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Objective climatology of cyclones in the Mediterranean region: a consensus view among methods with different system identification and tracking criteria

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ABSTRACT

The Mediterranean storm track constitutes a well-defined branch of the North Hemisphere storm track and is characterised by small but intense features and frequent cyclogenesis. The goal of this study is to assess the level of consensus among cyclone detection and tracking methods (CDTMs), to identify robust features and to explore sources of disagreement. A set of 14 CDTMs has been applied for computing the climatology of cyclones crossing the Mediterranean region using the ERA-Interim dataset for the period 1979–2008 as common testbed. Results show large differences in actual cyclone numbers identified by different methods, but a good level of consensus on the interpretation of results regarding location, annual cycle and trends of cyclone tracks. Cyclogenesis areas such as the north-western Mediterranean, North Africa, north shore of the Levantine basin, as well as the seasonality of their maxima are robust features on which methods show a substantial agreement. Differences among methods are greatly reduced if cyclone numbers are transformed to a dimensionless index, which, in spite of disagreement on mean values and interannual variances of cyclone numbers, reveals a consensus on variability, sign and significance of trends. Further, excluding 'weak' and 'slow' cyclones from the computation of cyclone statistics improves the agreement among CDTMs. Results show significant negative trends of cyclone frequency in spring and positive trends in summer, whose contrasting effects compensate each other at annual scale, so that there is no significant long-term trend in total cyclone numbers in the Mediterranean basin in the 1979–2008 period.

Keywords: Mediterranean region, cyclones, automatic tracking methods, tracks, cyclogenesis

1. Introduction

The Mediterranean region (MR) is one of the most active regions of the Northern Hemisphere in terms of cyclone activity, displaying a distinct regional maximum of cyclone numbers (e.g. Trigo et al., 1999; Ulbrich et al., 2009). The MR favours a wide variety of cyclogenesis mechanisms, such as the deepening of mid-latitude perturbations at the lee of the Pyrenees or the Alps, their fuelling by low-level moisture sources and/or by low-level baroclinicity along the coast, or the formation of thermal lows over warm inland regions (e.g. McGinley, 1982; Radinovic, 1986;

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Michaelides et al., 1999). As a consequence, the MR is prone to the occurrence of cyclones with a broad range of characteristics, from synoptic to mesoscale, and a variety of intensities and depths (see Lionello et al., 2006, and Ulbrich et al., 2012, for a general description).

Since the pioneering work published by the H.M.S.O. (1962), there have been many studies describing the most common features of cyclones in the MR, focusing on the most active areas, formation mechanisms, most common trajectories and impacts (e.g. Alpert et al., 1990; Trigo et al., 1999; Maheras et al., 2001; Trigo et al., 2002; Lionello et al., 2002; Nissen et al., 2010; Campins et al., 2011). Literature shows that there are three main cyclogenetic regions: the lee of the Atlas Mountains (Sharav cyclones), the lee of the Alps (Genoa cyclones) and over the Aegean Sea (e.g. Trigo et al., 1999). Other cyclogenetic areas include the Iberian Peninsula, the Black Sea and the Middle East. Furthermore, a non-negligible number of cyclones enter the MR from the Atlantic. As their relative importance varies strongly on seasonal terms, and cyclone activity also undergoes a strong interannual variability, a detailed characterisation of cyclone activity is necessary (Trigo et al., 2002; Campins et al., 2011; Garcies and Homar, 2011). In terms of impacts, Mediterranean cyclones often cause extreme precipitation and strong winds, leading to floods, landslides, storm surges and windstorm damage (e.g. De Zolt et al., 2006; Lionello et al., 2006, 2012; Nissen et al., 2010; Liberato et al., 2011; Pinto et al., 2013; Reale and Lionello, 2013; Messmer et al., 2015). Figure A.1 shows the MR with the geographical names used in this article.

The work presented here is based on state-of-the-art reanalysis data – the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) dataset (Dee et al., 2011) – and therefore provides an update of previous climatological studies, such as those mentioned in the previous paragraph. Furthermore, the analysis of cyclones characteristics and trajectories is not confined to a single cyclone detection and tracking method (CDTM), but considers the multi-method cyclone track database collected within the framework of the IMILAST project (Neu et al., 2013). Since the MR has been shown to be a region where it is important to be aware of differences produced by the choice of the CDTM (Raible et al., 2008), the analysis of such ensemble of cyclones and cyclone-tracks increases the robustness of the results compared to previous studies.

This study considers results generated by 14 different CDTMs, all based on objective criteria for cyclone identification and tracking. The various methods first identify cyclones as minima or maxima in near surface fields, for example mean sea level pressure (MSLP) or 1000-hPa geopotential height minima, or relative vorticity maxima at 850 hPa. The tracking is then performed by combining the centres identified in consecutive 6-hourly time steps and imposing a set of a priory conditions on the velocity admissible for mid-latitude cyclones. The resulting cyclone tracks and statistics enable a characterisation of the cyclone life cycle in both individual and climatological terms.

Section 2 describes briefly data and methods, while Section 3 presents the main results. Its initial part summarises the main features of Mediterranean cyclones. Its continuation consists of three subsections describing their characteristics (intensity, duration and speed), cyclogenesis areas and trends. Section 4 explores the differences among methods when considering weak, strong, slow and fast cyclones. Section 5 discusses the sources of uncertainty affecting the variability of cyclone frequencies. The results are briefly discussed and conclusions are presented in Section 6.

2. Data and methods

In this study, the MR is defined as the box extending from 9°W to 42°E and from 27°N to 48°N. A further division in four sectors, denoted as North-West (NW), North-East (NE), South-West (SW), South-East (SE), is used in some parts of the study using 38°N and 16.5°E as internal north-south and west-east boundaries, respectively (Fig. 1). In order to permit a direct comparison with results shown in Neu et al. (2013), the ERA-Interim data are used at 1.5° spatial resolution. This resolution may be too coarse to properly account for some small scale cyclones that occur in the MR (e.g. Trigo et al., 1999). Still, a systematic comparison of CTDMs with respect to their sensitivity to the resolution of the underlying data is beyond the scope of this paper and is left for a future study.

The analysis is based on 14 CDTMs that have contributed to the IMILAST archive (Table 1). Readers are addressed to Neu et al. (2013), particularly to its supplement 1, for the description of CDTMs,[1] of archive content and for a global intercomparison among CDTMs. All 14 CDTMs generate for each identified cyclone a track describing the positions of its centre and values of metric(s) of its intensity. However, they differ in a significant number of attributes such as (1) the use of different variables for cyclone identification (e.g. MSLP, vorticity, etc.), (2) the adoption of different procedures for identifying cyclones and combining the cyclone centres into a track, (3) the usage of different elimination criteria to filter out weak or artificial low-pressure systems (e.g. requiring a minimum pressure gradient, Laplacian or vorticity) and (4) different

[1]Method M07, which was not yet included in the IMILAST archive when Neu et al. (2013) was published, is described in Flaounas et al. (2014).

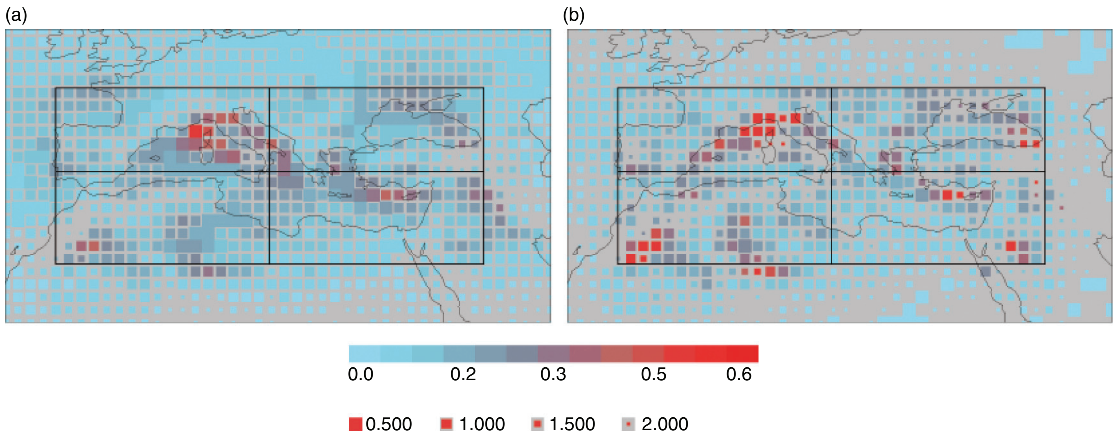

Fig. 1. Cyclone tracks and cyclogenesis in the Mediterranean region. (a) Track density according to the multi-methods mean. Colours represent the probability (%) that a cyclone track crosses each $1.5^{\circ} \times 1.5^{\circ}$ cell of the domain in the 6-hourly field (values according to the label bar below the panels). (b) Probability (%) that cyclogenesis occurs in each cell in the 6-hourly field. In both panels, only cyclones whose track crosses the Mediterranean region are considered. The filled fraction of each cell corresponds to the level of agreement (given by the normalised standard deviation) among methods as annotated below the panels. The large rectangle denotes the Mediterranean region with its subdivision in four sectors.

metrics for the intensity of the cyclones (e.g. minimum MSLP, minimum geopotential height, maximum vorticity). Table 1 provides a list with a brief description of each CDTM. The multi-CDTM mean (MCDTMmean; arithmetic mean) is used in several parts of this study to represent the results of the analysis and to provide a consensus view (with an assessment of its uncertainties). When no differently specified value is reported, the text refers to the MCDTMmean.

