CrossMark

ORIGINAL PAPER

The exceptionally wet year of 2014 over Greece: a statistical and synoptical-atmospheric analysis over the region of Thessaloniki

Konstantia Tolika[1] · Panagiotis Maheras[1] · Christina Anagnostopoulou[1]

Abstract The highest rainfall totals (912.2 mm) and the largest number of raindays (133 days), since 1958, were recorded in Thessaloniki during the year of 2014. Extreme precipitation heights were also observed on a seasonal, monthly and daily basis. The examined year presented the highest daily rainfall intensity, the maximum daily precipitation and the largest number of heavy precipitation days (greater than 10 mm), and it also exceeded the previous amounts of precipitation of very wet (95th percentile) and extremely wet (99th percentile) days. According to the automatic circulation type classification scheme that was used, it was found that during this exceptionally wet year, the frequency of occurrence of cyclonic types at the near surface geopotential level increases, while the same types decreased at a higher atmospheric level (500 hPa). The prevailing type was type C which is located at the centre of the study area (Greece), but several other cyclonic types changed during this year not only their frequency but also their percentage of rainfall as well as their daily precipitation intensity. It should be highlighted that these findings differentiated on the seasonal-scale analysis. Moreover, out of the three teleconnection patterns that were examined (Scandinavian Pattern, Eastern Mediterranean Teleconnection Pattern and North Sea-Caspian Pattern), the Scandinavian one (SCAND) was detected during the most of the months of 2014 meaning that it was highly associated with intense precipitation over Greece.

✉ Konstantia Tolika
diatol@geo.auth.gr

[1] Department of Meteorology and Climatology, School of Geology, Aristotle University of Thessaloniki, 55124 Thessaloniki, Greece

1 Introduction

Extreme precipitation events have been the main subject of interest in numerous climatological studies during the past years, due to their severe environmental and socioeconomic impacts in affected areas. The IPCC report on the management of the risks of extreme events, released on 2012 (Seneviratne et al. 2012), highlighted that there has been an increasing trend of the heavy precipitation events worldwide, indicating that daily rainfall was becoming more extreme. Even though the observed changes of extreme precipitation are far less coherent on a spatial scale, and not systematically significant from a statistical point of view compared to the respected temperature extremes (Alexander et al. 2006), this does not diminish the importance of investigating and analysing the nature, the characteristics and the physical mechanisms of such rainfall extremes, in order to provide updated and reformed policies on extreme management and human adaptation strategies. Several approaches have been suggested based on parametric or non-parametric statistics, thresholds, absolute values and extreme precipitation indices, in order to define an event as extreme (e.g. Klein Tank and Können 2003; Li et al. 2005; Tebaldi et al. 2006; Kyselý 2009; Anagnostopoulou and Tolika 2012). The analysis on different timescales plays also an important role, since both an isolated intense rainfall event as well as persisting and accumulated totals would affect the environment, ecosystems and human activities (Begueria et al. 2009). Moreover, the evolving climate characteristics and the rapid changes of the environment urge researchers to focus also to the changes in the frequency of these extreme events (IPCC 2012).

In the Mediterranean region, during the coldest period of the year (also generally the wettest), approximately 60% of the seasonal rainfall totals can be attributed to extreme events (Toreti et al. 2010). However, the results concerning the trends

🖄 Springer

of the extreme precipitation events in this region are contradicting. Alpert et al. (2002) showed that extreme daily precipitation increases despite the general decreasing trends of the rainfall totals. On the other hand, Lionello et al. (2010) report that for a quite large number of stations, extreme precipitation events did not show any significant trend, during that same extended cold/wet period. The only exception was Greece with significant negative trend which according to the authors could be attributed to the decreasing tendency of the intense Mediterranean cyclones. The complicated rainfall regime, due to the sharp terrain, the contrasts in the land-sea pattern, the regional geographical characteristics of each area, the existence of specific cyclongenesis centres, the influence of the Mediterranean Sea and also its location in the transitional tropical and extratropical atmospheric circulation zone, makes it more difficult but also highly interesting to assess the nature, features and physical mechanisms of the extreme rainfall events. Thus, several studies have been targeted on that subject. Kostopoulou and Jones (2005) underlined the contrasting trends of extreme precipitation indices depending on the selected region; positive trends of intense rainfall invents were found in central Mediterranean, while its eastern parts are characterized by negative trends. Begueria et al. (2009) analysed not only daily precipitation data but also precipitation events (peak intensity, magnitude and duration) aiming at a more thorough analysis of the extremes in north-eastern Spain. They have noted that the characteristics of the extreme events varied both on a seasonal and spatial scale due to the different atmospheric factors related to rainfall in the domain of the study. According to Rebora et al. (2013), both the sharp terrain of the area as well as the interaction between the sea and the atmosphere play an important role on extreme rainfall events. Moreover, Krichak et al. (2015) study focused mainly on the physical mechanisms associated with heavy precipitation events, concluding that during the cold period of the year, one of the main factors linked with rainfall extremes over the Mediterranean region is the transportation of North Atlantic Ocean humid air combined with evaporating water vapour from the ocean. Another point of view in the study of extremes is given by Drobinski et al. (2016) who, based on the Clausius-Clapeyron thermodynamics, examined their sensitivity to temperature variability over the French Mediterranean region. Finally, in their recent study, Raveh-Rubin and Wernli (2015) stressed also on the complex nature of extremes and their different regional behaviour, finding that in western Mediterranean, their intensity is higher during autumn, while in the eastern part, they intensify in winter.

Located in the eastern part of the Mediterranean basin and the southern part of the Balkan Peninsula, Greece presents also a complex geographical terrain, with the main continental area of both high and low altitudes (influenced by the Ionian and the Aegean Sea) as well as numerous islands of different sizes and geomorphological characteristics. For this heterogeneous area, attention has been given on rainfall extremes. Houssos and Bartzokas (2006) mention that over the north-western part of the country, the main cause of these extremes is either a low-pressure system located at the west of Greece or at the east or south of Greece. It was also found that in their highest percentage, extreme precipitation events are detected during winter, while they are much rarer during the warm period of the year. Using a long time series of daily precipitation data on an analysis focused for the capital of Greece, Nastos and Zerefos (2007) pointed out that the number of raindays above specific thresholds become statistically significant only after 1970 and conclude that precipitation in Athens becomes more extreme during this period. Extending their research on a larger part of Greece, the same authors (Nastos and Zerefos 2008) observed positive (non-statistical significant) trends of daily rainfall extremes (over 30 and 50 mm) in the eastern and southern eastern parts of the country. According to Houssos et al. (2008), the extreme precipitation conditions in Greece are associated with nine synoptic conditions, all having in common the intense cyclonic activity over central Mediterranean but differing in terms of their intensity at the surface and upper levels, the time of their occurrence and the surface air flow direction. Finally, contrary to previous studies, Kioutsioukis et al. (2010) demonstrated that for the time period 1955–2002, both the frequency and the intensity of extreme precipitation decreased in Greece even though the extreme precipitation percentage did not present a significant trend. This disagreement can be attributed to the different selection of the extreme indices, the different regions and the different time period of study, reinforcing one more time the complexity of the extreme rainfall nature and characteristics.

The study presented herein has two major scopes: the statistical investigation and analysis of the extreme wet year of 2014 on different timescales (annually, seasonally, monthly and daily) and the examination of the changes of the atmospheric circulation during this year in comparison to the previous 1958–2013 time period. Section 2 contains the data and methodology used in the study, followed by Sect. 3 where the results of the analysis are demonstrated. Finally, Sect. 4 presents the key conclusions and discussion on the subject of interest.

2 Data and methodology

The study was conducted using daily precipitation amounts measured at the meteorological station of Thessaloniki (Auth) covering the time period 1958–2014 (57 years). For the same timespan, we utilized daily geopotential heights for two different isobaric levels (1000 and 500 hPa) derived from the NCEP/NCAR data archive (Kalnay et al. 1996) for a 20° W–50° E and 20°–65° N window, with a spatial resolution

of 2.5° × 2.5°. An automatic and flexible classification scheme, primarily developed by Maheras et al. (2000) and further on improved and updated described in detail by Anagostopoulou et al. (2009), was used in the study. It consists of 12 circulation types, 5 anticyclonic (A) and 7 cyclonic ones (C), and the acronym that each types has refers to the location of its centre in comparison to the centre of the classification. For example, type Cne is a cyclonic type with its centre found at the north-east of the domain of interest. Figure 1 shows the location of the cyclonic types, which mainly interest us in the present study, where classification scheme was conducted centred almost over the centre of Greece (Cyclades area). The scheme provided a daily circulation type calendar, one for each geopotential levels, where every day is characterized by a specific circulation type.

