

Rainfall uncertainty in the Mediterranean: time series, uncertainty, and extreme events

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Abstract Temporal precipitation irregularities, extreme rainfall, or droughts represent great climate concerns and have major impacts on the natural environment. The present study focuses on 41 stations spread over the entire Mediterranean region. The datasets contain daily rainfall totals, with a median length of 56 years within the period of 1931–2006. The study aims at detecting significant trends in the time series and the uncertainties of four parameters: annual rainfall total, number of rain spells, the rain-spells yields, and rainy season length. In addition, it aims to detect significant temporal changes in the occurrence of extreme events of these parameters. Several methodologies have been used in this study, and the main conclusion is that despite the general assumption of tremendous changes in the rainfall regime, no significant temporal trends or uncertainty trends were found in most of the stations, neither in their annual totals, their number of rain spells, and their rain-spell yields, nor in their rainy season length. However, in the few cases that a significant trend was detected, former years tended to be wetter, longer, and with more abundant rain spells, while the opposite is seen in the later years; and uncertainty, tends to increase more than to decrease.

Abbreviations

| | |
|------|-------------------------------|
| MERR | most expected rainfall regime |
| NRS | number of rain spells |
| RRU | rainfall regime uncertainty |
| RSL | rainy season length |
| RSY | rain-spell yield |

| | |
|-------------|---|
| TOTAL | annual rainfall total |
| UI | uncertainty index |
| $\Delta(x)$ | departures of parameter (x) from the MERR or from the expected values after de-trending |

1 Introduction

Rainfall, like many other natural phenomena, is highly unpredictable. Temporal precipitation irregularities, droughts, and extreme rainfall represent great concerns in climate natural hazards and have major impacts on the natural environment and on society. The interest in these topics has increased and major efforts have been spent in learning about precipitation variability and predictability. Much attention is paid to future prospects regarding the climate change (Easterling et al. 2000a; Norrant and Douguédroit 2005).

The present study deals with three aspects of the rainfall regime: temporal trends, uncertainty, and extreme events. In the following paragraphs, a short review of previous studies is presented.

1.1 Temporal trends

On a global scale, New et al. (2001) detected a precipitation increase of about 9 mm over the twentieth century (a statistically significant trend of 0.89 mm per decade). As the present study focuses on the Mediterranean region, it is important to emphasize that the climate in this region is generally characterized by a complex pattern of seasonal variability with wide and unpredictable rainfall fluctuations from year to year (Ramos 2001; Ceballos et al. 2004).

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Therefore, tracking any kind of trends or shifts is a very complicated task to begin with. Several studies focused on the variability in the precipitation total. Most of these analyses have been carried out only for a part of the region, and most often were conducted for selected stations (De Luís et al. 2000; Brunetti et al. 2001a; b; 2004; González-Hidalgo et al. 2001; Ceballos et al. 2004).

Precipitation trends in the entire basin were analyzed in just a few studies, and a decrease in precipitation at seasonal and annual levels was pointed out. However, in many cases, this was a nonsignificant decrease during the second half of the twentieth century or there was not any linear trend during the last century (Norrant and Douguédroit 2005; Feidas et al. 2007).

Significant trends can be found only as isolated exceptions in a single region of Greece. Since 1984, Greece has entered into a dry period due to a significant decreasing trend, which was found in individual stations, e.g., in the mountainous regions of western Greece, whereas, for the entire Greek region it was less significant (Douguédroit and Norrant 2003; Maheras and Anagnostopoulou 2003; Norrant and Douguédroit 2005; Feidas et al. 2007).

Similar results of decreasing trends were identified also in other parts of the eastern Mediterranean. In Turkey, significant trends were detected only in 15 out of 91 stations. A complex pattern of seasonal variability was found: for all of Turkey's rainfall series, dry conditions were during the period 1955–1961, during the early 1970s, and from the early 1980s to 1993, whereas wet conditions occurred during the periods of 1935–1944 and 1951–1954, around the 1960s, and during the period 1975–1981 (Türkeş 1996). In northern Israel, a decreasing trend was identified for the period 1961 to 1990, while in the southern part of the country (characterized by a semiarid climate) an increase was identified (Goldreich 1995). Kutiel et al. (1996) analyzed the sequence of dry and wet seasons. One of their conclusions was that in recent decades dry sequences have been more intense, whereas wet sequences have been more common at the beginning of the twentieth century.

In the western Mediterranean, Maheras (1988) identified, within a dataset of 95 years, two principal and two secondary humid periods, and between them, there were one primary and one secondary dry periods. His conclusion was that precipitation in this region represents an approximate periodicity of 20 years. The principal results in Brunetti et al. (2001a) were that the number of wet days per year has decreased significantly all over Italy (mainly in winter) during a period of 46 years, while no significant trend was found in the annual rainfall total (TOTAL hereafter) in northern Italy (Brunetti et al. 2001a; b; 2004).

In northeastern Spain, the mean annual rainfall variation did not follow a consistent trend where dry, normal, and

wet years were not regularly distributed over time. However, during the most recent decades, lower annual variability (from year to year) was observed (Ramos 2001). In the last third of the twentieth century, a significant decrease in the TOTAL was found in the Duero basin (Spain), while in the two other units of the studied area (plain and rangeland), no such significant trends were found. Even though, the conclusion was that there is a greater variability in both inter- and intra-annual rainfall (Ceballos et al. 2004). In southeast Spain, Lázaro et al. (2001) used a *t* test to identify two different periods: a “wet” period from the beginning of the series (1967/1968–1973/1974) and a “normal” one (1974/1975–1996/1997). Applying a 10-year moving average in the Mediterranean parts of Spain revealed a relatively wet sequence until about 1910, followed by moderately dry years until 1945, with some very wet years in the 1930s, and a general increase in precipitation until 1970. The last period, since 1976, is characterized by a severe drought (Esteban-Parra et al. 1998). In Valencia, De Luís et al. (2000) found indications for a greater contrast in annual rainfall values from year to year.

1.2 Rainfall regime uncertainty

The term climatic uncertainty is related to the variability of a climatic parameter and refers to the inability to accurately estimate the magnitude of a certain climatic parameter at a given location and a given time. Climatic uncertainty may be detected in three different aspects:

Spatial uncertainty—refers to the inability to estimate or measure the location of the climatic features.

Temporal uncertainty—refers to the inability to estimate or measure the timing of the climatic features.

Magnitude uncertainty—refers to the inability to estimate or measure the intensity of the climatic features and therefore in its distribution.

The uncertainty level is influenced by each of these three dimensions.

The average of a climatic parameter may remain constant throughout a period of time, yet its variability may change over that period of time. When the variability decreases, the uncertainty decreases as well, and vice versa.

Paz and Kutiel (2003) introduced a methodological approach to define the degree of the rainfall regime uncertainty (RRU) in a given region. They calculated the most expected rainfall regime (MERR) as the median values of several components of the rainfall regime, e.g., the TOTAL, the number of rain spells (NRS), the rain-spells yields (RSY), rainy season length (RSL), and so on. These components were presented for the stations of Brindisi, Calarasi, and Jerusalem and for Valencia and Larnaca in Reiser and Kutiel (2006, 2007, respectively).

