# OBJECTIVE ASSESSMENT OF THREE STORM CASES OVER THE MEDITERRANEAN BASED ON NCEP-NCAR REANALYSIS DATA

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**Abstract.** The cyclones are dominant synoptic-scale features of the atmospheric circulation in the mid-latitudes influencing strongly the local weather, in particular causing severe weather events. The Mediterranean region is the most discernible secondary maximum of the cyclonic activity in the Northern hemisphere. Applying some base mathematics and well-known relations from the theoretical meteorology on the gridded NCEP-NCAR reanalysis datasets, an illustrative case study of three very intense storms in semi-automatic way is performed.

**Key words:** Mediterranean cyclones, Case study, cyclonic circulation, quantitative climatology

## Introduction

Cyclones represent the most important manifestation of the mid-latitude high-frequency variability, and play a fundamental role in the atmospheric large-scale horizontal (and vertical) mixing and in modulating the air–sea interaction. Cyclonic circulations, due to their frequency, duration and intensity, play an important role in the weather and climate over the entire Mediterranean region (Radinovic, 1987). A large spectrum of environmental variables and phenomena are associated with cyclones in the Mediterranean region. Wind, pressure, temperature, cloudiness, precipitation, thunderstorms, floods, waves, storm surges, landslides, avalanches, air quality and even the fog and visibility in the Mediterranean are influenced by the formation and passage of cyclonic disturbances. The Mediterranean area, although located to the south of the main Atlantic storm track that more directly affects western and northern Europe, is quite frequently subjected to sudden events of extreme and adverse weather, often having high social and economic impacts. (Lionello et al., 2006).

Better understandings of spatial and seasonal variability of Mediterranean cyclones as well as the mechanisms leading to cyclogenesis (lysis) are a major concern for the meteorology of the region, especially for those cyclones related to severe weather. Pioneering studies that include climatology of cyclones, cyclogenesis and track patterns in the Mediterranean are those by Pissarski (1955), Pettersen (1956) and Klein (1957). Information about mesoscale cyclones can be obtained from manual analyses. In these analyses, the analyst takes into account information, not present in the objective analysis, from conceptual models and, in some cases, from satellite imagery. The cyclones can be detected and characterized in these analyses by hand. However, the manual technique presents some disadvantages because it is very laborious and it is difficult to apply to long periods of time and to large areas. Also, the systematic computation of certain parameters is difficult as the domain of the cyclones is often too constrained. Furthermore, this method inevitably entails a certain degree of subjectivity. The subjectivity of the analyst affects the detection and location of the cyclones as well as some parameters such as the geostrophic vorticity or the lifetime of the cyclones. These difficulties would disappear if an automated method was used (Picornell et al., 2001). Based on the availability of hemispheric gridded data sets from observations, analysis and global climate models, objective cyclone identification methods were developed and applied to these data sets in the recent decades (see Ulbrich et al., 2009 for a comprehensive review). 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). Since 1990 (Alpert et al., 1990), most of the studies on climatology of the Mediterranean cyclones are based on objective analyses and objective techniques aimed at detecting and tracking the cyclones (see Lionello et al., 2006 for a comprehensive review). MEDEX (MEDiterranean EXperiment on cyclones that produce high-impact weather in the Mediterranean) is a Research and Development Project, framed into the World Weather Research Program of the World Meteorological Organization, whose main objective is to increase knowledge and improve forecasting of cyclones that produce high-impact weather in the Mediterranean (Genovés et al. 2006).

Mean goal of the presented short paper is to reveal the basic physical and mathematical approach that more or less is incorporated in almost all modern objective cyclone climatologies. Part of the possibilities of the methodology is demonstrated of three very intense storms that produce high-impact weather, especially over the eastern part of the domain. The numerical analysis is performed in semi-automatic way.

The paper is structured as follows: the second chapter is dedicated to the description of the methodology. The third chapter describes the choice of the dataset as well as the performed calculations. 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.

