IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 119, No. 2, April – June, 2015, pp. 159–184

Multivariable cyclone analysis in the Mediterranean region

Fanni Dóra Kelemen*, **Judit Bartholy**, and **Rita Pongrácz**

Eötvös Loránd University, Department of Meteorology
Pázmány P. sétány 1/A, 1117 Budapest, Hungary

**Corresponding author E-mail: kelemenf@nimbus.elte.hu*

(Manuscript received in final form September 22, 2014)

Abstract—This paper analyzes midlatitude cyclones identified and tracked in the Mediterranean region for the recent past, between 1981 and 2010. The Mediterranean region is especially interesting since the complex land orography favors lee cyclogenesis, and the warm sea area provides latent heat for the developing cyclones. These cyclones may result in heavy precipitation, even flood events affecting southern and central Europe, including Hungary.

Cyclones are identified using two different reanalyses, the ERA Interim reanalysis from ECMWF at 0.75° horizontal resolution and the NCEP-DOE R2 reanalysis at 2.5° horizontal resolution. For the identification, a multivariable approach is used to eliminate and assess the uncertainties rising from the choice of a specific variable, which is particularly important in the Mediterranean, where the systems are tend to be weak and shallow. Mean sea level pressure (MSLP), geopotential heights of the 1000 hPa, and the 850 hPa isobaric levels are used as main variables, and relative vorticity at 850 hPa isobaric level serves, an additional variable. The applied algorithm has uni- and bivariate modes. In the bivariate mode, relative vorticity at 850 hPa is added to the main variable.

The results suggest that time series of annual number of cyclones using the two reanalyses correlate significantly, however, using the higher resolution dataset, more cyclones can be identified. The largest and the smallest frequency of cyclones over the entire domain occur in spring and summer, respectively. The largest spread of the multi-variable ensemble is in summer, probably caused by non-frontal thermal lows. Furthermore, summer is mostly dominated by short-lived cyclones. The main cyclogenesis regions are the Gulf of Genoa and the Cyprus region, with some minor centers at the Adriatic Sea, the northern part of the Black Sea, and the Iberian Peninsula. The cyclone frequency trend is slightly increasing in most parts of the region, especially over the Adriatic Sea and near Cyprus. Hungary is affected annually by approximately 30 cyclones from the Mediterranean area, most frequently in spring.

Key-words: cyclone identification, cyclone tracking, cyclone climatology, Mediterranean region, reanalysis, MSLP, geopotential height, relative vorticity

1. Introduction

Mid-latitude cyclones play a major role in the general circulation of the atmosphere, they largely contribute to the energy transfer between the equatorial and the polar regions. The potential energy derived from the temperature differences of air masses along the frontal surface is transformed by cyclones into kinetic energy. Cyclones are basically large vortices, in which warm and moist air mixes with cold and dry air. Through this process, energy is transformed and released.

In the Mediterranean region, the presence of large warm sea surface almost completely surrounded by land (the Mediterranean sea is connected to the ocean only through narrow straits) and the orography both induce the evolution of cyclones. The cyclones occurring in this region transfer moist and warm air over the continental regions, then, as mixing with colder air, the embedded moisture condensates, often resulting in intensive precipitation. *Jansa et al*. (2001) showed that the majority of heavy rain events in the Mediterranean occurred in the vicinity of a cyclone center. Thus, these cyclones determine substantially the local weather and climate.

The cyclones associated with intensive precipitation can cause floods, or other severe weather events, like on March 15th, 2013 when a snowstorm hit Hungary. The snow even caused power-cut in some regions of the country. In large areas of Hungary snowdrift occurred, which resulted in chaotic traffic conditions, especially due to the coincidence of the storm with a national holiday. Also in 2013, severe flood occurred in Central Europe, which was mainly caused by the precipitation of three consecutive cyclones triggered by a cut-off at the upper level of the atmosphere (*Grams et al*., 2014). The relationship between Mediterranean cyclones and Central European floods is often mentioned, i.e., the Vb cyclone track from the *van Bebber* (1891) categories is usually associated with flood events (*Hofstätter et al*., 2012), for example the Danube flood in Central Europe in 2002 (*Ulbrich et al.,* 2003).

The aim of this study is (i) to analyze objectively the cyclones in the Mediterranean region with particular focus on the Genoa lows, (ii) to investigate the performance of the multivariable cyclone identification method, and (iii) to overview the climatology of those cyclones coming from the Mediterranean region, which directly affect Hungary.

The exact identification of a mid-latitude cyclone is difficult since there are no generally accepted criteria. Cyclone identification and tracking can be done by manually analyzing meteorological fields, however, for comprehensive analyses, objective methods must be used. The most commonly used method for cyclone identification is to search local extremes in a selected variable field, and connect the successive centers according to some constraints.

One of the most commonly used variable for cyclone identification is the mean sea level pressure (MSLP) (*Serezze*, 1995; *Lionello et al.,* 2002; *Hanson et* *al.,* 2004; *Bartholy et al*., 2008), which refers to the pressure information at a specific surface reduced from the geographic surface by using a temperature profile. This reduction estimates the pressure at sea level sometimes below the actual surface level. Since temperature profiles affect the MSLP values and they can be unusual at high elevations, the fields can produce anomalous patterns in the area of mountains. In addition to MSLP, some detecting algorithms calculate the gradient of MSLP as well, to find a cyclone center (*Picornell et al*., 2001; *Jansa et al.,* 2001). Others investigate the Laplacian of MSLP (*Murray* and *Simmonds,* 1991), which can be interpreted as the quasi-geostrophic relative vorticity (*Pinto et al.,* 2005). Besides quasi-geostrophic relative vorticity, relative vorticity at 850 hPa can also be used to identify cyclones (*Hodges et al.*, 2011*; Catto et al.,* 2010; *Woollings et al.,* 2010). 850 hPa isobaric level can be considered as the lowermost level of the free atmosphere. Relative vorticity has an advantage over MSLP, namely, it is more independent from the direct effects of topography. *Hoskins* and *Hodges* (2002) compared several cyclone climatology results using different fields, and they showed that relative vorticity is especially good when describing smaller-scale systems, which are typical in the Mediterranean region. On the other hand, the disadvantage of using relative vorticity is that at high resolution it becomes a very noisy field (*Hodges et al.,* 2011). Hence, a truncation of the field is necessary if relative vorticity field is the key element of the identification algorithm. Besides MSLP and relative vorticity, geopotential height of the 1000 hPa is also used to identify cyclones (*Trigo et al.,* 1999, 2000; *Alpert et al*., 1990).

Most of the studies considered only one specific variable to identify cyclones, sometimes including its derivatives, too. An exception is found in *König et al*. (1993), who used both the 850 hPa relative vorticity and 1000 hPa geopotential height, however, their algorithm considered these fields separately and later combined the information from the two fields along the lifecycle of a specific cyclone.

All Lagrangian cyclone identification methods are based on a search for local extremes in a selected gridded field. The most common approach is to investigate the neighboring points of a grid point. In many cases, only the 8 nearest neighboring points are analyzed (*Alpert et al.,* 1990; *Trigo et al*., 1999; *Hanson et al.,* 2004; *Maheras et al*., 2001) whether the values are larger or smaller than in the central point. Sometimes the evaluated area covers a larger region, i.e., 5×5 grid points or even more (*Bartholy et al*., 2008). Obviously, the investigated region size depends on the grid's horizontal resolution. For a 2.5° horizontal resolution grid, the investigation of the 8 neighboring points is adequate for cyclone center identification. In case of higher resolution grid, the investigated area should cover the same sized region, which evidently includes more grid points. Another way to find local minima in a gridded field is used by *Lionello et al.* (2002). They identified at each time step the sets of the steepest decreasing paths, which led to the same MSLP minimum by comparing the neighboring point values. *Picornell et al.* (2001) and *Jansa et al.* (2001) used MSLP for their studies, where the search of MSLP minimum was extended with the analysis of pressure gradients around the already found minimum points along eight major directions (E, NE, N, NW, W, SW, S, SE). If the gradient exceeds a threshold along at least six directions then the system is considered to an open cyclone, whereas if the gradients are sufficiently large along all the eight directions then the system is considered to be a closed cyclone. Open and closed systems have been distinguished at other studies, too (e.g., *Sinclair*, 1994; *Murray* and *Simmonds*, 1991; *Picornell et al.*, 2001). *Sinclair* (1994) analyzed the geostrophic relative vorticity (calculated from 1000 hPa geopotential height) and used MSLP to decide whether a system is closed or not. He considered a system to be closed in the Southern Hemisphere if its vorticity minimum was closer than 5° latitude to a pressure minimum.

To get a more comprehensive picture about cyclones, the identified centers are usually tracked by a criterion to follow the center along the lifecycle of the cyclone. In some studies the tracking is not included (e.g., *Jansa et al.*, 2001; *Finnis et al.*, 2007). The most common tracking technique is the nearest neighbor concept, where the continuation of one specific cyclone is that center in the following time step, which is located the nearest to the center of the preceeding step. The search for the nearest neighbor is sometimes specified in an area often asymmetric to the center, taking into account the typical eastward movement of the mid-latitude cyclones. For example, when a rectangular area around the center is evaluated, its west-east axis is longer than the north-south axis (*König et al.*, 1993). *Trigo et al.* (1999) used a method, which searches for the next cyclone center within an area determined by the maximum cyclone velocity (33 km/h westward and 90 km/h in any other direction). Another tracking approach (i.e., *Murray* and *Simmonds*,1991; *Sinclair,* 1994; *Pinto et al.*, 2005; *Wernli* and *Schwierz*, 2006) pre-estimates the new position of a cyclone, evaluates all the cyclone centers being close to this first guess location, and selects the most likely candidate. This technique is a good solution when the available time steps are not too frequent, so the cyclones' separation and displacement should be considered together. Tracking method of *Muskulus* and *Jacob* (2005) uses the Kalman filter approach, in which the matching is carried out by minimizing a weighted prediction error function. This technique has several advantages: (i) besides one previous time step, it can consider the whole lifetime of the cyclone, and (ii) estimating the error, which predicts the maximum distance for the next match.

