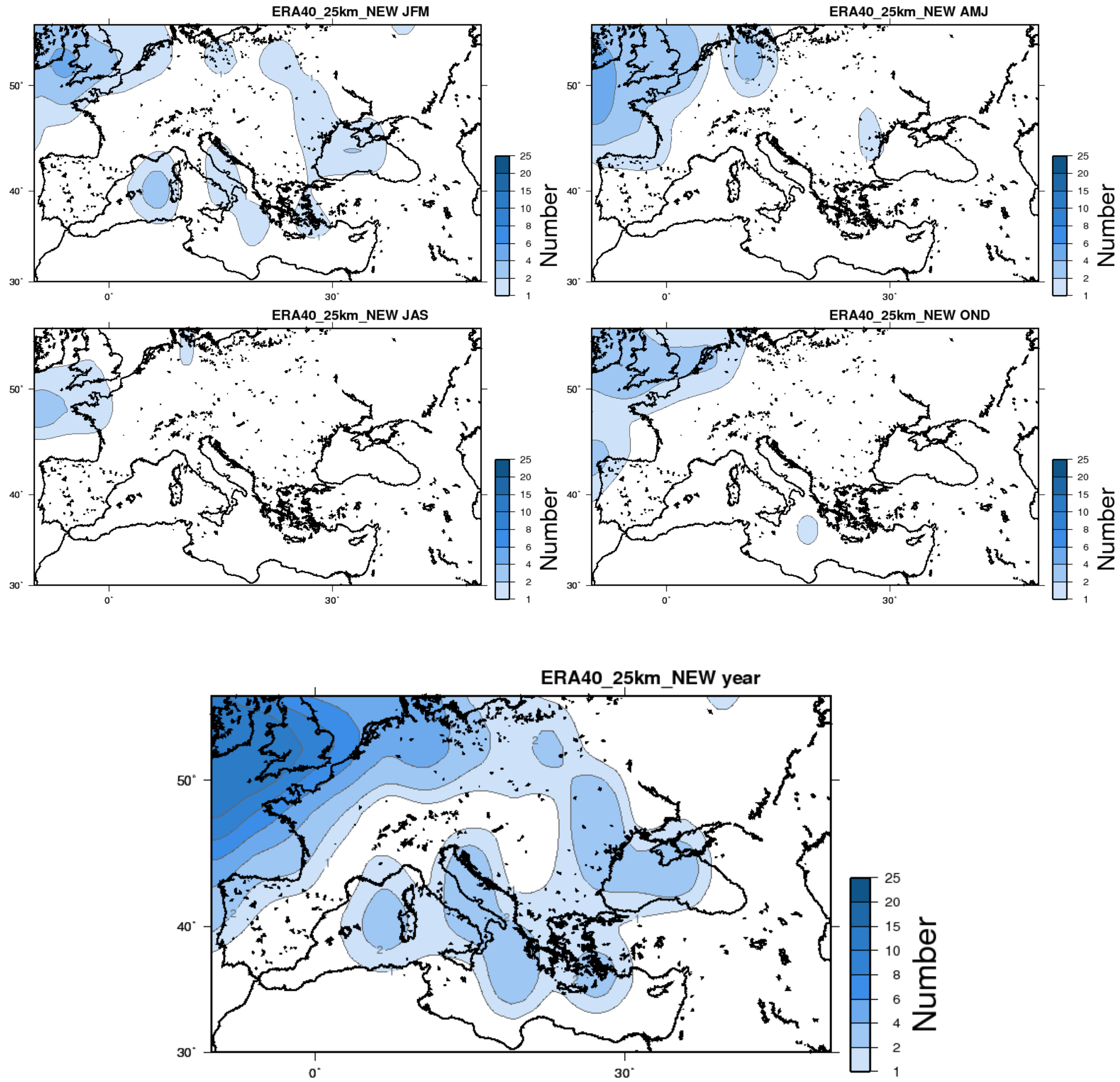
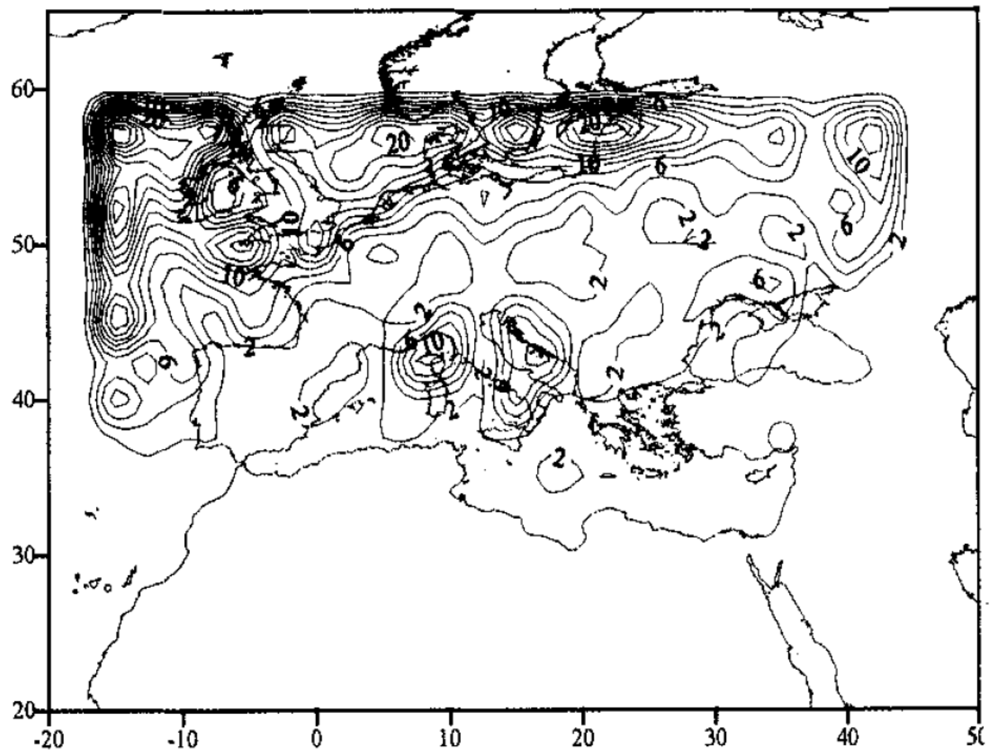


Figure 1. Number of warm-core cyclone detections of at least tropical storm strength, per 2x2 degree grid box, for RegCM3 simulation nested within ERA-40 reanalyses, 1981-2000, for each season and the annual totals. Detections are analysed for model output archived four times a day, as described in the text.