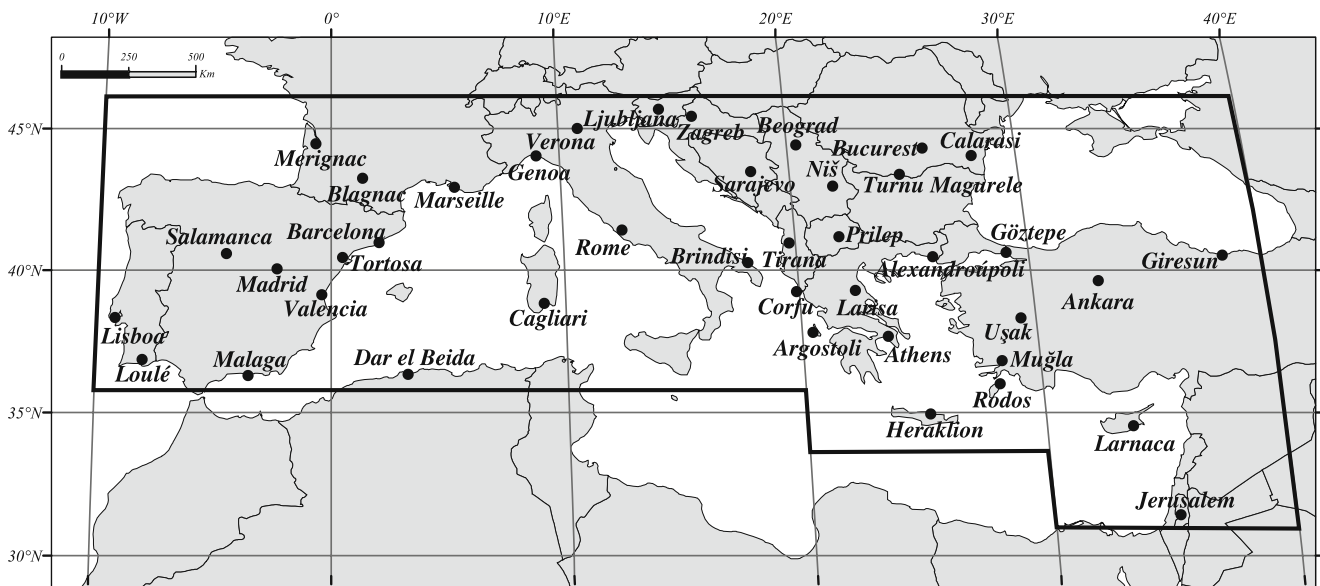


Fig. 1 The study area and the location of rain stations

Once the MERR is calculated, it is possible to define how much a season or a period varies from the MERR. This is done by estimating the departures of each component from the MERR (referred as Δ of the appropriate parameter) over the decades. To quantify the entire uncertainty degree of these departures, an uncertainty index (UI) was introduced, which summarizes the absolute departures of all components (Paz and Kutiel 2003).

This methodological approach was applied on 22 stations in Greece, for the period 1958–1999. The highest UI values were found in continental stations and in Crete. The departures from the TOTAL (Δ TOTAL) played the most dominant role in these highest values (Anagnostopoulou et al. 2008).

1.3 Extreme precipitation events

Changes in precipitation have often been quantified in terms of changes in the TOTAL over long averaging periods, e.g., annual, seasonal, and occasionally monthly. Such statistics, although quite useful for many applications, do not reveal important aspects of how precipitation changes over such a long averaging period (Karl and Knight 1998). There may be, for example, a shift towards fewer but more intense precipitation events in a period, or vice versa. Therefore, a change in the variance of the distribution will also have an important effect on the frequency of extremes along with a change in the average. This type of shift is distinguishable when the extreme extent is of at least one standard deviation below or above the average. However, the average and the standard deviation may change at the same time, consequently altering the

occurrence of extreme events in several different ways. Extreme events are considered good indicators for tracking climatic changes. Scientists use different criteria to define an extreme climatic event. This lack of consensus on the definition of extreme events, together with other problems, such as a lack of suitable homogeneous data for many parts of the world, likely means that it will be difficult, if not impossible, to say that extreme events in general have changed in the observed record (Kutiel 1990; Meehl et al. 2000; Easterling et al. 2000b; New et al. 2001).

Some examples for the accepted definitions were presented by Easterling et al. (2000a) and New et al. (2001) who set a definition according to the impact an event had on society. This impact may involve excessive loss of life, excessive economic or monetary losses, or both. Extreme events are sometimes represented in the tails of the distribution, that is, values that are far from the average or the median value of the series (Rodrigo 2002). Thus, extreme events were defined when the daily rainfall exceeded at least twice the standard deviation of the long-term average wet day rainfall at a specific location or according to their recurrence period (Kunkel et al. 1999; Fowler and Kilsby 2003).

Groisman et al. (1999) defined extreme events simply by setting a threshold of 50.8 mm/day. Alpert et al. (2002) analyzed the impact of a future reduction in annual rainfall on the temporal variability of rainfall intensities. They set thresholds which categorized “Heavy” daily rainfall as 32–64 mm/day, “Heavy-Torrential” as 64–128 mm/day, and “Torrential” as >128 mm/day. They identified a phenomenon in which, in the Mediterranean region, extreme daily rainfall increased despite the general decrease of the TOTAL.

Table 1 Main characteristics of rain stations

| Country | Station name | Longitude [°] | Latitude [°] | Study period |
|---------------------|------------------------|---------------|--------------|------------------------|
| Albania | Tirana | 19 47E | 41 20N | 1946–1986 |
| Algeria | Dar el Beida | 03 15E | 36 43N | 1940–2006 |
| Bosnia | Sarajevo | 20 60E | 42 70N | 1931–2005 |
| Croatia | Zagreb | 15 59E | 45 49N | 1931–2006 |
| Cyprus | Larnaca | 33 38E | 34 55N | 1931–2006 |
| France | Blagnac | 01 23E | 43 37N | 1947–2006 |
| | Marseille | 05 23E | 43 18N | 1931–2004 |
| | Merignac | 00 41W | 44 50N | 1947–2006 |
| Greece | Alexandroupoli | 25 55E | 40 51N | 1958–2000 |
| | Athens | 23 40E | 38 03N | 1955–2006 |
| | Argostoli | 20 29E | 38 11N | 1958–2000 |
| | Corfu | 19 55E | 39 37N | 1955–2006 |
| | Heraklion | 25 11E | 35 20N | 1955–2006 |
| | Larisa | 22 27E | 39 39N | 1955–2006 |
| | Rodos | 29 10E | 36 23N | 1958–2000 |
| Israel | Jerusalem | 35 13E | 31 46N | 1950–2004 |
| Italy | Brindisi | 17 56E | 40 38N | 1956–2004 |
| | Cagliari | 09 03E | 39 14N | 1951–2006 |
| | Genoa | 09 00E | 44 24N | 1949–1996 |
| | Rome | 12 35E | 41 47N | 1951–1998 ^a |
| | Verona | 10 52E | 45 23N | 1951–2006 |
| FYROM | Prilep | 21 57E | 41 33N | 1949–1995 |
| Portugal | Lisboa | 09 09W | 38 43N | 1947–2006 |
| | Loulé ^c | 08 00W | 37 15N | 1931–2005 |
| Romania | Bucurest | 26 06E | 44 25N | 1931–2006 |
| | Calarasi | 27 20E | 44 12N | 1938–2006 |
| | Turnu Magurele | 24 53E | 43 45N | 1938–2000 |
| Serbia | Beograd | 20 28E | 44 48N | 1936–2006 |
| | Niš | 21 54E | 43 20N | 1949–2006 |
| Slovenia | Ljubljana | 14 31E | 46 04N | 1950–2006 |
| Spain | Barcelona ^d | 02 09E | 41 23N | 1965–2001 |
| | Madrid | 03 41W | 40 25N | 1950–2006 |
| Turkey ^e | Malaga | 04 29W | 36 40N | 1943–2006 |
| | Tortosa | 00 29E | 40 49N | 1946–2006 |
| | Salamanca | 05 28W | 40 56N | 1945–2006 |
| | Valencia | 00 21W | 39 28N | 1938–2006 |
| | Ankara | 32 53E | 39 57N | 1948–2003 ^b |
| | Giresun | 38 23E | 40 55N | 1948–2003 |
| | Göztepe | 29 05E | 40 58N | 1948–2003 |
| Muğla | 28 22E | 37 13N | 1948–2003 | |
| Uşak | 29 24E | 38 41N | 1948–2003 | |

^a The season of 1978/9 was omitted due to lack of data

^b The seasons of 1964/5 and 1965/6 were omitted due to lack of data

^c Data obtained from Laboratorio Nacional de Engenharia Civil (LNEC), Portugal

^d Data obtained from University Politecnica de Catalunya

^e Data obtained from Turkish State Meteorological Service (TSMS)

Another accepted approach is to analyze the lowest and highest percentiles of precipitation, e.g., the 10th and the 90th or the 5th and the 95th percentiles. Suppiah and Hennessy (1998) identified a general increase in heavy rainfall intensity and a decrease in dry days, which led to an increase of the TOTAL in Australia. This method was also adopted in other studies, e.g., Haylock and Nicholls (2000),

Manton et al. (2001), Norrant and Douguédroit (2005), Becker et al. (2007), Dufek and Ambrizzi (2007), and Tolika et al. (2007).

