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Objective Climatology of the Cyclonic Circulation over the Mediterranean Based on Relative Vorticity Flux Estimation

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Abstract. A general climatological approach for estimation of the cyclonic circulation intensity is proposed and demonstrated. The method is based on a relatively simple, not concerning individual systems, scheme for calculation of the vorticity flux, which is physically one of the most adequate quantitative measures of circulation. The method is applied over the whole 66-year-long NCEP-NCAR gridded reanalysis dataset with the original time resolution over model domain covering entirely the Mediterranean Sea and the surrounding territories, which is a well-known secondary maximum of the cyclonic activity in the Northern hemisphere. Main aims of this long-term hintcast study is to demonstrate the possibilities of the proposed approach, revealing the spatial distribution of the circulation activity, its seasonal variations and possible presence of decadal trends. Most results confirm the facts known from other similar studies, but also others, newly or seldom treated, are pointed out.

Keywords: objective climatology, cyclonic vorticity flux, Mediterranean, long-term variations

The present paper is dedicated to the 60th anniversary of the work of A. Pissarski and in memory of prof. E. Syrakov.

1. INTRODUCTION

Extra-tropical cyclones, their paths and intensity, have been the subject of climatological and synoptical studies for more than a century. They are dominant synoptic-scale features of the atmospheric circulation in the mid-latitudes influencing strongly the local weather, in particular causing severe weather events.

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Due to the significant advantages of the automatic and semi-automatic objective methodologies, they have almost entirely replaced the manual synoptic-chart analysis in the past two decades. It has been proven that the application of numerical algorithms of gridded data, mainly from different reanalysis projects, is an effective approach for obtaining detailed storm statistics and, more generally, a spatially and temporally consistent picture of weather systems. The Lagrangian storm tracking has been widely recognized as an effective approach for analyzing detailed statistics of extratropical weather systems. Lagrangian approach provides information on the preferred locations of cyclone genesis and lysis, the average moving speed and lifetime of weather systems, and the difference between cyclone and anticyclone statistics. With advances in computer resources in recent decades, researchers have developed state-of-the-art automatic algorithms. The high socio-economic and theoretical relevance of such phenomena is the main motivator for the increased scientific interest. Consequently, a large number of research papers have been published in recent years, based either on reanalysis data or on Global Circulation Model (GCM) data (see Ulbrich et al., 2009 for a comprehensive review). Different thresholds, different physical quantities, and considerations of different atmospheric vertical levels add to a picture that is difficult to combine into a common view of cyclones, their variability and trends. An expression of the common drive for estimation of the current progress in the field was the IMILAST project - a community effort to intercompare extratropical cyclone detection and tracking algorithms, whose main aim was to reveal those cyclone characteristics that have been robust between different schemes and those that differ markedly (e.g., Neu et al. 2013).

As distinct hemispheric secondary center of cyclonic activity (Ulbrich et al., 2009), the Mediterranean is one of the most discernible focal points of this intensive interest. Pioneering studies for this region that include climatology of cyclones and cyclogenesis are those by Pisarski (1955), Pettersen (1956) and Klein (1957). Subsequent studies, using the same manual analyses and subjective detection, were able to investigate smaller scales, including also mesoscale features (Radinovic and Lalic, 1959; Radinovic, 1978; Genoves and Jansa, 1989). Objective cyclone identification and tracking methods have been first developed in this area by Alpert et al. (1990a and 1990b). Several studies have focused on dynamics, locations, frequency and temporal variability of genesis of the cyclones in the Mediterranean (Buzzi and Tosi, 1989; Tosi and Buzzi, 1989) and more recently the works of Trigo et al. (1999), Campins et al., (2000) Jansà et al (2001b), Maheras et al., 2001, 2002, Lionello et al., 2002 Picornell et al. (2001), Musculus and Jacob (2005), as well as many others. The study of the Mediterranean cyclones from a climatological point of view has been one of the objectives of the first phase of the WMO WWRP MEDEX (MEDiterranean EXperiment) project (Genovés et al. 2006, Jansà et al 2001b).

The main difference between the present study and most other dynamically oriented climatologies is the attempt to estimate the circulation activity, defined in terms of the relative vorticity flux for fixed time intervals, without inspecting features of individual cyclones and the related metrics (cyclone centers and tracks, track densities and cyclone frequencies, etc.).

The paper is structured as follows: the second chapter is dedicated to the motivation of the used methodology followed by the description itself. The third chapter describes the choice of the dataset as well as the performed calculations. The proposed novel approach is illustrated by one example. The core of the paper is in the fourth chapter, where the results are exposed and discussed. Summarizing remarks are listed and briefly commented on in the conclusion.

2. METHOD

Following the approaches based on an inspection of weather maps, many authors use cyclone core pressure at isobaric height of medium sea-level pressure (MSLP) or relative minima 1,000-hPa geopotential height fields as a mean measure of a low's intensity. Additional quantification of the cyclone intensity is implemented in several studies: the mean radial gradient (Blender et al. 1997, Trigo 2006, Raible et al. 2007, Rudeva and Gulev 2007) and/or, for example, the Laplacian of MSLP computed with a certain radius around the cyclone centre, as in Murray and Simmonds (1991) and Simmonds (2003). Musculus and Jacob (2005) find an 'area under the cyclone's influence' using a scheme originally designed for the identification of watersheds, applied on high resolution data. Such tesselation of the flow of strictly neighboring 'cyclonic' and 'anticyclonic' segments seems at least unusual in the synoptic scale dynamics, where these systems are frequently separated by large vorticity-free (i.e. 'neutral') zones.