3. Overview on Mediterranean cyclone characteristics

This section provides an overview of cyclones that belong to the branch of the storm track crossing the MR on the basis of the data uploaded on the IMILAST database. The analysis is not strictly limited to what happens inside the MR, because the computed statistics are based on the entire life cycles of the cyclones crossing this region,

Table 1. List of cyclone detecting and tracking methods used in this study with code number in the IMILAST dataset, used variable, adopted metric for cyclone intensity and main bibliographic reference for the description of each method

Method	Variable used in the cyclone detection	Metric used for cyclone intensity in this study	Main references for method description
M02	MSLP	MSLP min	Murray and Simmonds (1991), Pinto et al. (2005)
M06	MSLP, VORT, thermal and wind fields at 1 km altitude	MSLP min	Hewson (1997), Hewson and Titley (2010)
M07	Vorticity 850 hPa	Z850 max rel vorticity	Flaounas et al. (2014)
M08	MSLP	MSLP min	Trigo (2006)
M09	MSLP	MSLP min	Serreze (1995), Wang et al. (2006)
M10	MSLP	MSLP min	Murray and Simmonds (1991), Simmonds et al. (2008)
M12	MSLP	MSLP min	Zolina and Gulev (2002), Rudeva and Gulev (2007)
M14	Z850	Z850 max amplitude	Kew et al. (2010)
M15	Z1000	Z1000 min	Blender et al. (1997), Raible et al. (2008)
M16	MSLP	MSLP min	Lionello et al. (2002), Reale and Lionello (2013)
M18	Vorticity 850 hPa, MSLP	MSLP min	Sinclair (1994, Sinclair (1997)
M20	MSLP	MSLP min	Wernli and Schwierz (2006)
M21	Vorticity 850 hPa	Z850 max rel vorticity	Inatsu (2009)
M22	MSLP	MSLP min	Bardin and Polonsky (2005), Akperov et al. (2007)

Temporal resolution is 6 hours for all methods except M06, which uses 12-hourly data. The third column presents the metric for cyclone intensity that is used in this analysis (some methods allow multiple choices).

including also the parts of the track before the cyclone has entered and after it has left the MR.

3.1. *Spatial distribution and mean number of Mediterranean cyclones*

Figure 1a shows the annual density of cyclone tracks crossing the MR according to the MCDTMmean. The entire domain in the figure is divided in cells of $1.5° \times 1.5°$. Only cyclones with at least one point of their trajectory inside the MR are considered. The number of cyclones crossing each cell is counted (each cyclone is counted only once, even if it stays for more than one step in the same cell), and on this basis the probability that a cyclone track crosses each cell is computed for each CDTM. A value of 1 % indicates that a track crosses a given cell in one out of 100 fields. Considering that fields are 6-hourly resolved, this implies a cyclone crossing the cell once every 25 d, or equivalently about 14 cyclones crossing the cell in 1 yr. The fraction of cell filled represents the level of agreement among methods. This is expressed by a normalised standard deviation (stdev), which is computed as the ratio between stdev and mean value of the probability considering all CDTMs. Four discrete levels of normalised stdev have been adopted for filling a decreasing fraction of each cell and denote a correspondingly decreasing level of agreement: 0.5, 1.0, 1.5 and 2.0. Cells are left empty if the normalised stdev is larger than 3. Figure 1a shows the main branches of cyclone tracks. The most intense feature stems from the Gulf of Genoa in the northwest Mediterranean and descends along the Tyrrhenian and Adriatic Sea. Another branch departing south of the Atlas mountain ridge enters in the central part of the basin from south-west. The signature of the Cyprus low is evident in the Levantine basin. Further areas of large activity are located in the North Aegean Sea, the Black Sea and the Fertile Crescent. All these features are robust as they appear in all CDTMs with a similar level of probability.

Figure 2 further characterises Mediterranean cyclones providing some general information on the inter-monthly variation of their number. Figure 2a shows the annual cycle of the frequency of cyclones crossing the MR and their fraction (percentage) in terms of total Northern Hemisphere (NH) cyclone numbers. The CDTM uncertainty range is not negligible and larger in summer than in winter. Nevertheless, there is a substantial agreement among methods that the frequency of cyclones reaches a maximum in April and exhibits flat minimum from June to October.

The MCDTMmean number of cyclones crossing the MR amounts to 225 per year, with values ranging from 62 to 474 depending on the CDTM. Reasons for this large uncertainty are related to the differences among methods (as briefly mentioned in Section 2), with the use of different elimination criteria apparently playing a major role.

Mediterranean cyclones represent 7.5 % of the total cyclones occurring in the NH, with an uncertainty range of 3–10 % depending on CDTM. Considering that the area selected in Fig. 1 covers only about 3.8 % of the NH area, this means that the MR is among the areas with highest cyclonic activity in terms of the number of individual features. Overall, different CDTMs agree in the relative importance of the Mediterranean cyclone tracks having a maximum in April and a minimum in summer, with values of 10 % and less than 7 % of the NH totals, respectively. However, while CDTMs agree on the quantitative assessment for the period December–May, there is a substantial uncertainty for the period July–September.

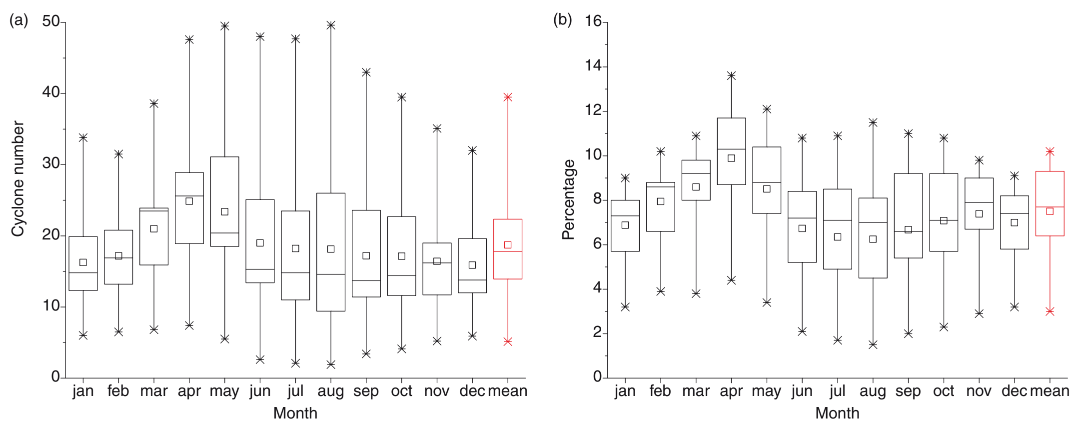

Fig. 2. Inter-monthly variation of (a) total number of Mediterranean cyclones and (b) relative frequency of NH cyclones crossing the Mediterranean region illustrated by box plots. Both panels show the annual cycle (calendar months on the x-axis) and the monthly mean value in red. The minimum and maximum values among CDTMs are denoted with ×. The upper and lower limits of the boxes correspond to 25th and 75th percentiles. The central bar denotes the median and the square the MCDTMmean.

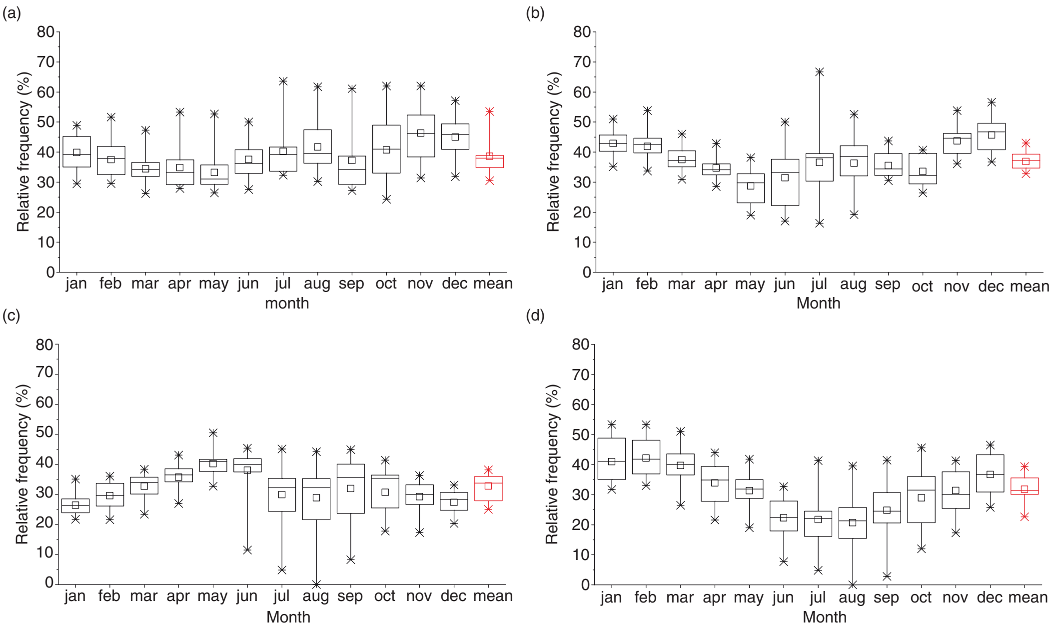

Fig. 3. Relative frequency of cyclones in the four sectors (Fig. 1) illustrated by box plots: (a) NW, (b) NE, (c) SW, (d) SE. Panels show the annual cycle (calendar months on the x-axis) and the annual average (the rightmost value marked in red). Values represent the percentage of cyclones crossing each sector with respect to the total number crossing the MR. The minimum and maximum values among CDTMs are denoted with ×. The upper and lower limits of the boxes correspond to the 25th and 75th percentiles. The central bar denotes the median and the square the MCDTMmean.