Osborn et al. (2000) and Osborn and Hulme (2002) defined extreme events as daily precipitation contributing at least 10% of the seasonal TOTAL. Livada et al. (2008) focused on return periods of an extreme value and set

Fig. 2 Schematic representation of **a** the possible relationships between the trend of a parameter (represented by the *trend line*) and the trend of its variability (represented by the *oscillating curve*), **b** the absolute departures when no de-trending is applied, and **c** the absolute departures after de-trending. The *horizontal axis* represents a time scale

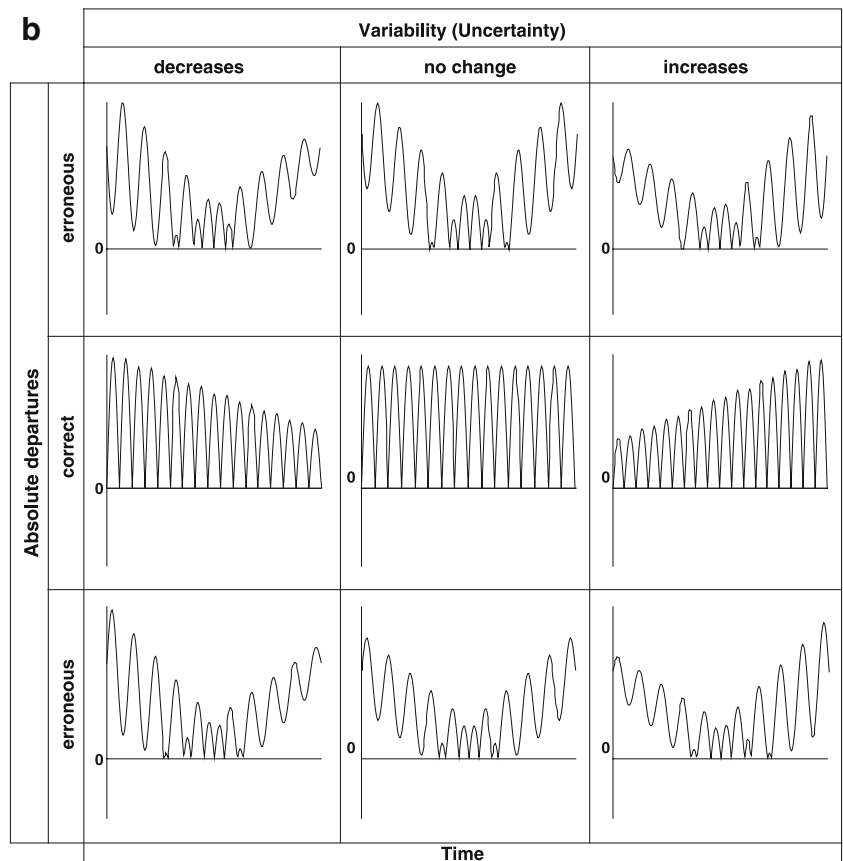
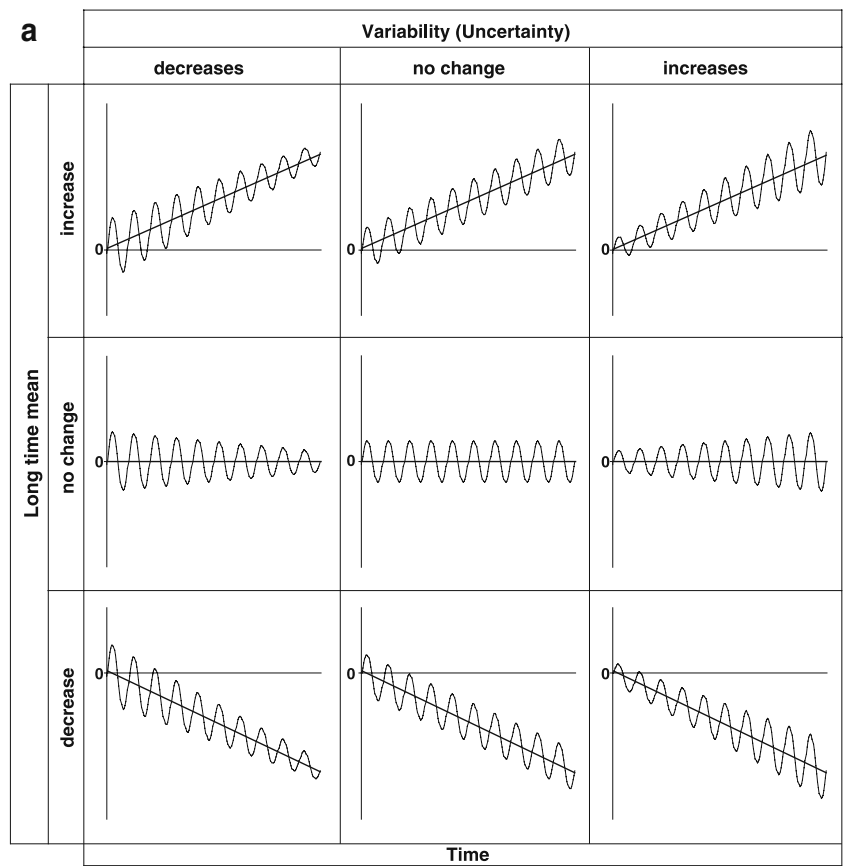
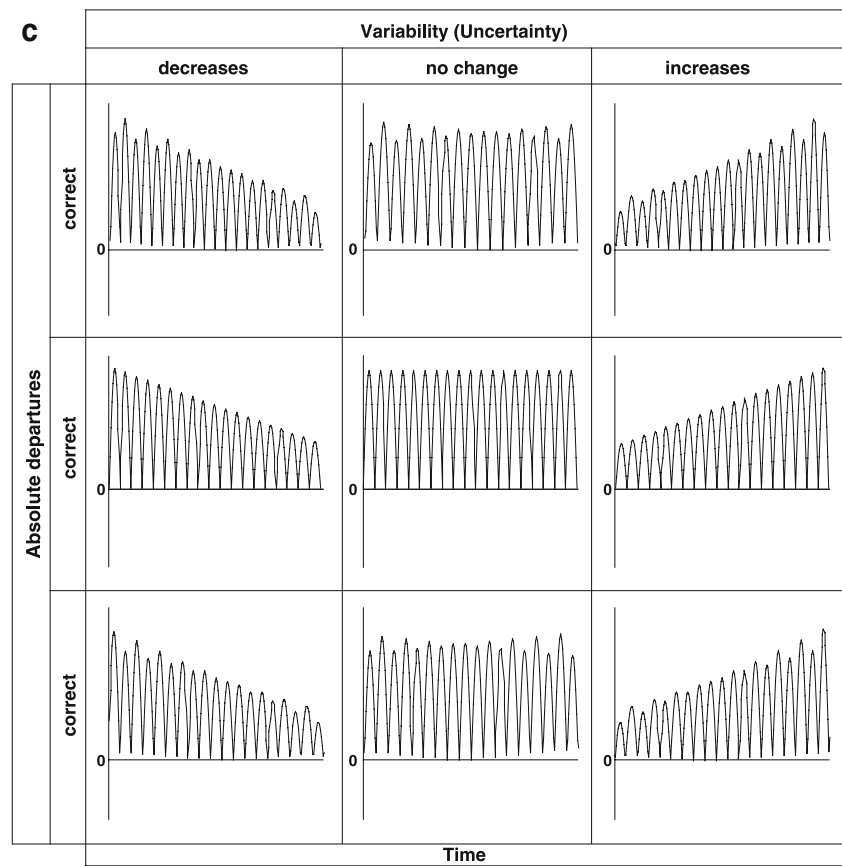


Fig. 2 (continued)



recurrence intervals, like 1 year or longer. They concluded that extreme values are more frequent in spring time in the northern parts of Greece, while in the southern and the south-eastern parts, extreme rainfall amounts are more frequent during winter. In the north-west of the country, the average precipitation depth per extreme precipitation day is approximately 48 mm, and the number of extreme precipitation days per year is approximately five. However,

during the study period (1970–2002), certain fluctuations have been recorded and most of them were associated with atmospheric circulation changes within the Mediterranean. In the late 1970s, high frequency of extreme precipitation days was recorded, their frequency decreased around the 1990s. In recent years, the occurrence of extreme events appears to be around normal again (Houssos and Bartzokas 2006).