Alternatively (or in some studies as an addition) to the consideration of MSLP minima, a number of schemes identify maxima in low-level (e.g., 850 hPa) vorticity (Hodges 1994, Sinclair 1997, Hewson and Titley 2010). The use of this metric implies an extension to the definition of cyclones, so that not only features with closed isobars are considered. Many authors state (for instance Hodges et al. 2003) that vorticity is more focused at the high-frequency end of the synoptic range, while SLP is better at capturing the low-frequency margin. A problem in using vorticity as the only parameter is the larger number of small-scale maxima (compared to MSLP minima), which makes the procedure much more dependent on the spatial resolution of the data.

A common weakness of all single-point intensity diagnostics is the attempt to assess intensity by only one value, ignoring the spatial (even the planar!) extent of the systems. The author's opinion is that this approach for such vast and asymmetric structures as the mid-latitude cyclones seems physically not sufficient. Emphasizing this fact, Sinclair (Sinclair 1997) presents two examples, in which the systems have similar core-point vorticities, but distinguishably different strengths. He states, that the circulation, equivalent to the area enclosed by a curve times the mean vorticity over the area (i.e. the flux of the vorticity which is equivalent to the line integral of velocity around the boundary of the area – see further), is a more realistic measure of cyclone strength because it takes into account both the size and rotation rate of the system. The unit of measure of the vorticity flux is m^2s^{-1} or, for convenience, CU, where 1 CU=10^7 m^2s^{-1}. Following Radinovic (1997) the horizontal domain of a cyclone can be defined as the area of positive (relative) vorticity around the cyclone centre, bounded by the zero-vorticity line. In this manner the vorticity distribution field presents the natural way for distinction between the cyclone domain and its surrounding region (vorticity-free or anticyclonic areas). So, a more concise definition of the cyclone intensity or strength could be: *The cyclone intensity is equal to the flux of the cyclonic (i.e. positive in the Northern and negative in the Southern hemisphere) relative vorticity trough the area around the cyclone centre, bounded by the zero-vorticity line (see the Appendix for the mathematical description).* The main difficulty with circulation calculations lies in defining the region of cyclonic airflow associated with each vortex, especially in cases of multi-core depressions, when many centers share a common zero-vorticity line. Nevertheless, the physical richness and consistency of the vorticity flux as an objective cyclone intensity estimator, determines the increased use of this measure (see, for example, Picornell et al. 2001). Many computational procedures exist, one of the most elaborated is proposed by Sinclair (Sinclair, 1997).

Main goal of the present study is to estimate the cyclonic circulation over the model domain without identification of individual systems. As a result we can obtain the spatial and temporal distribution of the cyclonic flux trough this area as a general (i.e. without accounting the contribution of every cyclone) measure of the cyclonic *circulation intensity* over the region of interest.

Let n_{ij} be the number of corners of the gridcell with lower left corner at the grid point with indexes i and j, where the vorticity ξ_{ij} is positive. Obviously, n_{ij} can take only five values: 0, 1, 2, 3 and 4, where the values 0 and 4 are in the cases when this gridcell is completely in or out of the area, occupied by the cyclonic flow. If n_{ij} is equal to 1, 2 or 3, the zero-vorticity line, whose exact position is not known, splits the gridcell. The idea is to estimate the 'cyclonic part' of the gridcell's area as:

$$\Delta s_{ij}^{c} := \frac{n_{ij}\Delta s_{ij}}{4} \approx \frac{n_{ij}\Delta y(\Delta x_j + \Delta x_{j+1})}{8} \tag{1}$$

Here Δy is the cell side along the meridian, Δx_j and Δx_{j+1} are the cell sides along the model's parallel with index j and j+1.

Continuing the upper idea, the average positive (cyclonic) vorticity in the gridcell is equal to:

$$\overline{\xi_{ij}^{c}} := \begin{cases} \dfrac{\sum\limits_{i,j,\xi_{ij}>0} \xi_{ij}}{n_{ij}}, & n_{ij} \neq 0 \\ 0, & n_{ij} = 0 \end{cases} \tag{2}$$

Finally, we can obtain the cyclonic vorticity flux trough the gridcell:

$$\Phi_{ij}^{c} = \overline{\xi_{ij}^{c}}.\Delta s_{ij}^{c} \tag{3}$$

Keeping in mind that the flux is an additive quantity, the total one over a certain region can be obtained by simple summing of single shares over the calculated by equation (3) contributions for all gridcells included in this region. In particular, it is possible to estimate the flux of an individual cyclone by summing the fluxes for all gridcells inside the zero-vorticity line around the corresponding vertex. Such a task, however, is not the subject of the paper.