Finally, aiming to investigate the link of the atmospheric circulation with the extreme rainfall conditions of 2014 over a much more extended geographical domain, we utilized the NCEP/NCAR time series and calculated the monthly anomaly patterns of 2014 raindays (in comparison to the mean period (1981–2010) both for the 1000 and the 500 hPa isobaric levels in order to analyse the possible differences of the circulation during the extreme wet year of 2014. The spatial window was extended to 30° N–80° N and 20° W–45° E.

3 Results

3.1 The statistical analysis of the extreme precipitation of 2014

The year of 2014 was without doubt the wettest year in the observational history of the Thessaloniki meteorological station since 1958. With 912.2 mm, it broke by far the record that was previously held by the year 1987 with 650.4 mm. It should also be mentioned that this annual total is more than double than the mean average annual precipitation of the previous time period 1958–2013 (446 mm) highlighting even more the "extremity" of the specific year. Moreover, it was not only the year with the highest precipitation totals but also the one with the largest number of raindays. One hundred thirty three were measured (above the threshold of 0.1 mm) in Thessaloniki during 2014 (41.3 days higher than the mean of the past period), while 121 days was the previous maximum that was observed in 1963 (Fig. 2). In order to quantify even better how extreme this year was, from the annual totals and the raindays point of view, we compared these values with the *mean + 2stdev* respectively. For precipitation (raindays), the values regarding 2014 were by 277.1 mm (12 days) higher than the mean + 2stdev values.

Still, when we analysed our data on a seasonal basis, this "extreme" first impression based on the annual results slightly differentiated. Winter 2014 was the second wettest winter of the study period with 229.0 mm (the maximum was observed in 1969 with 273.8 mm) and ranks fifth regarding raindays (37), while the maximum was 50 days during the year of 1969 (Fig. 3). In the case of spring, 174.6 mm (2014) and 36 days (2014) were measured, while the maxima were found in 1987 (202.2 mm) and 1969 (40 raindays). Conversely, summer and autumn are more extreme seasons. The summer of 2014 was the wettest summer since 1958 with 245.8 mm (mainly due to a 1-day rainfall analysed further below). Autumn presented not only the highest precipitation totals (262.8 mm) but also the highest number of raindays (both with the year of 1962 with 36 days). Both these seasons, as well as winter, during 2014 exceeded the mean + 2stdev values as regards the seasonal rainfall height. Especially for autumn, the number of raindays of the studied year exceeds the statistical mean + 2stdev value too (Fig. 3). It is worth mentioning that regarding the 2014 raindays, it was found in one of our recent studies

Fig. 1 The location of the cyclonic types used in the study. The *circle symbol* shows the centre of the classification. The *star symbol* shows the geographical location of Thessaloniki
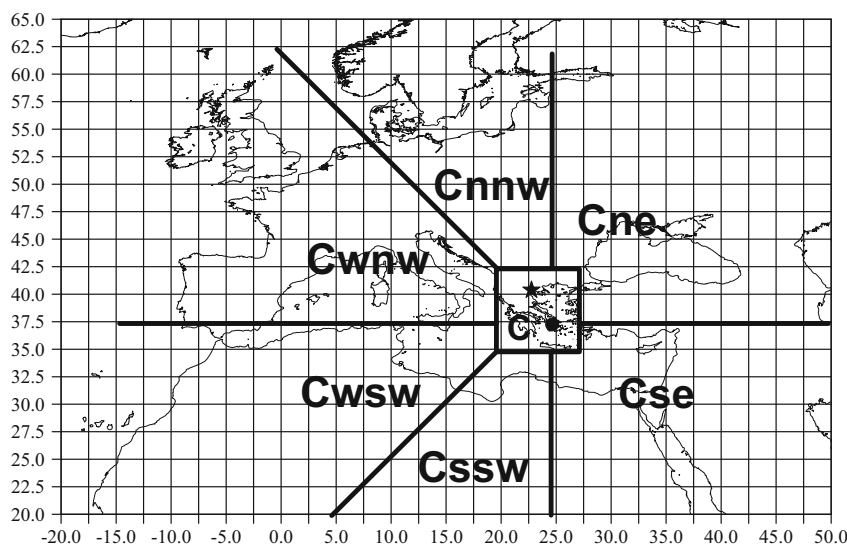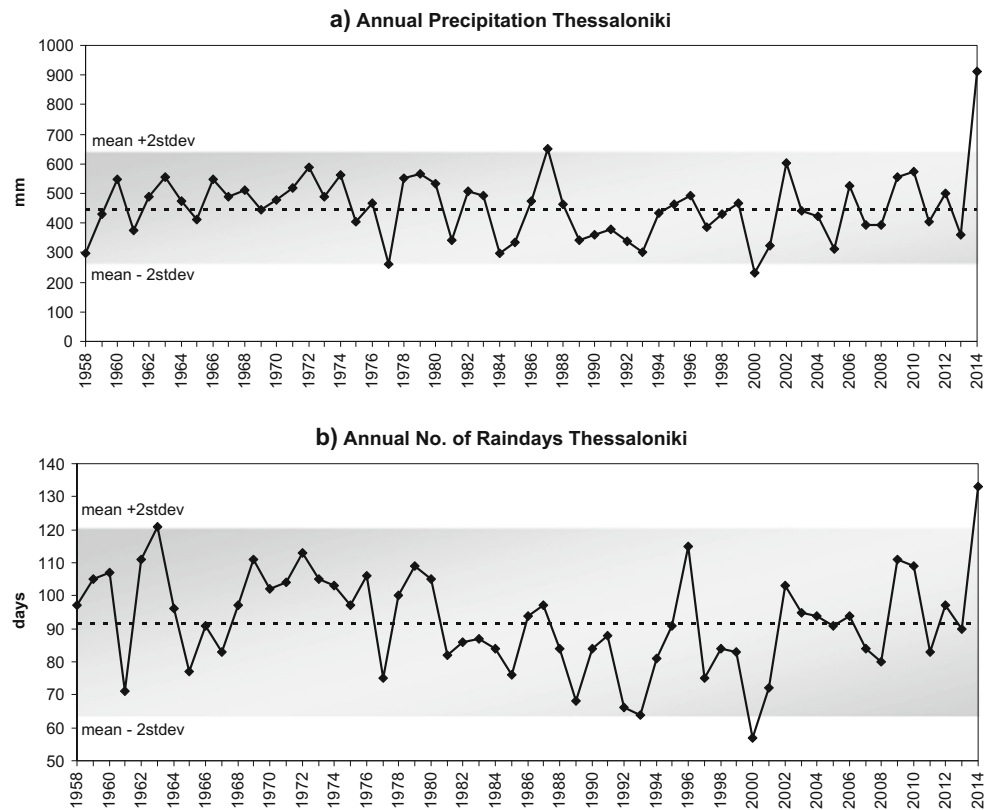
Fig. 2 Annual precipitation heights (**a**) and number of raindays (**b**) in Thessaloniki during the period 1958–2014. The *shaded area* is between (mean − 2stdev and mean + 2stdev). The *dotted line* represents the mean value of the period

(Maheras et al. 2016) that during this year, the high rainfall intensity days presented also high frequency of occurrence. In comparison to the mean number of days with heights greater than 10 mm of the period 1958–2013 which was 13 days, the year of 2014 presented 27, while for the other two categories

Fig. 3 Comparison of the seasonal precipitation (*upper graph*) and number of raindays (*lower graph*) of 2014 (*black dots*) with the mean + 2stdev equivalent values (*bars*)

(raindays >20 mm and raindays >30 mm), their mean numbers were 4 and 1.5 days, while for 2014, they were 9 and 5 days respectively. Analogous conclusions were derived from the seasonal analysis too (Maheras et al. 2016).