To gain subregional insight, the seasonal cycle and the monthly fraction of Mediterranean cyclones are estimated for the four sectors (Fig. 3). Tracks are rather uniformly distributed among the four sectors, though they are more frequent in the two northern parts: 39 % [31 %; 54 %] of cyclones cross NW, 37 % [33 %; 43 %] NE, 33 % [25 %; 38 %] SW, 32 % [23 %; 39 %] SW. Here, the reported values are the MCDTMmean and the inter-CDTM range (among squared brackets). Note that a single cyclone can be counted more than once as it crosses more than one sector and thus the sum is larger than 100 %. In fact, about 40 % of cyclones cross at least two sectors. The annual cycle has different phases in the four sectors. NW and NE have a similar annual cycle (except that the maximum occurs in December for NE and in November for NW) and both show a secondary maximum in August. The SW has two maxima: the most pronounced in May and a secondary one in September–October. The SE has the largest annual cycle amplitude, with a well-defined maximum in February and a minimum in summer (June to August).

3.2. *Intensity, speed and duration of Mediterranean cyclones*

A cyclone characteristic that is often used for describing their intensity is the so-called lifetime MSLP minimum, i.e., the minimum MSLP during the lifetime of a cyclone. For NH and Mediterranean cyclones, the most likely value of the lifetime MSLP minimum is about 1002 hPa as illustrated in Fig. 4 by their distribution. However, the upper and lower tails have different weight in the two domains. For the lower tail of the distribution, less than 2 % of the Mediterranean cyclones reach a minimum lower the 978 hPa, while about 10 % of the NH cyclones are below this threshold. Considering the upper tail, only 15 % of NH cyclone lifetime MSLP minima remain above 1006 hPa during their whole life, while this happens for about 22 % of the Mediterranean cyclones. This indicates that the distribution of lifetime MSLP minimum for the MR is displaced to higher values than the ones for the entire NH. Note, however, that pressure minima needs to be regarded with caution as an absolute measure of cyclone intensity, particularly given the relatively low latitude of the Mediterranean Basin (Trigo et al., 1999; Ulbrich et al., 2009).

Figure 5 is analogous to Fig. 4, except it presents the average speed of the cyclone centres. For both NH and Mediterranean cyclones, the most likely values are in the range from 24 to 32 km/h, but fast cyclones are less likely in the MR than in the rest of the NH. In fact, about only 5 % of Mediterranean cyclones have an average speed higher than 56 km/h, while more than 10 % of the NH cyclones are faster than this threshold.

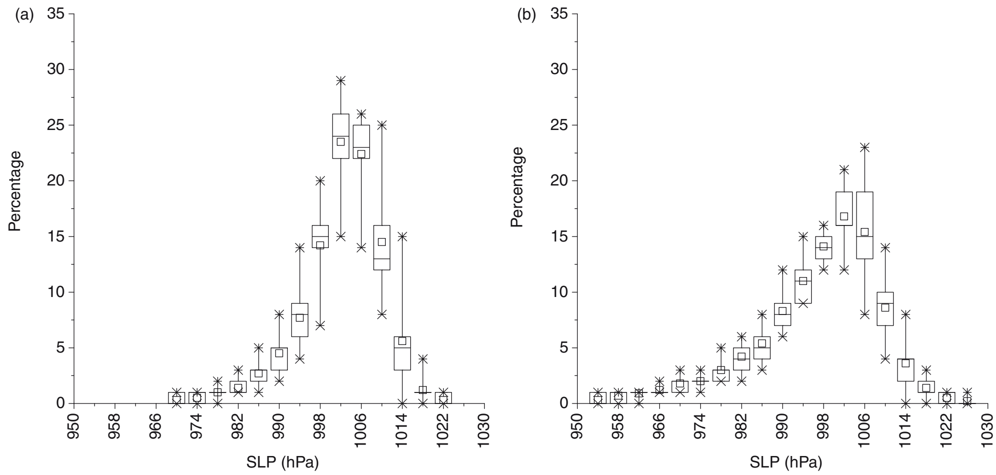

Fig. 4. Relative frequency (%) of cyclones as function of their lifetime MSLP minimum considering 4 hPa wide bins and covering the range from 930 to 1030 hPa illustrated by box plots: (a) Mediterranean cyclones and (b) the NH cyclones. The minimum and maximum values among CDTMs are denoted with ×, the upper and lower limits correspond to 25th and 75th percentiles, and the central bar denotes the median and the square the MCDTMmean.

Additionally, a similar distribution as for the cyclone speed is deduced for the cyclone duration (Fig. 6). Cyclones with a duration shorter than 1 d cannot be considered, because a minimum of five steps was required for the inclusion of a track in the IMILAST archive (for the CDTM using a 6-hourly step). This standardisation was introduced because the duration threshold is a parameter of free choice in most methods and has a rather straightforward impact: a shorter duration threshold will increase the number of cyclones considerably and thus might mask the influence of other methodological differences. In this figure, cyclones detected in n steps were assigned a duration of (n-1/2)· 6 hours. The two panels of Fig. 6 show that duration tends to be shorter for Mediterranean cyclones than for NH cyclones, but in this case differences between the two distributions are smaller than for speed and lifetime SLP minimum.

Note that the general purpose of this article is to provide a revised climatology of Mediterranean cyclones as diagnosed using a wide range of tracking methods, and not to discuss the dynamical factors that are responsible e.g. for intensity and speed of cyclones (such local baroclinicity

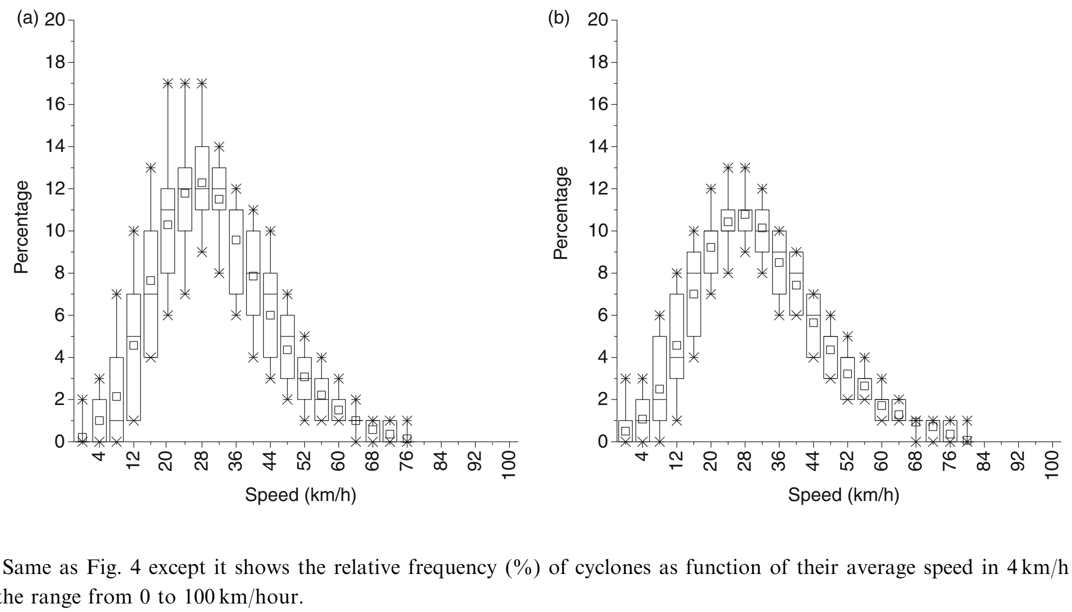

Fig. 5. Same as Fig. 4 except it shows the relative frequency (%) of cyclones as function of their average speed in 4 km/h wide bins covering the range from 0 to 100 km/hour.

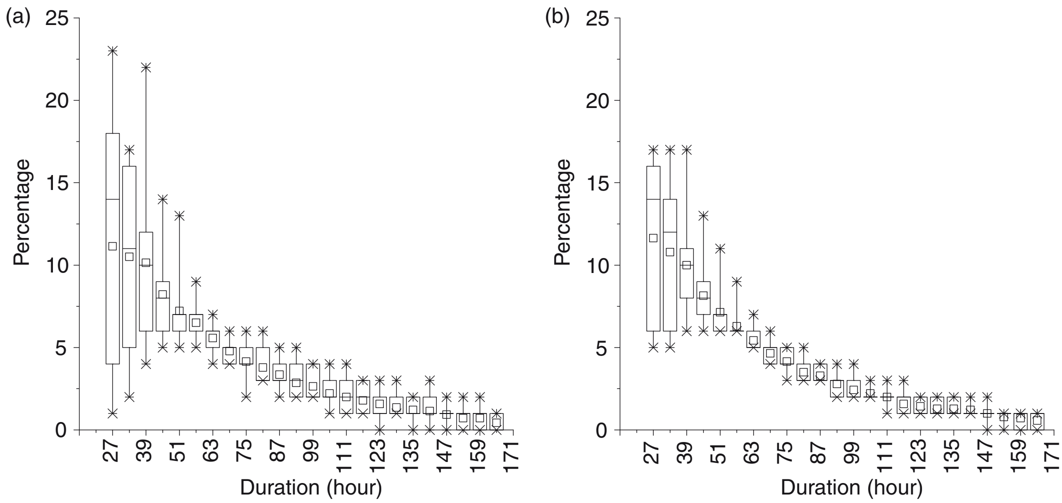

Fig. 6. Same as Fig. 4 except it shows the relative frequency (%) of cyclones as function of their duration in 6-hour wide bins covering the range from 24 to 174 hours.

and mid-troposphere flow, e.g. Raible et al., 2010). The dominant dynamical factors for cyclone intensification and speed are complex and vary between seasons. Thus, the analysis of the dynamics of Mediterranean cyclones is out of the scope of this study.