The described novel approach differs relevantly from most other studies (Neu et al. 2013), which core is set of algorithms for calculation of the characteristics (vertex centers, trajectories, life-time aspects, etc.) cyclone-by-cyclone. Usually further, to obtain long-term climatologies, statistical and ensemble analysis is performed. Main advantage of the proposed method is its conceptual and mathematical simplicity. This allows in particular escaping from a lot of sophisticated and demanding procedures such as individual cyclone identification and calculation of the intensity cyclone-by-cyclone, which is very significant especially for long periods of time. Important merit is also the absence of any (wide used in other studies) assumptions i.e. empirical thresholds, which more or less affect the physical objectivity of the procedure. Most obvious drawback is the limitation to only one, ‘bulk’ characteristic of the circulation state, which constrains the analysis possibilities only over this metrics.

3. USED DATA AND PERFORMED CALCULATIONS

The data used in this study are the time series of 6-h wind produced during National Centers for Environmental Prediction (NCEP) National Centre for Atmospheric Research (NCAR) 40-year reanalysis project (Kalnay et al., 1996), converted in plain ASCII format in the Climatic Research Unit, University of East Anglia. The data set consists of grid point values of the 850 hPa level real (not geostrophic!) wind in a grid of 2.5°×2.5°, allowing the study of synoptic scale cyclones. The full time span of 66 years (1948–2013) is covered at 00:00, 06:00, 12:00 h and 18:00 h co-ordinated universal time (UTC).

The modeling domain extends between latitudes 22.5°N and 55.0°N, and longitudes 12.5°W and 47.5°E including completely the Mediterranean, the surrounding territories and the Black Sea.

The finite difference method is applied to calculate the vorticity field at 850 hPa. The reasons for selection of this isobaric level hPa are manifold. First, according to the traditional concept, the (well) developed tropospheric cyclone is better expressed in the low levels. On the other hand, however, mainly the turbulent friction in the planetary boundary layer alters the flow, which makes the near surface layer unsuitable for such analysis. In the bigger part of the vorticity-based cyclone studies, the 850 hPa level is the most preferable one. Many authors (Sinclair, 1994, Picornell et al. 2001 and etc.) point out the inherent 'noisiness' of the vorticity and the consequence that small-scale features can mask higher scales. Applying the Cressman filter (Cressman, 1959) is widely used in the objective cyclone analysis technique to overcome this problem. After some tests, Picornell (Picornell et al. 2001) states, that the value of 200 km of the Cressman's filter tuning parameter, often called 'radius of influence', provides accurate description of Western Mediterranean cyclones. This distance is smaller than the horizontal grid resolution in the bigger part of the domain, which makes such preprocessing unnecessary in our case.

Figure 1 shows an illustrative application of the proposed approach to one case of a well-developed cyclone over the eastern Mediterranean on 31 December 2000. Due to the (general) absence of aerological soundings over Europe at 18 UTC, respectively weather map on the selected isobaric level AT850, the synoptical situation is visualized with a manual surface map from the NIMH-BAS archive, as shown on the left pane. As can be seen, the weather over the Central and Eastern Mediterranean is dominated by a deep (the MSLP in one station near the low's minimum is 996,9 hPa) single-core cyclone eastwards from Sicily. The cyclone is surrounded by an anticyclonic belt over Central Europe in the north and over the northeastern part of the Balkan Peninsula in the northeast. A secondary low is placed over Ukraine. On the right pane of figure 1 are given the vorticity in each grid node and the cyclonic vorticity flux trough each gridcell, calculated with the proposed method, at AT850 correspondingly. The comparison between the pictures on left and right panes shows that the maximal flux is located in the cell containing the vorticity maximum, and decreasing radially, turns to zero in the gridcells, whose all corners are with negative (i.e. anticyclonic) vorticity. Again, the flux is positive near the upper right corner of the domain, over the secondary low. The continual zones with positive flux are interpreted as separate lows and their intensity is obtained by integrating the flux over them.

One of the main merits of the chosen approach, based on the above proposed method, is the indicative force of the vorticity flux over a certain area – first, it is a very robust integral (over the space) criterion of absence or presence of cyclonic activity there and, if such is present, of its magnitude. Thus, the first step in the performed calculations is to compute it for every time step for the whole 66-years period.

Past and future trends in cyclone characteristics, or, more generally, of cyclone activity, are an important issue in the discussion of climate change impacts. In this context, the knowledge of interannual and decadal variability is indispensable for assessing the importance of observed or projected trends. From climatological point of view it is essential to process 'sufficiently' long datasets to achieve statistically robust, respectively representative results. Many authors (Neu et al, 2013) emphasize the principal impossibility to perform comprehensive diagnosis of long-term trends using 20-year and, in some studies, even shorter datasets. The most often used criterion for time scale judgment in this sense is the standard 30-year long World Meteorological Organization (WMO) period (see, for example, Baddour and Kontongomde 2007). It is worthy to underline, that among all (at least these freely available) the NCEP-NCAR reanalysis is with the longest time coverage, which makes it preferable for climatological studies, as the presented in this paper.