Finally, the analysis of the rainfall totals on a monthly scale showed that even though none of the 2014 months exceed the absolute maximum, however, in some cases, the monthly amounts can be characterized as extreme. From Fig. 4 (left column), it can be seen that in the case of June, July, September and December, the 2014 precipitation totals are higher than the statistical parameter's value of mean + 2stdev. In addition, it was found that the precipitation heights of the same months were higher not only from the 90th and 95th percentile (generally characterizing heavy precipitation) but also the 99th percentile placing these values in the extreme distribution area. The same analysis was conducted for the monthly raindays (Fig. 4, right column). In this case, the values found for April, June and November reach the mean + 2stdev but without exceeding it. From the comparison with the three calculated percentiles (90th, 95th and 99th), it was observed that only in June the number of 2014 raindays was greater than the 99th value. Yet, it should be noted that the April's, November's and December's raindays are between the 95th and 99th range meaning that these 2014 presented worth noticing number of days of rain too.
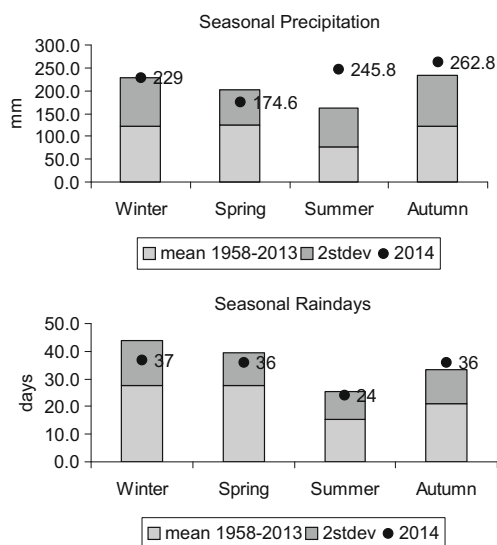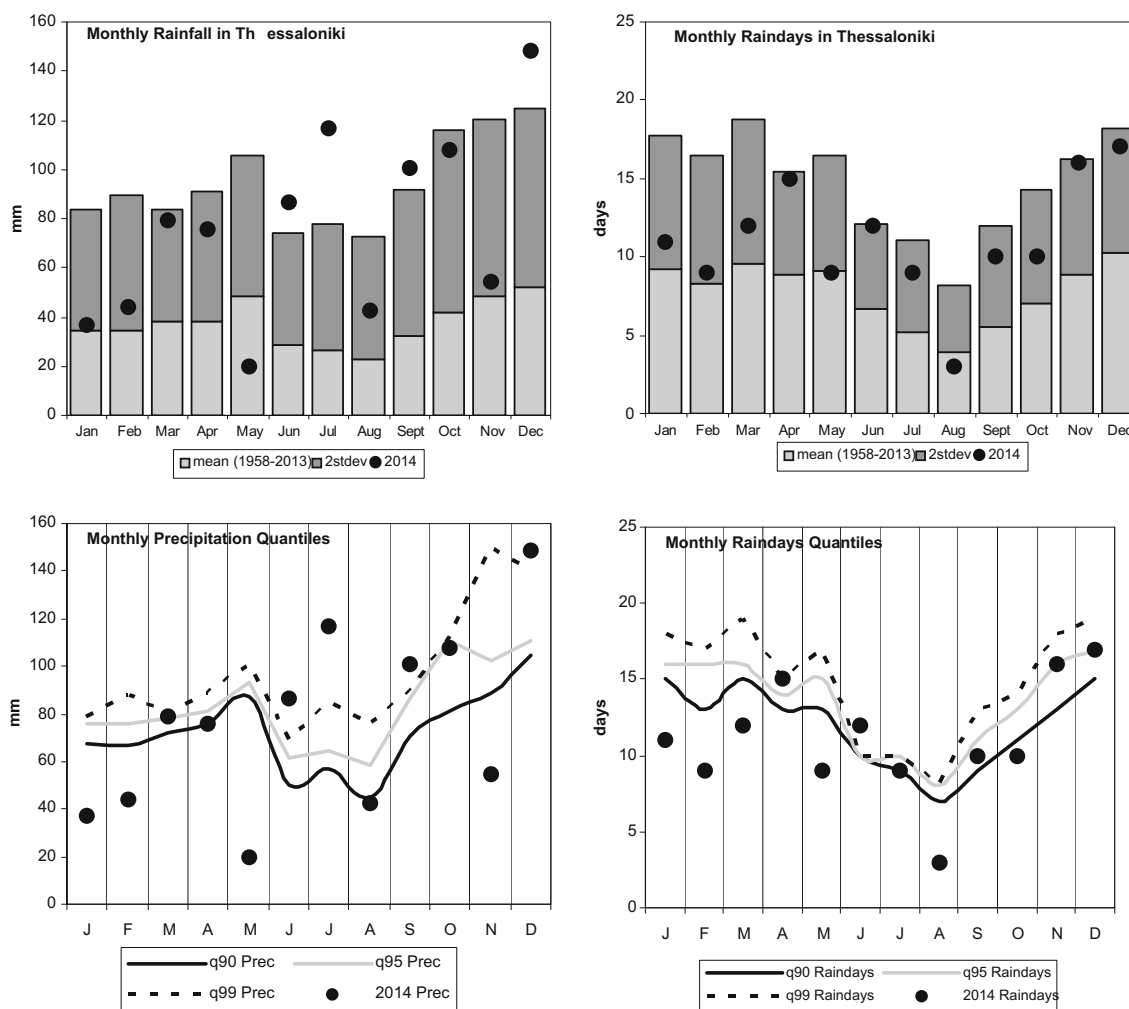
Fig. 4 Comparison of the monthly precipitation and number of raindays of 2014 of 2014 (*black dots*) with the mean + 2stdev equivalent values (*bars*) (*upper graphs*). Comparison of the monthly precipitation and number of raindays in 2014 with the 90th, 95th and 99th percentile (*lower graphs*)

3.2 Analysis of extreme precipitation indices during 2014

Aiming on a more thorough analysis of the extreme precipitation characteristics of the year 2014, six extreme rainfall indices (both absolute and threshold type indices, Table 1), widely used in literature (*EU-funded Statistical and Regional Dynamical Downscaling of Extremes (STARDEX,* http://www.cru.uea.ac.uk/project/stardex) were computed.

Overall, as illustrated in Fig. 5, five out of the six indices presented their highest values during the year of 2014. Specifically, from the SDII index, it can be concluded that with 6.9 mm/day, this year was not only the wettest and with the largest number of raindays on an annual basis but also the intensity of the daily rainfall reached the maximum. The second maximum was observed several years ago, in 1987 with 6.7 mm/day. Regarding the maximum daily precipitation (RX1day), the highest value of the index was also observed during the examined year (107.3 mm), followed by the year of 1985 with 98 mm. It is worth noticing that this present

maximum was observed during the summer and actually on 16 July, 2014. Moreover, 2014 was characterized by the highest number of heavy precipitation days (R10m, 27 days), while in the case of the next index R20m, it did not break the record found in 1974 (11 days) and took the second place (9 days with precipitation higher than 20 mm). Finally, the extreme characteristics of 2014 are also confirmed from the last two threshold indices. The amount of precipitation from very wet days as well as extremely wet days was observed during the year of interest with 472.6 and 256.8 mm respectively. These values were by 174.6 and 83.3 mm higher than the previous maximums.

### 3.3 Examination of the synoptic conditions during the year of 2014

The first step in the examination of the changes in the atmospheric circulation over the Greek region, during the year of 2014 that may have resulted to these exceptionally high

Table 1 The extreme precipitation indices studied

Index acronym	Index name	Definition	Units
1. SDII	Simple daily intensity index	Ratio of annual precipitation to the number of wet days (threshold 0.1 mm)	mm/day
2. RX1day	Wettest day	Maximum daily precipitation	mm
3. R10m	Heavy precipitation days	Number of days with precipitation >10 mm	days
4. R20m	Very heavy precipitation days	Number of days with precipitation >10 mm	days
5. R95p	Precipitation from very wet days	Amount of precipitation from days >95 percentile	mm
6. R99p	Precipitation from extremely wet days	Amount of precipitation from days >99 percentile	mm

precipitation amounts, was to detect the changes in the frequency of occurrence of the cyclonic types, from the classification scheme, both for the previous period 1958–2013 but also for the year of interest. We decided to investigate only the cyclonic types, since the precipitation amounts that are associated with the anticyclonic ones are of a very low percentage, lower than 10% of the annual totals (Maheras et al. 2004). Aiming also on a more thorough analysis of the synoptic conditions over Greece, the daily classification calendar was computed for two different atmospheric levels: the first