Table 2 Significant trends for all parameters and the changing year

| Parameter | Station name | Equation | Trend shifting year | <i>r</i> |
|-----------|--------------|-------------------------------------|---------------------|----------|
| TOTAL | Dar el Beida | $y = -0.351x^2 + 19.976x + 444.443$ | 1969 | 0.65 |
| NRS | Dar el Beida | $y = -0.007x^2 + 0.365x + 28.246$ | 1967 | 0.50 |
| | Verona | $y = -0.003x^2 + 0.012x + 44.158$ | 1953 | 0.40 |
| | Salamanca | $y = -0.008x^2 + 0.471x + 35.805$ | 1975 | 0.37 |
| | Argostoli | $y = 0.015x^2 - 0.815x + 34.729$ | 1986 | 0.46 |
| RSY | Corfu | $y = 0.011x^2 - 0.619x + 37.071$ | 1984 | 0.40 |
| | Brindisi | $y = 0.073x + 13.029$ | | 0.33 |
| | Rodos | $y = 0.017x^2 - 0.811x + 34.535$ | 1982 | 0.32 |
| | Dar el Beida | $y = -0.008x^2 + 0.466x + 15.693$ | 1970 | 0.51 |
| | Rome | $y = -0.006x^2 + 0.379x + 13.847$ | 1983 | 0.46 |
| | Prilep | $y = -0.004x^2 + 0.173x + 10.393$ | 1971 | 0.40 |
| | Verona | $y = -0.005x^2 + 0.290x + 15.107$ | 1980 | 0.31 |
| RSL | Barcelona | $y = -1.245x + 315.563$ | | 0.32 |
| | Bucurest | $y = -0.508x + 329.989$ | | 0.31 |

Stations are sorted according to the direction of their trend (first positive and then negative) and to the correlation coefficient (*r*) in a descending order

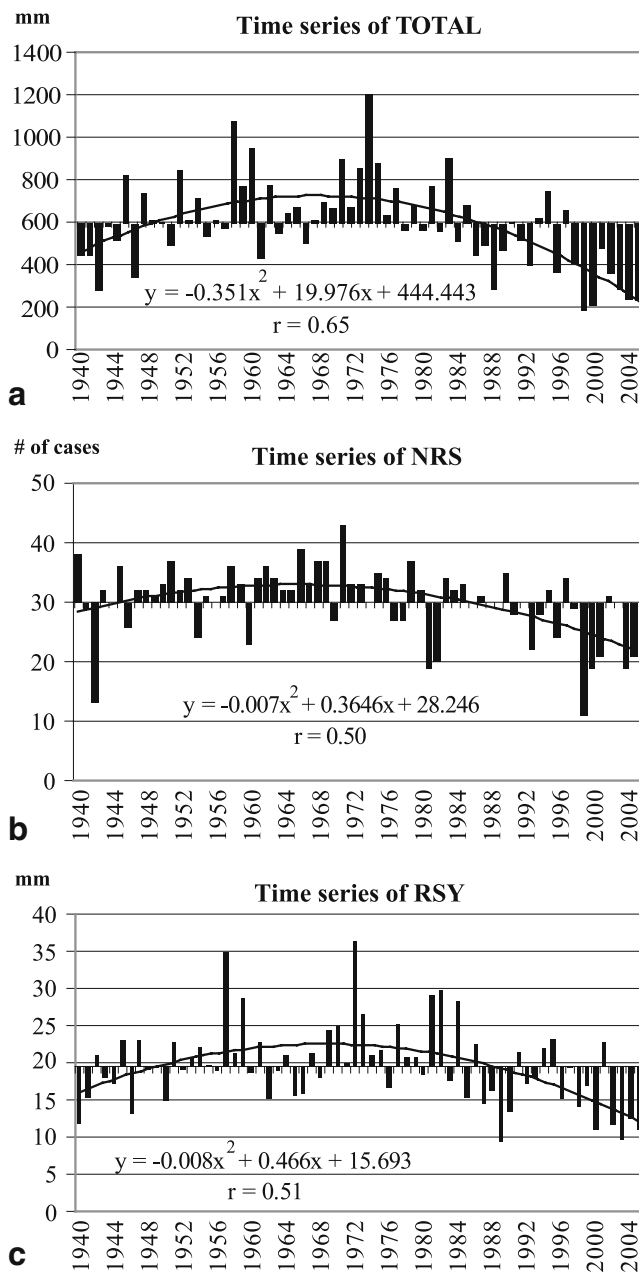


Fig. 3 Some examples of significant trends of **a** TOTAL, **b** NRS, and **c** RSY in Dar el Beida. The horizontal axis crosses the vertical one at the median or average value of each parameter

1.4 Scopes of the present study

The present study presents additional aspects of four parameters: TOTAL, RSL, NRS, and RSY (as described in details by Reiser and Kutiel 2007) regarding their temporal trends, uncertainty, and extreme values. This is achieved for the entire Mediterranean basin based on the same data set.

The detailed objectives of this research are:

1. To detect significant trends ($p < 0.05$) in the time series of four parameters: TOTAL, RSL, NRS, and RSY

2. To detect significant trends ($p < 0.05$) in the uncertainty of these four parameters
3. To detect significant temporal changes ($p < 0.05$) in the occurrence of extreme events of these parameters
4. To detect if there is any spatial distribution of significant trends of the previous objectives

2 Study area and data

The study area, presented in Fig. 1, includes most of the Mediterranean basin, represented by 41 rain stations, between longitudes 10°W and 40°E and latitudes 30° and 46°N (excluding the North African coasts). Daily rainfall data within the period of 1931 and 2006 were obtained from the European Climate Assessment & Dataset (ECA&D). A dataset of at least 36 years was used for each station (Table 1). The selection of stations was based on the availability of entire data sets without missing data (with very few exceptions, see Table 1), and therefore, no further process of completing data was necessary. Data was tested for homogeneity and was proved to be homogenous.

3 Methodology

The methodological process includes the following steps done in every station:

3.1 Trends in the time series

- A polynomial of the 1st order (linear) or the 2nd order was fitted to the time series of the TOTAL, the average NRS, and the average RSY of all durations and the RSL.
- Significant ($p < 0.05$) trends were retained and presented.

3.2 Trends in the rainfall regime uncertainty—RRU

- Departures of the TOTAL, NRS, RSY, and RSL of each year from the corresponding MERR were calculated.
- For the significant trends, the departures were calculated from the de-trended values (see below).

Figure 2a presents various possible relationships between a certain trend of a parameter and a certain trend of its variability (represented by the oscillating curve). The average of a climatic parameter may remain constant

Table 3 Significant trends for all uncertainty parameters and the changing year

| Parameter | Station name | Equation | Trend shifting year | <i>r</i> |
|----------------|----------------|----------------------------|---------------------------|----------|
| ΔTOTAL | Prilep | $y=0.001x^2-0.045x+1.018$ | 1968 | 0.39 |
| | Giresun | $y=0.001x^2-0.042x+1.356$ | 1984 | 0.33 |
| | Athens | $y=0.001x^2-0.051x+1.201$ | 1981 | 0.33 |
| | Calarasi | $y=0.000x^2-0.027x+1.000$ | 1966 | 0.32 |
| | Merignac | $y=0.000x^2-0.005x+0.689$ | 1959 | 0.29 |
| | Rome | $y=0.001x^2-0.043x+1.091$ | 1974 | 0.29 |
| | Tortosa | $y=-0.000x^2+0.022x+0.704$ | 1968 | 0.31 |
| ΔNRS | Larisa | $y=0.001x^2-0.066x+1.399$ | 1983 | 0.32 |
| | Ankara | $y=0.000x^2-0.035x+1.329$ | 1986 | 0.33 |
| | Brindisi | $y=0.001x^2-0.036x+1.006$ | 1977 | 0.32 |
| | Rodos | $y=0.001x^2-0.046x+1.322$ | 1988 | 0.32 |
| ΔRSY | Argostoli | $y=0.003x^2-0.164x+2.829$ | 1986 | 0.64 |
| | Tirana | $y=0.0009x^2-0.06x+1.4881$ | 1980 | 0.44 |
| | Merignac | $y=0.014x+0.408$ | | 0.42 |
| | Rome | $y=0.000x^2-0.009x+0.662$ | 1963 | 0.31 |
| | Salamanca | $y=-0.0125x+1.1731$ | | 0.36 |
| | Tortosa | $y=-0.001x^2+0.044x+2.250$ | 1968 | 0.34 |
| ΔRSL | Argostoli | $y=0.019x+0.359$ | | 0.37 |
| | Larnaca | $y=0.001x^2-0.038x+1.163$ | 1967 | 0.34 |
| | Athens | $y=0.001x^2-0.017x+0.775$ | 1972 | 0.34 |
| | Rodos | $y=0.001x^2-0.038x+1.275$ | 1996 | 0.33 |
| | Turnu Magurele | $y=-0.001x^2+0.039x+0.446$ | 1967 | 0.33 |
| | Valencia | $y=-0.001x^2+0.037x+0.290$ | 1976 | 0.29 |
| | UI | Rodos | $y=0.002x^2-0.128x+3.810$ | 1988 |
| Argostoli | | $y=0.004x^2-0.170x+4.055$ | 1980 | 0.39 |
| Athens | | $y=0.002x^2-0.070x+2.812$ | 1973 | 0.36 |
| Tirana | | $y=0.001x^2-0.085x+3.301$ | 1989 | 0.35 |
| Giresun | | $y=0.001x^2-0.055x+3.278$ | 1976 | 0.34 |
| Larnaca | | $y=0.001x^2-0.080x+3.297$ | 1971 | 0.32 |
| Malaga | | $y=0.019x+1.789$ | | 0.31 |
| Turnu Magurele | | $y=-0.001x^2+0.043x+2.200$ | 1960 | 0.32 |

Stations are sorted according to the direction of their trend (first positive and then negative) and to the correlation coefficient (*r*) in a descending order

throughout a period of time (as illustrated in the central row), yet its variability may change over that period of time. When the variability decreases, the uncertainty decreases as well (left chart in the central row), and vice versa (right chart in the central row).