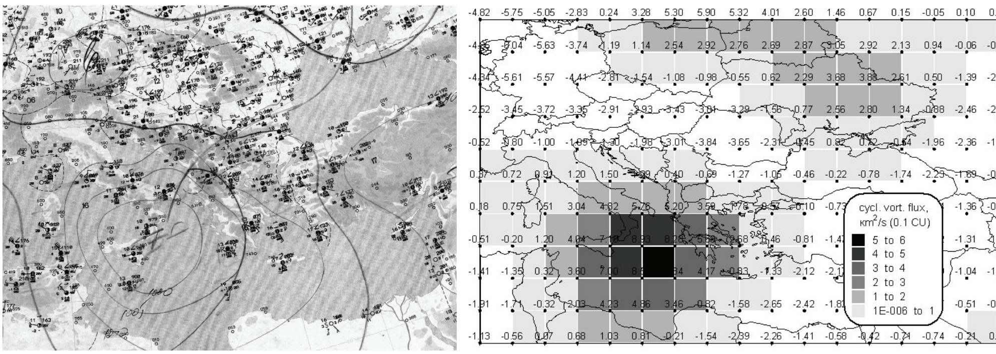

Fig. 1. Hand-drawn surface synoptic map for 31.12.2000 at 18 UTC (on left, NIMH-BAS archive) and calculated vorticity (unit: CVU) in each grid node and cyclonic vorticity flux in each gridcell (see legend) respectively for the same situation (on right).

In the more than half a century after the work of Petersen (1956), many other studies (Alpert et al. (1990a and 1990b), Trigo et al. (1999), Trigo et al. (2002)) reveal the irregular spatial, seasonal and diurnal distribution of the Mediterranean cyclones according to their cyclogenesis and lysis regions, life cycle aspects, and tracks. Therefore, from methodological point of view, the correct long term comparisons have to be performed over monthly or seasonal averages and not simply over fixed time-length (years, decades) periods. So, the calculated for each 6 hours daily means are additionally averaged for each season. The whole time span is divided equidistantly in three 22 year long time periods: 1948-1969, 1970-1991 and 1992-2013 and the traditional four meteorological seasons (December–February, DJF; March–May, MAM; July–August, JJA; September–November, SON) segmentation is applied, although some criticism to the latter (Trigo et al 1999) exists. To keep the consistency of this article however, only results for the two 'main' seasons, namely winter and summer, are presented here. The correct comparability between the seasonal averages is ensured with recalculation of these quantities for standard 90-day period. Thus the inconsistency between summer and winter as a result of their different durations is avoided.

Despite the above listed considerations about the applicability of the core-point vorticity as a cyclone strength measure, this value is calculated for all detected maxima for a rough judgment of the strength. Here, the traditional manner of detecting the location, respectively of the value, of the maxima is performed: The vorticity in each node is compared with that in all eight surrounding grid points, followed by interpolation within the gridcell. The calculations show, that only in a few time frames (isolated cases) it is greater than 12 CVU (1 CVU = $10^{-5}s^{-1}$). Thus, the range between 0 and greater than or equal to12 CVU is divided into four categories and each detected maximum is allocated to one of them. The number of events in each category in each gridcell for the periods of interest is an additional statistic in the assessment of the spatiotemporal variations of the cyclonic activity in the domain.

On the first calculation step, the vorticity flux field for the current time frame and then the daily averages as mean of the corresponding four consecutive ones are obtained. Simultaneously, the vorticity maximum statistics, as prescribed above, are computed. All intermediate results are stored in catalogue and data base files, which allows further and separate processing, in particular adopting other ideas. Second, after an additional averaging procedure, the seasonal daily averages for each 22-year time period, are calculated. They express in most concise form the main results of the presented study and are shown on figures 3-5.

A logical next step is to try to asses the long-term variations of the calculated quantities. The above described 22-year seasonal means, which, in the frame of the adopted approach, can be treated as climatic representatives for the corresponding periods. As the proposed method estimates the overall cyclonic flux in fixed grid rather than of non-stationery objects (individual systems, tracks, etc.) methodologically the simplest way for such assessment is to obtain the relative changes of one time period relative to the other two. For conciseness again, only the relative changes of the last period to the first are presented here, as shown on figures 6 and 7.

To point out the zones with more robust tendencies, which are thought as most significant for the regional climate, the gridcells without monotonic (i.e. if the change of the second period to the first and the third to the second are not with the same sign) are discarded (differently color coded on the corresponding figures).

4. RESULTS AND DISCUSSION

The climatology of cyclones in the domain is highly influenced by the almost enclosed Mediterranean Sea, which is an important source of energy and moisture for cyclone development. Major role in the steering and deflecting air flows plays its complex land topography. Moreover, being located within the transition between the subtropical high-pressure belt and the mid-latitude westerlies, the Mediterranean is also subject to strong interannual variability of cyclone activity (Lionello et al. 2006). The outcomes of the most modern automated procedures allow assessment of the cyclonic activity distribution in different terms - areas where cyclogenesis tends to occur (as, for, example in Trigo et al. 1999, 2002), storm-tracks densities (Picornell et al. 2001, Muskulus and Jacob 2005, Trigo et al. 2006), cyclone centers counts (Maheras et al. 2001) or frequently combination of them. Due to the above mentioned limitation of the proposed approach, the applied estimators in the presented study are the overall cyclonic flux and the categorized number of vertices. Although the obtained results can be analyzed further, the main issues can be briefly divided and summarized in the following sections:

- Geographical and the seasonal distribution
- Long-term (inter time-period) variations.

Main result according the geographical distribution can be concise formulated as:

- Statistically the most robust in all seasons and time periods region of the cyclonic activity in is the the domain over the Ligurian, Tyrrhenian and Ionian seas, where the most intense cyclonic flux and centers with the highest core-point vorticity have been detected.