## Methodology

Following Radinovic (1987) the horizontal domain of a cyclone is defined as the area of positive (in the North hemisphere) vorticity around the cyclone centre, bounded by the zero-vorticity line. After the paper of Sinclair (1997), many authors use the cyclonic circulation as main estimator of the cyclone strength. The author's opinion is that the circulation is a physically the most consistent measurement of cyclone strength because, as stated by Sinclair (1997), it takes into account both the size and rotation rate of the system. The reasons for using this parameter in front of any other (like the pressure or the vorticity in the core point of the low) as a measure of the cyclone strength were detailed and referenced in Picornell et al. (2001) and Campins et al. (2006), and coincident with those argued by Sinclair.

According the definition, the flux $\Phi$ of some vector (in our case the wind velocity $u$) trough area $S$ is equal to:

$$\Phi_u = \iint_S \vec{u}.d\vec{s} \tag{1}$$

Applying the Stokes theorem, which states equivalence between the circulation $C$, defined as the line integral of the vector around a closed path $L_s$ and the flux of the vector's vorticity trough the area, bounded by this path area $S$, we can write:

$$C = \oint_{L_s} \vec{u} \cdot d\vec{r} = \iint_S (\vec{\nabla} \times \vec{u}) \cdot d\vec{s} \tag{2}$$

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 (2) can be replaced with the vertical vorticity component, traditionally marked in the meteorology with $\xi$:

$$\xi := (\vec{\nabla} \times \vec{u})_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{3}$$

The integral on the right side of equation (2), namely the vorticity flux $\Phi_\xi$ according equation (1), can be estimated as follows:

$$\Phi_\xi = \iint_S (\vec{\nabla} \times \vec{u}).d\vec{s} = \iint_S \xi.d\vec{s} \approx \overline{\xi} \iint_S d\vec{s} = \overline{\xi}.S_c \tag{4}$$

Thus, $C$ is roughly equal to the area $S_c$ enclosed by the curve $L_s$ times the mean vorticity $\overline{\xi}$ over the area. If obtained separately, as shown in the next chapter, $S_c$ can be used as additional measure of the cyclone's magnitude. Assuming circular shape with diameter $D_c$

of the cyclone and movement with constant tangential velocity $v_\tau$ along this circle, we can obtain:

$$C = \oint_{L_s} \vec{u} \cdot d\vec{r} = v_\tau \oint_{L_s} d\vec{r} = \pi v_\tau D_c = 2 v_\tau \sqrt{\pi S_c} \qquad (5)$$

finally:

$$v_\tau = \frac{C}{2\sqrt{\pi S_c}} = \frac{\Phi_\xi}{2\sqrt{\pi S_c}} \qquad (6)$$

Thus the computation of the cyclonic circulation, as measure of its strength, is in natural way connected with the calculation of other significant quantities as the size/diameter and representative velocities (linear or angular - most often the mean tangential velocity along the cyclone's boundary). The SI-unit of measure of the vorticity flux is $m^2.s^{-1}$ or, for convenience in the meteorology, CU, where 1 CU=$10^7$ $m^2.s^{-1}$. For example, if the cyclonic area is 1000000 square kilometers (approximately a circle with diameter 1128 km, which is typical value for North Atlantic cyclones or very big Mediterranean ones) and the mean vorticity trough this domain is $5.10^{-5}$ $s^{-1}$(CVU), the circulation will be 5 CU and, according the second relation in (6), the mean tangential velocity $v_\tau$ along the boundary will equal 14 m/s.

The main difficulty with circulation calculations lies in defining the region of cyclonic airflow associated with each vertex (i.e. cyclone center), especially in cases of multi-core depressions, when many centers share a common zero-vorticity line. Basic idea in most algorithms is: starting from the cyclone centre, a search is made radially outward looking for the location where $\xi = 0$. In the study of Picornell et al. (2001) the points where the (geostrophic in this case) vorticity is zero are searched along the east, north, west and south directions (principal axes) and they are joined by means of four portions of ellipse. The initial horizontal domain of the cyclone is then obtained by adding the four quarters of elliptical areas, limited by the portions of ellipse and the principal axes ('pseudo-ellipse'). More precisely, in other studies (Sinclair, 1997; Campins et al., 2006) the search is performed along more radial axes (i.e. with smaller angular increment) but generally such procedures requires interpolation between the gridnodes which can be very computationally demanding.