(a)



(b)

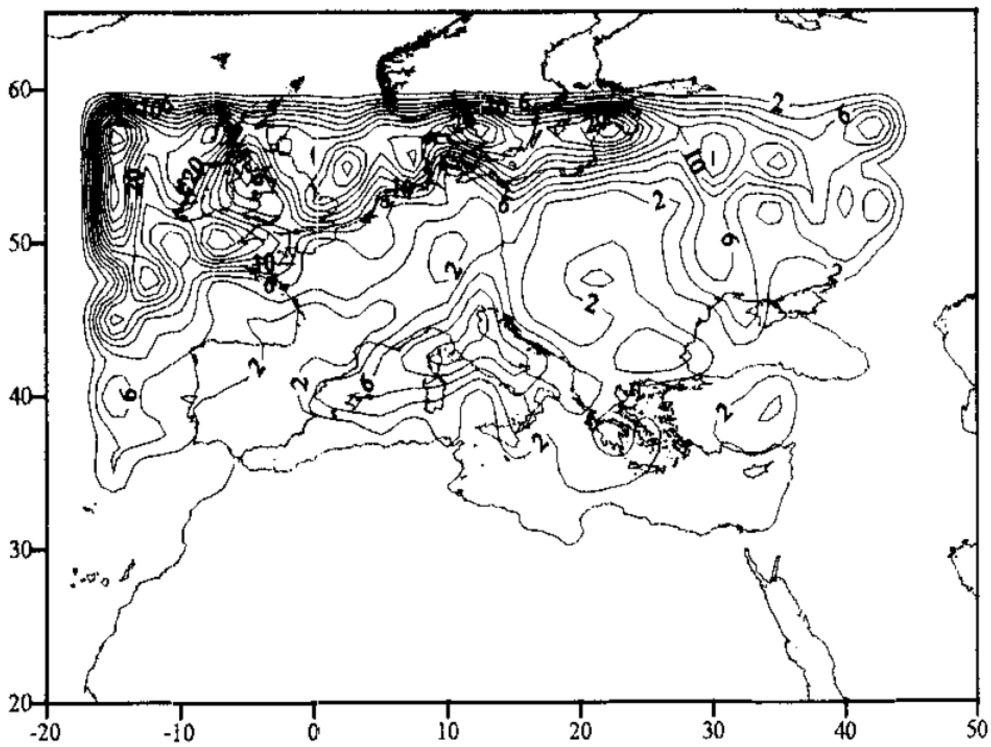


Figure 2. Average number of cyclonic disturbances with central pressures less than 995 hPa, per winter season (DJF) per 2.5 degree grid square, for (a) 0000 UTC and (b) 1200 UTC; from Maheras et al. (2001).

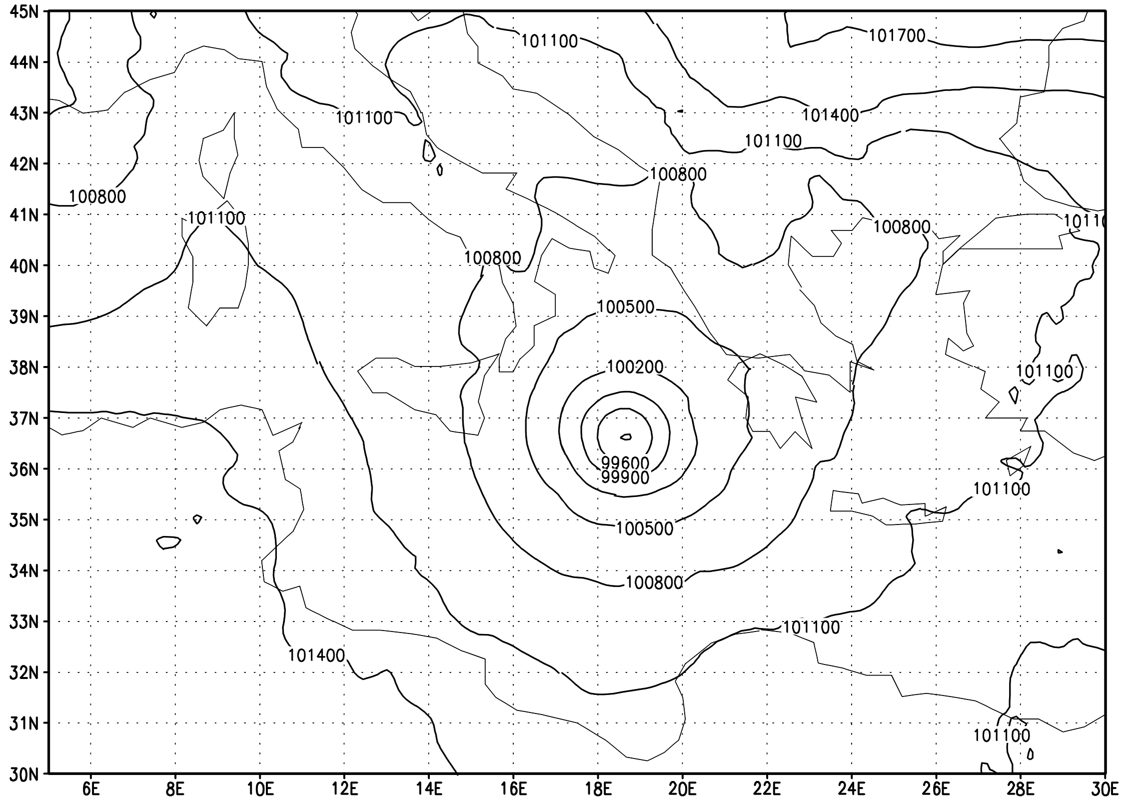


Figure 3. Simulated medicane case of 00Z Oct. 23 1994. Contour interval is 300 Pa.