Part of the systems, originate from other regions, for instance northern Africa, as shown in Genovés et al. (2006), but obviously during their propagation and life-cycle development they reach the phase of maximal development here, causing the strongest climatologically averaged vorticity flux. As shown on figures 3-5, the gridcells with the maximum total amount (i.e. sum of counts in all four categories) of centers are located in the central Mediterranean. Second, here are concentrated those in the first two categories (with core-point vorticity above or equal to 9 CVU and between 6 and 9 CVU), although this zone is elongated in the southeast direction to Cyprus, which is a cyclogenetic region (Trigo et al. 1999, Trigo et al. 2002).

Generally, this result agrees with the conclusions of many other studies obtained with different methodologies, selection criteria and data sets (e.g. Alpert et al. 1990a,b Campins et al., 2000, Maheras et al. 2001, Picornell et al. 2001, Musculus and Jacob 2005). The relatively coarse resolution of the dataset and nature of the proposed approach, however, does not allows resolving sub-areas as in other dynamically oriented methodologies (Campins et al., 2000, Picornell et al. 2001).

The decadal averaged seasonal vorticity flux shows also another distinguishable pattern, namely:

- In all time periods a sea/land difference in the cyclonic activity is observed and as a whole it is greater over the seas. The contrast is most clearly expressed during the winter.

This fact can be explained in general with the role of latent heat release and diabatic processes. As stated in Lionello et al.(2006) this is a key issue in the Mediterranean cyclogenesis.

According many studies (see, for example Lionello et al. 2006), the overall synoptic activity over the entire basin has a well-defined annual cycle, being more intense in the period from November to March which corresponds to the so-called storm season. This study reveals overall the same seasonal variation pattern:

- Generally the cyclonic activity over the domain is more prominent in the winter than in the summer, especially over the above described region.

The mechanisms typical of winter cyclogenesis in the Mediterranean exhibit contrasting characteristics with those most common in spring and summer seasons, with intermediate situations in spring and autumn. Our study reveals, that in the three time periods the average summer vorticity flux over the seas of increased activity is roughly between 3 and 6.10^{-2} CU, and in winter, again roughly, it is between 5 and 9.10^{-2} CU. In terms of number of detected centers this seasonality is significantly better expressed: During the summer, only in a few gridcell events in the second, and almost not at all in the first category, are realized. Opposite, in the winter, the number of events in the second category is relatively great, reaching in the internal part of the domain a couple of tens. Using the NCEP-NCAR datasets for the period 1958-1997, Maheras (Maheras et al. 2001) also reveals especially high frequency of cyclone centers in the Gulf of Genoa, which is the most discernible activity region in our study, and more preferably for the intense cyclones. The Mediterranean cyclones are in general more similar to the Atlantic cyclones in winter than in summer (Campins et al., 2005). In winter there are strong links between synoptic upper-troughs and local orography and/or low-level baroclinicity observed over the northern Mediterranean coast. As stated in Lionello et al. 2006, winter cyclogenesis occurs essentially along the northern coast in three major areas characterized by strong baroclinicity: the lee of the Alps, and over the Aegean and Black Seas, when an upper-trough moves over the relatively warm water basins. For the third and the fourth category, containing the centers with core-point vorticity greater than or equal to 3 and lower than 6 CVU, and lower then 3 CVU respectively, the picture seems converse, although not clearly expressed: in significant part of the domain the number of centers in summer is greater than in winter. Obviously during its development one cyclone traverses from one category to another and these facts alone are not sufficient for more general conclusions, but point to the known from many studies fact (Maheras et al. 2001, Picornell et al. 2001, Trigo et al. 2002), that in the summer the cyclonic activity is dominated by shallow, as a rule barotropic and short-living depressions (Ulbrich et al. 2009).

However, one clearly standing out exception of this pattern has to be emphasized: A very strong cyclonic maximum in the summer (especially in the first time period) is revealed over Anatolia. This maximum is stronger even than the winter one over the Tyrrhenian Sea – in terms of the vorticity flux and especially in terms of the number of cyclonic centers: for example in the first time period the Anatolian (summer) maximum has peak vorticity flux between 10 and 12. 10^{-2} CU and a number of centers in the second and third category 59 and 580 respectively. On the other hand, the Tyrrhenian (winter) maximum has a vorticity flux between 7 and 9. 10^{-2} CU and a little bit greater number of centers in the second category – 76, but only 169 in the third.

Usually, the Anatolian center of activity is considered rarely in most climatological studies for the Mediterranean. Fisher (1978) explains this semi permanent cyclonic center (“Anatolian low” in terms of MSLP) with the northwestern expansion of the Indian subcontinent monsoonal low combined with the intense heating over the Middle East. The formation of big overheated air mass is strengthened especially over a terrain with specific orography (the Anatolian plateau) during the summer. In the works of Kotroni et al. (1997) and Chronis et al. (2011) this low, in constellation with high pressure system over the Balkans, is considered as prerequisite for strong north-north-east winds over the Aegean Sea, known as Etesian winds. Maheras et al. (2001) treats this center as part of the eastern Mediterranean one, but, however, relation to synoptic scale cyclones was not revealed. In the means of the proposed approach this case demonstrates how the long time integration of the cyclonic fluxes of weak, but frequent (semi permanent) vertices can produce result, commensurable or even greater than those of significant, but seldom structures. This fact can be observed as limitation of the possibility for assessment, based only on the gridded vorticity flux. The method have to be applied in combination with other estimators, as for example as demonstrated in this study, the categorized number of center counts.