Original authors idea is to estimate the size and the circulation of the cyclone without explicit determination of the zero-vorticity line. Thus, 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 $\xi_{ij}$ is positive. Obviously, $n_{ij}$ can take only five values: 0, 1, 2, 3 and 4. 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 and 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 $\Delta s_{ij}^{c}$ as:

$$\Delta s_{ij}^{c} := \frac{n_{ij}\Delta s_{ij}}{4} \approx \frac{n_{ij}\Delta y(\Delta x_{j} + \Delta x_{j+1})}{8} \tag{7}$$

Here $\Delta y$ is the cell side along the meridian, $\Delta x_{j}$ and $\Delta x_{j+1}$ are the cell sides along the model's parallel with index *j* and *j+1* as shown on figure 1.

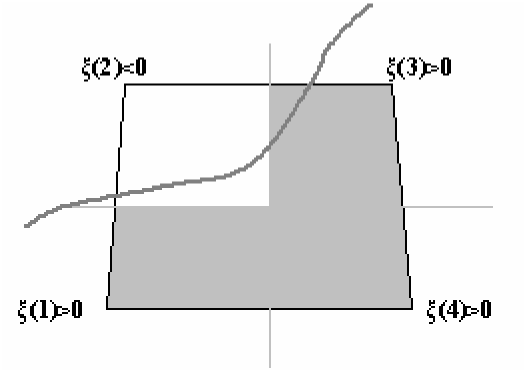


**Fig. 1** Schematic illustration of the proposed method. The zero-vorticity line (shown in bold) crosses the gridcell and thus $n=3$. The 'cyclonic part' (grayed) of the gridcell is estimated as ¾ from the whole and the average cyclonic vorticity-$(\xi_1+\xi_3+\xi_4)/3$

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

$$\overline{\xi_{ij}^{c}} := \begin{cases} \dfrac{\sum\limits_{i,j,\xi_{ij}>0} \xi_{ij}}{n_{ij}}, & n_{ij} \neq 0 \\ 0, & n_{ij} = 0 \end{cases} \tag{8}$$

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

$$\Phi_{ij}^{c} = \overline{\xi_{ij}^{c}}.\Delta s_{ij}^{c} \tag{9}$$

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 (9) contributions for all gridcells included in this region. In particular, it is possible to estimate the flux of an individual cyclone by summing the gridcell fluxes over the area which includes this object. The borders can be found inspecting the vorticity sign around the corresponding vorticity maximum. Obviously such approach lacks accuracy. However, due mainly to its simplicity, it can be used for case studies of well isolated structures as demonstrated later.

## 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 for Quarter-Spherical Window (0°N-90°N; 90°W-90°E) in a grid of 2.5°×2.5°, allowing the study of synoptic scale cyclones. 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. The reasons for selection of this isobaric level are manifold, but will be not discussed here. 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 maximums of the time-series of the overall (i.e. the integrated over the whole domain) flux can be treated as rough proxy for cyclonic activity at the corresponding time. In such a fashion an outstanding peaks that correspond to very intense lows, as this shown on figure 2, can be easily detected.