If no de-trending was performed, and the departures would have been calculated from the MERR, the results would have been misleading. For example, the upper row in Fig. 2a illustrates three different cases in which there is an increase trend in the parameter with a decrease in the uncertainty (left), no change in the uncertainty (middle), and an increase in the uncertainty (right). If the departures would have been calculated from the MERR (the horizontal line), without de-trending, they would decrease towards the middle of the period and then increase towards its end, in all three cases (upper row in

Fig. 2b) regardless of the actual conditions. The departures calculated after the de-trending process (upper row in Fig. 2c) are in accordance with the actual conditions (upper row in Fig. 2a).

The same is true if the parameter presents a decrease, as in the lower row in Fig. 2a. Absolute standardized deviations (the uncertainty) were calculated.

ΔNRS is calculated according to Eq. 1 and measures how much the number of rain spells of a given duration [days] in a certain year varies from the average:

$$\Delta NRS = \frac{\sum_{d=1}^k \frac{|NRS_{(d)} - \overline{NRS}_{(d)}|}{\sigma_{(NRS_{(d)})}}}{k} \tag{1}$$

d indicates rain-spell duration [days], *k* represents how detailed the repartition into rain spells' categories is.

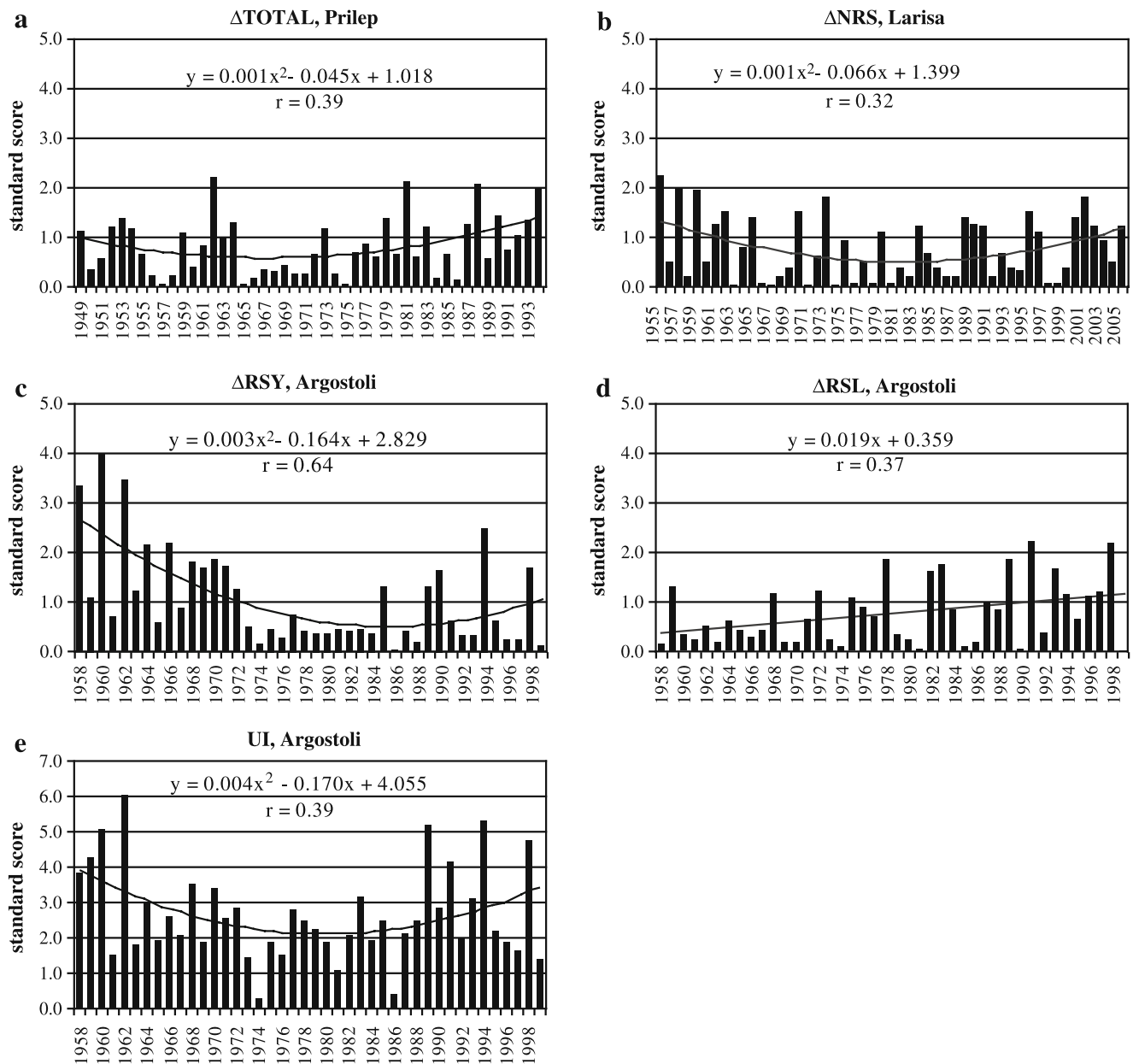


Fig. 4 Some examples of time series of departures from the mean (or de-trended) series of **a** Δ TOTAL, **b** Δ NRS, **c** Δ RSY, **d** Δ RSL, and **e** UI from Prilep, Larisa, and Argostoli and significant trends

Δ RSY is calculated according to Eq. 2 and measures how much the yield of rain spells of a given duration [days] in a certain year varies from the average:

$$\Delta\text{RSY} = \frac{\sum_{d=1}^k \frac{|\text{RSY}_{(d)} - \overline{\text{RSY}_{(d)}}|}{\sigma(\text{RSY}_{(d)})}}{k} \quad (2)$$

The significance of d and k are the same as in Eq. 1.

It is usually preferable to use the median upon the average when describing rainfall features due to the skewed distribution. However, as in most stations in the majority of the years (>50%), there were no rain spells with durations

longer than 3 days; the use of the median would provide zeros both for the NRS and the RSY. Therefore, for these two parameters, the average was used.