Depending on the identification technique and the aim of a particular study, additional filtering of the identified cyclones is possible. The most common filtering is to use thresholds for the cyclones' lifetime and/or for the MSLP of their centers. For instance, the lifetime of accepted cyclones should last longer than 12 hours (*Trigo et al.*, 1999), and the pressure of the cyclone center should be lower than 1000 hPa (*Gulev et al.*, 2001; *Muskulus* and *Jacob*, 2005).

Bartholy et al. (2008) considered different lifetime thresholds for Atlantic-European and Mediterranean cyclones (3 days and 1 day, respectively).

For some special applications, the extension of the cyclone must be calculated, e.g., *Hanson et al.* (2004) and *Trigo et al.* (1999) applied the definition from *Nielsen* and *Dole* (1992), according to which the cyclone radius is the distance between the center and the outermost closed isobar. *Muskulus* and *Jacob* (2005) used a watershed segmentation method for cyclone identification, and also for determining the area of the cyclones. *Piocornell et al.* (2001) defined the cyclone area as the positive geostrophic vorticity area around the center. The zero vorticity line is determined along the four main directions (N, E, S, W), and these points form an ellipse, which is the final cyclone area.

Due to the lack of exact identification of cyclone tracks, several cyclone tracking methods are available, and they can be used for cross-validation. The manual analyses are highly influenced by the subjective choices made by the analyst. The Intercomparison of Mid Latitude Storm Diagnostics (IMILAST) project (*Neu et al.*, 2013) made an effort to investigate the method-related uncertainties of cyclone identifications, and concluded that the results can be sensitive to several aspects of the applied method. They found important differences in the interannual variability and geographical distribution of cyclones in the Mediterranean. That is why we use a multivariable cyclone identification ensemble in this study for this region. In our identifying system, the same algorithm forms several individual methods with different variables used to identify cyclone centers. This way the uncertainties arising from the variable choice are assessed and taken into account in the final conclusions.

The paper briefly presents the used two reanalyses in Section 2. Then, in Section 3, the methodology and composition of the multivariable ensemble are described. In Section 4, the results of the cyclone time series based on the two reanalyses are compared, then, the ERA Interim results are analyzed in detail. The features of the ensemble are investigated, then the annual variability and trends of cyclones are analyzed. The section is closing with a short analysis of the cyclones passing over Hungary. The study ends with the discussions (Section 5) followed by the conclusions (Section 6).

2. Data

The present cyclone analysis is based on reanalysis data forming a spatially and temporally appropriate resolution, regular database, which is needed for the objective. Here, two available reanalyses are selected, the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA Interim) (*Dee et al.*, 2011) and the reanalysis data from the National Centers for Environmental Prediction (NCEP) and the National Energy Research Supercomputing Center (NERSC) of the Department of Energy (DOE) (*Kanamitsu et al.*, 2002) (NCEP-

DOE R2), which is the updated NCEP/NCAR (National Center for Atmospheric Research) reanalysis. Both datasets are available from 1979 up to the recent past, and we use the data for the 30-year period between 1981 and 2010. Both of the reanalyses are widely used for cyclone climatology studies. Preceding reanalyses of ECMWF (i.e., ERA-15, ERA-40) were earlier used by *Alpert et al*. (1990), *Sinclair* (1994), *Trigo et al*. (1999), *Hoskins* and *Hodges* (2002), *Hanson et al*. (2004), *Wernli* and *Schwierz* (2006), *Bartholy et al.* (2008), *Catto et al.* (2010). Some of these studies, e.g., *Trigo et al*. (1999), *Alpert et al*. (1990) and *Bartholy et al.* (2008) investigated the Mediterranean region. NCEP reanalyses were also used for cyclone analysis in general (e.g., *Hanson et al*., 2004; *Pinto et al.*, 2005; *Hodges et al.*, 2011), and for the Mediterranean region, too (e.g., *Maheras et al.,* 2001).

ERA Interim is constructed with a use of a spectral model, whose horizontal resolution is expressed by its truncation number T255 indicating the number of waves used to represent the data. This horizontal resolution corresponds with a lat-lon 0.75°×0.75° regular grid, and the data can be downloaded in this interpolated form.

The NCEP-DOE R2 dataset is available on a 2.5°×2.5° horizontal resolution lat-lon grid, which we interpolated to a 0.75°×0.75° grid to achieve the same grid resolution as ERA Interim. The interpolation was made by a bicubic spline method. *Pinto et al.* (2005) showed that the use of spline interpolation improves the localization of cyclones. The improvement is mainly due to the better spatial representation of cyclone centers, however, this method does not add any extra information to the original data. The bicubic spline interpolation produces a smooth field from the original data, since it utilizes both the first and the second derivatives of the original data. The interpolation formula is smooth in the first derivative and continuous in the second derivative.

Both ERA Interim and NCEP-DOE R2 are used with a 6-hour temporal resolution.

The area investigated in this study is the Mediterranean region from 29.25°N to 55.5°N and from 11.25°W to 42.75°E, which is approximately the Med-CORDEX region (*Ruti et al.,* 2015), and thus, it eases future comparison of our reanalysis results to the climate simulations interpolated on the Med-CORDEX domain.

Pressure and geopotential fields are directly available from both database. The relative vorticity field is available only in case of the ERA Interim reanalysis. In order to use similar methodology and ensure consistency in the analysis, we calculate vorticity from the wind fields both from ERA Interim and NCEP-DOE R2.

3. Method

A multivariable ensemble approach is used in this study to assess uncertainties due to the selection of specific cyclone identification method. Several objective methods exist for identifying mid-latitude cyclones using more or less similar (however, not exactly identical) criteria. The advantages of objective methods are shown in *Jansa et al.* (2001), where more cyclones were found with using an objective analysis of high resolution model data than with the human-based subjective analysis. The objective analysis has special advantages in the areas with less measurements and meteorological experiences. Furthermore, the assessment of differences in objective methods is studied in the framework of the IMILAST project (*Neu et al.*, 2013), which is an explicit community effort to intercompare extratropical cyclone detection and tracking algorithms.

The definition of a mid-latitude cyclone is not entirely exact, it is commonly characterized as a low pressure system, which rotates in positive direction (in the Northern Hemisphere). Consequently, the identification of an extratropical cyclone is not standardized either. The different tracking methods capture different aspects of these mid-latitude low pressure systems.

For this presented analysis, we developed our own cyclone identification and tracking method based on previous studies and experiences found in the literature. The uni- and bivariate versions of our method search for extremes in gridded fields. The univariate version uses one specific variable field, which is selected from different variables related to pressure or geopotential height. The bivariate version consists of a combination of two fields, where the second field is always the relative vorticity at 850 hPa isobaric level, whose maxima are located. The relative vorticity is selected on the basis of *Hoskins* and *Hodges* (2002) who showed its importance in case of the Mediterranean small scale systems. The minima of the basis variable field are searched successively in regions of 15×15 grid points corresponding to 11.25°×11.25° area (when using 0.75° horizontal resolution data), which is approximately the typical size of a Mediterranean cyclone. In the relative vorticity field, the maxima are located in regions of 11×11 grid points, which is more appropriate due to the smaller scale structures of this field.

For the univariate version, three variables are selected to find their minima: in addition to the most commonly used MSLP, 1000 hPa and 850 hPa geopotential heights are also considered. The 1000 hPa geopotential height has already been successfully used in the Mediterranean region (e.g., *Trigo et al.,* 1999). The 850 hPa geopotential height is selected, since its tracking statistical characteristics are similar to MSLP's (*Hoskins* and *Hodges*, 2002), and moreover, it represents the same level as the relative vorticity, which might help in the identification of extremes.

The cyclone tracking algorithm is based on a nearest neighbor search procedure, which uses specific search regions to find the sequential steps of a trajectory. Around each cyclone center a rectangular search region is defined (*König et al.*, 1993), where the continuation of the trajectory is searched in the next time step. The rectangular area extends more in the west-east direction than in the north-south taking into account the mainly eastward propagation of cyclones. If two possible next locations are found within the search region, the nearest one will be selected. The analysis considers only the cyclone tracks exceeding 1 day lifetime threshold similarly to other studies (*Neu et al.*, 2013; *Hanson et al.*, 2004; *Wernli* and *Schwierz*, 2006).

The use of three basic variables, and the uni- and bivariate versions of the method (*Table 1.*) results in six different cyclone track time series, from which an ensemble is formed and analyzed together instead of the difficult decision to identify the one and only ideal method.

Table 1. The set up of the multivariable ensemble for cyclone identification

Univariate	**Bivariate**
U1 Mean sea level pressure (MSLP)	B1 Mean sea level pressure (MSLP) + Relative vorticity at 850 hPa level (RV850)
U2 Geopotential height of the 1000 hPa level (Z1000)	B2 Geopotential height of the 1000 hPa level (Z1000) + Relative vorticity at 850 hPa level (RV850)
U3 Geopotential height of the 850 hPa level (Z850)	B3 Geopotential height of the 850 hPa level (Z850) + Relative vorticity at 850 hPa level (RV850)

For further analysis, the cyclone area for each identified cyclone center is determined. Cyclone domain is defined in a 11.25°×11.25° lat-lon area centered on the cyclone center and located where the relative vorticity is positive. This definition is sufficient for detecting the effect of a passing cyclone, however, it is insufficient for detailed analysis of weather fronts or other smaller scale phenomena.