No significant (in comparison with the surrounding territories) cyclonic activity is detected over the Black Sea.

At first sight this conclusion contradicts to the one in Trigo et al. (2002), where the eastern part of the Black Sea is revealed as a cyclogenetic region, using, however, different datasets (origin and time span) and a different approach. Analyzing the cyclonic tracks over the Eastern Mediterranean Flocas (Flocas et al. 2010), detects noticeable number over the Black Sea, which conclusion is supported also by other studies (Neu et al. 2013). A possible reason for the apparent disagreement is the fact that the average cyclonic flux might be quite low in that area due to very early stages of cyclone development. Consequently ‘cyclogenetic area’ and ‘area of intense (overall) cyclonic circulation’ according our approach, can not be treated as synonyms.

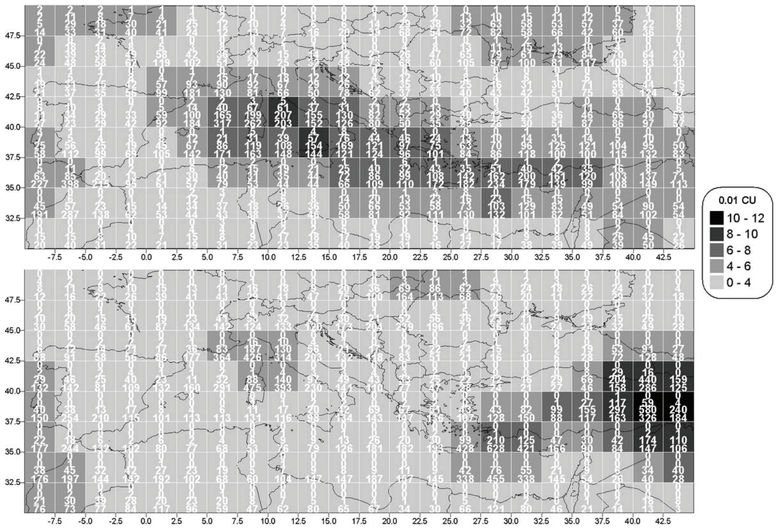

Fig. 2 Average daily cyclonic flux for the first time slice (1948-1969) during the winter (upper pane) and summer (lower pane). The number of the detected cyclone centers during all winters/summers in the time slice with core-point vorticity below 3 CVU, between 3 and 6 CVU, between 6 and 9 CVU and greater than 9 CVU in each gridcell are shown in the first (lowest), second, third and fourth text register respectively.

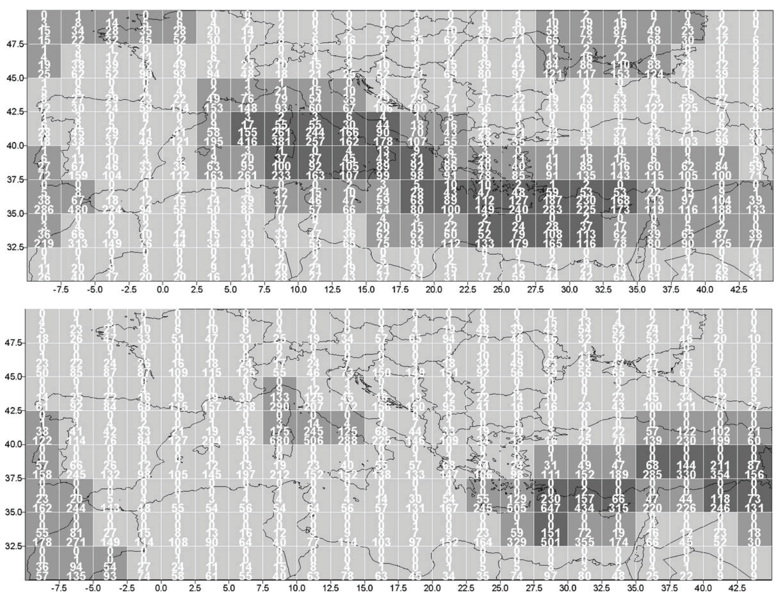

Fig. 3 Same as Figure 2, but for the second time period (1970-1991)