Fig. 5 Values of the six extreme precipitation indices for the period 1958–2014
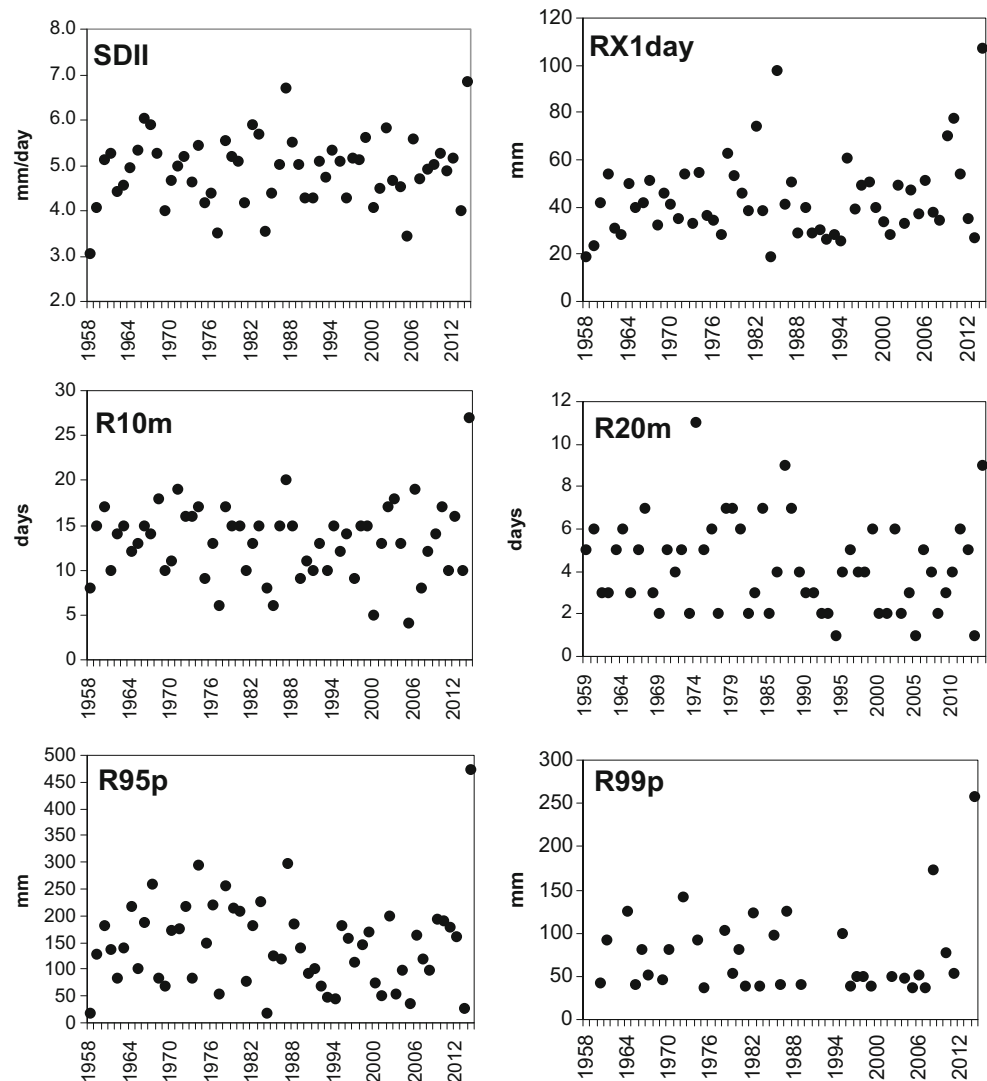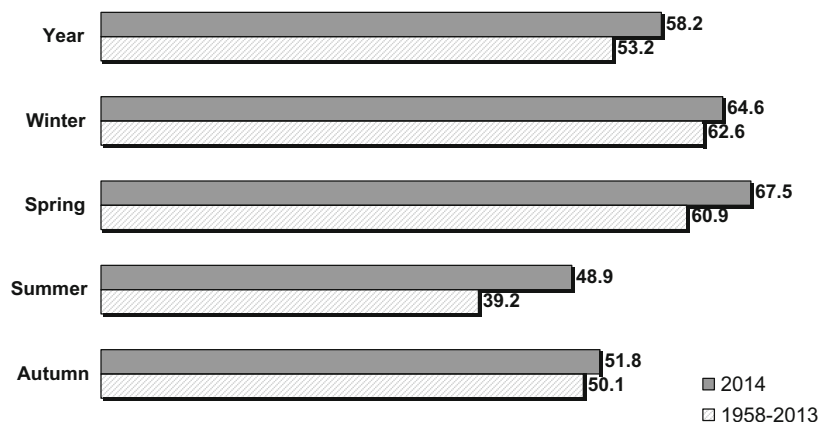
near the surface (1000 hPa) and the second one at 500 hPa. What was primarily noted from this comparison is that generally the cyclonic types, annually, were more frequent during the year of 2014, at the 1000 hPa level, with their frequency of occurrence rising from the 53.2% of the 1958–2013 period to 58.2% in 2014 (Fig. 6a). This increase can be mainly attributed to changes in their percentages during spring and summer. This means that these two seasons were actually more "cyclonic" with the total percentage of occurrence of the cyclonic type changes from 60.9% (1958–2013) to 67.5% (2014) for spring and from 39.2% (1958–2013) to 48.9% (2014) for the summer months. Figure 7 compares the results of the frequency of occurrence of each cyclonic type separately for those two levels, on an annual and seasonal basis for the past period (1958–2013) and for the year of 2014. In detail, on an annual basis, the most frequent cyclonic type for the past years used to be Cse (13.3%) followed by the type C (12.2%). In 2014, that changed and the prevailing type was the one that its centre is over the centre of the domain of study (C) with a percentage of occurrence of almost 18% (with statistically significant differences regarding its occurrence frequency). The second most frequent one is type Cne (11.8%), while type Cse comes third with a percentage of 9.5%. From the seasonal

analysis, it became evident that there is a general increase of the frequency of type C. However, during winter, the most frequent type remains Cse (15.9%), but its percentage of occurrence is quite lower than its mean frequency during the past years (19.1%). It should also be noted that only Cne type presented statistically significant differences during this season. For the other three seasons, type C has the highest percentage of occurrence, and in spring, it reaches almost the value of 20% (Fig. 7, left column).
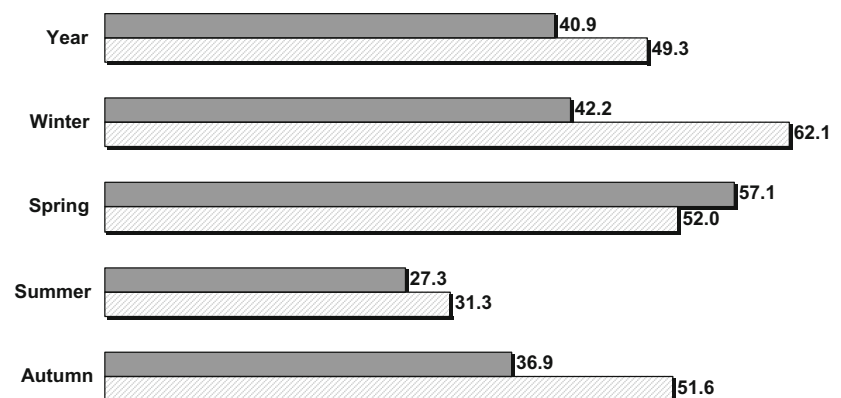
At the 500 hPa, the atmospheric conditions during 2014 were "less cyclonic" than the previous time period. The total percentage of the cyclonic types (40.9%, 2014) was almost 10% lower than the mean percentage of the 1958–2013 years (49.3%). On the seasonal basis, winter and autumn were found to present the most significant changes, with the percentage of occurrence of the examined type decreasing approximately 20% in 2014. The winter percentages were 42.2% (2014) versus 62.1% (1958–2013), and the autumn ones were 36.9% (2014) to 51.6% (1958–2013). For the other two seasons, the changes in the total percentages were not so large, and only during spring, the cyclonic types were more frequent in 2014 compared to the previous period (Fig. 6b).