The cyclones are investigated seasonally, for this purpose their genesis date determines the seasonal membership. We consider December, January, and February as winter, from March until May as spring, June, July, and August as summer, and finally from September till November as autumn.

For the analysis, cyclone track density maps are calculated. Cyclone track density values denote the number of cyclone tracks crossings per 0.75°×0.75° cells in each season during the investigated entire 30 years. Since unequal-area grid is used for the counting of cyclones per grid cells, the effect of changing area per latitude is calculated. However, the difference is negligible considering the scales used in this study. Furthermore, cyclone genesis density maps are calculated similarly to the track densities, except that only the starting points of the trajectories are considered.

In the 30-year time series of track density maps trends are detected in each grid cell. To find the trend coefficient, linear regression is used where the explanatory variable is the year and the dependent variable is the number of cyclones per year. For the trend analysis, the second coefficient of the linear regression is used, which is the slope of the fitted regression line. In each grid point and in case of all ensemble members, the trend coefficients are evaluated whether or not they are statistically significant, and only the significant values are used.

4. Results

4.1. Reanalysis comparison

The above described methodology is applied to construct six cyclone track time series using the ERA Interim and six time series using the NCEP-DOE R2 reanalysis. In our study, first, the differences of the results using the two datasets are evaluated. Overall, more cyclones are found using the ERA Interim reanalysis (around 75 cyclones annually) than the NCEP-DOE R2 (around 64 cyclones annually), which has lower horizontal resolution. Nevertheless, the courses of the time series of the annual numbers of identified cyclones are quite similar (*Fig. 1*), the correlation coefficient is 0.86, which is statistically significant at the 0.05 level. The spreads of both ensembles are 20 in average. In the first half of the time period, the peaks of the lines (i.e., the large cyclone numbers) are in the same years (1984, 1988, 1991, and 1996). In the second half of the period, the peaks are somewhat shifted relative to each other. The results of using the two reanalyses agree on the general growing trend, which is statistically not significant.

The empirical distributions of the cyclone lifetimes are shown in *Fig. 2.* Evidently, less cyclones are found with longer trajectory, this is valid for the identified cyclones using both reanalyses. The largest difference (21%) between the frequencies of cyclones is in case of the shortest living cyclones. These results suggest that more weak and small cyclones can be identified using the ERA Interim reanalysis that typically occur in the Mediterranean region. This can be explained partially by the higher resolution of ERA Interim reanalysis, which affects the representation of orography as well as other small scale physical processes, and these affect the development and appearance of cyclones in the reanalysis.

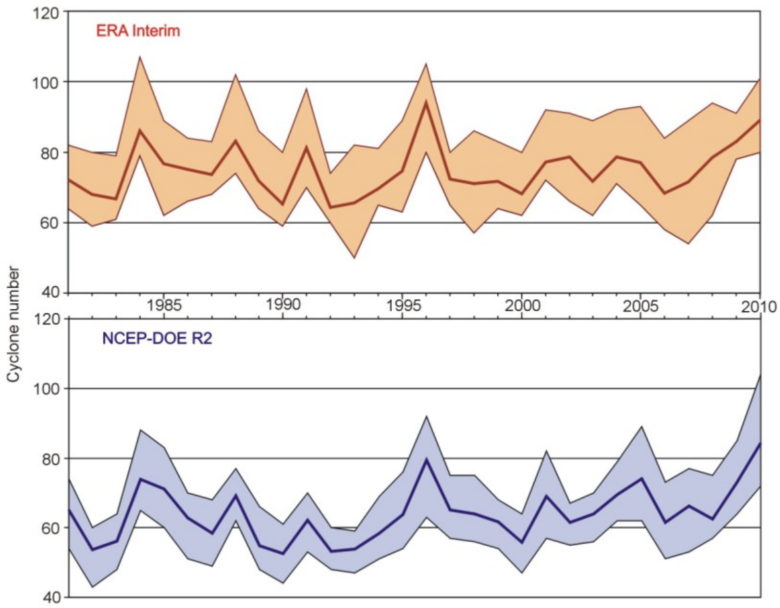

Fig. 1. Time series of the multivariate cyclone identification ensemble from the two reanalyses, ERA Interim (top) and NCEP DOE R2 (bottom). The solid line presents the mean of the ensemble (the average cyclone numbers in each year), and the light colored band presents the spread of the ensemble (the maximum and minimum cyclone numbers in each year).

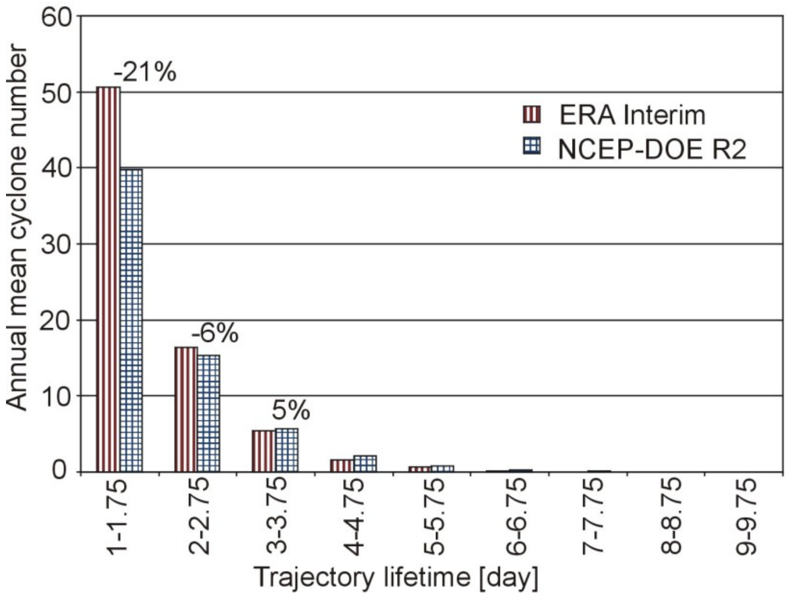

Fig. 2. Histogram of the cyclone lifetime using the two reanalyses. The values above the columns indicate the differences in percentages compared to the results using ERA Interim data.

The results of the comparison suggest, that the higher resolution ECMWF reanalysis is more appropriate for identifying cyclones in the Mediterranean region. Therefore, in the further analyses of cyclones, we use only the ERA Interim based cyclone identification.

4.2. Investigation of the ensemble

The evaluation of the ensemble members are shown through the members' cyclone track density maps and a cyclone lifetime histogram. The comparison presents the features of the different variables, which contributes to the quality of the ensemble mean.

30 years seasonal cyclone track densities are mapped for all the four seasons and all the six members of the multivariable ensemble. Here only the maps for summer (when the ensemble spread is the largest) are shown in *Fig. 3*. The large spread between the ensemble members is most likely caused by the occurrences of thermal lows, which are non-frontal low pressure areas and can not be detected at all levels, neither in the vorticity field. The mean of the ensemble, nevertheless, compensates the effect of using different variables (shown later in *Fig. 7c*). The overall patterns are very similar, the largest cyclone density values occur in the Gulf of Genoa and the southwestern coasts of Turkey, additionally, intense cyclone activity is present over the Iberian Peninsula and the northern part of the Black Sea. The differences between the maps are mainly in the cyclone density values, and not in the spatial patterns, which are basically very similar. The methods using MSLP or geopotential height at 1000 hPa level (i.e., information close to the surface) result in more cyclones, and thus, larger cyclone track density values, which might be the influence of the orography. Furthermore, the limiting effect of the relative vorticity as a second variable is noticeable. The standard deviation of the ensemble mean cyclone track density field in summer is around 2.45 cyclones per 30 years on average over the domain, with the maximum of 87.1 occurring near Cyprus. This means that the largest difference between the two extremes of the entire ensemble is approximately 3 cyclones per grid cell annually, which occurs during the summer months.

After the cyclone track density analysis, the multivariable ensemble is also evaluated in terms of cyclone lifetime. Identified tracks lasting at least 1 day are considered in this analysis. The histogram (*Fig. 4*) clearly shows decreasing numbers for longer-lived cyclones in case of all the six members of the ensemble. In general, the identified numbers of cyclones with 1, 2, 3, … days lifetime are similar in all members of the ensemble. The only exception is member U2, where considerably more cyclones are identified with less than 2 days lifetime. Furthermore, using relative vorticity at 850 hPa geopotential level as a second variable, B1, B2, B3 identify somewhat less cyclones in each category than the corresponding U1, U2, U3. On higher levels the effects of orography are smaller and the meteorological fields are smoother, therefore, relatively more longer-lived cyclones can be identified in case of U3 and B3 than using the other variables closer to the surface. The difference between U3 and B3 are so small that it cannot be detected on the scale of the histogram, but the limiting effect of using the relative vorticity together with the basic variable can be detected in this case, too. The small difference might be due to the fact that in both cases the used variables are from the 850 hPa level, which is less sensitive to the orography and does not show the thermal lows. Furthermore, in case of B3, the tilt of the cyclone axis does not complicate the identification of the cyclone centers, unlike in case of B1 and B2, where two different levels are considered and two slightly biased extremes have to be connected to find a cyclone center.

For the further analysis, the mean of the ensemble is used, which incorporates the different characteristics of the ensemble members. Therefore, it gives a more reliable picture about the features of the identified cyclones.