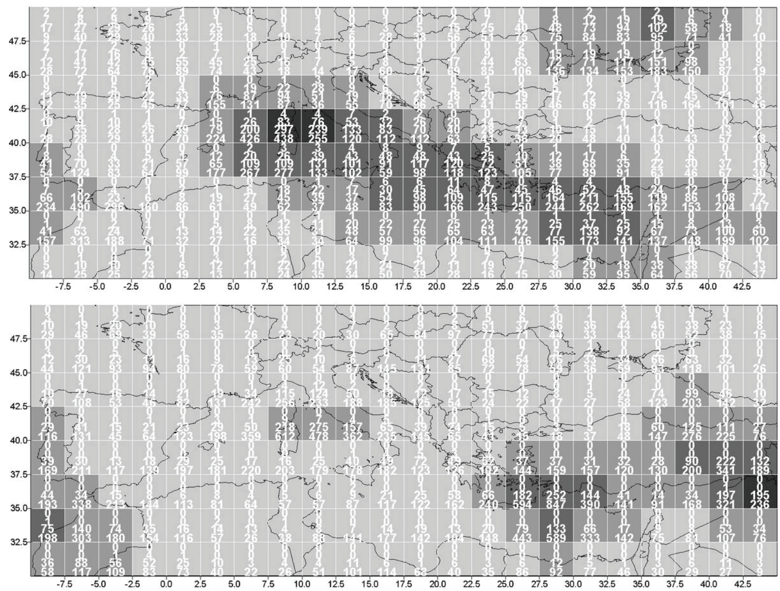

Fig. 4 Same as Figure 2, but for the third time period (1992-2013).

The long-term (inter time-period) variations assessment also highlights significant features. Continuing the concise presentation stile of the previous section, the following most remarkable issues can be outlined.

Over the bigger, compact marine part of the domain (as over the bigger part of the whole domain), which, as previously stated, is the main region of cyclonic activity, the relative change of the mean winter vorticity flux of the second time period (1970-1992) to the first one (1948-1969) and that of the third (1992-2013) to the second, are not with the same sign, i.e. the time change of period-to-period vorticity flux field is not monotonic.

A monotonic increase of the mean summer vorticity flux (spatially very roughly averaged) relatively 30-50% is revealed over the bigger marine part of the domain, although this quantity varies significantly in the different seas of the Mediterranean. Monotonic increase with relative high values (over 50%) of the summer vorticity flux is revealed also over a couple of neighboring gridcells in different parts of the domain, but most significant seems the one on the south domain border, around the Gulf of Sidra. This significance is caused not only by the value of the increase, but also by the fact, that this area is a well-known cyclogenetic region, origin of some of the most severe storms over the Central Mediterranean (Genovés et al. 2006).

Accordingly, for the Anatolian centre of cyclonic activity, a discernible decrease of the vorticity flux is observed over the autumn, winter and spring (the pictures for the autumn and spring are not shown), but not for the summer, which, as discussed above, is the season of the most pronounced manifestations of this activity.

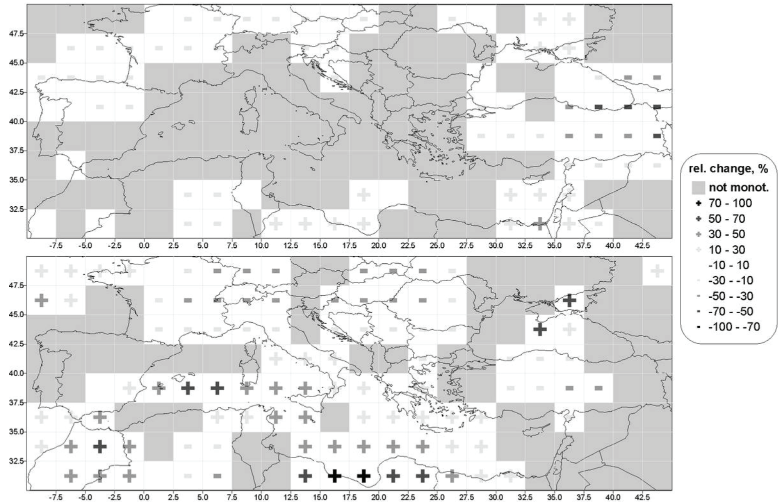

Fig. 5 Relative change of the average daily cyclonic flux of the last time period to the one of the first for the winter (upper pane) and the summer (lower pane). The gridcells without monotonic change are grayed.

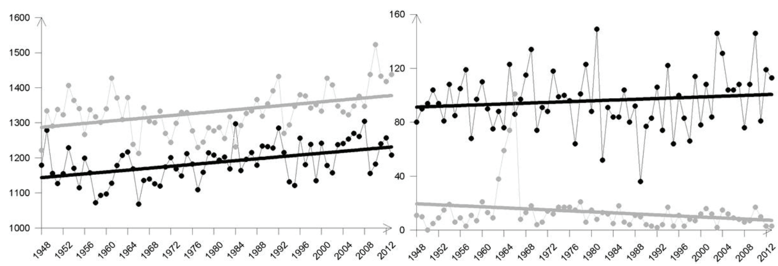

Fig. 6 Time series for the total (on left) and strong/very strong (on right) seasonal cyclone center counts. The datasets, respectively the trend lines, for the winters are shown in black and for the summers – in grey.

A basic approach for computing cyclone frequencies is counting their number of occurrence (from the identification scheme) or positions (from tracks) in grid squares (either simply on a fixed latitude-longitude grid, or referring to a fixed area size). Similar to the IMILAST long-term estimation approach (Neu et al 2013), we have constructed also the time series of the total and of the strong and very strong seasonal cyclone center counts in the domain during the winter and summer season, as shown in Figure 6. Here ‘count’ means all centers found at any time step and ‘strong’ and ‘very strong’ – cyclones with core-point vorticity between 6 and 9 CVU and above or equal to 9 CVU (the upper two bins according to our classification) respectively. The significant seasonal difference in both ensembles is clearly outlined – in all years, except 1984, the number of all winter centers is smaller than the summer's. In contrast, the number of strong and very strong centers in winter is greater in all years, except one remarkable outlier, the year 1964.