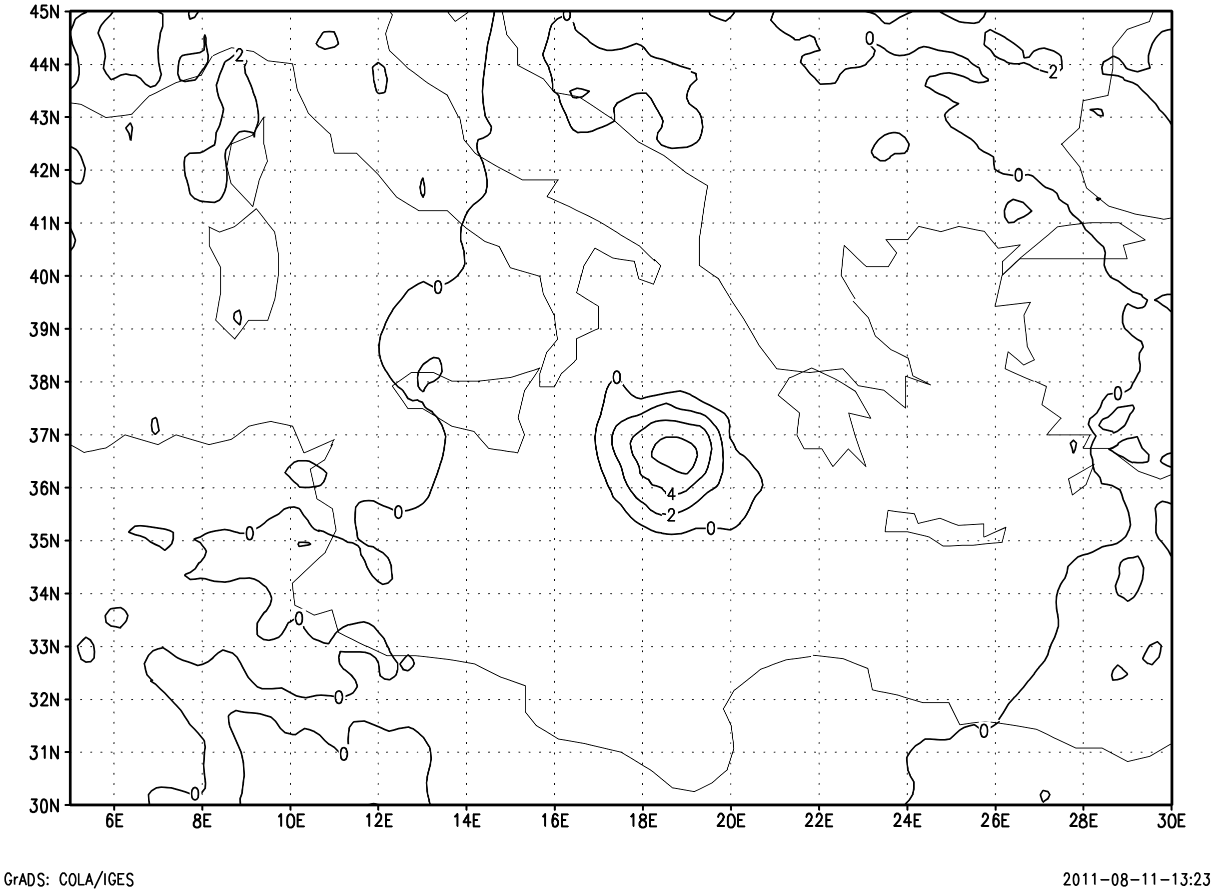


Figure 4. The same as Figure 3 but for the sum of the mid-tropospheric temperature anomalies. Contour interval is 2 degrees.

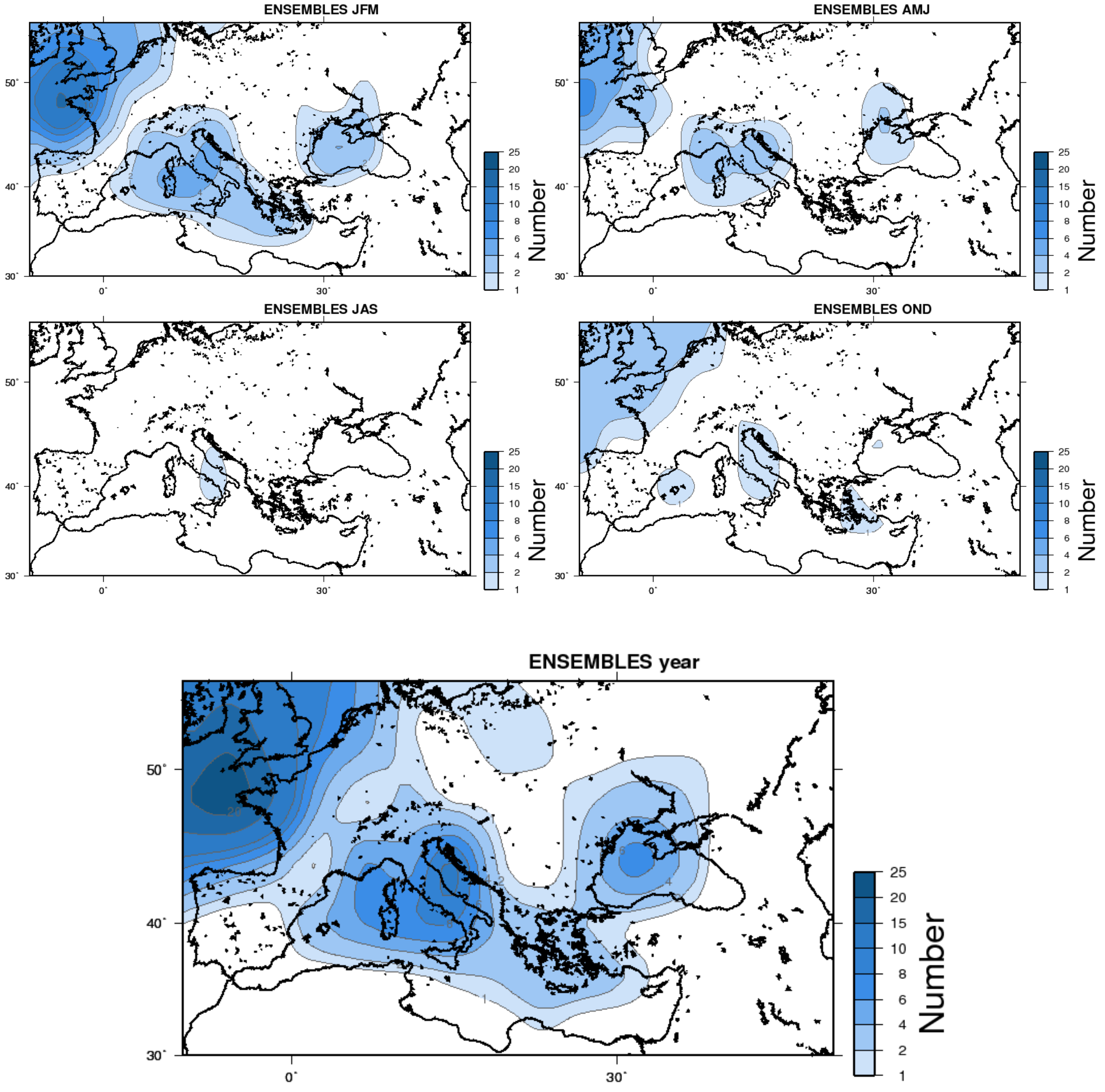


Figure 5. The same as Fig. 1 except nested within the output of the ECHAM5 GCM, for the seasons indicated.