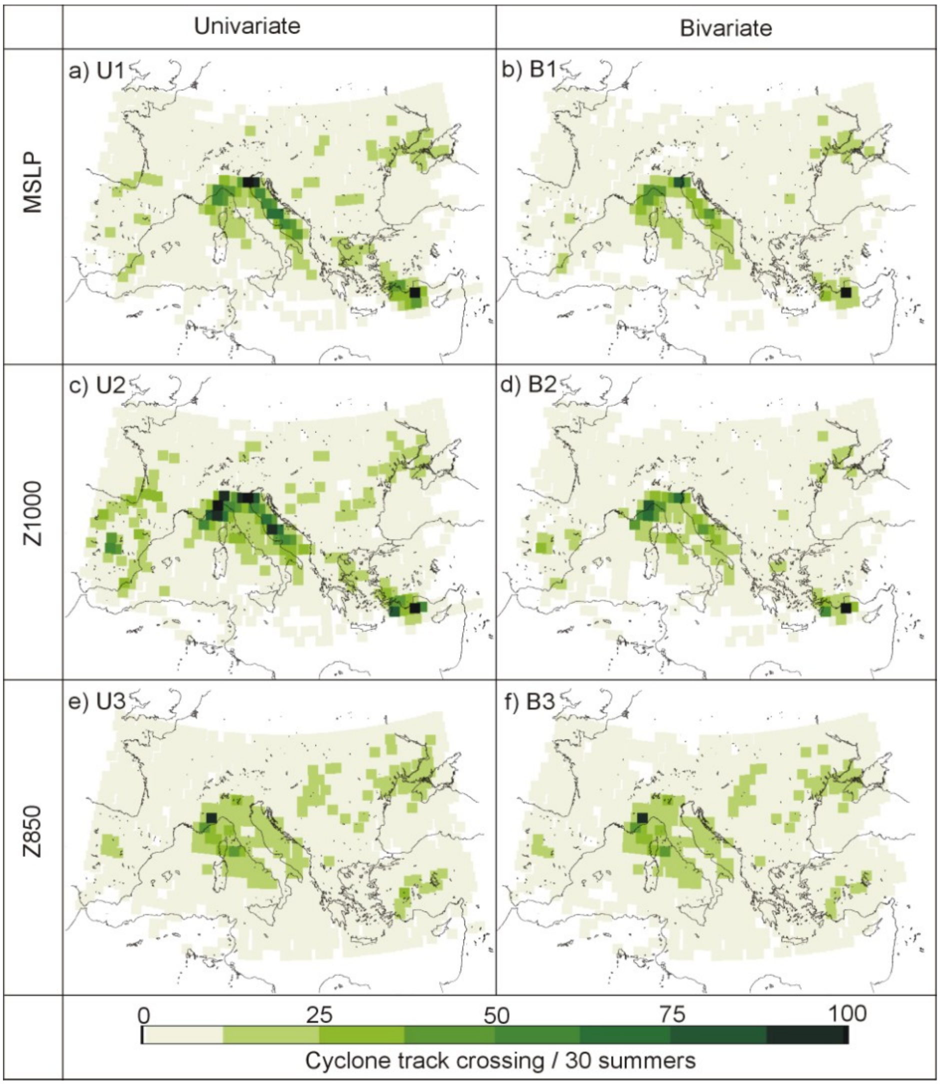

Fig. 3. Cyclone track density maps for summer (1981–2010) from the six members of the multivariable ensemble.

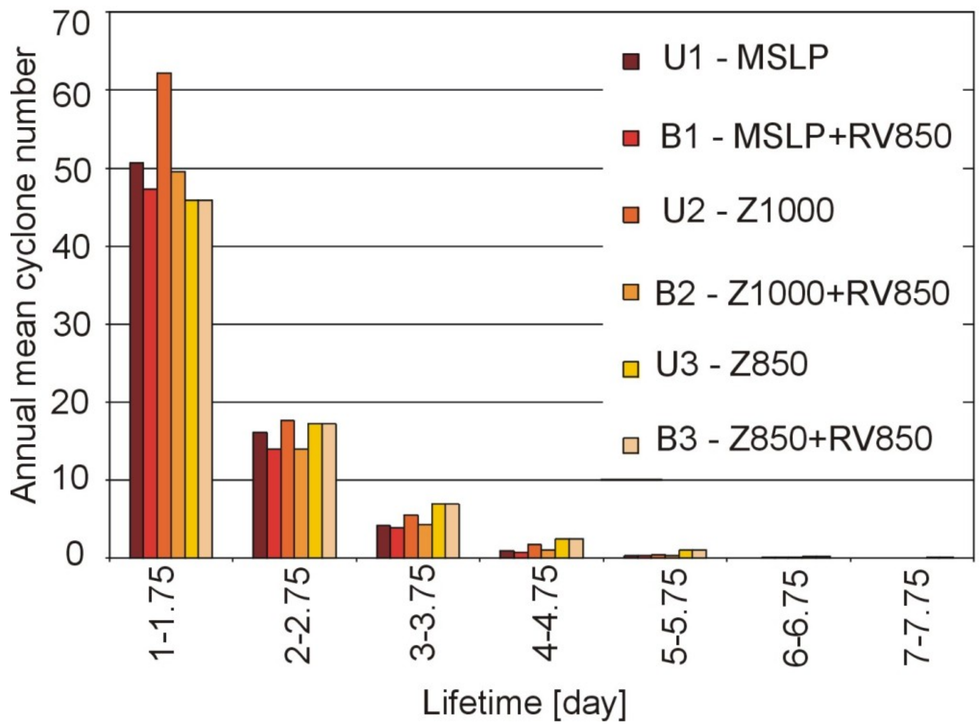

Fig. 4. Cyclone lifetime histogram for all members of the multivariable ensemble.

4.3. Annual cyclone distribution

The annual distribution of cyclones for the whole area is presented in *Fig. 5*. Geographical location and extension of the investigated area highly influence the cyclone frequency and its seasonal distribution. In our study we mainly focused on cyclogenesis areas of the Genoa region, the Aegean Sea, and Cyprus. Other low pressure areas (e.g., over the Iberian Peninsula, the Black Sea) might be also important, however, they are not completely covered here, since their locations are at the border of our domain. Cyclogenesis centers outside Europe (e.g., Saharan lows, Middle East cyclones) are not considered, either. The frequency analysis within the year suggests that the least number of cyclones is in summer. The only exception can be found when the univariate identification is applied using the 1000 hPa geopotential U2 field, in this case the minimum occurred in autumn. The largest and the smallest differences between frequency results of the various identifications occur in summer and winter, respectively. The cyclone identification methods result the maximum cyclone frequency in either spring or winter. Nevertheless, the maximum of the ensemble mean is in spring. Our findings are in a good agreement with those of *Hofstatter* and *Chimani* (2012), who analyzed *van Bebber*'s (1891) track V types between 1961 and 2002, and found their maximum frequency in April and minimum in July.

Cyclogenesis points are counted in every grid cell during the 30 years for every season and for every ensemble member. The results of the members are averaged seasonally, the ensemble means per season are presented in *Fig. 6*. The most active cyclogenesis area is certainly the Gulf of Genoa, which is basically permanent throughout the year. The absolute maximum of genesis event per 0.75°×0.75° grid cell is in the summer near Cyprus (25 cyclogenesis in one particular grid cell per 30 years). Nevertheless, the spatial extensions of genesis centers are small in summer compared to the rest of the year, so the maximum genesis per grid cell is reached by having many genesis episodes in the same relatively small area, and not by having many cyclogenesis overall in the entire domain. The overall seasonal numbers of genesis in the whole area are higher in any other season than summer. The maximum number of cyclogenesis in the whole investigated area occurs in spring. The genesis area near Cyprus is also present throughout the year, but extends less than in the Gulf of Genoa. In both areas, the cyclones are mainly formed over the lee side of the mountains. In winter the Adriatic Sea appears as an additional genesis center, whereas in spring some genesis occur over the Aegean Sea, too. Finally, in summer the Iberian center becomes more prominent. Our findings strengthen the results of *Trigo et al.* (1999).

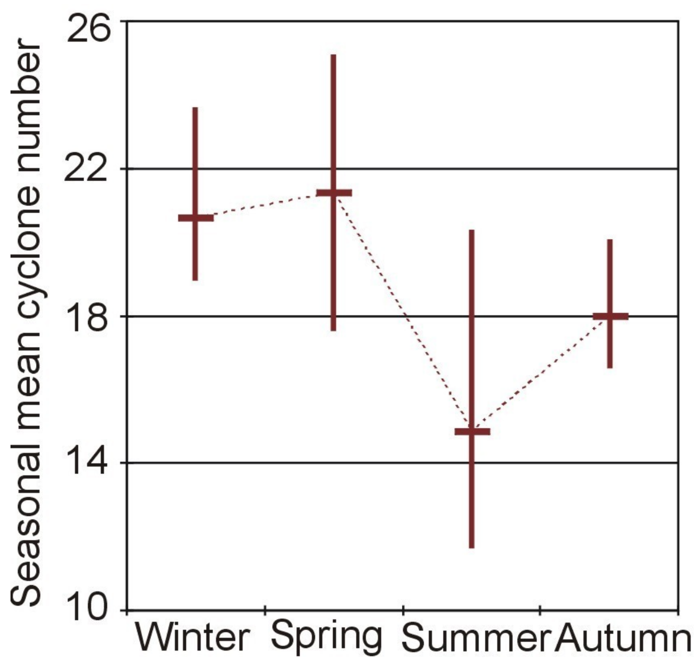

Fig. 5. Mean seasonal frequency of identified cyclone tracks using the 6 time series (horizontal line: ensemble mean, vertical line: ensemble spread).