A counting of cyclone centres (without any differentiation on intensity), based on the NCEP re-analysis, which covers the period 1958–1997, shows a reduction of the number of cyclones in western Mediterranean and an increase in the East (Maheras et al., 2001). Linear fit to the data leads roughly to a 15% increase/decrease. Changes are not seasonally homogeneous. The IMILAST-analysis reveals, that most participating methods indicate increase of the total number of (North hemispheric) cyclone centers over the winters in the 1989–2009 period and decrease of the deep (core pressure below 980 hPa) ones, although with significant differences between the methods. Further, it is emphasized, however, that hemispherically averaged trends do not provide information about regional shifts of cyclone occurrence. Thus, results obtained for a limited domain as ours, can not be directly compared with the IMILAST ones or such from other studies, for example Bartholy et al. (2006). The linear regression fit lines of our time series are with so small slope (the absolute value is smaller than 1.4 counts/year for all four) and so poor (the coefficient of determination is smaller then 25% for all) that any statements for persistence of long-term trends, at least for any statistical significance, based only on these results, would be incorrect. Exploring these intermediate outputs with a more productive method, in particular for seeking robust annual and decadal tendencies, can be a subject of further studies.

5. CONCLUSION

Combining optimally clear meteorological meaning and deep physical contents on the one hand and the possibility of relatively easy computation from freely available data on the other, the relative vorticity flux demonstrates features of a perfect cyclonic systems estimator. Main result, described in the paper is the proposed novel approach for estimating of the cyclonic flux in grid, using the wind components in the gridnodes as a part of the author's idea to assess the cyclonic activity overall for fixed region and time frame, rather as a statistic for individual lows. The method is transparent, free from empirical thresholds, conceptually simple, and, as result, computationally not demanding. It can be practically without change adapted for different datasets/regions and periods. Inspecting digital charts, it is possible to use it for dynamical analysis of separate cyclones in semi-automatic manner. The method gives the opportunity to obtain the cyclone size (horizontal extend) and mean vorticity separately, which is significant for assessment of individual systems. The study proves, that even with such a general approach, not considering individual objects, meaningful outcomes can be achieved, revealing significant features of the cyclonic activity in the Mediterranean and its long-term variations. As many times mentioned, the outcomes according the regions with increased cyclonic activity and the annual variation of this activity generally express basic facts of the synoptical meteorology and climatology of the Mediterranean, but that does not reduce its value, rather, it can be considered as a kind of dynamical explanation. They are in principal good agreement with the modern concepts – results from computationally-oriented studies (see again Lionello et all. 2006 for a comprehensive review). As shown in the case of the Anatolian low however, the method shows, also weaknesses – retrieving only the gridded overall flux, it is not possible to discriminate between the summarized contribution of frequent and shallow from one site and rare, but significant structures from other. The use of the full 66 year (until the end of 2013) time span of the NCEP-NCAR Reanalysis dataset for such, preliminary indeed, long term objective assessment, is novel. It gives the possibility for treatment of three distinct (i.e. fully non-overlapping) 22-years time periods, which are itself with significant length for climatological analysis. The comparison between the averaged seasonal fluxes, which is also novel, for these time-periods performed in this study, reveals interesting patterns. Among them, most climatologically relevant seems the monotonically increased flux in the Gulf of Sidra, which is recognizable cyclogenetic region.

At the end, we need to emphasize that is methodologically reasonable to aspect some differences between the outcomes of the presented study and others, most of them treating every cyclone separately. Ever since the beginning it was underlined that due to various reasons the results of similar, much more sophisticated methods, can differ from each other. In this context the presented study has to be accepted as a small step toward the understanding of the complex nature of the cyclonic activity over the Mediterranean.

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APPENDIX

Applying the Stokes theorem, which states equivalence between the circulation *C*, defined as linear integral of some vector (in our case the velocity *u*) around a closed path L_s and the flux of the vector's vorticity trough the area, bounded by this path *S*, we can write:

$$C = \oint_{L_s} \vec{u} \cdot d\vec{r} = \iint_S (\vec{\nabla} \times \vec{u}) \cdot d\vec{s} \tag{A.1}$$

Due to the fact that the dot product between the horizontal vorticity components $(\vec{\nabla}\times\vec{u})_x$, $(\vec{\nabla}\times\vec{u})_y$ and the surface element $d\vec{s}$ is equal to zero, the cross product in the right side of equation (1) can be replaced with the vertical vorticity component, traditionally marked with ξ:

$$\xi := (\vec{\nabla}\times\vec{u})_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad \text{(A.2)}$$

The integral on the right side of equation (1) can be estimated as follows:

$$C = \iint_S (\vec{\nabla}\times\vec{u}).d\vec{s} = \iint_S \xi.d\vec{s} \approx \bar{\xi}.S_c \qquad \text{(A.3)}$$

Thus, C is roughly equal to the area S_c enclosed by the curve L_s times the mean vorticity $\bar{\xi}$ over the area. If obtained separately from the mean vorticity, which is possible with the proposed method, S_c can be used as additional measure of the cyclone's magnitude.

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