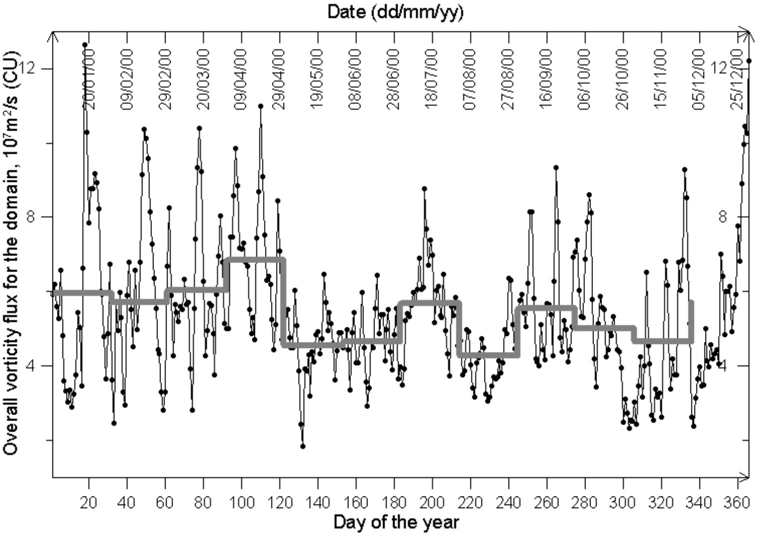


**Fig. 2** Time series for the overall cyclonic flux trough the domain for the year 2000. The step plot shows the monthly averages. The very high value on the right ridge of the figure reveals strong activity in day 366 (31 December).

Resolving this task using other methods can be very time-consuming. The computation of these time series for the full 66-year (1948-2013) time span of the dataset reveals the first, second and third maximums of the daily average, which are on the 03.02.1954, 07.02.2012 and 08.02.1996 and are equal to 18.0 CU, 16.4 CU and 15.7 CU correspondingly. Next necessary step is to find the positions of all vorticity maximums for the time frame of interest, which are potential cyclone centers. The traditional manner of detecting the location, respectively of the value, of the maxima is performed automatically: The vorticity in each node is compared with that in all eight surrounding grid points, followed by interpolation within the gridcell, as illustrated in one other case (not observed here further) on figure 3

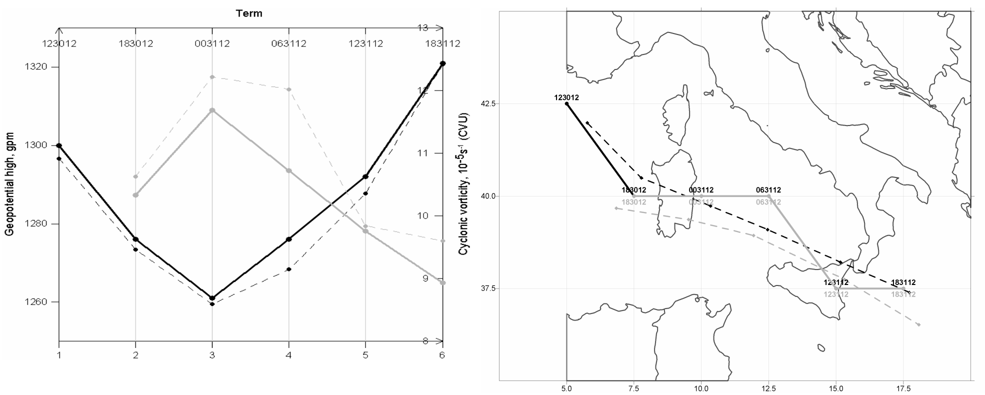


**Fig. 3** (Left) Time series (time lebel: hhddmm, year 2000) of the 850 Hpa geopotential high (in black) and cyclonic vorticity (in gray) of the selected cyclonic center. (Right) Corresponding tracks. The solid lines on both panes connect the non-interpolated (i.e. gridnode value and position) and the dashed – the interpolated values. The value and position of the vorticity centre at 123012 is not computed in this case due to the absence of derivate (respectively vorticity) at the left domain border.

The maximal value of the vorticity for a single vertex is calculated for the one, detected on 21.01.1981 18 UTC and is equal to 13.2 CVU. Although the tracking of individual systems is out of the scope of this work, the created digital maps with vorticity maximums allow performing such a task for short intervals in semi-automatic manner. Thus, applying the most widely used (Ulbrich et al., 2009) nearest-neighbor search and inspecting consecutive time frames, the tracks of the selected lows for four time steps before and four time steps after (or 48 hours as a whole) the moment of maximal core-point vorticity, are constructed as shown on figure 4. The most important feature, the determination of the region of cyclonic airflow, is performed using the prescribed in the previous section method. A simple four-directional search along horizontal and vertical axes, obtaining a rectangular area, occupied by the low is applied. Further, the cyclone 'size' and intensity is obtained by summarizing automatically the cyclonic part of the cell and fluxes trough every gridcell, contained in this area in accordance with Eq. (7) – (9). Finally, applying Eq. (5) and (6) the diameter $D_c$ and mean tangential velocity $v_\tau$ are calculated.