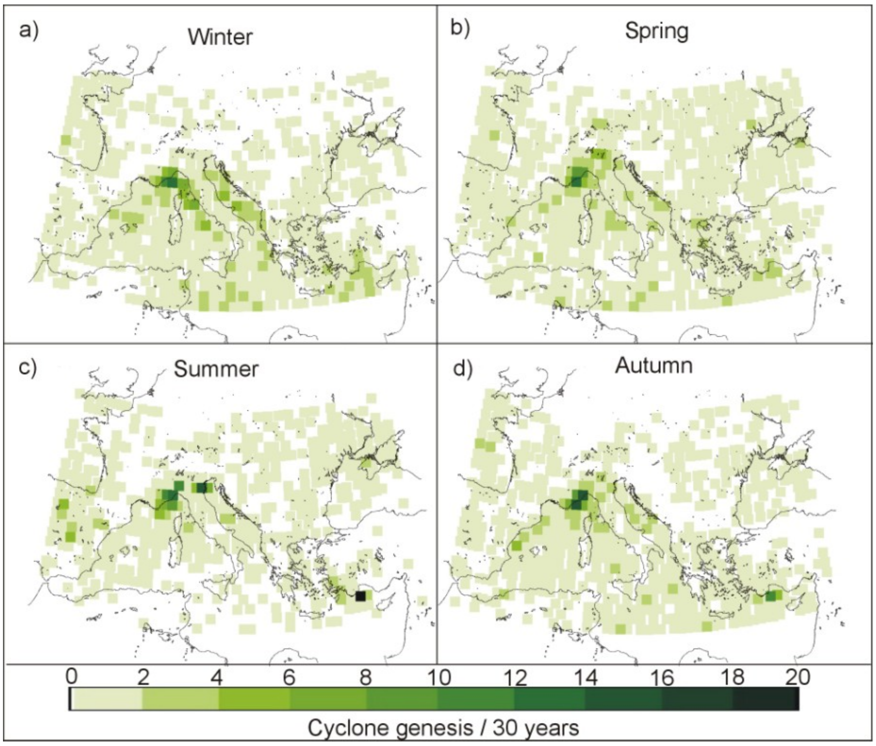

Fig. 6. Seasonal cyclogenesis center numbers from the mean of the multivariable ensemble (1981–2010).

The seasonal track density maps (*Fig. 7*) indicate seasonally the number of cyclone centers crossing each grid cell during the entire 30 years, averaged for the 6 ensemble members. (Note that the whole cyclone areas are not fully represented here, since we focus on the cyclone centers and their close vicinity only.) In general, the most frequent cyclone tracks are the Vd tracks from van Bebber's cyclone track classification (*van Bebber,* 1891), which typically turns south after Gulf of Genoa along the Adriatic Sea. The patterns in the equinox seasons are similar, the main differences listed as follows: (i) in spring the Black Sea cyclone pathway region is more extended and shows its largest activity, (ii) in autumn the region near Cyprus is more active with larger number of cyclones. This can be explained by the temporal extension of the high summer cyclone activity in the Cyprus area. The high track density regions concentrate around the genesis regions, i.e., the Gulf of Genoa, Cyprus, and the northern part of the Black Sea. The spatial extension of the cyclone track density is the largest in winter, whereas the maximum cyclone crossing per grid cell occurs in summer in an isolated point. This implies that the overall cyclone activity in the investigated area is the most intense in winter. The summer cyclones isolated maximum is due to that they tend to follow the same tracks, live shorter, and thus, they affect only the vicinities of their genesis region. This is highlighted in *Fig. 8,* which indicates that the ratio of short trajectories is the largest in summer. In *Fig. 5*, the annual number of spring cyclones is the highest of all season, but this cannot be seen in *Fig. 7*, where winter cyclones are spatially more extent. This is explained by the fact that in spring the absolute value of short cyclones is maximal (*Fig. 9*). So the difference between the numbers of spring and winter cyclones is compensated by the length of the cyclone lifetime.

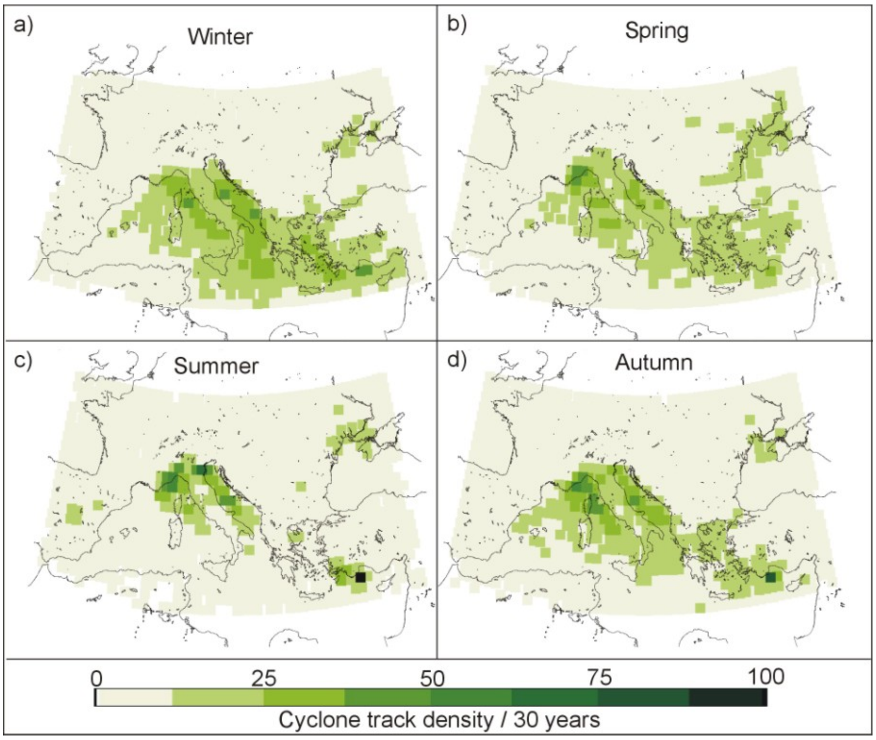

Fig. 7. Seasonal cyclone track density maps from the mean of the multivariable ensemble (1981–2010).

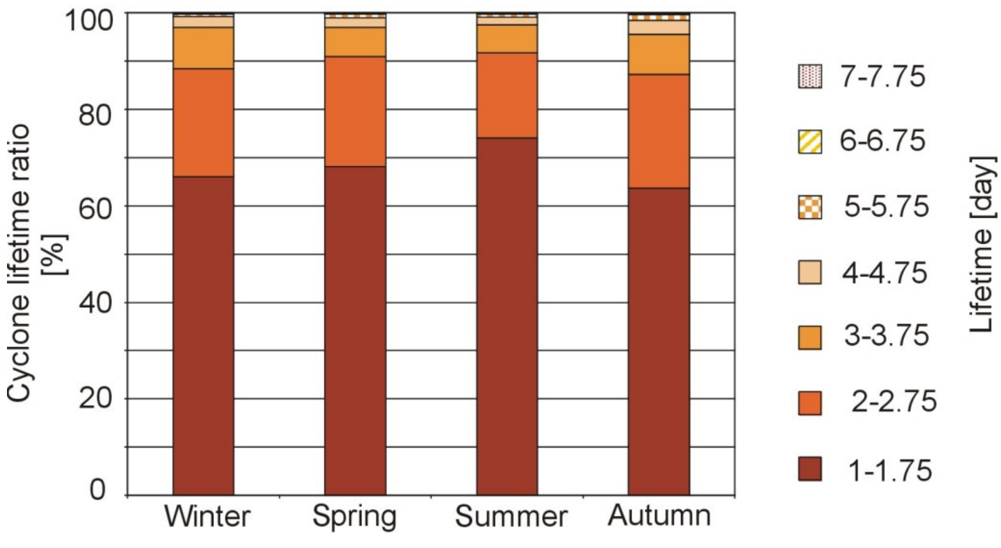

Fig. 8. Seasonal distribution of average cyclone lifetime frequency from the multivariable ensemble.

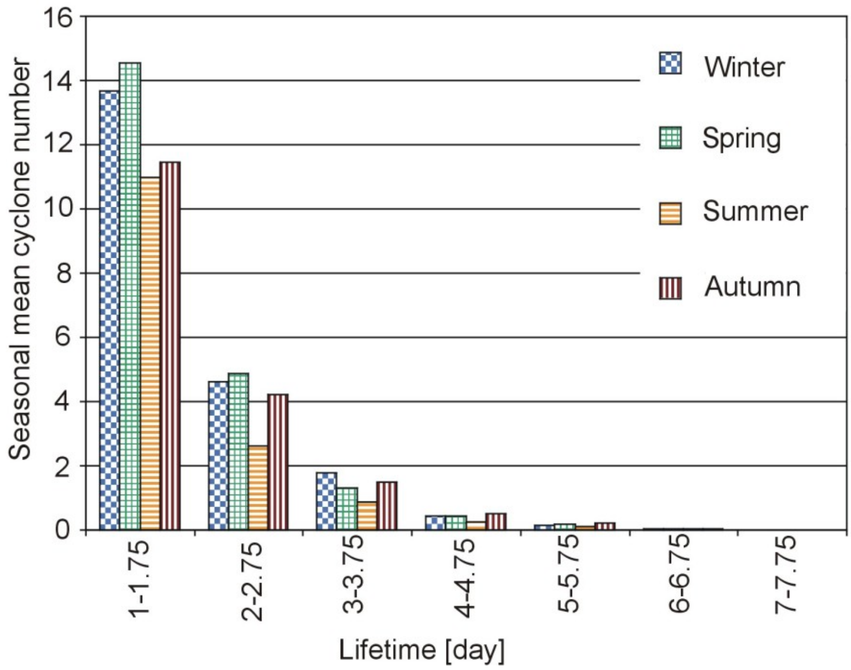

Fig. 9. Histogram of ensemble mean cyclone lifetimes for all seasons.