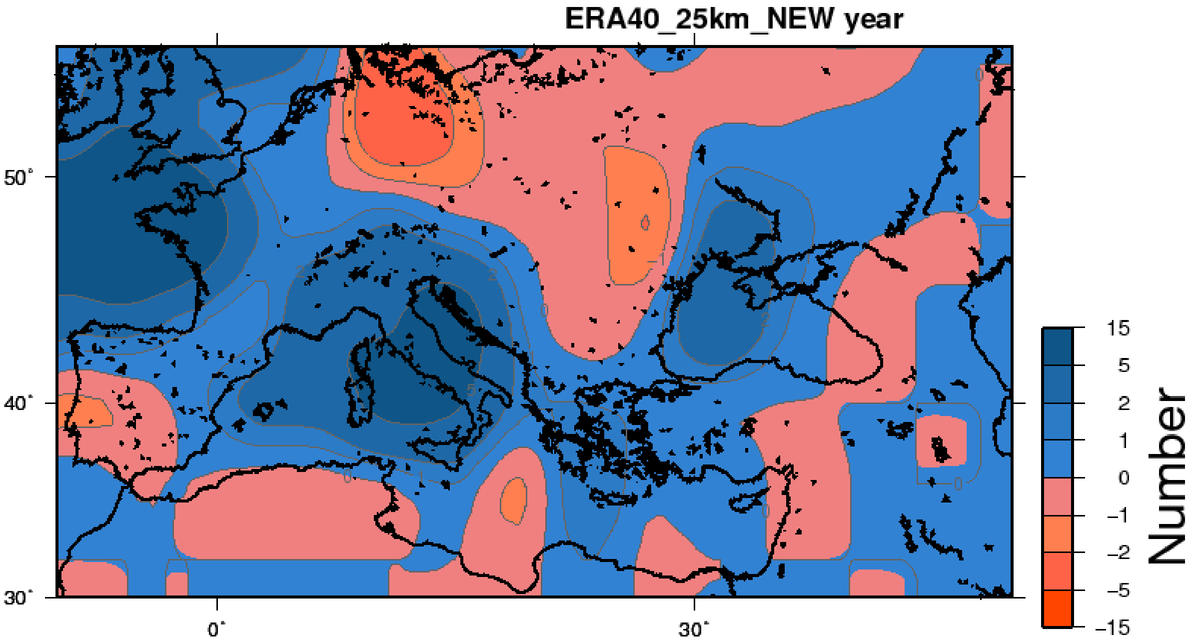
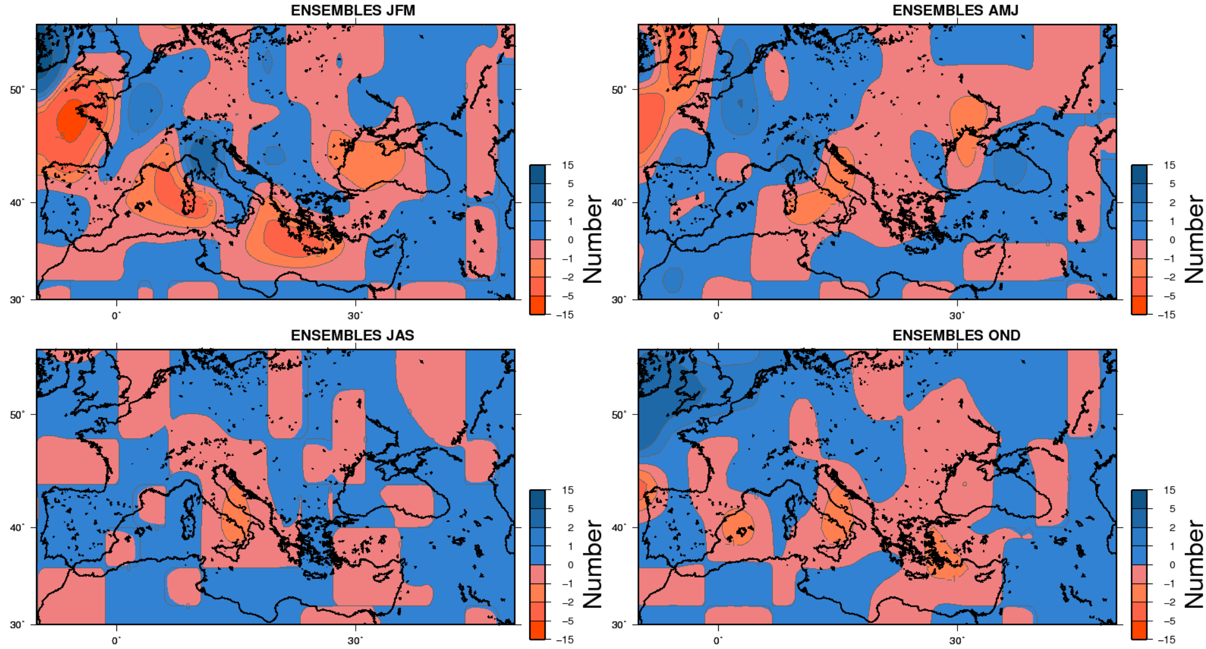


Figure 6. The same as Fig. 1 except for difference in cyclone occurrence, entire year, ECHAM5-forced run minus ERA-40 forced run.

(a)



(b)