## Results and comments

Only a first sight about the representation of some calculated features for the selected storms will be addressed, following partly the presentation manner in Genovés et al. (2006).

All of the four observed cases correspond to very deep one- or multi-core lows and at least three among them are reason for severe weather over broad regions in Southeast Europe (for the case from 2012 see, for instance Chervenkov (2012), no documentation has been found at the moment of writing this paper for the case in 1954). The synoptical treatment of these events, however, is out of the scope of the present work. The cyclone from the case in 1996 is dynamically of very complex structure – an extremely elongated (roughly from Greenland in the northwest to Crete in the southeast) depression with multiple circulation vertices. To apply the simple relations, as the equation above, to such a structure, even for rough judgments, can lead to serious discrepancies. Thus, only the three cases from 1954, 1981 and 2012 are treated further. Table 1 summarizes the main obtained results according the mean features of the selection.

According the classification of Guijarro et al. (2006), moderate cyclones are those with circulation greater or equal than 4 and less than 7 CU and grater than 7 – as a strong. Analyzing the SL-geostrophic vorticity, Genovés et al. (2006) finds that the maximum of the circulation's probability density function is located around 3 GCU. The 90% of the cyclones have values of circulation below 6 GCU and 7 GCU, respectively, in the western and eastern Mediterranean, when only the moments of maximum development of the cyclones are considered. Trigo et al. (1999) reveals, that, depending of the sub region and the season (the variability is significant!), the Mediterranean cyclone radii are roughly between 300 and 600 km. Applying these quantitative criteria, the selected cases can be really judged as severe manifestation of cyclonic activity in the Mediterranean. Table 1 shows that all of the cyclones occurred in winter, which is in the accordance with the well-known fact for annual maximum of the cyclonic activity during this season.

**Table 1** Main features of the selected cyclones according column caption

| | Case 1 | Case 2 | Case3 |
|---|---|---|---|
| Time, hh dd/mm/yyyy | 06 UTC 02/02/1954 | 18 UTC 21/01/1981 | 18 UTC 06/02/2012 |
| Location, Lat., Long. | 40.88N; 11.58E | 35.55N; 18.80E | 36.72N; 20.76E |
| Maximal vorticity, CVU | 10.4 | 13.2 | 12.8 |
| Circulation, CU | 15.7 | 12.5 | 14.2 |
| Cyclonic size $S_c$, $10^3$ $km^2$ | 7919 | 4140 | 5410 |
| Equivalent diameter $D_c$, km | 3175 | 2296 | 2334 |
| Mean tangential velocity $v_\tau$, m/s | 15.7 | 12.5 | 19.5 |

The storm in 2012 produced heavy snowfalls over a big part of the Balkan Peninsula and additionally very strong winds with gusts (and resultant high waves) on the western Black Sea coast, causing various damages on the infrastructure. The cyclones in 1954 and 2012 have a similar African origin and the 1981 event corresponds to a Genoa cyclone. The last case is investigated deeper by Genovés et al. (2006) and it is placed in the third place in the severity storm rank-list, where the ordering criterion was the maximal geostrophic circulation. They have obtained a storm track relatively near (qualitatively compared indeed) to the one on figure 2 and term of maximum development/ maximal circulation 21.01.1981 12 UTC and 13.77 geostrophic circulation units (CGU) respectively. These values are also close to their analogs in Table 1 despite the different method and dataset (ERA40) used in the study.

Concluding this section, it is worth commenting the case 1954. Here, the procedure of bounding the cyclonic air flow reveals that the zero-vorticity line is closed inside the domain, but the corresponding calculated circumference is not. The reason is the zonal elongation of this low. Thus, the depicted circle underestimates the cyclone size in the west-east and overestimates it in the south-north direction. This example, together with the remarks for the cyclone in February 1996, shows that estimation of the characteristics based on simple averages has to be performed carefully and the more correct interpretation of the quantities from (4) are 'equivalent by circular form' rather than 'mean' one.