4.4. Trends

In the investigated 30 years, the changes in annual cyclone numbers are analyzed by calculating the linear trend coefficient of all ensemble members in each grid point. Then, the average value of the individual ensemble members is evaluated. *Fig. 10* shows the significantly positive (top) and negative (bottom) trend coefficients as well as the standard deviation (middle) of the ensemble coefficients. The majority of the significant trend coefficients are positive, located mainly along the Adriatic Sea and southwestern Turkey. Moreover, increasing cyclone numbers are present around the Balearic Island and Sardinia, the Pyrenees, Transylvania, Bulgaria, the Bosporus, and along the coasts of Tunisia. Decreasing tendencies are smaller and more dispersed, they are found at some parts of southern Italy, the region eastward from Malta, the middle part of France, and the northern part of the Black Sea along the Crimean Peninsula. The standard deviation of the ensemble members' trend coefficients shows that the difference between the ensemble members is larger where the detected change is larger.

4.5. Cyclones passing over Hungary

In our study, besides the full domain-based analysis, we also aim to evaluate the comprehensive role of the Mediterranean cyclones on the climate of the Carpathian Basin. For this purpose, those cyclones are selected, whose domain passed over Hungary.

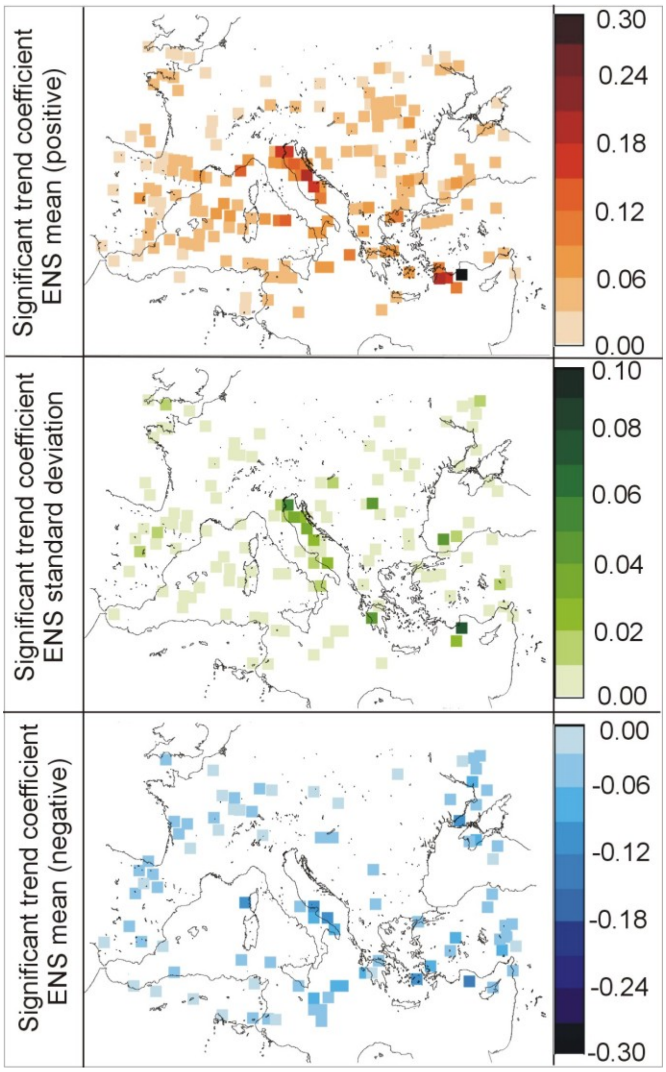

Fig. 10. Spatial distribution of significant trend coefficients (top and bottom: positive and negative coefficients of the ensemble mean, respectively, middle: standard deviation of the significant trend coefficients).

As a result of our analysis, we found that in an average year, roughly 30 cyclones influence the weather in Hungary. This does not include all cyclones affecting Hungary, but mostly the cyclones from the Genoa genesis area, since in our domain we focus on cyclones from the Mediterranean (*Fig. 7*). The time series (*Fig. 11*) correlate strongly with the time series of the whole area (upper part of *Fig. 1*), the correlation coefficient is 0.62, and it is statistically significant at the 0.05 level. The average spread of the ensemble is 11 cyclones/year, which is naturally less than the spread for the whole domain (23 cyclones/year). The local maxima of the cyclones passing over Hungary and the local maxima of all the identified cyclones are not always in the same years. The coincidence of the two maxima is more frequent towards the end of the period (e.g., in 1996, 2001, 2005, and 2010).

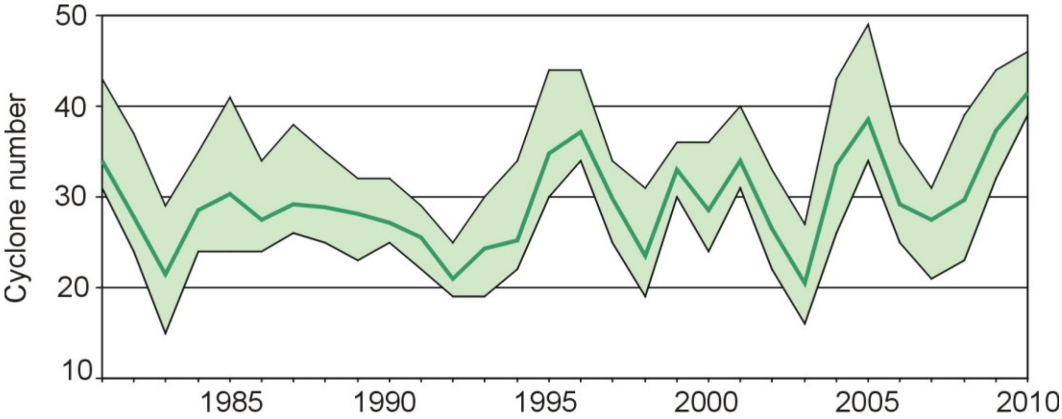

Fig. 11. Time series of the cyclones effecting Hungary from the multivariate cyclone identification ensemble. The solid line presents the mean of the ensembles (the average cyclone numbers in each year), and the light colored band presents the spread of the ensemble (the maximum and minimum cyclone numbers in each year).

The annual distributions of cyclone frequency over Hungary (*Fig. 12*) and the whole domain (*Fig. 5*) are somewhat different. Most of the cyclones occur in spring in both cases, however, the maximum is more robust for the Carpathian Basin, all members of the ensemble have their maximum occurrences in spring, and the relative difference between spring and the other seasons is larger than for the whole domain. Thus, the analysis suggests that the Mediterranean cyclones affect largely the spring weather of the Carpathian Basin. Furthermore, the largest spreads of the ensembles are in summer implying larger uncertainties in this season probably due to thermal lows.

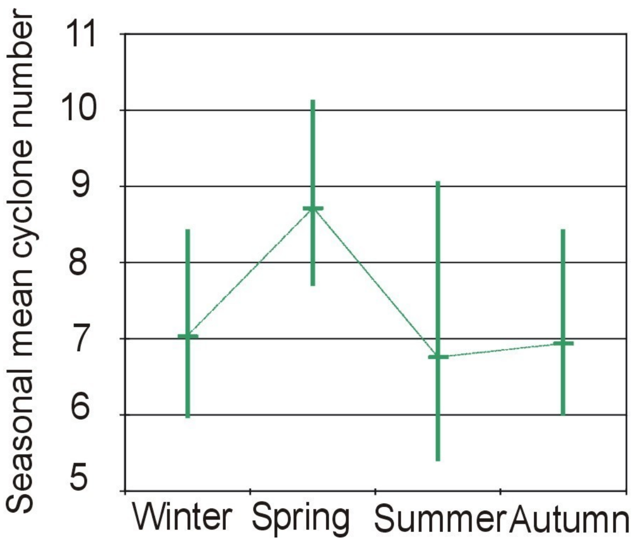

Fig. 12. Mean seasonal frequency of cyclone tracks passing Hungary from the 6 time series (horizontal line: ensemble mean, vertical line: ensemble spread).

5. Discussion

One of the main aims of the study is to develop an adequate cyclone identification method. The evaluation of the method starts by applying it on two different reanalyses, ERA Interim and NCEP-DOE R2, and comparing the results. This comparison provides useful information about the method itself, and also about the datasets. If the pattern or the general features of the results are similar then it can be concluded that the method is not sensitive to the small differences in the reanalyses. However, the differences of the cyclone numbers in the two reanalyses are probably due to general differences of the datasets. These are caused by the different systems used for the production, e.g., data assimilation, physical parameterizations, or the higher/lower resolution of the reanalyses. We found that the correlation is high between the results from the two reanalyses, and ERA Interim datasets include more cyclones. This clearly suggests that the method is adaptable for different datasets. The more cyclones in ERA Interim is probably due to the higher resolution, which better represents the orography, the physical processes, and also their effects. Thus, the primarily orographic cyclogenesis in the Mediterranean is identified more properly in ERA Interim.