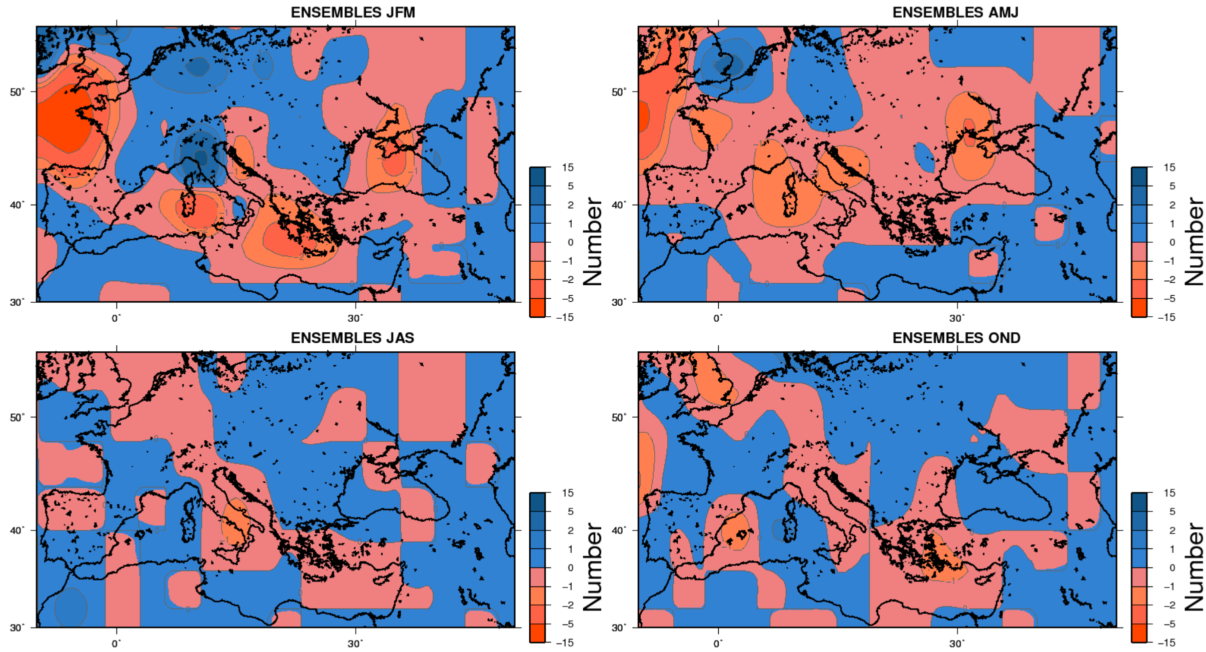
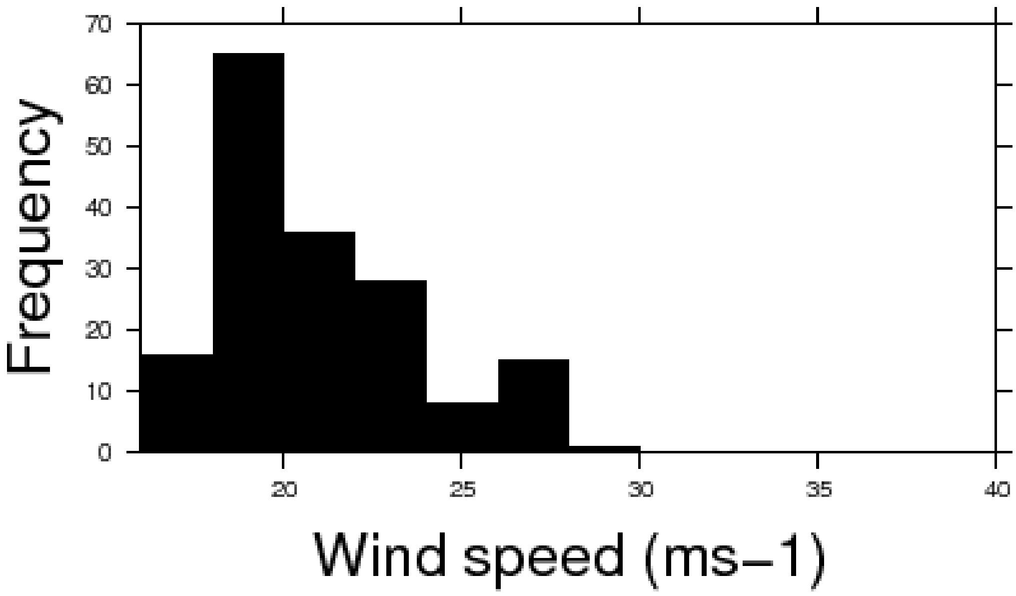


Figure 7. Differences in numbers of lows between ECHAM5-nested simulations from current-climate simulation, for (a) 2041-2060; and (b) 2081-2100, for each season.

(a)



(b)

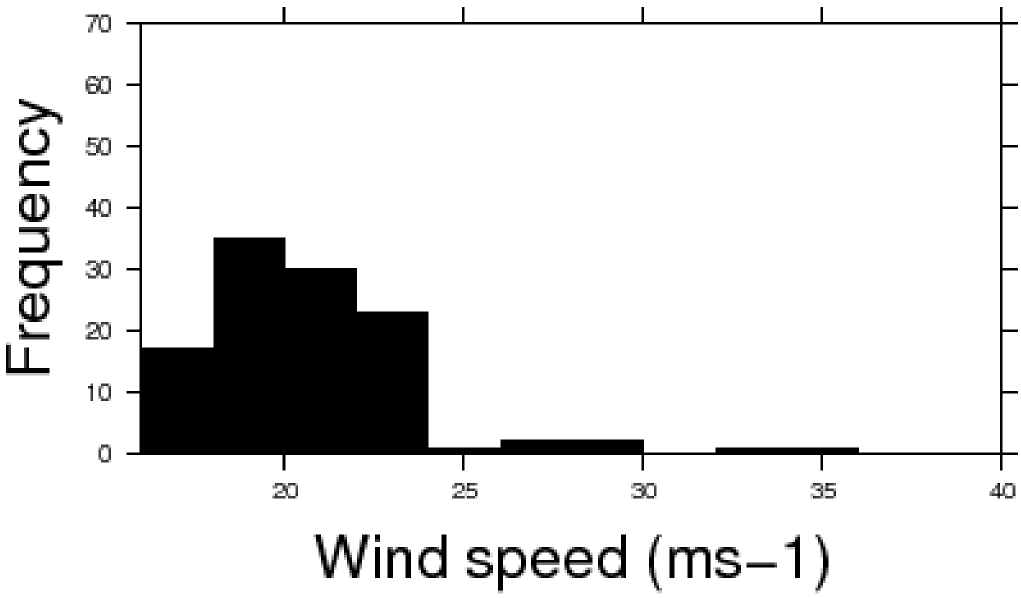
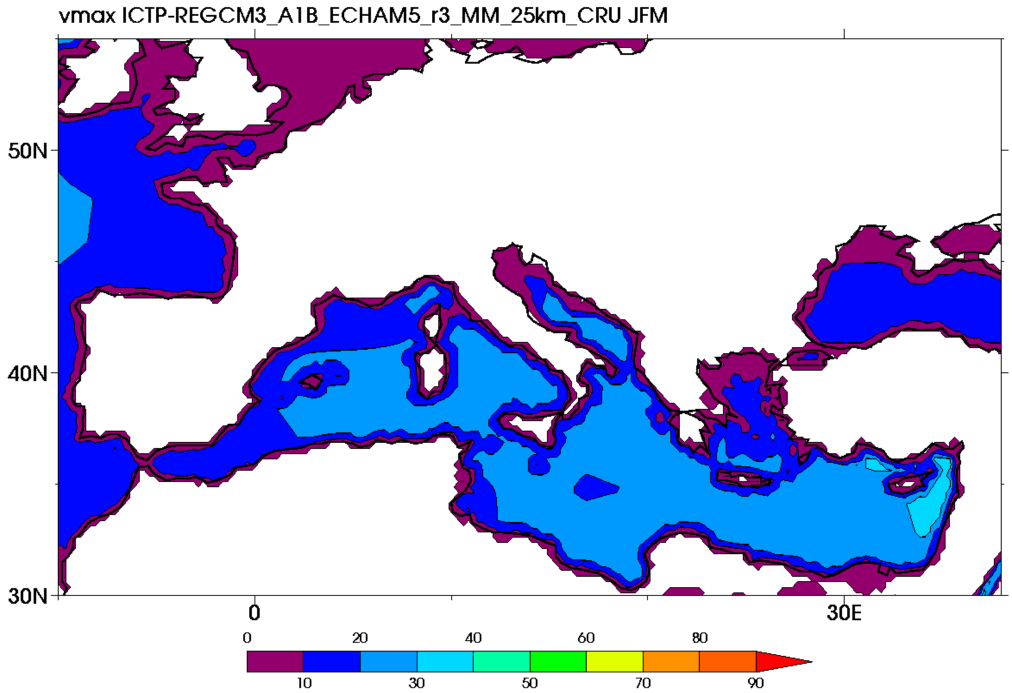