Fig. 6 Frequencies of occurrence of the cyclonic types in total for the 1000 hPa (**a**) and the 500 hPa (**b**) levels. *Grey bars* refer to 2014 and *stripped bars* to the period 1958–2013

a) **Frequency of occurence (%) of the cyclonic types at 1000hPa**

Season	2014	1958-2013
Year	58.2	53.2
Winter	64.6	62.6
Spring	67.5	60.9
Summer	48.9	39.2
Autumn	51.8	50.1

b) **Frequency of occurence (%) of the cyclonic types at 500hPa**

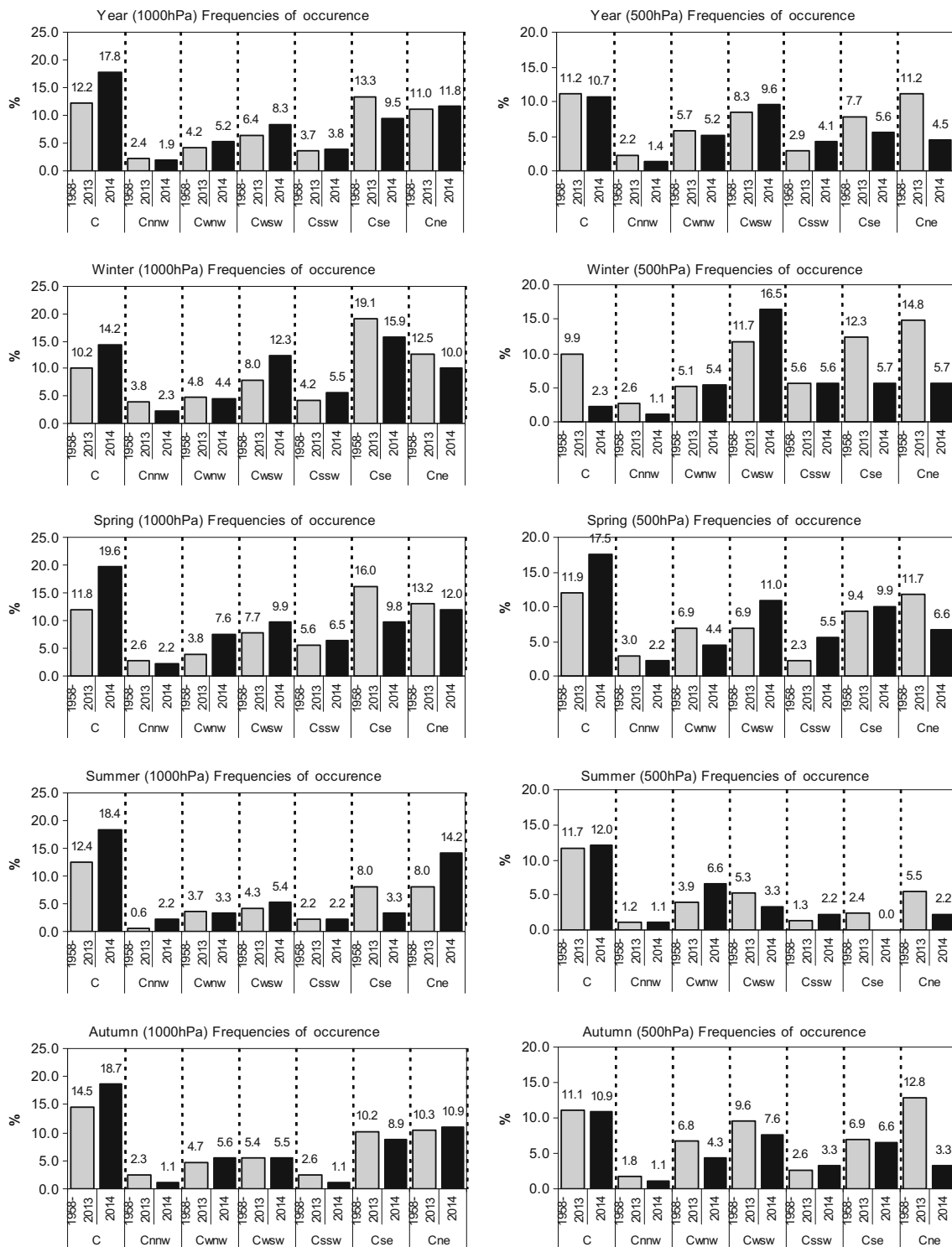| Season	2014	1958-2013
Year	40.9	49.3
Winter	42.2	62.1
Spring	57.1	52.0
Summer	27.3	31.3
Autumn	36.9	51.6

Fig. 7 Annual and seasonal frequencies of occurrence (%) of the cyclonic circulation types for the period 1958–2013 (*grey bars*) and 2014 (*black bars*). The *left column* refers to the 1000 hPa classification and the *right column* to the 500 hPa classification

From the per type 500 hPa analysis (Fig. 7, right column), it was found that the annual frequencies of occurrence changed regarding the prevailing type. During the past years, the most frequent cyclonic types were C and Cne with a percentage of 11.2%, while during the year of 2014, that changed. C

(10.7%) still remains the most frequent from the cyclonic types, followed by Cwsw (9.6%), while the frequency of occurrence of Cne decreased significantly (4.5%), with statistically significant differences of its frequency of occurrence. During winter, the type that prevailed changed from Cne

(14.8%, 1958–2013) to Cwsw (16.5%, 2014), while in spring and summer, the most frequent cyclonic type remained the one with its centre just above Greece (C). However, for spring, its frequency of occurrence raised from 11.9% (1958–2013) to 17.5% (2014), while in summer, it remained almost the same. Finally, during the autumn months, Cne was the prevailing from the cyclonic types during the past years with 12.8% frequency of occurrence followed by type C (11.1%). Conversely, in 2014, type C is the most frequent one (10.9%) and the second highest percentage is found in type Cwsw (7.6%). The application of the t test on a significance level of 0.05 should that only type C (winter), type Cse (summer) and type Cne (autumn) presented statistically significant differences in their frequency of occurrence in comparison to the past time period.

Further on, since our main concern in the present study was the notable precipitation characteristics of 2014, we compared the changes in the rainfall percentages that are attributed to each of the cyclonic types as well as the intensity of precipitation per type. Thus, we calculate these parameters both for the period 1958–2013 and the year of interest, and the comparison was made (Table 2).

As regards the 1000 hPa, it was a common finding, both on the annual and seasonal analysis that the rainiest cyclonic type is the one located at the centre of Greece (type C). The percentage of rainfall associated with this type varies from 24.8% for winter to 37.2% for autumn. The results concerning the year of 2014 showed that not only the frequency of types changed but also the ones connected with the highest percentage of precipitation. The rainiest circulation type varied depending on the timescale. On an annual scale, C was found to be the "wettest" cyclonic type since 40.9% of the total rainfall is attributed to it. For winter, spring, summer and autumn, the cyclonic types that are mainly associated with rainfall are Cse (34.1%), C (58.4%), Cne (57.5%) and C (76.1%) respectively. For the isobaric level of 500 hPa, the results had some differences. With an exception of winter (Cwsw, 29.4%) for the other seasons and annual, type C was still the one that was mainly associated with the highest percentage of rainfall during the years 1958–2013. However, these percentages are quite lower than the 1000 hPa ones, pointing out that precipitation was more evenly distributed among the cyclonic types. For the year of interest, on the year basis, the classification at 500 hPa showed also that C is the wettest one (38.7%), and in winter, it is Cwsw (36.9%). For the other three seasons, once again, type C is mainly connected with rainfall amounts, and especially for summer and autumn, this type is associated with more than 50% of the total seasonal precipitation heights.