Δ RSL is calculated according to Eq. 3 and measures how much the length of a certain year varies from the median RSL:

$$\Delta\text{RSL} = \frac{|RSL - \text{med}_{(RSL)}|}{\sigma_{(RSL)}} \quad (3)$$

An UI comprises the following standardized components: The absolute average deviation of the NRS (Δ NRS), absolute average deviation of the RSY (Δ RSY), and

Table 4 Significant *t* tests results for all parameters

| Station name | TOTAL | NRS | RSY | RSL |
|----------------|-------|-------|--------|-------|
| Dar el Beida | 0.016 | 0.016 | 0.036 | n.s. |
| Alexandroupoli | 0.045 | 0.002 | n.s. | n.s. |
| Argostoli | 0.018 | 0.010 | n.s. | n.s. |
| Marseille | 0.013 | n.s. | <0.001 | n.s. |
| Jerusalem | 0.035 | n.s. | 0.045 | n.s. |
| Corfu | 0.016 | n.s. | n.s. | n.s. |
| Valencia | 0.035 | n.s. | n.s. | n.s. |
| Rodos | 0.047 | n.s. | n.s. | n.s. |
| Tortosa | n.s. | 0.015 | n.s. | n.s. |
| Rome | n.s. | n.s. | 0.001 | n.s. |
| Niš | n.s. | n.s. | 0.033 | n.s. |
| Beograd | n.s. | n.s. | n.s. | 0.042 |
| Bucurest | n.s. | n.s. | n.s. | 0.017 |
| Malaga | n.s. | n.s. | n.s. | 0.019 |
| Brindisi | n.s. | n.s. | n.s. | 0.025 |
| Madrid | n.s. | n.s. | n.s. | 0.050 |

Stations are sorted according to the number of significant results in a descending order

absolute median deviation of the RSL (Δ RSL), as presented in Eq. 4.

$$UI = |\Delta NRS| + |\Delta RSY| + |\Delta RSL| \quad (4)$$

The TOTAL is the product of NRS by RSY, according to Eq. 5:

$$TOTAL = NRS \times RSY \quad (5)$$

Therefore, it is not part of the UI and does not appear in Eq. 4. However, Δ TOTAL was calculated separately according to Eq. 6 as another measure of uncertainty quantifying how much a certain year varies from the median TOTAL:

$$\Delta TOTAL = \sum_{d=1}^k \left| \frac{TOTAL_{(d)} - \overline{TOTAL}_{(d)}}{\frac{\sigma_{(TOTAL)}}{k}} \right| \quad (6)$$

The significance of *d* and *k* are the same as in Eq. 1.

- An analysis of the time series of the absolute standardized deviations of all components in the previous step was made by fitting a polynomial (linear or second order).

In order to detect the shifting year of any significant 2nd order polynomial (of both the parameters and the uncertainty):

- The derivative of the function was calculated and equaled to 0.

3.3 Extreme events

- The lowest and highest 10% of the TOTAL, the NRS, the RSY, and the RSL were sampled in each station and their average was calculated (separately for each group). A *t* test assessed whether the timing of the lowest and highest 10% of years, respectively, are statistically different ($p < 0.05$), from one another.

3.4 Spatial trends

- The spatial distribution of the significant temporal trends, significant uncertainty trends, and their shifting years was checked.

4 Results and discussion

4.1 Trends in the time series

All together, 164 trends were tested (four parameters in 41 stations). In most stations, no significant trends were found and only 14 significant trends ($p < 0.05$, 8.5% of the total analyzed trends) were detected (Table 2). Assuming that 5% of the analyses may be significant randomly, the obtained results are only slightly above this value. This means that the general belief of a tremendous change in the rainfall regime is not fully supported by the results. Dar el Beida is the only station in which significant trends were found in three out of the four analyzed parameters: TOTAL, NRS, and RSY, demonstrating also the highest correlation coefficients. Their time series and polynomial trends are presented in Fig. 3.

4.1.1 TOTAL

Only one significant polynomial (2nd order) trend was found in Dar el Beida. Ten consecutive years, between 1966 and 1975, were wetter than the median conditions. The last 8 years of the period were much drier. These facts may explain the increase from 1940 to 1968 and their decrease, since (Fig. 3a). The TOTAL is the outcome of the multiple of NRS by RSY. Therefore, the correlation coefficient (*r*) is the highest 0.65.

4.1.2 NRS

Three significant polynomial (2nd order) trends were found in Dar el Beida (Fig. 3b), Verona, and Salamanca (Table 2). According to these trends, there were decreases in the NRS since 1967, 1953, and 1975, respectively.

4.1.3 RSY

In four out of the eight significant trends, a decrease was found since the 1970s; in three, there has been an increase since the 1980s. Finally, in Brindisi, a positive linear trend was found (Table 2). In Dar el Beida, an increase was observed between 1940 and 1970, and the yields have decreased since (Fig. 3c).

4.1.4 RSL

Two significant negative linear trends were found, in Barcelona and in Bucurest (Table 2). In these two stations, a shortening of the RSL by 12 and 5 [days/decade], respectively, was observed.

4.2 Trends in the rainfall regime uncertainty—RRU

Altogether, 205 trends were tested for the RRU: the trends of the Δ TOTAL and the trend of the UI and the three trends of its components in all 41 stations. Only 31 trends (15.1%) were significant. In 23 stations, no significant trends were found at all. In 15 stations, there was at least one parameter with a significant trend, while in Athens, Argostoli, and Rodos, three significant trends were identified. Generally, most trends presented a polynomial type in which there was a shift from a negative trend to a positive one around the 1960s, 1970s, or 1980s. This means that the uncertainty increased since these decades. However, these trends' coefficients are small, ranging between 0.29 and 0.64 with an average of 0.35 (Table 3).

Figure 4 presents some examples of time series of departures from the mean (or de-trended) series. Each box represents the absolute annual departure from these series. For each time series, a polynomial (1st or 2nd order) was fit and is presented.

4.2.1 Δ TOTAL

Figure 4a presents the time series of Δ TOTAL and the positive significant trend found in Prilep, as an example. Four years with large departures (>2.0) from the median TOTAL conditions were found. Two years (1962 and 1981) were wetter compared to the median (506.2 mm) with 784.3 and 774.9 mm, respectively. The other 2 years (1988 and 1994) were drier than the median conditions with only 275.8 and 288.0 mm, respectively. There were seven consecutive years, between 1965 and 1972, with relatively small departures (<0.5), meaning that the TOTAL in these years was similar to the median conditions. The uncertainty trend shifted since 1968, and the increase was probably caused by 10 years with relatively large departures (>1.0) at the second half of the research period. Prilep has the highest correlation coefficient (0.39) out of all seven significant

trends found for the Δ TOTAL. As presented in Table 3, in six of them, an increase in uncertainty has been detected mainly since the 1980s. In Tortosa, the uncertainty increased until 1968 and since then, it has decreased.

4.2.2 Δ NRS

Figure 4b presents the time series of Δ NRS and the positive significant trend found in Larisa, as an example. The largest departures from the average NRS conditions were at the beginning of the series (2.3 in 1955, 2.0 in 1957 and 1959). Overall, there were 18 years with scores of >1.0 , distributed all over the series. Based on a second order polynomial, the changing tendency was found to occur in 1988, from decreasing to increasing uncertainty. Only three other significant trends were found. All were negative in the early decades, and the uncertainty increased since the end of the 1970s and the 1980s (Table 3).

4.2.3 Δ RSY

The time series of Δ RSY in Argostoli, as an example, are presented in Fig. 4c. Within the first 15 years, between 1958 and 1972, 12 years had large scores (>1.0). In the second half of the series, especially in the 1980s, departures were relatively low. Hence the yields of rain spells in this period were close to the average values (26.3 mm).

Departures (from the average or the expected values after de-trending) may be either negative or positive, meaning less or more yields for a single rain spell, respectively. For example, the standard scores were almost equal in both 1985 and 1989 (1.3), however, yields (30.8 mm), were above the expected value after de-trending (22.6 mm) in 1985 and below (14.3 mm) the expected value after de-trending (22.5 mm) in 1989. In 3 years (1958, 1960, and 1962), departures were larger than 3.0; all presented more abundant yields for a single rain spell than the average condition (37.3, 40.2, and 39.7 mm, respectively).

A significant trend was found, with an increase in the uncertainty since 1986, but yet not reaching the maximum values of the 1960s. This shift in the trend was caused mainly due to 5 years with large departures at the end of the analyzed period (1985, 1989, 1990, 1994, and 1998). The correlation coefficient of the temporal variability (0.64) of this trend is relatively very high.

Only six significant trends were found; three presented an increase since the 1960s (in Rome) and since the 1980s (in Argostoli and Larnaca). In Merignac, a positive linear trend was found. Salamanca presented a negative linear trend, and in Tortosa until 1968 the uncertainty increased and since then, it has decreased (Table 3).

4.2.4 ΔRSL

Time series of ΔRSL for Argostoli, as an example, are presented in Fig. 4d. Years with the largest departures are more frequent in the second part of the period, when the highest departures were obtained in the last decade. The RSL in 1982 was as long as 257 days, and in 1983, it was only 149 days. However, the departures from the median RSL (206 days) were almost the same (1.6 and 1.8, respectively). The uncertainty increases moderately, and a positive linear significant trend was found. Similarly to the results found for the ΔRSY , only six trends were found. In four of them, an increase was found since the 1970s (in most cases), and the linear trend in Argostoli. Two other trends were found in Turnu Magurele and Valencia, in which the uncertainty in RSL decreased since 1967 and 1976, respectively (Table 3).