Figure 8. Histograms of storm maximum wind speed for (a) current climate (1981-2000); and (b) for 2081-2100, with a bin width of 2 ms^{-1}

(a)



(b)

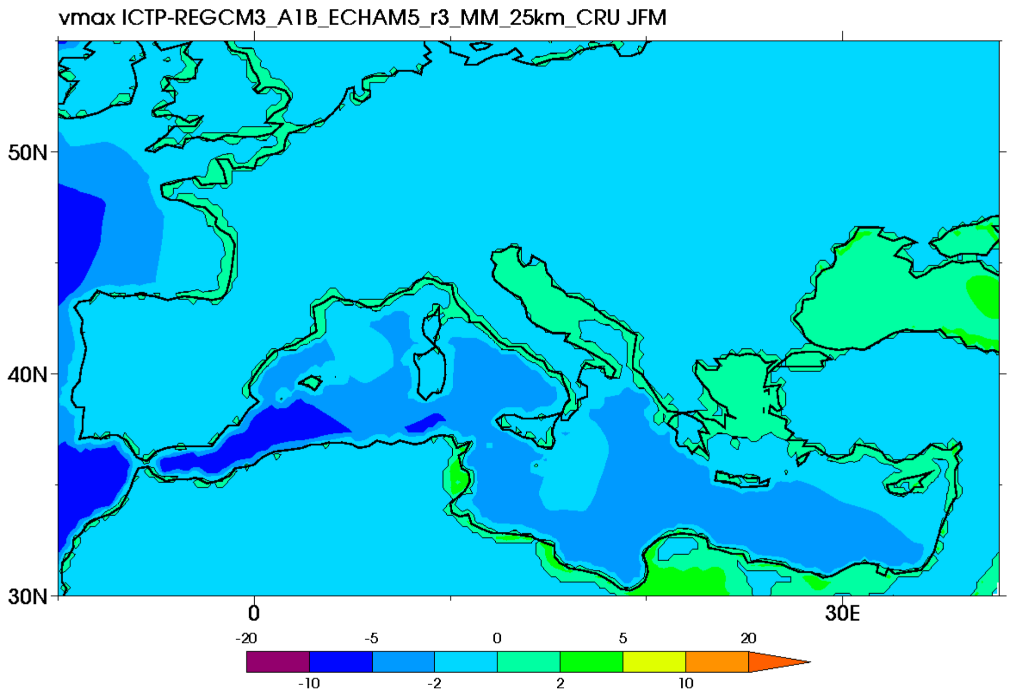


Figure 9. (a) MPI as expressed by maximum low-level wind speed (Vmax) for ECHAM5 RegCM3 run, JFM 1981-2000; (b) Difference inVmax, 2081-2100 minus 1981-2000, ECHAM5 RegCM3 run.

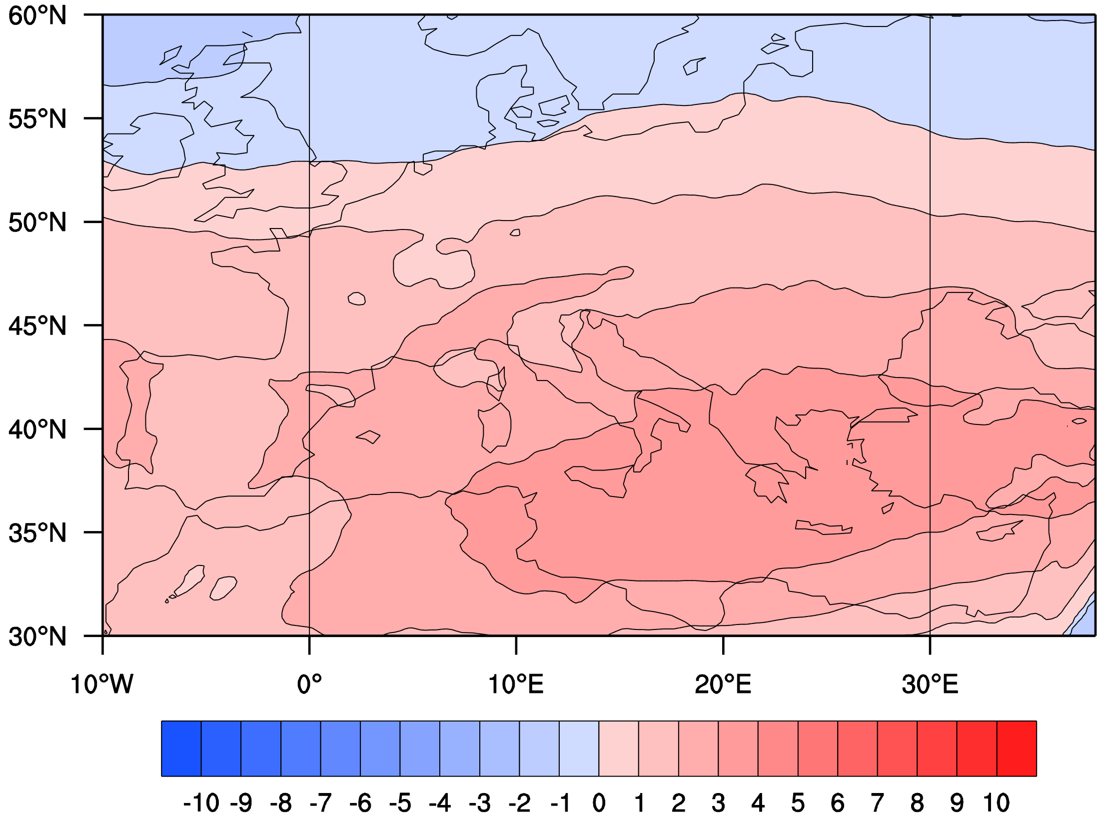
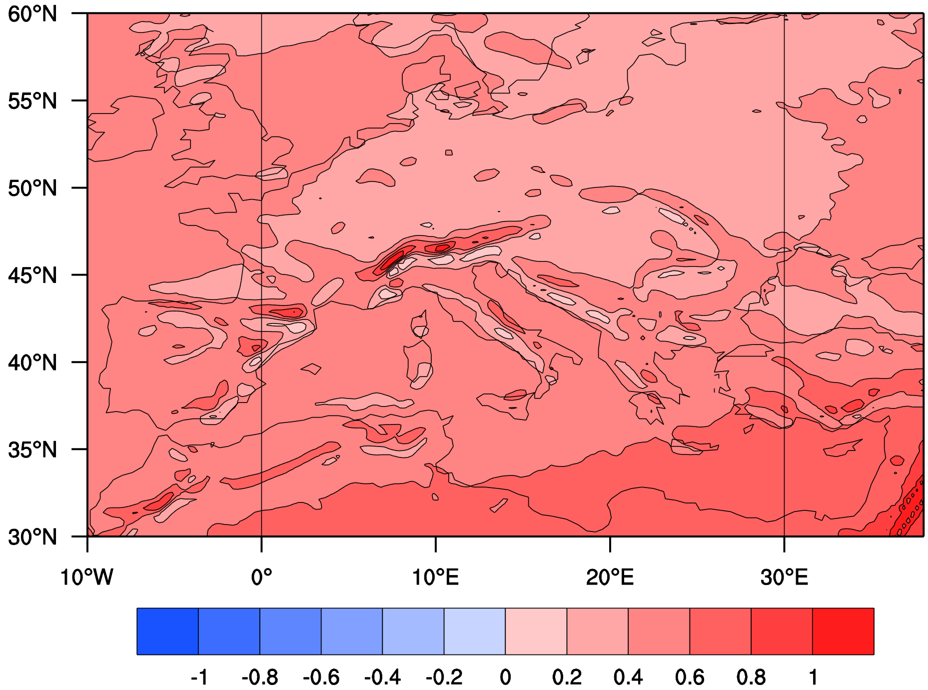
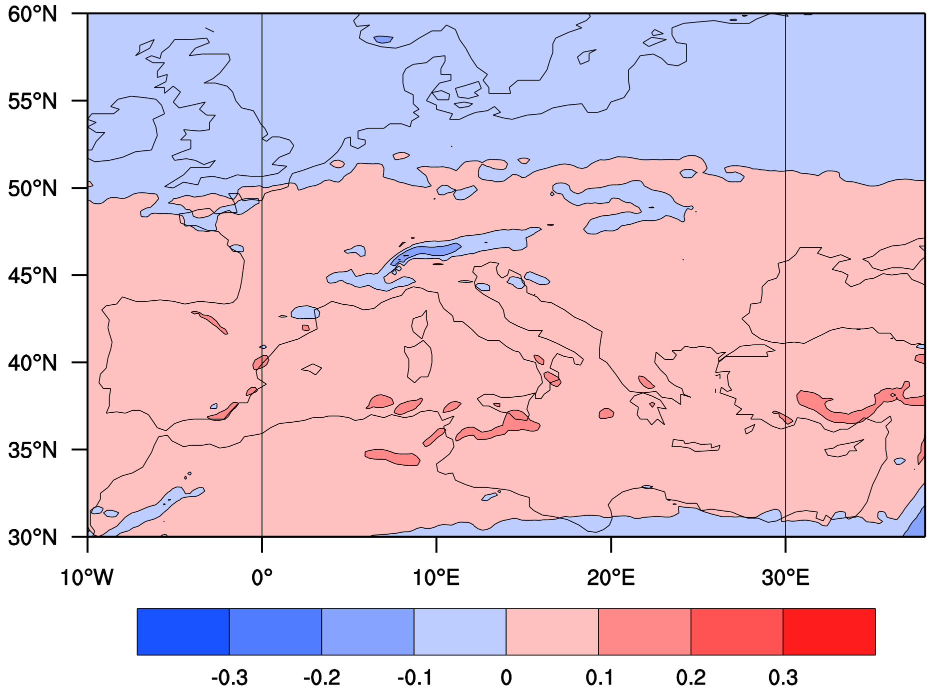