Table 2 Percentage of precipitation (%) and rainfall intensity (mm/day) per cyclonic type for the year 2014 and the period 1958–2013 (italic values in the brackets)

2014 (1958–2013)		C	Cnnw	Cwnw	Cwsw	Cssw	Cse	Cne
Percentage of rainfall (%) per cyclonic type								
1000 hPa	Year	*40.9 (29.1)*	0.1 (1.3)	4.2 (7.8)	8.1 (11.1)	0.9 (5.3)	11.1 (14.2)	21.7 (9.2)
	Winter	18.6 *(24.8)*	0.6 (1.9)	0.0 (9.8)	26.5 (18.0)	1.8 (7.5)	*34.1* (17.9)	12.4 (8.0)
	Spring	*58.4 (26.6)*	0.0 (2.0)	21.5 (7.2)	3.0 (8.8)	2.4 (6.9)	2.3 (18.3)	10.7 (11.4)
	Summer	11.6 *(26.7)*	0.0 (0.1)	0.1 (4.2)	0.2 (4.1)	0.0 (1.6)	0.0 (10.0)	*57.5* (8.1)
	Autumn	*76.1 (37.2)*	0.0 (0.8)	0.2 (8.7)	2.9 (11.2)	0.0 (4.0)	6.9 (9.2)	3.5 (8.7)
500 hPa	Year	*38.7 (19.6)*	0.0 (2.4)	10.0 (12.6)	15.1 (20.7)	5.4 (3.4)	4.1 (5.6)	2.9 (10.1)
	Winter	5.4 (14.9)	0.0 (3.0)	0.4 (10.5)	*36.9 (29.4)*	4.1 (5.9)	14.5 (7.3)	7.6 (12.3)
	Spring	*31.8 (21.1)*	0.2 (3.4)	15.9 (11.6)	24.3 (20.7)	11.6 (3.6)	0.6 (8.0)	3.8 (11.9)
	Summer	*53.8 (26.6)*	0.0 (0.8)	1.7 (13.4)	2.6 (7.5)	7.8 (1.7)	0.6 (4.3)	1.0 (5.3)
	Autumn	*58.1 (18.2)*	0.0 (2.0)	22.0 (15.2)	1.7 (20.6)	0.0 (1.7)	0.8 (2.3)	0.2 (9.1)
Precipitation intensity (mm/day) per cyclonic type								
1000 hPa	Year	8.9 *(6.4)*	0.7 (2.8)	6.4 (5.1)	6.2 (5.2)	2.1 (4.9)	5.6 (4.6)	*10.4 (4.0)*
	Winter	3.9 *(5.9)*	0.7 (2.2)	0.0 (5.0)	*12.1* (5.5)	2.1 (5.1)	9.8 (4.2)	5.7 (2.7)
	Spring	8.5 *(5.7)*	0.0 (3.4)	*9.4* (5.0)	1.3 (4.2)	2.1 (4.4)	1.0 (4.5)	3.1 (4.3)
	Summer	5.7 *(6.5)*	0.0 (1.7)	0.2 (4.5)	0.5 (3.8)	0.0 (4.5)	0.0 (5.5)	*23.6* (5.5)
	Autumn	*14.3 (7.4)*	0.0 (3.1)	0.4 (5.7)	3.8 (6.2)	0.0 (5.7)	3.0 (5.2)	4.6 (4.8)
500 hPa	Year	*12.2* (5.6)	0.6 (3.6)	10.1 (5.6)	7.3 (6.6)	4.9 (4.2)	4.7 (3.8)	3.8 (3.9)
	Winter	4.1 (4.8)	0.0 (4.1)	4.6 (1.0)	10.6 *(6.3)*	4.8 (4.3)	*11.1* (4.1)	5.8 (3.4)
	Spring	6.2 (5.6)	0.3 (3.2)	*9.3* (5.6)	4.7 (6.2)	5.1 (3.7)	1.1 (3.4)	3.3 (3.9)
	Summer	*22.1 (6.5)*	0.0 (3.4)	2.1 (6.1)	6.3 (5.7)	4.8 (4.2)	1.4 (3.7)	2.4 (3.8)
	Autumn	13.9 (5.9)	0.0 (4.0)	*19.3* (6.1)	4.5 (7.7)	0.0 (5.6)	0.7 (4.8)	0.4 (5.1)

The maximum values in each case are marked in italics

Finally, several differences were noted between the past 56 period and the year 2014, regarding the intensity of rainfall per type, from the analysis that was performed (Table 2, lower part). For 1958–2013 mean results, it seems that at the 1000 hPa, the wettest cyclonic type presented also the highest precipitation intensity (type C). The intensity ranges between 5.7 mm/day (spring) and 7.4 mm/day (autumn). On the other hand, the wet and intense cyclonic types do not match during 2014 in all cases. For example for winter of 2014, even though Cse was the wettest type, Cwsw was the one with the highest intensity of daily rainfall with 12.1 mm/day. For spring, type C was associated with almost 60% of the seasonal totals. Yet, its rainfall intensity was not the highest one, leading to the conclusion that this type presented also a quite large number of raindays (8.5 mm/day compared to type Cwnw presenting the maximum with 9.4 mm/day). A significant difference between the results of the past years and 2014 was detected during summer where the daily precipitation intensity of type Cne has highly increased from 5.5 mm/day (1958–2013) to 23.6 mm/day (2014). In autumn, also the intensity of type C almost doubled, from 7.4 mm/day during the previous years to 14.3 mm/day in 2014. Regarding the 500 hPa level, the maximum of rainfall intensity for the period 1958–2013 does not present a large range, varying from 6.2 mm/day (spring, Cwsw) to 7.7 mm/day (autumn, Cwsw). For the extreme year of 2014, the cyclonic types with the maximum values appear to be more intense (from 9.3 mm/day (spring, Cwnw) to 22.1 mm/day (summer, C). Only for summer the results on the most intense type match, in comparison with the period 1958–2013.

In general, comparing the frequency of occurrence of the cyclonic types during 2014 between the two examined isobaric levels, it was found that at 500 hPa was not only less cyclonic than the previous time period but a significant difference between 500 hPa (40.9%) and 1000 hPa (58.2%) was also indicated. The observed decrease in the frequency of occurrence of the cyclonic types at the isobaric level of 500 hPa during 2014 can be explained and attributed to the methodology that the classification scheme is based on, since the location of the type centre plays a major role. It is known that there is no coincide of the depression centres at 1000 and 500 hPa, and the 500 hPa one is generally located at the north-west of the 1000 hPa centre (Maheras et al. 2002). Thus, a type C at 1000 hPa (it is the circulation type with the most intense decrease in frequency at 500 hPa compared to 1000 hPa during 2014) could be a type A or Asw (anticyclonic types) at the 500 hPa level due to the displacement of the depression centre to the north in comparison to the 1000 hPa surface. This conclusion is reinforced by the fact that these two anticyclonic types (A and Asw) presented the highest increase in their frequencies at 500 hPa compared to their 1000 hPa frequencies (not shown). A northern shift of the depression trajectories at

500 hPa during 2014 seems to play also an important role to the decreasing frequency trend of the cyclonic types at this level, supported by the fact that the two cyclonic types Cse and Cne present a pronounced decrease in their frequencies at the 500 hPa level, in 2014.

3.4 Links with the general atmospheric circulation

The atmospheric geopotential anomaly patterns that dominated during the year of 2014 were examined at both levels 1000 and 500 hPa. However, due to the clearer representation of the teleconnection patterns at 500 hPa, we decided to present them only in the present study (Fig. 8). The most intriguing finding was the very weak and in some cases almost absent North Atlantic Oscillation (NAO) signal during this year, probably due to the changes of the atmospheric circulation over the Atlantic Ocean and especially the western Europe and Mediterranean region. It was noted that this "weak" NAO pattern has been replaced by other teleconnection patterns, such as the Scandinavian one (Barnston and Livezey 1987) which was never detected before in previous studies of extreme rainfall in Greece. In general, the locations of the negative and mainly the positive anomaly centres vary throughout the year. For each month, other than NAO, widely used teleconnection patterns (Scandinavian Pattern (SCAND; Barnston and Livezey 1987), Eastern Mediterranean Teleconnection Pattern (EMPI; Hatzaki et al. 2007, 2009) and North Sea-Caspian Pattern (NCP; Kutiel and Benaroch 2002)) were identified. Specifically