4.2.5 UI

As aforementioned and presented in Eq. 4, the UI is composed of three components. Overall, eight significant trends of the UI were found. In six stations, there was an increase since the 1970s (in most cases), meaning that the uncertainty has increased in recent years. In Malaga, a positive linear trend was found, meaning a continuous increase in uncertainty. In Turnu Magurele, a decrease in the uncertainty since 1960 was detected (Table 3).

Figure 4e presents the time series of the UI in Argostoli with a clear distribution of high departures at the beginning and at the end of the series, hence uncertain periods in general. In the 1970s and 1980s, the index was relatively small, meaning that the rainfall regime was relatively constant.

It is important to emphasize that it is not necessary that if a trend was found in a time series of a certain parameter, its variability will change. For example, although Dar el Beida presents three significant temporal trends, no trend was found in their variability. On the other hand, Rome presents trends for both NRS and its variability, ΔNRS , and RSY and ΔRSY and in Argostoli for RSY and ΔRSY . However, in most stations where a trend in a certain parameter was found, no trend in its uncertainty was detected and vice versa.

4.3 Extreme events

Table 4 summarizes the significant t test results for the TOTAL, the NRS, the RSY , and the RSL, indicating that the averages of the two timings of the extremes are statistically different and independent of one another (one from the other). In all stations, only 22 significant results ($p \leq 0.05$) were found (13.4%). In most stations, none of the parameters presented significant results. Eight stations (19.5% out of all stations) presented significant values

Fig. 5 The average years and values of the lowest (*squares*) and the highest (*triangles*) 10% of the TOTAL in **a** Dar el Beida, **b** Marseille, **c** Corfu, **d** Argostoli, **e** Rodos, **f** Alexandroupoli, **g** Valencia, and **h** Jerusalem. The *bars* indicate (\pm) one standard deviation of the timing and the magnitude for both the lowest and highest values. The analyzed period is *shaded*. Stations are sorted in an ascending order, according to the difference between the years with the highest and lowest extremes

(between 0.013 and 0.047) in the t test of the TOTAL. Only four stations (9.7%) present significant values for the NRS (0.002–0.015). Five stations (12.2%) for the RSY (<0.001 –0.045), and six stations (14.6%) for the RSL (0.017–0.050).

Figures 5, 6, 7, and 8 illustrate the significant cases (presented in Table 4) for TOTAL, NRS, RSY , and RSL, respectively. Each figure presents the average years, the average values, and ± 1 standard deviation bars for both the values and the years. Stations are sorted in an ascending order, according to the difference between the years with the highest and lowest extremes.

4.3.1 TOTAL

In six out of the eight stations that presented significant results in the TOTAL, the wettest years occurred prior to the driest years. This means that the former period was characterized with extremely wet years, while in the later period there were more extremely dry years. Jerusalem and Valencia are the only stations in which high extreme TOTAL values occurred later (874 mm in 1985 and 747 mm in 1979) than the low extremes (227 mm in 1965 and 266 mm in 1960). Similar results were reported by Alpert et al. (2002).

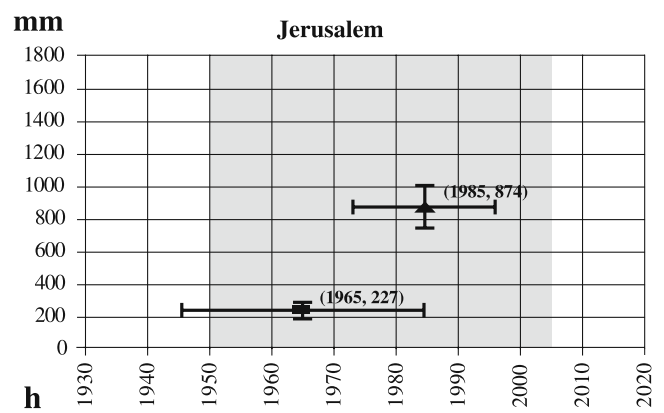
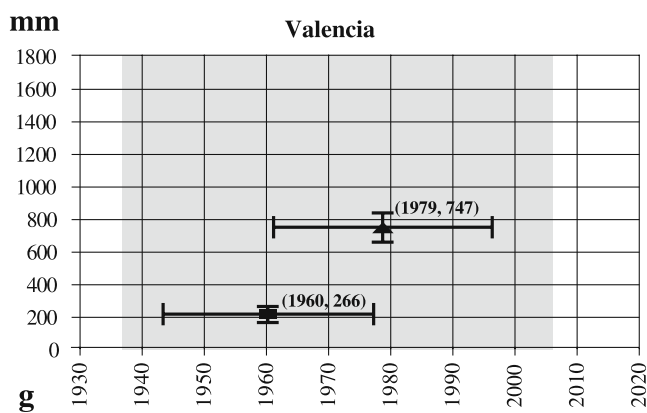
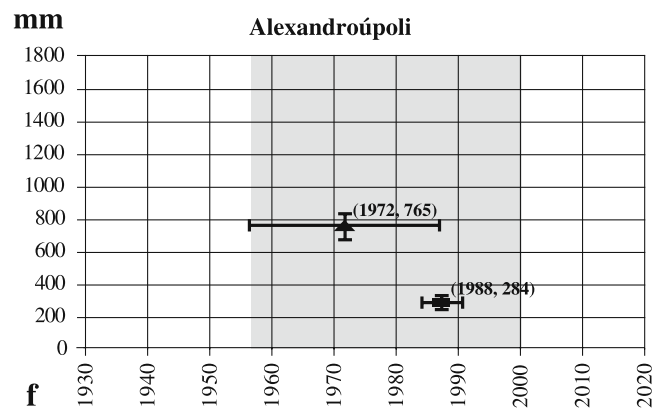
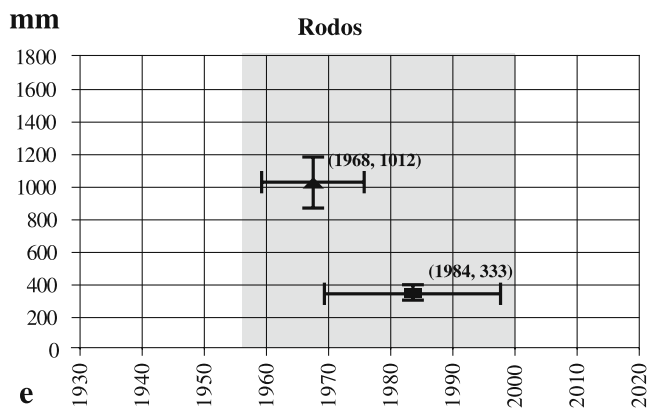
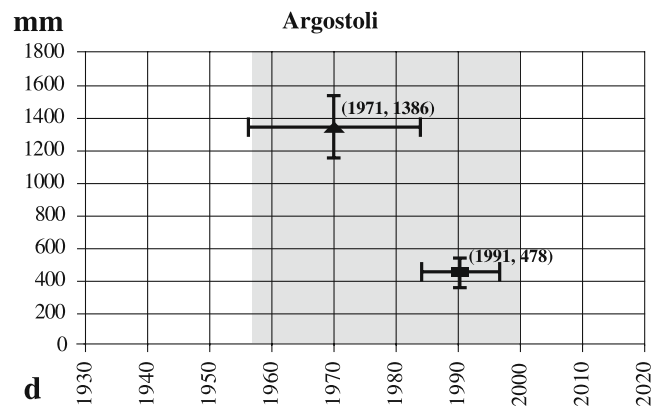
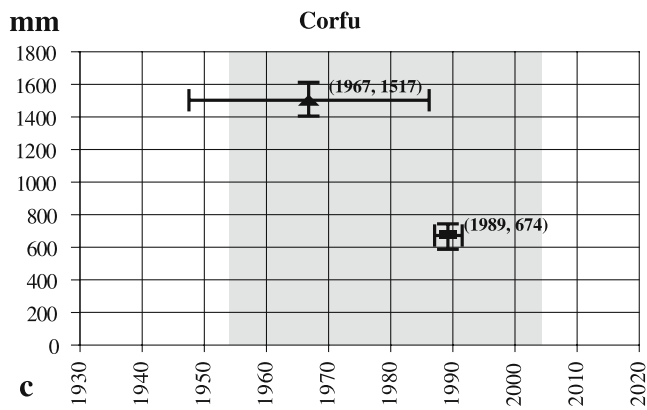
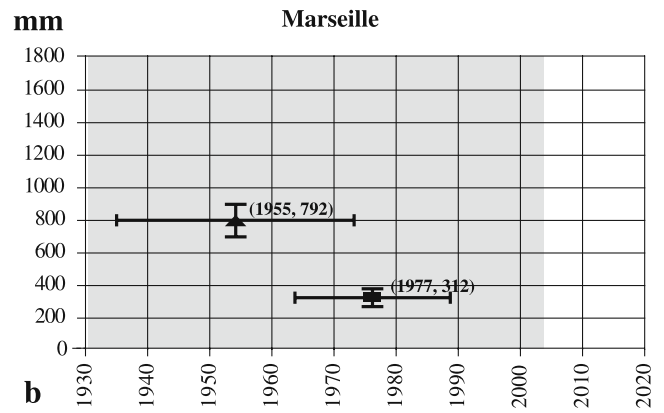
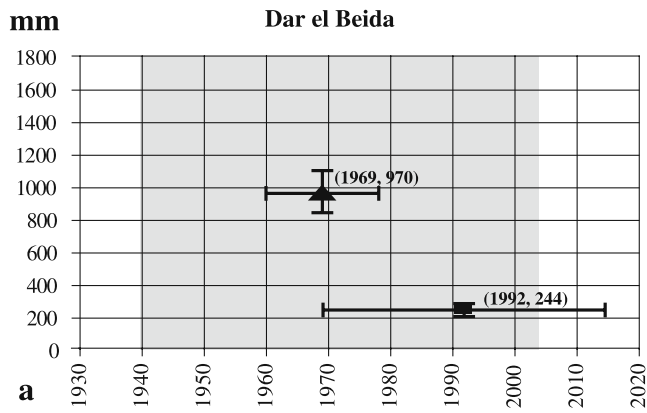
In Dar el Beida, 23 years separated between the average timing of the 10% wettest years (970 mm in 1969) and the average timing of the 10% driest years (244 mm in 1992; Fig. 5a). This difference is 16 years in Rodos (between 1968 with 1012 mm and 1984 with 333 mm) and Alexandroupoli (between 1972 with 765 mm and 1988 with 284 mm; Fig. 5e, f).