3.3. *Cyclogenesis*

CDTMs agree that most of the Mediterranean cyclones are generated in the MR, with 76 % of cyclogenesis occurring inside the region according to the MCDTMmean and an uncertainty from 61 % to 85 % depending on the method. This corresponds to a yearly average number of 173 cyclogenesis occurring inside the MR with an uncertainty from 46 to 401. This large uncertainty is consistent with the large spread in the overall number of cyclones in the MR, (as discussed in Section 3.1). Fig. 1b shows the cyclogenesis areas for cyclones crossing the MR with the level of consensus among CTDMs. Consensus for location of cyclogenesis is lower than for tracks (Fig. 1a), suggesting that CDTMs tend to disagree more on the location where cyclones are first detected than on the rest of their track. However, main locations such the north-western Mediterranean, North Africa south of the Atlas Mountains, Levantine basins close to the coast of Anatolia and to a lesser extent the northern Aegean and Black Seas are identified by all methods (Fig. 1b).

On the subregional scale, the relative importance of cyclogenesis on an annual basis is estimated in the four sectors of the MR and surrounding areas: Atlantic (Atl), Asia (As), Africa (Afr), Europe (Eu). Results are shown in Fig. 7. Within the MR, NW and NE account for the largest share (22 % and 21 %, respectively) with SE and SW contributing 18 % and 15 %, respectively. About 11 % of cyclones arrive from the Atlantic (here defined as the whole area west of 9°W, west border of the MR). A small, but still relevant number of cyclones enter the domain from Africa (here defined as the area south of 27°N with longitude within the range 9°W to 42°E). Rarely cyclones originate from Asia (here defined as the whole area east of 42°E, east border of the MR) or Europe (here defined as the

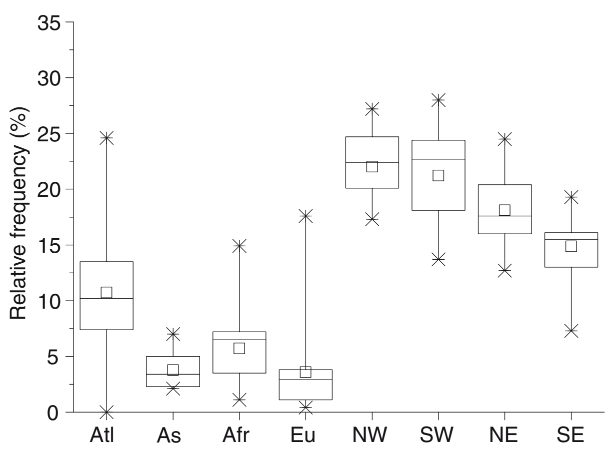

Fig. 7. Relative frequency (%) of cyclogenesis occurring in the four sectors marked in Fig. 1 (NW, NE, SW, SE) and outside of the MR: Atlantic (Atl), Asia (As), Africa(Afr), Europe (Eu). The minimum and maximum values among CDTMs are denoted with ×, the upper and lower limits correspond to 25th and 75th percentiles, and the central bar denotes the median and the square the MCDTMmean.

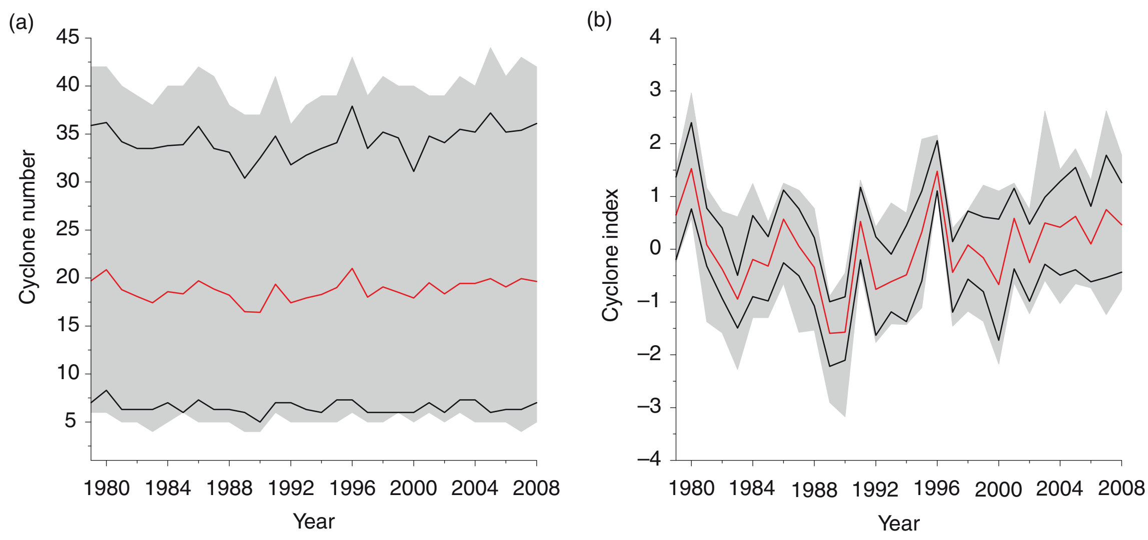

Fig. 8. (a) Time series of total annual cyclone number and (b) normalised cyclone number index (see text for details). The central red line shows the MTCMmean, the lower and upper black lines show the 10th and 90th percentiles of the CDTM results, and the whole grey area corresponds to the spread of all data.

area north of 48°N with longitude within the range 9°W to 42°E).

As for the cyclone track frequency, also the cyclogenesis is subject to seasonality, which is illustrated for the eight regions in Fig. A.2. All values represent relative frequencies (%) with respect to the total annual number of cyclones crossing the MR. The annual cycle of the relative frequency of cyclones arriving from the Atlantic features a large and rather flat maximum covering most of the cold season. The small number of cyclones entering from Europe has the peculiarity of contributing to the total number more in the warm than in the cold season. The NW and SW have an annual cycle with a small amplitude, a maximum in April and a relatively large number of cyclogenesis during the whole year, but in the NW there is also a second maximum in November. Other differences among the four sectors of the MR are evident: the NE presents a large maximum in spring and a minimum in winter, the SE a maximum in march and a minimum in summer.

3.4. *Trends in the 1979–2008 period*

The large difference in cyclone counts derived by different CDTMs reaches almost one order of magnitude and implies a wide uncertainty in the cyclone time series (Fig. 8a, Table A.1). This superficially suggests that no consensus is possible when interpreting time series in terms of climate variability and trends. However, if the individual time series C_i are transformed to a normalised index $c_i = (C_i - \mu)/\sigma$ by subtracting for each method the respective mean μ and dividing by the standard deviation σ, a substantial consensus is identified (Fig. 8b) and a common behaviour emerges. Table 2 shows the μ and σ values that have been used for computing the index for annual number of cyclones crossing the MR. The fourth column shows the ratio between σ and μ in percentage, which varies between 5 % and 14 %. Even though σ generally increases with μ (Fig. 9), this ratio depends on the method, and needs to be accounted for as a source of uncertainty among CDTMs.

Table 2. Method (first column), the mean monthly number of cyclones crossing the MR (μ, second column) and its standard deviation (σ, third column) as used for the computation of the cyclone index (Fig. 8b)

Method	μ	σ	σ/μ (%)
M02	17.8	2.1	12
M06	39.2	1.9	5
M07	6.3	0.7	10
M08	16.7	1.6	9
M09	39.5	2.2	6
M10	5.2	0.7	14
M12	22.3	1.4	6
M14	14.0	1.1	8
M15	15.0	1.7	11
M16	22.0	1.3	6
M18	17.9	1.8	10
M20	23.8	1.7	7
M21	6.9	0.9	13
M22	16.2	1.4	8

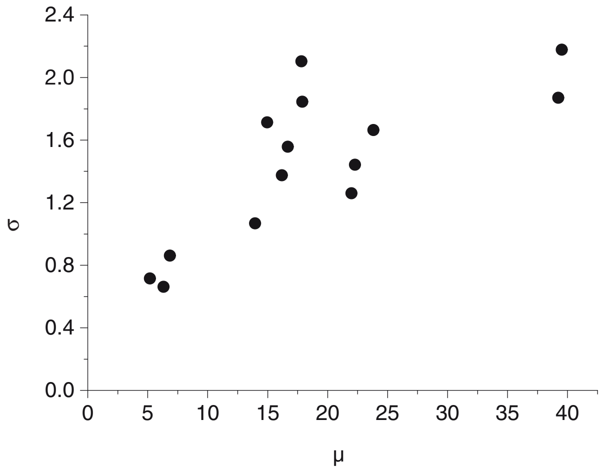

Fig. 9. Standard deviation σ (y-axis) as function of the mean monthly number μ (x-axis) for annual number of cyclones crossing the MR for the 14 CDTMs considered in this study.

The time series of the cyclone index for the four sectors within the MR are shown in Fig. 10. Interannual variability of cyclone number is significantly linked for sectors in the same latitudinal band, with correlation values of 0.57 linking both the NW and NE time series and the SW and SE time series. Correlations are lower between the northern and southern sectors. The SE sector departs significantly from the rest, and its time series presents a poor correlation with the NW and NE time series (0.13 and 0.15, respectively). This is strongly suggestive of different atmospheric circulation regimes influencing the south-eastern part of the Mediterranean compared to the rest of the Basin.