- The positive phase of the SCAND which is mainly associated with increased precipitation over the Mediterranean region is observed during January, March, April, July, August, September, October and November. A positive anomaly centre is located at the northern part of Europe (mainly over Scandinavian) and a negative one at western and south-western Europe where in some cases, it extends over the Mediterranean region. Especially for January and November, it can be noted that the observed anomaly distribution is an intermediate pattern between the negative phase of NAO and the positive SCAN phase. Both of them are linked with higher rainfall totals over the Mediterranean.
- The positive phase of EMPI is found during May, June and December. As Hatzaki et al. (2007, 2009) mention, this positive phase is highly connected with increased precipitation totals over eastern Mediterranean and especially Greece.
- The negative phase of NCP with a slight displacement of the centres of the two poles is observed during February. This phase is once more associated with increased precipitation over eastern Mediterranean.
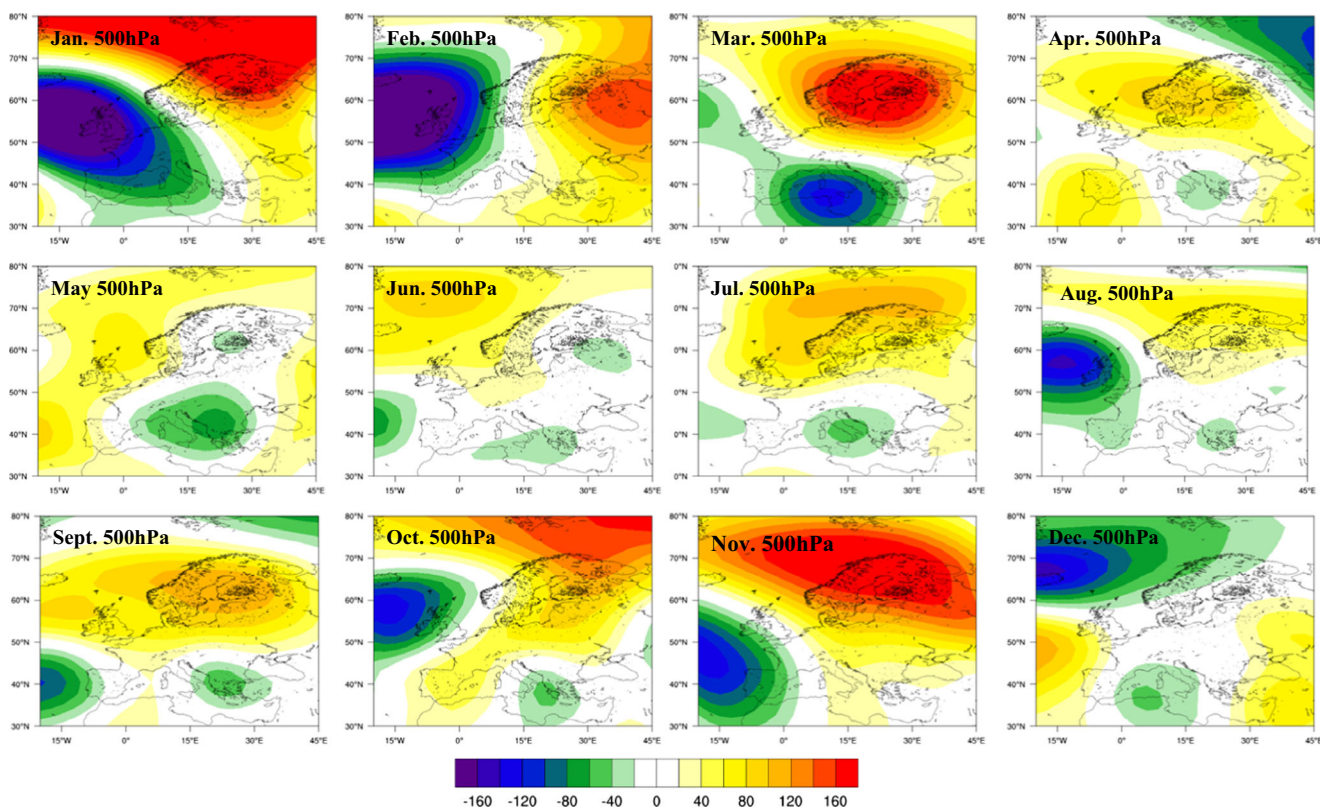
Fig. 8 Monthly anomaly patterns of 2014 raindays (in comparison to the mean period 1981–2010) at the 500 hPa isobaric level

4 Conclusions and discussion

There are several key conclusions derived from this study:

- With 912.2 mm and 133 raindays measured during 2014 in the region of Thessaloniki and taking into account that both the annual rainfall heights and number of raindays present a slight negative (no statistically significant trend) during the years from 1958 to 2014, it is evident that 2014 can be characterized as the wettest one since the beginning of the study period. The exceeding 277.1 mm from the statistical parameter of (mean + 2stdev) cannot be attributed to the natural variability of precipitation over the region but could probably be linked to anthropogenic impact to the climate of Thessaloniki. Moreover, this exceptionally wet year was not only detected in Greece, but it possibly was a more large-scale phenomenon over the Balkan Peninsula since extreme precipitation heights were also detected in the Serbian region (Tošić et al. 2016).
- The computation of several extreme precipitation indices also strengthened the exceptional rainfall characteristics of 2014. Even though these indices presented either positive (SDII, RX1day, R10m, R99p) or negative trends (R20m, R95p), 2014 exceeded the previous maximum in five out the six of them. Specifically, it presented the highest daily rainfall intensity (SDII) as well as the maximum daily

precipitation amount (RX1day). The examined year had the highest number of heavy rainfall days (R10m) and the greatest amounts of precipitation higher than the 95th and 99th percentiles.
- Another worth mentioning change that was observed during 2014 was the fact that the proportions of seasonal precipitation also differentiated. In general, during the past years, approximately 27–28% of the annual precipitation is attributed to winter, spring and autumn, while the equivalent percentage does not exceed 18%. During 2014, these proportions changed. Of total precipitation, 29% is due to the autumn heights, 26.9% to summer (highlighting once more the exceptionally wet summer of that year), 25.1% to winter and only 19.1% to spring. Even though previous studies showed that generally over Greece the extremes are mainly observed during winter (Houssos and Bartzokas 2006; Lionello et al. 2010), in our case, from a statistical point of view, mainly summer and autumn are the extreme seasons with the first presenting the maximum seasonal heights since 1958 and the second both the maximum precipitation and number of raindays.
- The summer maximum is mainly due to a 1-day precipitation. The 107.3 mm measured during a summer day (15 to 16 July, 2014) was the absolute maximum found for the station of Thessaloniki, and it is more than triple the threshold value of the 35 mm that was defined as an

extreme precipitation event for this specific station (Anagnostopoulou and Tolika 2012). A detailed analysis of the meteorological synoptic conditions during that day is given by Pytharoulis et al. (2016) mentioning that the intense precipitation, accompanied by lighting activity was not only influenced by the synoptic factors but also from the topography of the area of Thessaloniki, such as the almost closed and swallow Bay of Thessaloniki, that is in several case can play the role of a "lake" where the water, especially during summer, gets really warm during the evening hours contributing to the enrichment of the air humidity and thus to the atmospheric instability (Maheras and Balafoutis 1981).

- Year 2014 is characterized by a larger number of cyclonic days (in comparison to the period 1958–2013), at 1000 hPa, which is mainly attributed to the increased frequencies of occurrence of the cyclonic types during spring and summer. In general, the prevailing type is C (centred over the central part of Greece) with a south–south-western, south or south–south-east humid wind flow affecting the Thessaloniki region. A quite similar surface depression pattern was also detected by Houssos et al. (2008), with the cyclonic centre located over Peloponnisos, with was, according to the authors, highly associated with extreme precipitation events in Thessaloniki. Our finding comes also in accordance with Toreti et al. (2010) who noted that at SLP surface, the three clusters that are mainly related with extreme precipitation over the eastern Mediterranean present a low-pressure anomaly centre over the Aegean Sea.

- Focusing on the 500 hPa analysis, it was found that during this exceptional year from a rainfall point of view, the most frequent cyclonic types were C (during year, spring, summer and autumn) and Cwsw (during winter). These two types were also highly associated with heavy precipitation conditions over the eastern Mediterranean in one of our previous studies (Tolika et al. 2007). According to the authors, C and Cwsw types are characterized by successive cold and warm air flows and kinetic and potential energy exchange, which depend to the deepening of the depression as well as the intensity of the cold air intrusion could lead to extreme rainfall conditions over the action area.

- Over the seasonal scale, it was detected that during 2014, the characteristics of the cyclonic types differ depending on the examined season. For autumn, which was characterized as the most extreme season, the most frequent type (C) is not only both the rainiest and the most intense one at both isobaric levels. Conversely, for summer, the findings on the type's characteristics are quite more complicated. Even though type C was still the most frequent one, it can be characterized as the wettest and the most intense (precipitation-wise) one only at 500 hPa, while at the near

surface level, type Cne is the one that is mainly associated with rainfall (amounts and intensity). Thus, extreme precipitation seems to be highly depended on seasonal conditions and physical and atmospheric mechanisms that are associated with rainfall extremes. The different timescale that an analysis is conducted could lead to different conclusions on the atmospheric patterns that are linked with extreme precipitation events. Even though Steinbrich et al. (2005) study referred to a region with very different climatic characteristics (south-western Germany), their analysis derived to analogous conclusions on the seasonal differentiation.