Other studies also evaluated the differences between the cyclone climatologies using different reanalyses. For instance, *Hanson et al.* (2004) investigated North Atlantic cyclones between 1979 and 2001, identifying them through MSLP data from NCEP reanalysis (2.5°×2.5°) and from ECMWF ERA-15 reanalysis (1.125°×1.125°) (ERA-15 was extended using operational analyses for the end of the examined period). They concluded that the cyclone climatology from ECMWF data was more comprehensive at all scales. In addition, more very weak and more very strong cyclones were found using the ECMWF data than the NCEP data. *Trigo* (2006) compared storm-tracks using ERA-40 (T159 interpolated to a 1.125°×1.125° regular grid) and NCEP/NCAR (T62 interpolated to a 2.5°×2.5° regular grid) data in the December-March season between 1958 and 2000. It was shown that the main characteristics of genesis and lysis areas in the results of two reanalyses are similar, however, the numbers of storms differ appreciably. Similarly to *Hanson et al.* (2004), the higher resolution ECMWF reanalysis produced more cyclones than the NCEP/NCAR reanalysis. Furthermore, ERA-40 favored the detection of small (sometimes even subsynoptic) scale systems, which are present in the Mediterranean region (*Trigo et al.*, 1999). *Hodges et al.* (2011) compared four reanalyses, i.e., the ERA-Interim (T255), NASA-MERRA (2/3° longitude, 1/2° latitude), NCEP-CFSR (T382), and the JRA25 (T106), focusing on the winter cyclones in both hemispheres between 1989 and 2009. The number, spatial distribution, intensity distribution, track, and lifecycle of cyclones were all compared for the four reanalyses. The conclusions suggest that from a simple intercomparison it is not possible to decide which reanalysis represents the reality better, only the disagreement between the results can be seen. They found that the spatial differences are small and not significant between the reanalyses, however, there are some orographic regions (e.g., the Mediterranean storm track) where the differences are relatively large. These differences might be the result of the different representation of orography in the reanalyses. Overall, the cyclone numbers and spatial distribution in the new, higher resolution reanalyses are similar, and more realistic than using the lower resolution reanalysis (i.e., JRA25).

According to the previous studies and our own experiences, cyclone identification in the Mediterranean region is difficult due to the frequent occurrence of small and weak systems. The comparisons of reanalyses suggest that (i) the high resolution reanalyses are more appropriate to recognize these systems, and (ii) ECMWF reanalysis is successful in identifying them.

Through the development of the objective cyclone identification method, several variables were tested but no clear distinction could have been made. Different variables have different advantages, so their ensemble are kept and analyzed. MSLP and 1000 hPa geopotential height are both close to the surface, which can be considered as a clear advantage, since a surface-based system is the object of the identification. On the other hand, they are more influenced by the orography, which is a disadvantage. Cyclones are defined as low pressure systems, this is why MSLP is one of the basic variables, but it is a derived field which can cause errors. Cyclones are also rotating systems, this is why relative vorticity at the 850 hPa level is included as a second variable. The advantage of using a second variable, next to the low level values is that only realistic, vertically extent formations are identified. The disadvantage of using the 850 hPa relative vorticity is that it might not be present through the whole lifetime of the cyclone, or it cannot be found in the vicinity of the first level extreme because of the tilt of the cyclone. Thus, the usage of two variables together limits the identified centers. These effects are less obstructive if both variables are from the same level, this is why geopotential height at 850 hPa level is also included. The disadvantage of this configuration is that the shallow, early, or occluding systems are not always detectable. The analysis of the results from the different ensemble members shows the potentials of the multivariable method. In the near-surface variables (Z1000 and MSLP), higher cyclone track densities are present than in the higher level (Z850). It does not necessarily entail that from the near-surface variables more cyclones are identified, just that the cyclones tend to use the same path more frequently. This can be due to the orography, which influences the variable fields, and thus, the tracking too. On the other hand, on the 850 hPa level more numerous longer trajectories are detected, the tracking is more successful than in the lower levels. Besides these differences between the basic variables, in general the use of an additional variable, i.e., relative vorticity, decreases the cyclone number, but it affects less the longer trajectories. Thus, it serves mainly to omit the weak, short-lived cyclones.

The cyclones in the domain identified by the multivariable ensemble are dominantly the cyclones originated from the Gulf of Genoa, and also include some other genesis areas as southwestern Turkey, the Adriatic Sea and the Iberian Peninsula. The minimum cyclonic activity throughout the year is in summer, when the spread of the ensemble is the largest. The explanation for this probably is the appearance of thermal lows, which are not captured in all variables. They are not aimed to be captured anyway, since they are non-frontal pressure depressions. The most active period is the winter-spring half year. In spring there are more cyclones in our ensemble, but the track density maps show more spatially extent cyclone activity in winter. Although it seems to be a contradiction, winter cyclones have longer lifetimes so they contribute more to the track density maps than spring cyclones. Despite of the largest track density extension in winter, the isolated per grid maximum value is in summer. This means that the summer cyclones' paths more overlap, and produce extreme high track density in a cell than the winter cyclones'. The major cyclone pathway on the track density maps is van Bebber's Vd class, furthermore, Vb and Vc tracks are rare but sometimes occur.

Cyclones transport moisture, heat, and energy, that is why they have an important role in the local weather events of the area hit by their path. Both increase and decrease in their frequency can cause extreme events such as floods or droughts (e.g., *Grams et al.*, 2014). The investigation of trend coefficients in our analysis suggests that in the 30-year period, increasing linear trend is present in larger area than decreasing trend (almost twice as many grid cells). Also, the average of the positive trend coefficients is higher than the negative coefficients'. There are some more pronounced areas where the coefficients are higher, and in many neighboring grid cells the trends are statistically significant, e.g., over the Adriatic Sea. Nevertheless, there is no detectable sign of any north-south or west-east shift in the cyclone track densities.

The average radius of Mediterranean cyclones is between 300 km and 500 km (*Trigo et al.* 1999), their effects on local weather can certainly be observed in the whole area inside their domain not only focusing on their center regions. Therefore to select the cyclones affecting the weather of Hungary, the area where the domain of a cyclone swept through were calculated. The annual variability of these cyclones is a bit different from the general analysis. Namely, the most active season is clearly spring. The difference between spring and winter is almost as large as between spring and summer unlike in case of the entire domain. This implies that among the cyclones originated from the Gulf of Genoa, more cyclones follow northerly paths in spring than in winter.

6. Conclusions

Detailed cyclone analysis covering the time period between 1981 and 2010 was presented in this paper for the Mediterranean region. The spatial focus has been selected on the basis of the importance in influencing local weather throughout Southern and Central Europe, since these cyclones transfer moist air from the sea to the land and are often associated with heavy precipitation and/or flood events. On the basis of the discussed results, the following conclusions can be drawn.

(1) A multivariable cyclone identification and tracking process system was developed, which consists of uni- and bivariate modes of a general method with three basic variables (MSLP, geopotential height at 1000 hPa and 850 hPa), and one additional variable (relative vorticity at 850 hPa) in case of the bivariate mode. Evaluation of the individual ensemble members showed that the use of relative vorticity as a second field has a limiting effect. Furthermore, it was found that the methods using the 850 hPa level geopotential height and/or relative vorticity result in more long-lived cyclone tracks than the others. Overall, our results are in good agreement with previous analyses, highlighting that our developed method is appropriate to use for the identification of cyclones in the Mediterranean region.

(2) Data for the cyclone identification was derived from two reanalyses, i.e., ERA Interim and NCEP DOE R2 to evaluate both the method and the datasets. More cyclones were found using the ERA Interim data, mainly because of more numerous short-lived cyclones, which is probably due to the higher resolution of ERA Interim compared to NCEP DOE R2. Nevertheless, the time series of the two ensemble means from the two reanalyses correlate strongly with each other, therefore, we conclude that the method is not sensitive to small differences in the dataset. Due to the mentioned conclusions detailed analysis was presented only on the basis of cyclone tracks using ERA Interim datasets.

(3) The largest spread of the individual ensemble members occurred in summer possibly because of the presence of thermal lows. However, the spatial distribution of cyclone track density maps of the six ensemble members did not show large differences.

(4) The main cyclogenesis areas in the investigated domain are the Gulf of Genoa and the region around Cyprus, both located on the lee side of a mountain, which enhances cyclogenesis. Moreover, other minor cyclogenesis centrums can be identified over the Iberian Peninsula in summer and the Adriatic Sea in winter.

(5) The largest cyclone number occurred in spring, whereas the analysis of cyclone track density resulted in that the area affected by the cyclones is

the largest in winter, the circulation is more intense in winter. The cyclone lifetime analysis showed that although the number of cyclones is larger in spring than in winter, there are more short cyclones in spring, thus, they do not affect as large areas as winter cyclones. This implies that the cyclonic activity in the Mediterranean is mostly in the winter-spring period. The lowest cyclone activity was found in summer, also the total extension of cyclone passes is the least in summer, although the maximum value of cyclone tracks crossing a grid point occurs in summer. This means that although the number of cyclones is the lowest in summer, they are typically short-lived and they do not get too far from their genesis areas.

(6) The long-term tendencies of cyclone track density for the entire 30-year period are evaluated on the basis of the linear trend coefficients. Considering the whole domain, we found more grid points with statistically significant increasing trends than decreasing, and the absolute mean value of the trend coefficients is slightly higher in case of the positive trends than the negative trends. The most intense growing occurred along the Adriatic Sea and near Cyprus.

(7) In order to investigate the cyclones directly affecting the local weather in Hungary, the cyclone area is defined around the identified cyclone centers, and the cyclones whose domain affects the country are selected. The time series of the cyclones passing over Hungary correlate strongly with the cyclone number time series of the whole domain. The average frequency of Mediterranean cyclones passing over Hungary is 29.5 per year, most of them occurred in spring, similarly to the overall cyclone number in the whole investigated domain.