For specific months of the year (not shown), there are indications that significant trends in the number of cyclones crossing the MR exist. More than 25 % of CDTMs suggest a negative trend in May–June and a positive trend in August–September, both significant at the 95 % confidence level (Fig. 10). These opposite tendencies cancel each other on the annual scale and no long-term tendency of cyclone number is present when considering annual values (Fig. 11).

The significant positive trend of cyclone number in late summer (August and September) for the whole MR can be attributed to a widespread weak increase in all sectors (Fig. 12), which is not significant in any of them. Similarly, the negative trend in late spring (May–June) for the whole MR is generally not significant in individual sectors, as there is only some consensus on its significance in May for NE, and SW. The NE sector appears to be the most affected by negative trends, which are present in December–January and April–May. Finally, the trend is significantly negative in the SE and SW in February.

4. Weak versus strong and slow versus fast cyclones

Cyclones crossing the MR feature a broad range of characteristics in terms of MSLP minima, speed and duration through their lifetime. Previous assessments of cyclone

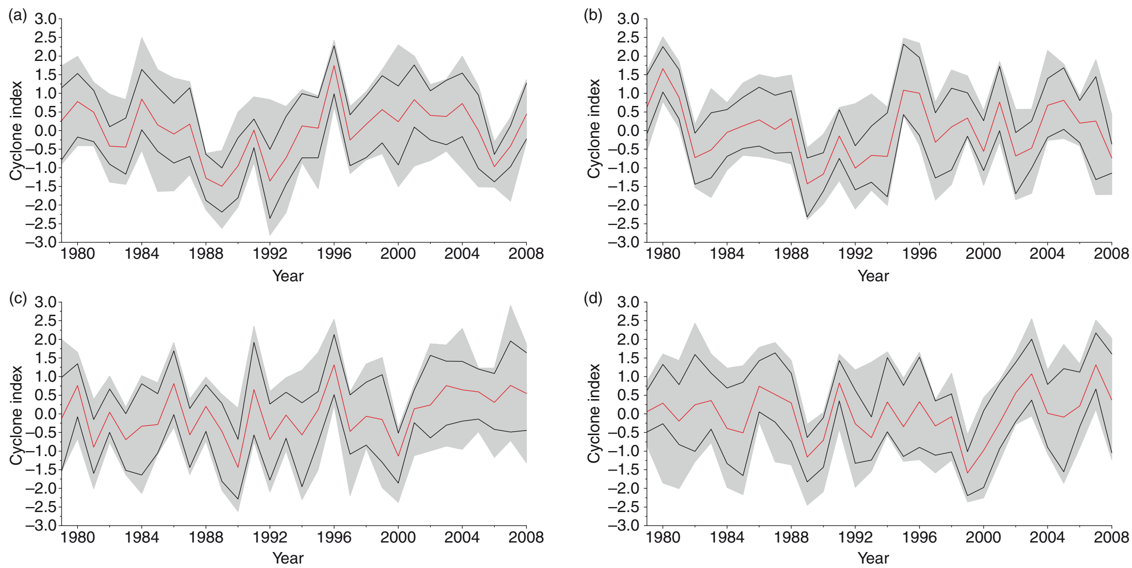

Fig. 10. Time series of cyclone number index for the four sectors of the Mediterranean region. (a) NW, (b) NE, (c) SW and (d) SW. The central red line shows the MTCMmean, the lower and upper black lines show the 10th and 90th percentiles of the CDTM results, and the whole grey area corresponds to the spread of the data.

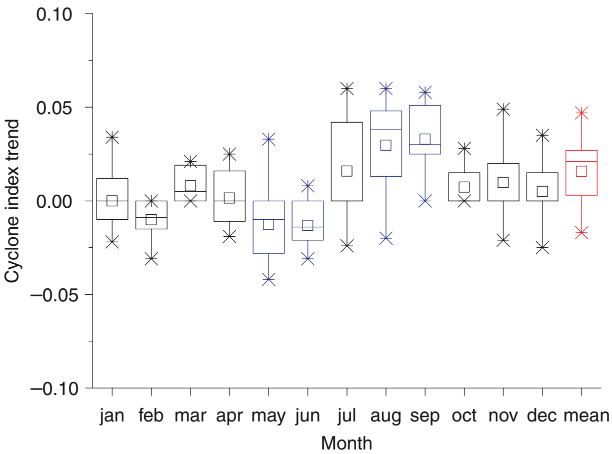

Fig. 11. Annual cycle of trends of cyclone number index. The red symbol on the right of the panels denotes the trend of the mean monthly cyclone number. Blue symbols (May, June, August, September) denote months where at least 25 % of CDTMs present statistically significant trends with the same sign.

activity in the MR have already indicated that warmer months are characterised by a high frequency of thermal lows (e.g. Trigo et al., 1999, 2002; Hoinka and Castro, 2003). Being associated with localised inland heating, these are generally stationary systems and often relatively weak. Given the pronounced differences when compared with transient cases, in terms of both cyclone characteristics and tracks, this section will consider separately 'weak', 'strong', 'slow' and 'fast' cyclones. Again, the agreement and the deviations among CDTMs are presented.

4.1. *Weak cyclones*

In this study a cyclone is considered 'weak' if the difference between the largest and lowest value of the central MLSP minima is smaller than 4 hPa during its lifetime. This criterion is not based on the lifetime MSLP minimum, which would heavily depend on season, latitude and long-term variability of the large-scale circulation, but on the variation of the intensity of the cyclone during its life cycle.

For methods M07, M14, M15 and M21, which do not include MSLP as a metric for cyclone intensity, the criterion is a threshold relating the difference between maximum and minimum values of the intensity, with different 'ad hoc' thresholds being used. A threshold of $1.5{\cdot}10^{-5}\ s^{-1}$ has been adopted for M07 and M21, whose metric is the maximum of 850-hPa relative vorticity. A threshold value of 30 m has been adopted for M14 (whose metric is the amplitude of the cyclone estimated as the difference between the local background and the core geopotential) and also for M15 (whose metric is the minimum value of the 1000-hPa geopotential height). All selected thresholds are meant to be roughly equivalent, though, of course, the comparison among thresholds when

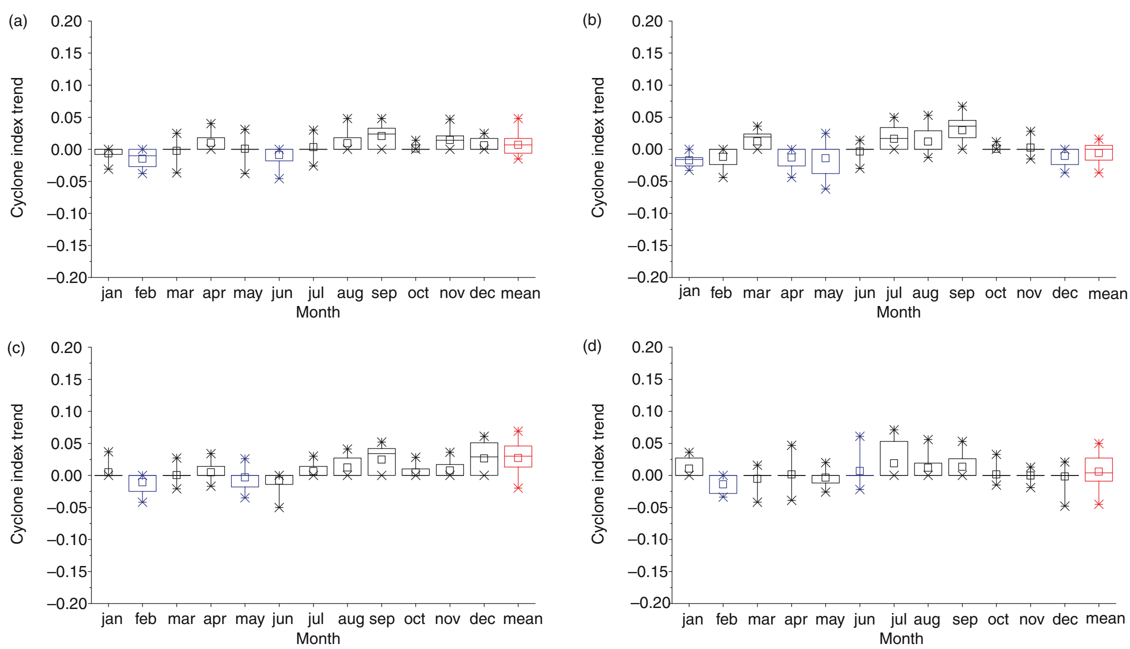

Fig. 12. Trends of the cyclone number index for the four sectors of the Mediterranean region. (a) NW, (b) NE, (c) SW, (d) SW. The red symbol on the right of the panels denotes the trend of the mean monthly cyclone number. Blue symbols denote months where at least 25% of CDTMs present statistically significant trends with the same sign.

different metrics are involved cannot be made in precise terms. The 30 m value adopted for methods M14 and M15 is comparable to (in general slightly smaller than) the increase of level producing a 4-hPa pressure decrease from the mean sea level. The relation between the $1.5{\cdot}10^{-5}\,s^{-1}$ vorticity threshold adopted for M07 and M21 and a threshold for pressure is more problematic. Some reasoning can be attempted using the association between vorticity and Laplacian of pressure around the cyclone minimum, but the resulting threshold value depends on the defined radius of the cyclone and the argument can be given only in a rather qualitative way.