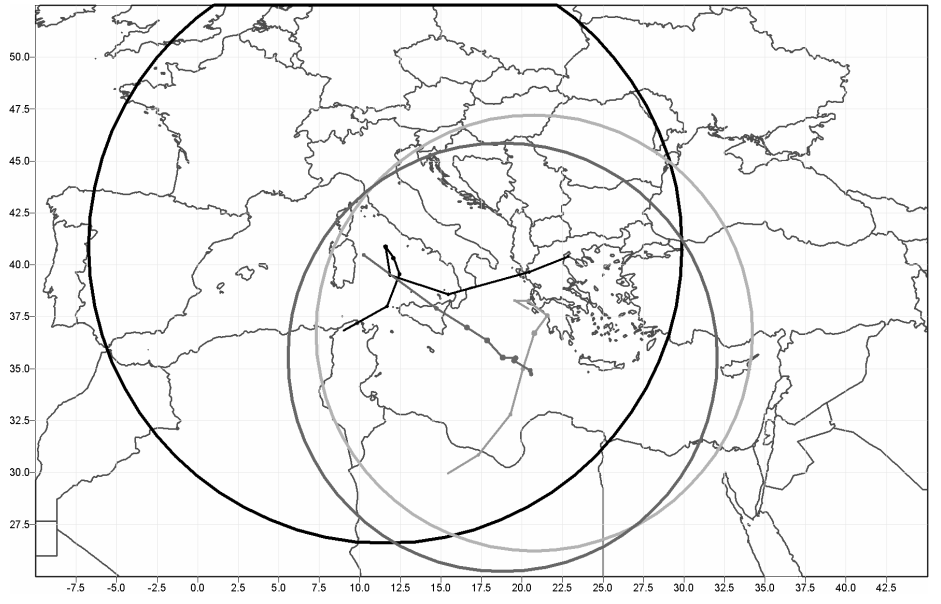


**Fig. 4** Figure 4 Obtained 48-hour tracks and cyclones circumferences (according Table 1) centered over the moment of the maximal core-point vorticity for the cases 1954 (in black), 1981 (in dark grey) and 2012 (in light grey). The size of the location symbols for each time step is proportional (same scale for all cases) to the core-point vorticity magnitude.

## Conclusion

The paper is concise presentation of some of the base mathematics and physical ideas, which are in the fundamental of the objective assessment of the cyclonic features. In the last decades this, most used approach, has proved his efficiency in obtaining and for analyzing detailed statistics of extratropical weather systems, in particular Mediterranean ones. Consequently many detailed databases were produced; some of them freely-available (see, for example, the web-page of MEDEX: medex.inm.uib.es). The presence nowadays of long-term gridded datasets, from reanalysis projects and/or global circulation models from one hand and the increased computational resources from other, determines the prevailing role of the approach also in the future. The work demonstrates that even with the proposed, fairly simplified indeed, method; meaningful quantitative estimations can be achieved. Such results are widely used in many sinoptical, climatological, hydrological and etc. studies. Finally, it is worth to emphasize, that the dynamically oriented research has to continue further, especially in the hydro-meteorological institutes in the dense-populated Mediterranean countries, due to the high theoretical and socio-economical importance of the phenomena.

**Acknowledgments**. To NCEP-NCAR for providing free of charge data and to the Climatic Research Unit, University of East Anglia for the reformatting of these data in convenient form and its further online redistribution.

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**Обективен разбор на три случая с бури над Средиземнорието, основан на данните от реанализа на NCEP-NCAR**

Хр. Червенков

**Резюме**: Циклоните са доминиращата особеност със синоптичен мащаб на циркулацията на умерените ширини като оказват силно влияние на метеорологичното време, в частност обуславяйки опасни обстановки. Средиземноморието е най-ясно различимият район - вторичен максимум на циклоналната активност в Северното полукълбо. Като се прилагат някои основни математически съотношения и добре познати зависимости от динамичната метеорология, е проведен обективен разбор на три случая с интензивни циклонални бури главно с демонстративна цел.