(8) Our presented results can serve as an adequate reference for further studies using global and regional climate model outputs for the identification of mid-latitude cyclones, which are key elements of the future climatological conditions, especially in Europe. For a complex region like the Mediterranean, the use of regional climate models is especially essential, since they are more appropriate to reconstruct and describe local features compared to the global climate models.

Acknowledgments: Research leading to this paper has been supported by the following sources: the Hungarian Scientific Research Fund under grant K-78125, the European Union and the European Social Fund through project FuturICT.hu (TÁMOP-4.2.2.C-11/1/KONV-2012-0013), also the AGRARKLIMA2 project (VKSZ_12-1-2013-0001).

The NCEP DOE Reanalysis 2 data for this study was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. The ERA Interim data for this study was downloaded from the website of the European Centre for Medium-Range Weather Forecasts (ECMWF), http://data-portal.ecmwf.int/data/d/interim_full_daily/. We would like to acknowledge the organisations for their efforts to prepare these databases.

References

Alpert, P., Neeman, B.U., and *Shay-El, Y.,* 1990: Climatological analysis of Mediterranean cyclones using ECMWF data. *Tellus, 42,* 65–77.

Bartholy, J., Pongrácz, R., and *Pattantyús-Ábrahám, M.,* 2008: Analyzing the genesis, intensity, and tracks of western Mediterranean cyclones. *Theor. Appl. Climatol. 96,* 133–144.

van Bebber, W.J., 1891: Die Zugstrassen der barometrischen Minima nach den Bahnenkarten der Deutschen Seewarte für den Zeitraum von 1870–1890. *Meteorol. Z. 8,* 361–366.

Catto, J.L., Shaffrey, L.C., and *Hodges, K.I.,* 2010: Can Climate Models Capture the Structure of Extratropical Cyclones? *J. Climate 23,* 1621–1635.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berridford, P., Polis, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Kallberg, P., Kohler, M., Matricardi, M., McNally, A.P., M.Monge-Sanz, B., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P., Tavolato, C., Thepaut, J.N., and *Vitart, F.,* 2011: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. Roy. Meteor. Soc. 137*, 553–597.

Finnis, J., Holland, M.M., Serreze, M C., and *Cassano, J J.,* 2007: Response of Northern Hemisphere extratropical cyclone activity and associated precipitation to climate change, as represented by the Community Climate System Model. *J. Geophys. Res. 112(G4),* G04S42.

Grams, C.M., Binder, H., Pfahl, S., Piaget, N., and *Wernli, H.,* 2014: Atmospheric processes triggering the Central European floods in June 2013. *Nat. Hazard. Earth Sys. Discussions, 2,* 427–458.

Gulev, S.K., Zolina, O., and Grigoriev, S., 2001: Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. *Climate Dynamics 17,* 795–809.

Hanson, C.E., Palutikof, J.P., and *Davies, T.D.,* 2004: Objective cyclone climatologies of the North Atlantic? A comparison between the ECMWF and NCEP Reanalyses. *Climate Dynamics 22,* 757–769.

Hodges, K.I., Lee, R. and *Bengtsson, L.,* 2011: A Comparison of Extra-tropical Cyclones in Recent Re-analyses; ERA-INTERIM, NASA-MERRA, NCEP-CFSR and JRA25. *J. Climate, 24,* 4888–4906.

Hofstätter, M. and *Chimani, B.,* 2012: Van Bebber's cyclone tracks at 700 hPa in the Eastern Alps for 1961–2002 and their comparison to Circulation Type Classifications. *Meteorol. Z. 21,* 459–473.

Hoskins, B.J. and *Hodges, K.I.,* 2002: New Perspectives on the Northern Hemisphere Winter Storm Tracks. *J. Atmos. Sci. 59,* 1041–1061.

Jansa, A., Genoves, A., Picornell, M.A., Campins, J., Riosalido, R., and *Carretero, O.,* 2001: Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach. *Meteorol. Appl. 8,* 43–56.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M., and *Potter, G.L.,* 2002: NCEP–DOE AMIP-II Reanalysis (R-2). *Bull. Amer. Meteorol. Soc. 83,* 1631–1643.

König, W., Sausen, R., and *Sielmann, F.,* 1993: Objective Identification of Cyclones in GCM Simulations. *J. Climate 6,* 2217–2231.

Lionello, P., Dalan, F., and *Elvini, E.,* 2002: Cyclones in the Mediterranean region: the present and the doubled CO 2 climate scenarios. *Climate Res. 22,* 147–159.

Maheras, P., Flocas, H.A., Patrikas, I., and *Anagnostopoulou, C.,* 2001: A 40 year objective climatology of surface cyclones in the Mediterranean region: spatial and temporal distribution. *Int. J. Climatol. 21,* 109–130.

Murray, R.J. and *Simmonds, I.,* 1991: A numerical scheme for tracking cyclone centers from digital data Part I: development and operation of the scheme. *Australian Meteorol. Mag. 39,* 155–166.

Muskulus, M., and *Jacob, D.,* 2005: Tracking cyclones in regional model data : the future of Mediterranean storms. *Adv. Geosci. 2,* 13–19.

Neu, U., Akperov, M.G., Bellenbaum, N., Benestad, R., Blender, R., Caballero, R., Cocozza, A., Darce, H.F., Feng, Y., Fraedrich, K., Grieger, J., Gulev, S., Hanley,J., Hewson, T., Inatsu, M., Keay,K., Kew, S.F., Kindem, I., Leckebusch, G.C., Liberato, M.L.R., Lionello, P., Mokhov, I.I., Pinto, J.G., Raible, C.C., Reale, M., Rudeva, I., Schuster, M., Simmonds, I., Sinclair, M., Sprenger, M., Tilinina, N.D., Trigo, I.F., Ulbrich, S.,Ulbrich, U., Wang, X.L., Wernli, H., 2013: IMILAST: A

Community Effort to Intercompare Extratropical Cyclone Detection and Tracking Algorithms. *Bull. Amer. Meteorol. Soc. 94,* 529–547.

Nielsen, J.W. and *Dole, R.M.,* 1992: A survey of extratropical cyclone characteristics during GALE. *Mon Weather Rev 120,* 1156–1167

Picornell, M.A., Jansá, A., Genovés, A., and *Campins, J.,* 2001: Automated database of mesocyclones from the HIRLAM(INM)-0.5° analyses in the western Mediterranean*. Int. J. Climatol. 21,* 335–354.

Pinto, J.G., Spangehl, T., Ulbrich, U., and *Speth, P.,* 2005: Sensitivities of a cyclone detection and tracking algorithm: individual tracks and climatology. *Meteorol. Z. 14, 823–838.*

Ruti, P.M., Somot, S., Giorgi, F., Dubois, C., Flaounas, E., Obermann, A., Dell'Aquila, A., Pisacane, G., Harzallah, A., Lombardi, E., Ahrens, B., Akhtar, N., Alias, A., Arsouze, T., Aznar, R., Bastin, S., Bartholy, J., Béranger, K., Beuvier, J., Bouffies-Cloché, S., Brauch, J., Cabos, W., Calmanti, S., Calvet. J-C., Carillo, A., Conte, D., Coppola, E., Dell'Aquila, A., Djurdjevic, V., Drobinski, P., Elizalde-Arellano, A., Gaertner, M., Galàn, P., Gallardo, C., Gualdi, S., Goncalves, M., Jorba, O., Jordà, G., L'Heveder, B., Lebeaupin-Brossier, C., Li, L., Liguori, G., Lionello, P., Maciàs, D., Nabat, P., Onol, B., Raikovic, B., Ramage, K., Sevault, F., Sannino, G., MV Struglia, Sanna, A., Torma, C., Vervatis, V., 2015: MED-CORDEX initiative for Mediterranean Climate studies *(submitted to BAMS, October 2011, resubmitted in August 2014, resubmitted in March 2015)*

Serreze, M.C., 1995: Climatological aspects of cyclone development and decay in the Arctic. *Atmosphere-Ocean, 33,* 1–23.

Sinclair, M.R., 1994: An objective Cyclone Climatology for Southern Hemisphere. *Month. Weather Rev. 122,* 2239–2256.

Ulbrich, U., Brücher, T., Fink, A.H., Leckebusch, G.C., Krüger, A., and *Pinto, J.G.,* 2003: The central European floods of August 2002: Part 2 –Synoptic causes and considerations with respect to climatic change. *Weather, 58,* 466–471.

Trigo, I.F., Davies, T.D., and *Bigg, G.R.,* 1999: Objective Climatology of Cyclones in the Mediterranean Region. *J. Climate 12,* 1685–1696.

Trigo, I.F., Davies, T.D., and *Bigg, G.R.,* 2000: Decline in Mediterranean rainfall by weakening of Mediterranean cyclones. *Geophys. Res. Lett. 27,* 2913–2916.

Trigo, I.F., 2006: Climatology and interannual variability of storm-tracks in the Euro-Atlantic sector: a comparison between ERA-40 and NCEP/NCAR reanalyses. *Climate Dynamics 26,* 127–143.

Wernli, H. and *Schwierz, C.,* 2006: Surface Cyclones in the ERA-40 Dataset (1958 – 2001). Part I: Novel Identification Method and Global Climatology. *J. Atmos. Sci. 63,* 2486–2507.

Woollings, T., Hoskins, B., Blackburn, M., Hassell, D., and *Hodges, K.,* 2010: Storm track sensitivity to sea surface temperature resolution in a regional atmosphere model. *Climate Dynamics 35,* 341–353.