The relative frequency of ‘weak’ cyclones with respect to the total number strongly varies between CDTMs, in a range from 6 % to 42 %. In general, CDTMs that diagnose a large number of cyclones and/or a large fraction of cyclones with short duration have the largest percentage of ‘weak’ cyclones. The absolute number (Fig. 13a) and percentage (Fig. 13b) of ‘weak’ cyclones are larger in summer than in other seasons and exhibit a well-defined minimum in winter. The two methods M07 and M21 (both adopting a metric based on vorticity) are exceptions as they exhibit no clear annual cycle. ‘Weak’ cyclones have consistently high values of lifetime MSLP minima, with core pressure lower than 992 hPa in only 0.5 % of cases and with a most likely value of 1006 hPa. They tend to move slowly, with a most likely speed of 24 km/h and less than 10 % of them are faster than 50 km/h. They have generally a short duration (90 % of them shorter than 66 hours). Their track density map (not shown) presents features very similar to those in Fig. 1a, suggesting that they do not tend to characterise any specific area or feature in the MR.

4.2. Strong cyclones

In this study, ‘strong’ cyclones are defined as those with metrics exceeding three times the thresholds used for ‘weak’ cyclones. In practice MSLP minimum of ‘strong’ cyclones varies in a range larger than 12 hPa for all methods adopting the MSLP minimum as metric describing the intensity. For the methods M07, M14, M15 and M21, the following thresholds were used: $4.5{\cdot}10^{-5}\,s^{-1}$ for M07 and M21, 90 m for M14, and M15.

The relative frequency of ‘strong’ cyclones with respect to the total number strongly varies between CDTMs, in a range from 8 % to 42 %. The annual cycle of ‘strong’ cyclones has opposite phase (Fig. 14) compared to ‘weak’ cyclones, being most frequent in December and January and least frequent in August. This statement applies to both the actual number of ‘strong’ cyclones and their relative frequency with respect to the total number of cyclones crossing the MR. The two methods adopting vorticity as metric are an exception to this general behaviour featuring a rather flat annual cycle in terms of the relative frequency of ‘strong’ cyclones, or even peak values in June and September. The most likely lifetime MSLP minimum of ‘strong’ cyclones is within the range 992–1000 hPa, and 25 % of ‘strong’ cyclones have lifetime MSLP minima

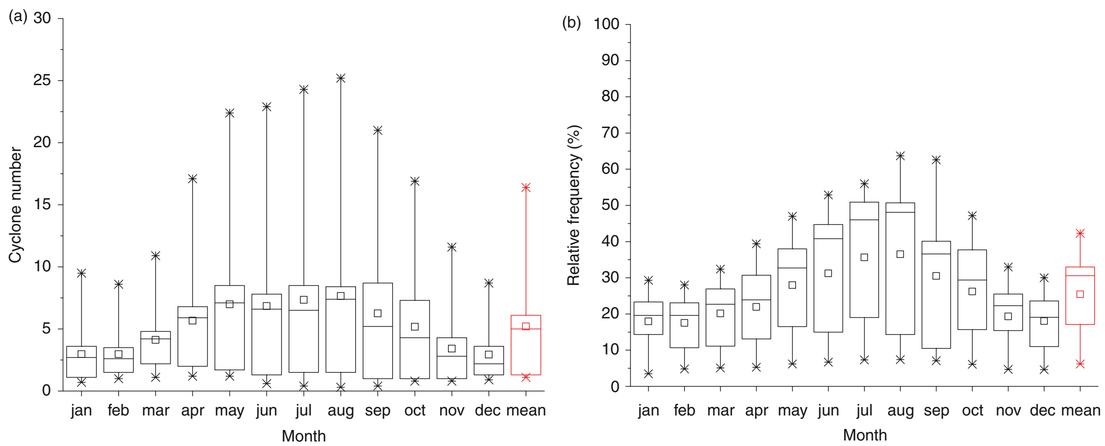

Fig. 13. Inter-monthly variation of total number and relative frequency of ‘weak’ cyclones in the Mediterranean region: (a) annual cycle of the number of ‘weak’ cyclones crossing the Mediterranean region and (b) annual cycle of the percentage of ‘weak’ cyclones with respect to the total number of Mediterranean cyclones. Both panels show the annual cycle (calendar months on the x-axis) and its mean annual value in red on the right of the panels. In the panels, the minimum and maximum values among CDTMs are denoted with ×, the upper and lower limits of the boxes correspond to 25th and 75th percentiles, and the central bar denotes the median and the square the MCDTMmean.

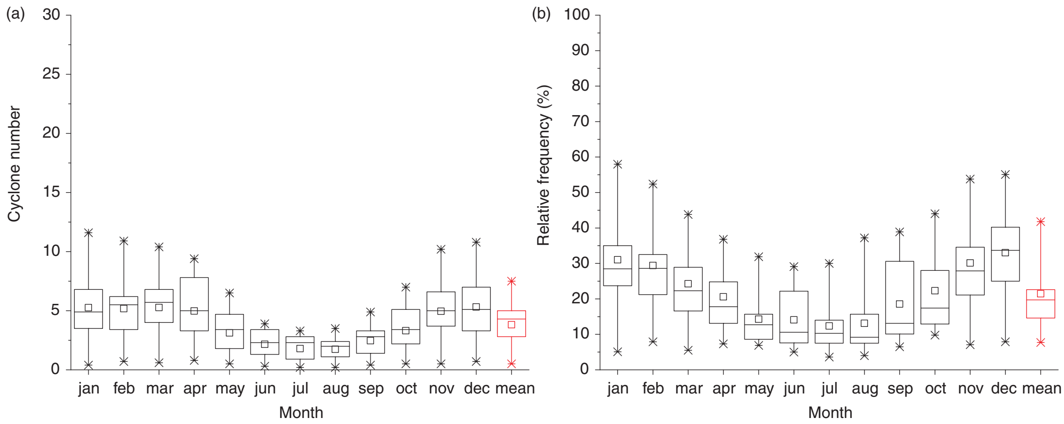

Fig. 14. Same as Fig. 13 except it shows 'strong' cyclones.

below 988 hPa. They tend to move faster (their most likely value is in the range 26–34 km/h) and live much longer than 'weak' cyclones (75 % of strong cyclones have a duration longer than 66 hours). The relation between duration and intensity is explained mainly by the persistency of deep lows, but is also strongly linked to the criterion used for the definition of 'strong' cyclones. In fact, a cyclone with a long lifetime, during which its centre follows a long trajectory, is likely to exhibit a broad range of intensity values and therefore to be classified 'strong'.

4.3. *Slow cyclones*

In this study, a cyclone is considered 'slow' if the average speed (computed considering its whole life cycle) of its centre is lower than 12 km/h. Note that M08 adopts this same criterion as a threshold for tracking cyclones and therefore it does not include 'slow' cyclones. This special feature of M08 has somehow forced to use this threshold for all methods. 'Slow' cyclones are much less frequent than 'weak' cyclones for most (but not all) CDTMs, but they have a similar annual distribution with a maximum in summer (Fig. 15a, b). Their most likely SLP lifetime minimum is 1006 hPa, and only 1.5 % of them reach intensity values below 992 hPa. Their duration is not necessarily short, with 20 % of them persisting longer than 96 hours. The uncertainty is large in terms of both the actual number of 'slow' cyclones and their tracks. There is some consensus among CDTMs, suggesting that they tend to concentrate in a few small areas which basically correspond to all regions where cyclogenesis occurs. This means that 'slow' cyclones are formed in the usual locations, but do not move away from their starting point. This is an indication that 'slow' cyclones (as defined here) are not only generally thermal lows and a large fraction of them is produced by other mechanisms, such as orographic cyclogenesis.

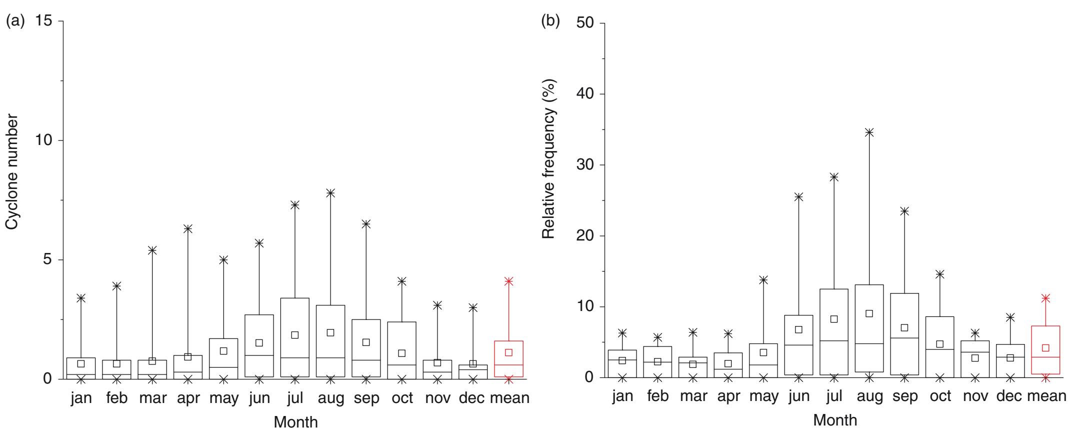

Fig. 15. Same as Fig. 13 except it shows 'slow' cyclones.