Figure 10. Difference in vertical wind shear, JFM, 2081-2100 minus 1981-2000, ECHAM5 RegCM3 run.

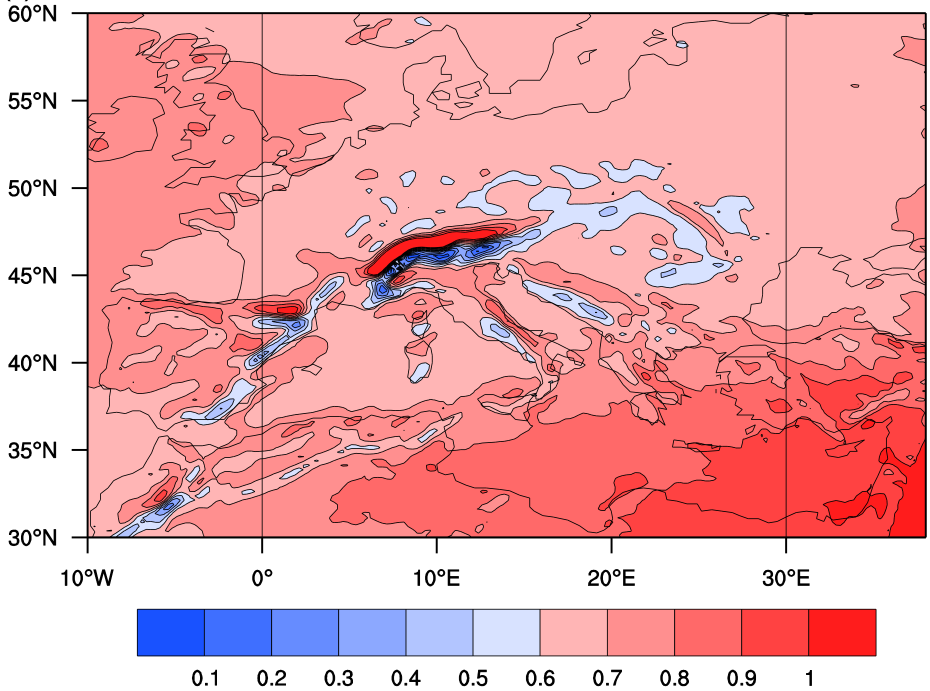
(a)


60°N
55°N
50°N
45°N
40°N
35°N
30°N
10°W
0°
10°E
20°E
30°E
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

(b)


60°N
55°N
50°N
45°N
40°N
35°N
30°N
10°W
0°
10°E
20°E
30°E
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

(c)



(d)