- To sum it up, it should be mentioned that the extreme rainfall activity during 2014 in Greece was on one hand a result of the increased frequency of some cyclonic types (e.g. C, Csw, Cne) depending on the atmospheric level and the season and on the other hand to the increased percentage of precipitation attributed most of the times to the same type and to their increased daily rainfall amount (intensity).

- Finally, even though previous studies of precipitation extremes over Greece showed that these events are connected with the NAO index (positive phase precipitation reduction, Kioutsioukis et al. 2010), in our study, it was demonstrated that the monthly 2014 geopotential anomalies for both atmospheric levels in respect to the known teleconnection patterns (SCAN, EMPI, NCP) revealed that the prevailing pattern is the Scandinavian one (in 8 out of the 12 months). This is a quite surprising finding since it was never observed before that SCAN teleconnection is so highly associated with intense precipitation over Greece. It seems that during 2014, the under study physical factors that resulted to the formation of the atmospheric over the eastern Atlantic, Europe and Mediterranean played a substantial role to this exceptional frequency of occurrence of the SCAN teleconnection pattern leading to the extreme rainfall amounts during 2014 in our country.

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank AMG, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Kumar KR, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res-Atmos 111:D05109

Alpert P, Ben-Gai T, Baharad A, Benjamini Y, Yekutieli D, Colacino M, Diodato L, Ramis C, Homar V, Romero R, Michaelides S, Manes A (2002) The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values. Geophys Res Lett 29(11):1536

Anagnostopoulou C, Tolika K (2012) Extreme precipitation in Europe: statistical threshold selection based on climatological criteria. Theor Appl Climatol 107:479–489

Anagostopoulou C, Tolika K, Maheras P (2009) Classification of circulation types: a new flexible automated approach applicable ot NCEP and GCM datasets. Theor Appl Climatol 96:3–15

Barnston AG, Livezey RC (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon Weather Rev 115:1083–1126

Begueria S, Vicente-Serrano SM, Lopez-Moreno JI, Garcia-Ruiz M (2009) Annual and seasonal mapping of peak intensity, magnitude and duration of extreme precipitation events across a climatic gradient, northeast Spain. Int J Climatol 29:1759–1779

Drobinski P, Alonzo B, Bastin S, Da Silva N, Muller C (2016) Scaling of precipitation extremes with temperature in the French Mediterranean region: what explains the hook shape? J Geophys Res Atmos 121:3100–3119. doi:10.1002/2015JD023497

Hatzaki M, Flocas H, Asimakopoulos DN, Maheras P (2007) The eastern Mediterranean teleconnection pattern: identification and definition. Int J Climatol 27:727–737

Hatzaki M, Flocas H, Giannakopoulos CH, Maheras P (2009) The impact of the eastern Mediterranean teleconnection pattern at the Mediterranean climate. J Clim 22:977–992

Houssos EE, Bartzokas A (2006) Extreme precipitation events in NW Greece. Adv Geosci 7:91–96

Houssos EE, Lolis CJ, Bartzokas A (2008) Atmospheric circulation patterns associated with extreme precipitation amounts in Greece. Adv Geosci 17:5–11

IPCC (2012) Managing the risks of extreme events and disasters to advance climate change adaptation. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York 582 pp

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Met Soc 77:437–471

Kioutsioukis I, Melas D, Zerefos C (2010) Statistical assessment of changes in climate extremes over Greece (1955–2002). Int J Climatol 30:1723–1737

Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. J Clim 16: 3665–3680

Kostopoulou E, Jones PD (2005) Assessment of climate extremes in the eastern Mediterranean. Meteorog Atmos Phys 89:69–85

Krichak SO, Barkan J, Breitgand JS, Gualdi S, Feldstein SB (2015) The role of the export of tropical moisture into midlatitudes for extreme precipitaion events in the Mediterranean region. Theor Appl Climatol 121:499–515. doi:10.1007/s00704-014-1244-6

Kutiel H, Benaroch Y (2002) North Sea-Caspian Pattern (NCP)—an upper level atmospheric téléconnection affecting the eastern Mediterranean: implications on the regional climate. Theor Appl Climatol 72:173–192

Kyselý J (2009) Trends in heavy precipitation in the Czech Republic over 1961–2005. Int J Climatol 29:1745–1758

Li Y, Cai W, Campbell EP (2005) Statistical modelling of extreme rainfall in southwest western Australia. J Clim 18(6):852–863

Lionello P, Abrantes F, Congedi L, Dulac F, Gacic M, Gomis D, Goodess C, Hoff H, Kutiel H, Luterbacher J, Planton S, Reale M, Schröder K, Struglia MV, Toreti A, Tsimplis M, Ulbrich U, Xoplaki E (2010) Introduction: Mediterranean climate-background information. The climate of the Mediterranean region. Elsevier, Amsterdam ISBN: 978-0-12-416042-2

Maheras P, Balafoutis CH (1981) Essai d'interprétation du rythme diurne des orages d'été dans la région de Thessalonique. Recherches géographiques à Strasbourg 13-14:161–168

Maheras P, Patrikas I, Karacostas T, Anagnostopoulou C (2000) Automatic classification of circulation types in Greece: methodology, description, frequency, variability and trend analysis. Theor Appl Climatol 67:205–223

Maheras P, Flocas HA, Anagnostopoulou C, Patrikas I (2002) On the vertical structure of composite surface cyclones in the Mediterranean region. Theor Appl Climatol 71:199–217

Maheras P, Tolika K, Chr A, Vafiadis M, Patrikas I, Flocas H (2004) On the relationships between circulation types and changes in rainfall variability in Greece. Int J Climatol 24:1695–1712

Maheras P, Kolyva-Machera F, Tolika K, Anagnostopoulou C (2016) Les précipitations exceptionnelles de l'année 2014 dans la Grèce septentrionale. XXXIXe Colloque de l'Association Internationale de Climatologie, Lausanne-Besançon, 2016, 309–314 (in french)

Nastos PT, Zerefos CS (2007) On extreme daily precipitation totals at Athens, Greece. Adv Geosci 10:59–66

Nastos PT, Zerefos CS (2008) Decadal changes in extreme daily precipitation in Greece. Adv Geosci 16:55–62. doi:10.5194/adgeo-16-55-2008

Pytharoulis I, Kotsopoulos S, Tegoulias I, Kartsios S, Bampzelis D, Karacostas T (2016) Numerical modeling of an intense precipitation event and its associated lightning activity over northern Greece. Atmos Res 169(2016):523–538

Raveh-Rubin S, Wernli H (2015) Large-scale wind and precipitation extremes in the Mediterranean: a climatological analysis for 1979–2012. Q J R Meteorol Soc 141:2404–2417. doi:10.1002/qj.2531

Rebora N, Molini L, Casella E, Comellas A, Fiori E, Pignone F, Siccardi F, Silvestro F, Tanelli S, Parodi A (2013) Extreme rainfall in the Mediterranean: what can we learn from observations? J Hydrometeorol 14:906–922

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X (2012) Changes in climate extremes and their impacts on the naturalphysical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge and New York, pp 109–230

Steinbrich A, Uhlenbrook S, Reich T, Kolokotronis V (2005) Raum-zeitliche Zusammenhange zwischen Großwetterlagen und ¨Starkniederschlagen in Baden-Württemberg. WasserWirtschaft 11: 14–19

Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA (2006) Going to the extremes: an intercomparison of the model simulated historical and future changes in extreme events. Clim Chang 79:185–211

Tolika K, Anagnostopoulou C, Maheras P, Kutiel H (2007) Extreme precipitation related to circulation types for four case studies over the Eastern Mediterranean. Adv Geosci 12:87–93

Toreti A, Xoplaki E, Maraun D, Kuglitsch FG, Wanner H, Luterbacher J (2010) Characterisation of extreme winter precipitation in Mediterranean coastal sites and associated anomalous atmospheric circulation patterns. Nat Hazards Earth Syst Sci 10(5):1037–1050

Tošić I, Unkašević M, Putniković S (2016) Extreme daily precipitation: the case of Serbia in 2014. Theor Appl Climatol. doi:10.1007/s00704-016-1749-2