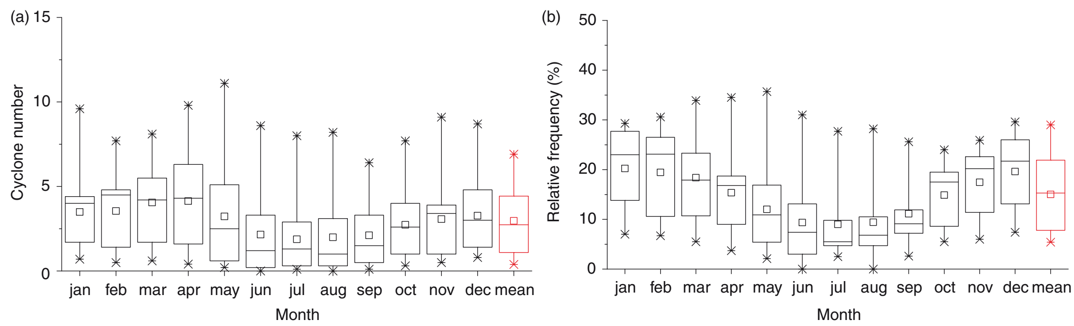

Fig. 16. Same as Fig. 13 except it shows 'fast' cyclones.

4.4. *Fast cyclones*

'Fast' cyclones are defined as those moving at an average speed higher than 48 km/h. Most methods count the largest number of 'fast' cyclones in April, but the largest percentage of 'fast' cyclones occurs in December and January (Fig. 16). They are rare in summer. 'Fast' cyclones do not reach particularly low values of lifetime MSLP minima. Their most likely value is 1002 hPa, and only 10 % of them reach values below 988 hPa. They tend to have a not particularly long duration, with only 30 % of them exceeding 66 hours.

5. Sources of uncertainty affecting the variability of cyclone frequencies

These results (Sections 3 and 4) suggest that there is a consensus among CDTMs on statistics describing the climatology of cyclones in spite of some outliers. This section discusses to which extent different classes of cyclones (specifically the 'weak', 'strong', 'fast' and 'slow' cyclones, as they are described in Section 4) are affected by discrepancies between the different CDTMs.

To gain further insights in the level of agreement among CDTMs, a track-by-track comparison has been carried out. The comparison assesses the agreement between pairs of CDTMs and has been applied to (1) all cyclones and (2) all cyclones minus 'weak and slow' systems. The method is based on Blender and Schubert (2000) and compares individual trajectories extracted by the CDTMs with each other. Thereby, a spatio-temporal metric is used to measure the deviation of the trajectories following the settings given in Neu et al. (2013). The number of agreeing trajectories is considered in relation to the total number of trajectories of the method, which identifies less cyclones, resulting in the so-called matching rate. Further details concerning the track-by-track comparison approach are given in Blender and Schubert (2000), Raible et al. (2008) and Neu et al. (2013). In general, the matching rate between CDTM pairs in the MR varies between roughly 30 % and 80 %. By excluding 'weak and slow cyclones', the number of CDTM pairs with agreement larger than 60 % increases from 43 to 55 and the number of those with agreement lower than 50 % decreases from 24 to 18. Therefore, an improvement is found by excluding 'weak and slow' systems. It is eventually lower than expected as it does not concern all CDTM pairs and in some cases the comparison deteriorates (Table A.1). There are two possible explanations for this result: First, when the track-by-track comparison involves a CDTM that has a small relative frequency of 'weak and slow' cyclones, their exclusion has a marginal effect on the results. Second, when the track-by-track comparison is performed between two CDTMs that include cyclones tracks of stationary minima close to mountain areas, their exclusion has likely a negative effect on the level agreement as their tracks are likely very similar in the two CDTMs. Similar statement holds true for heat lows.

An alternative perspective on the agreement among cyclone frequencies can be obtained without actually addressing the level of agreement in individual cyclone tracks. Consider the ratio

$$R = \frac{P_M}{P_N}, \quad (1)$$

between interannual variability of the MCDTMmean and its uncertainty. The former is given by the variance of the MCDTMmean

$$P_M = \frac{\sum_{i=1}^{N_{years}} (M_i - \mu_M)^2}{N_{years}}, \quad (2)$$

where M_i is the annual value and μ_M is its mean. The uncertainty of MCDTMmean is given by the mean variance of the CDTM values respect to the MCDTMmean:

$$P_N = \frac{1}{N_{years} N_{methods}} \sum_{i=1}^{N_{years}} \sum_{k=1}^{N_{methods}} \left(C_i^k - M_i\right)^2, \quad (3)$$

Table 3. Values of the ratio R [eq. (1)] between interannual variability of the MCDTMmean and its uncertainty

Group of cyclones	*R*
All cyclones: number	0.01
All cyclones: index	1.15
Weak cyclones: index	0.18
Strong cyclones: index	1.17
Slow cyclones: index	0.17
Fast cyclones: index	0.46
All but weak and slow cyclones: index	1.40

First line considers the actual number of cyclones. Following lines consider the index compute for different groups: all cyclones (second line) and for the four groups ('weak', 'strong', 'slow', 'fast' in lines 3–6) described in Section 4. The last line considers the index computed excluding 'weak' and 'slow' cyclones.

where C_i^k is the number of cyclones detected by the method k in the year i. Small values of R are associated to a large level of uncertainty, because these values indicate differences among CDTMs that are much larger than the interannual variability of the MCDTMmean. On the contrary, given large values of R the opposite occurs and time series converge along the MCDTMmean. Results (Table 3) show that the uncertainty in terms of cyclone numbers is unacceptably large and masks its interannual variability. However, a substantial improvement is obtained when considering the cyclone index (introduced in Section 3.4). Further, indexes of 'weak' and 'slow' cyclones are affected by a much larger uncertainty than those of 'strong' and 'fast' cyclones. Their exclusion from the statistics leads to a reduction of the level of uncertainty and to the largest value of R among those considered in Table 2.

Note that both the R values (Table 3) and the track-to-track comparison (Table A.1) support the idea that excluding 'weak and slow' cyclones leads to a reduction of the uncertainty associated with the differences among CDTMs. However, changes in R and in the track-to-track comparison cannot be linked by a linear relation and the improvement appears more convincing considering the former than the latter. The errors of individual CDTMs, which are assumed to have a substantial random component, tend to compensate each other when computing the MCDTMmean (and also the individual mean of each CDTM), while they do not cancel each other in a track-to-track comparison. This explains why the impact of excluding 'weak and slow' cyclones is different in the two cases and suggests that the interpretation of cyclone counting climatologies leads to robust results, though scores of a track-to-track comparison are not always satisfactory.

6. Summary and conclusions

The characteristics of cyclonic activity in the MR are analysed based on 14 different CDTMs applied to the same dataset (ERA-Interim for the period 1979–2008). While differences in the cyclone counts among CDTMs in the MR span over almost one order of magnitude, the percentages of geographical and monthly distribution show an acceptable agreement. This mixture of consensus and disagreement among CDTMs has been the basic motivation of this intercomparison study and its attempt to identify information that is not affected by uncertainty.

The robustness of well-known features of spatial and intra-annual variability that are recurrent in studies describing Mediterranean cyclones (e.g. Alpert et al., 1990; Trigo et al., 1999; Maheras et al., 2001; Lionello et al., 2002; Trigo et al., 2002; Nissen et al., 2010; Campins et al., 2011) is confirmed by this CDTM intercomparison. The most intense features in the cyclone spatial distribution include: (1) a branch that from the northwest Mediterranean descends along the Tyrrhenian and Adriatic Sea, (2) another branch that from south of the Atlas mountain ridge enters the central part of the basin from south-west, (3) the signature of the Cyprus low in the Levantine basin and (4) other areas of large activity that are located in the North Aegean Sea, the Black Sea and the Fertile Crescent. There is substantial agreement among methods that these areas are among those with highest cyclonic activity when counting the number of individual features.

CDTMs agree that the frequency of cyclones in the MR has a maximum in April and a flat minimum from June to October. However, this overall behaviour results from an annual cycle with slightly different phases in the four sectors considered – NW, NE, SW and SE. They all present two annual maxima, with the exception of SE. NW and NE have a similar annual cycle (except in the NE the maximum occurs in December while in the NW in November) and both show a secondary maximum in August. The SW has two maxima: the larger one in May and another in September–October. The superposition of secondary maxima with different phases in the sectors is the explanation for the flat behaviour of the annual cycle during the warm season when considering the whole MR.

CDTMs further agree that most of cyclones crossing the MR are generated inside the region, with the NW and NE sectors accounting for the largest share. The north-western Mediterranean, North Africa south of the Atlas Mountains, Levantine basins close to the coast of Anatolia and to a lesser extent the northern Aegean and Black Seas are well-defined areas where cyclogenesis is frequent. The largest fraction of cyclones entering the MR arrives from the Atlantic, and considerably fewer of them from North Africa. The number of cyclones entering from other directions is extremely small. Finally, the presence of trends in the cyclone number index is identified only at monthly scale with some agreement on negative trends in May–June and positive in August–September, which cancel each other out on the annual scale.

The large differences among the total number of cyclones counted by different CDTMs mask the good level of agreement among CDTMs in terms of the general characteristics of cyclone activity such as storm tracks, cyclogenesis areas, interannual variability and trends. Although the presence of outliers recommends in any case a multi-CDTM approach, different CDTMs tend to agree both on the spatial distribution of cyclone tracks and on the location of cyclogenesis. They also tend to agree when considering the description of inter-monthly variability and statistics of cyclone characteristics such as minimum SLP, duration and speed of propagation. Furthermore, considering the period 1979–2008, they agree in terms of absence of significant trends for most months and in the identification of few positive (in late summer) or negative (in late spring) monthly trends. The agreement of different CDTMs on trends is also supported by a previous study of Ulbrich et al. (2013) who assessed future climate change.