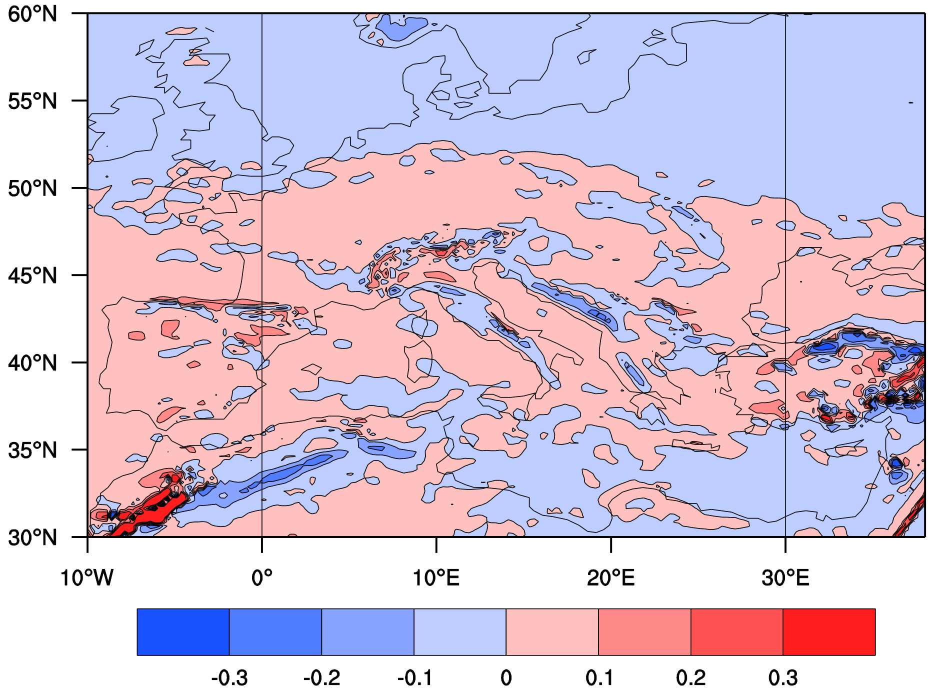
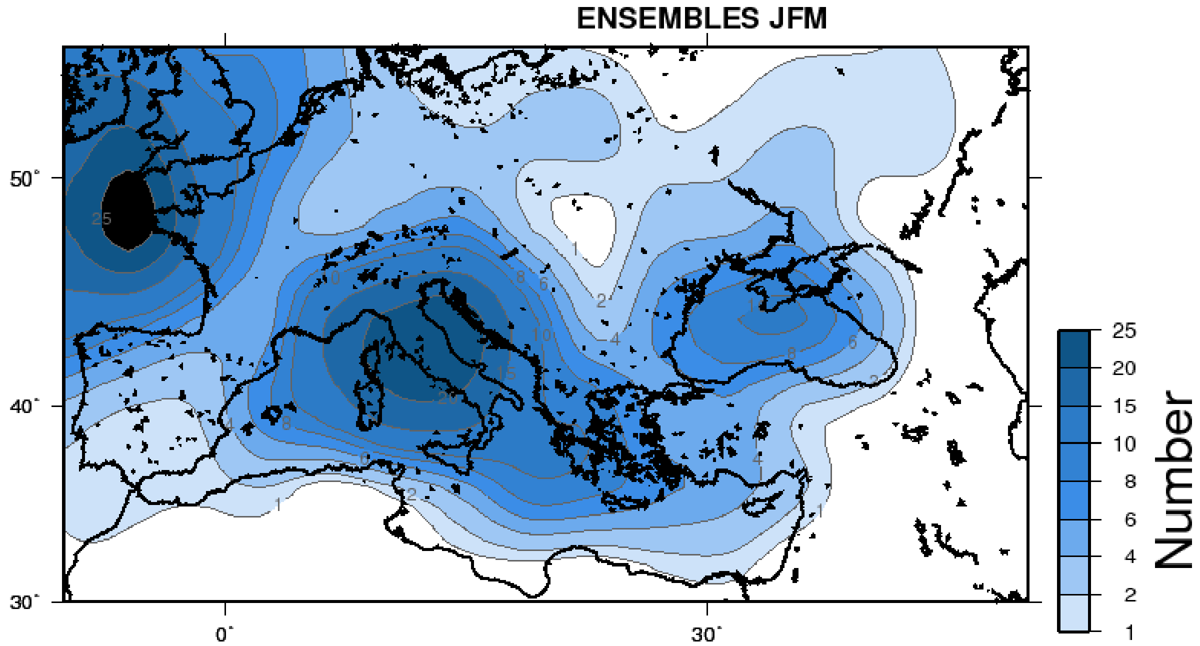


Figure 11. (a) JFM current climate 600 hPa EGR; (b) Difference in 600 hPa EGR, 2081-2100 minus 1981-2000; (c) JFM current climate 850 hPa EGR; (d) Difference in 850 hPa EGR, 2081-2100 minus 1981-2000.

(a)



(b)

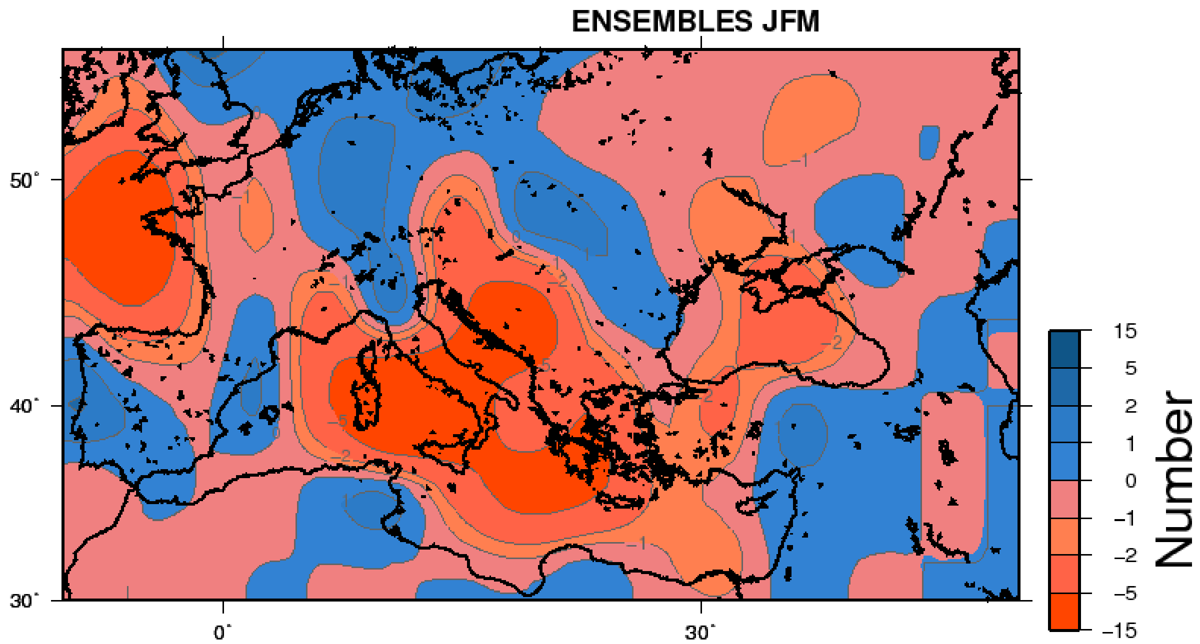


Figure 12. (a) The same as Fig. 5 (JFM only) but for storms of tropical storm strength that do not satisfy the warm core criteria; (b) the difference for these storms, future minus current climate.