Differences among methods when dealing with 'weak' and 'slow' cyclones are a substantial source of uncertainty, as they also depend on the selection criteria and thresholds adopted by methods for the identification of an individual cyclone. Excluding 'weak' and 'slow' cyclones from the computation of cyclone statistics improves the agreement among CDTMs, with a rather modest but clear effect, in terms of both the track-to-track comparison and the cyclone tracks frequencies.

7. Appendix

A.1. Geographical features in the Mediterranean region

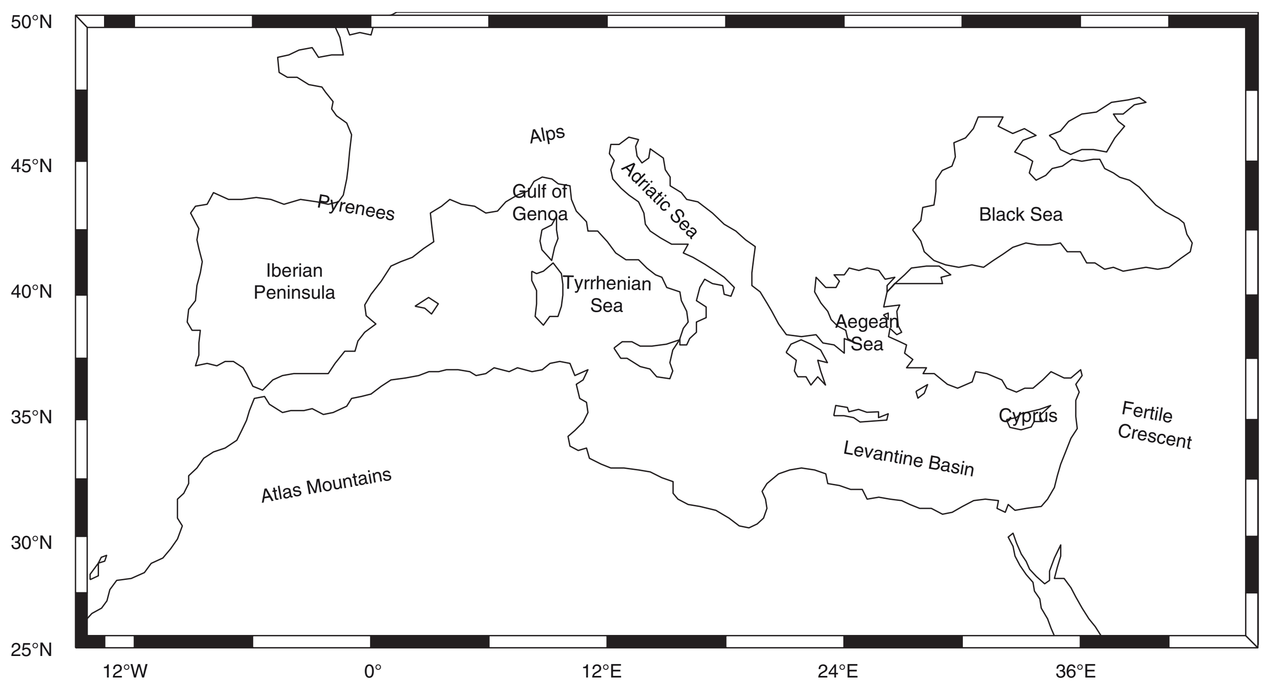

Fig. A.1. Geography of the Mediterranean region with geographical names used in this article.

A.2. Relative frequency of cyclones entering the Mediterranean region from surrounding regions and annual cycle of cyclogenesis occurring in the four sectors of the Mediterranean region

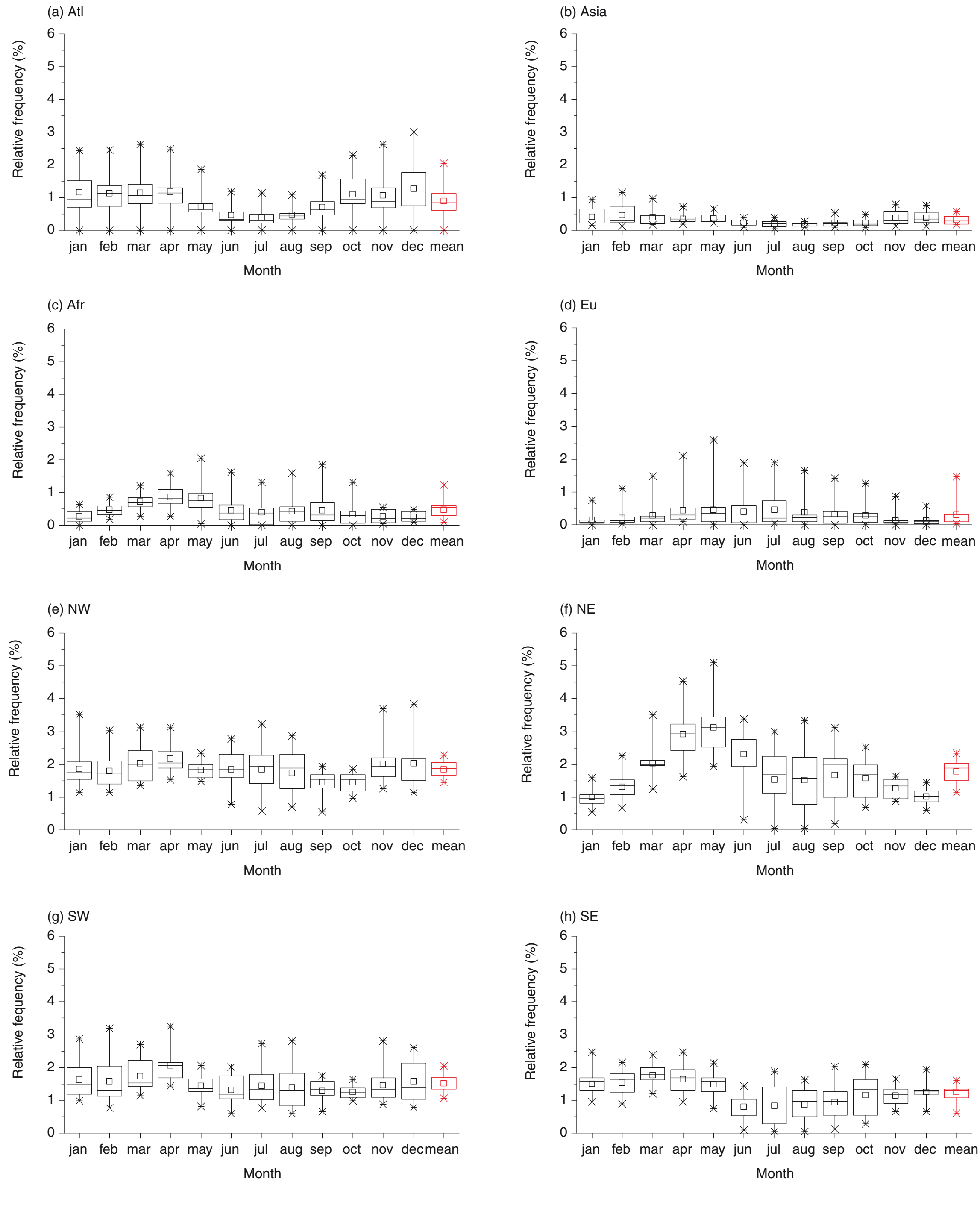

Fig. A.2. Annual cycle of relative frequency (%) of cyclones entering the MR from adjacent areas [(a) Atlantic, (b) Asia, (c) Africa, (d) Europe], and of cyclogenesis in the four sectors of the MR [(e) NW, (f) NE, (h) SW, (g) SE]. Values represent percentage with respect to the total annual average number of cyclones crossing the MR.

A.3. Track-by-track comparison among CDTMs

Table A.1. Results of the track-by-track comparison among CDTMs considering cyclones in the MR

Method		M02	M06	M07	M08	M09	M10	M12	M14	M15	M16	M18	M20	M21	M22
	x100	**64**	**93**	**23**	**60**	**142**	**19**	**80**	**50**	**54**	**79**	**64**	**86**	**24**	**58**
M02	**59**	100	42	77	50	60	63	48	50	60	49	44	49	67	49
M06	**66**	38	100	64	50	48	62	35	44	48	40	37	38	61	48
M07	**17**	81	63	100	73	77	50	66	59	74	69	66	65	55	72
M08	**42**	59	48	71	100	78	68	55	51	57	63	43	60	69	62
M09	**85**	55	46	76	75	100	79	66	72	73	78	54	73	77	85
M10	**12**	78	66	57	72	81	100	59	48	64	65	56	62	48	71
M12	**66**	49	35	71	62	60	67	100	57	54	52	47	51	65	58
M14	**29**	69	48	62	59	75	52	69	100	46	62	46	57	56	52
M15	**45**	61	46	77	60	70	76	57	61	100	56	47	56	67	54
M16	**57**	48	39	70	65	71	69	58	71	56	100	46	58	67	71
M18	**60**	45	34	72	51	49	68	46	62	51	45	100	44	64	43
M20	**55**	47	39	63	60	70	61	55	61	54	57	44	100	64	68
M21	**19**	69	59	55	66	75	52	67	52	68	66	66	60	100	68
M22	**39**	60	47	70	65	83	72	65	61	61	73	53	67	64	100

The upper-right triangle of the matrix (red shading) shows the total number of cyclones (second row, grey marked) and the nominal percentage agreement (relative to the lower number of tracks produced by the two methods) when both methods detect a track at a similar place and time. The lower-left part of the matrix (blue shading) shows the number of cyclones (second column, grey marked) and the agreement when 'weak and slow' cyclones are excluded. Light and dark shading denote agreement larger than 50 % and 70 %, respectively.

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