Furthermore, in Alexandroupoli and in Corfu, extremely dry years occurred in a relatively very short period with a standard deviation of only 3 and 2 years, respectively (Fig. 5f and c).

4.3.2 NRS

Significant results in the NRS were found in four stations. In all cases, the years with extremely high NRS were concentrated in the first part of the research period, while years with low NRS were on the average during the later period. This means that the earlier period was characterized by an extremely large number of rain spells, while in the latest period there were much less rain spells (Fig. 6).

Around the 1960s, Argostoli and Dar el Beida experienced higher NRS within the seasons, and in the late 1980s, their number was extremely lower. Overall, there were



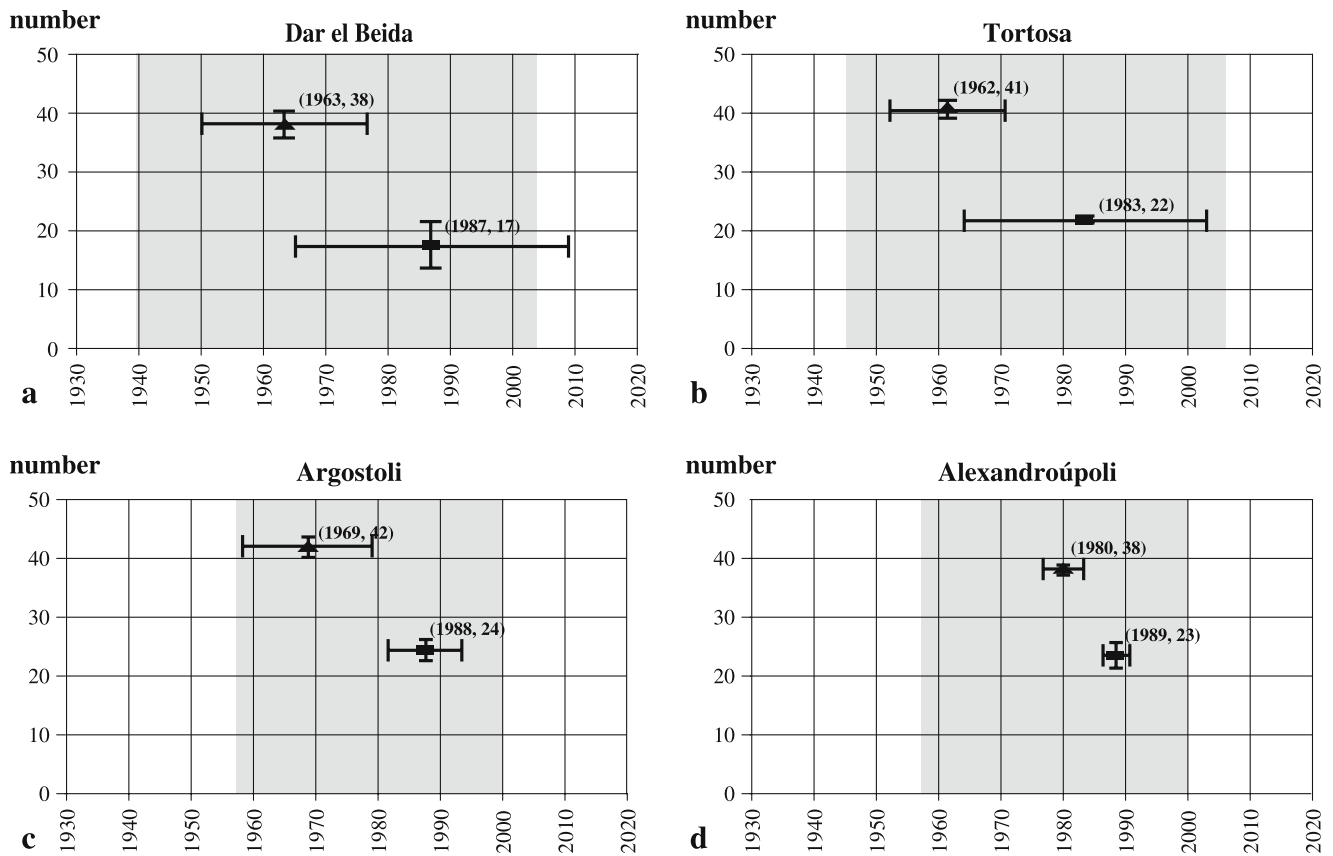


Fig. 6 Same as Fig. 5, but for the NRS, in **a** Dar el Beida, **b** Tortosa, **c** Argostoli, and **d** Alexandroupoli

more extreme wet rainy seasons in the 1960s and there were more extremely dry seasons in 1980s, in both stations (Fig. 5a, 6a, 5c, and 6c, respectively).

In Alexandroupoli, the differences between the two averages of the lowest NRS and the highest NRS is only 8 years, both extremes (low and high NRS), occurred in the second part of the analysis period. Hence, the period since the 1980s was very extreme compared to the period of 1958–1979. The temporal standard deviations are relatively small, only 3 years for the low NRS and 2 years for the high NRS (Fig. 6d).

4.3.3 RSY

In three out of the five stations (Dar el Beida, Marseille, and Niš) the wettest RSY were recorded in the first part of the researched period, while the years with the driest yields were in the second part. This means that the earlier period was characterized by extremely wet rain spells, while in the latest period there were more extremely dry rain spells (Fig. 7).

In Marseille, extremely abundant rain spells were in the 1950s, while around the 1980s, extremely poor rain spells were more frequent. However, standard deviations are relatively high with 13 years for the RSY (Fig. 7a).

In Dar el Beida, the high extremes occurred about two decades (19 years) earlier than the low extremes (1973 and 1992, respectively, Fig. 7c). However, Jerusalem and Rome are the two examples in which high extreme RSY values significantly occurred later (1985 in both stations) than the low extremes (1965 and 1957, respectively, Fig. 7d, e).

4.3.4 RSL

In four out of the five stations, the longest RSL were concentrated in the first part of the research period, while the years with the shortest seasons were in the second part (Fig. 8). Only in Madrid, there were more extreme short rainy seasons during the first part of the analyzed period, while more extreme long seasons in the second. The differences between the two averages of the longest RSL and the shortest RSL ranged between 27 years in Bucuresti (1954 and 1981, respectively) and 11 years in Madrid (1981 and 1970, respectively).

4.4 Spatial trends

Since the number of significant temporal trends was small, both for the parameters and their uncertainties, the spatial

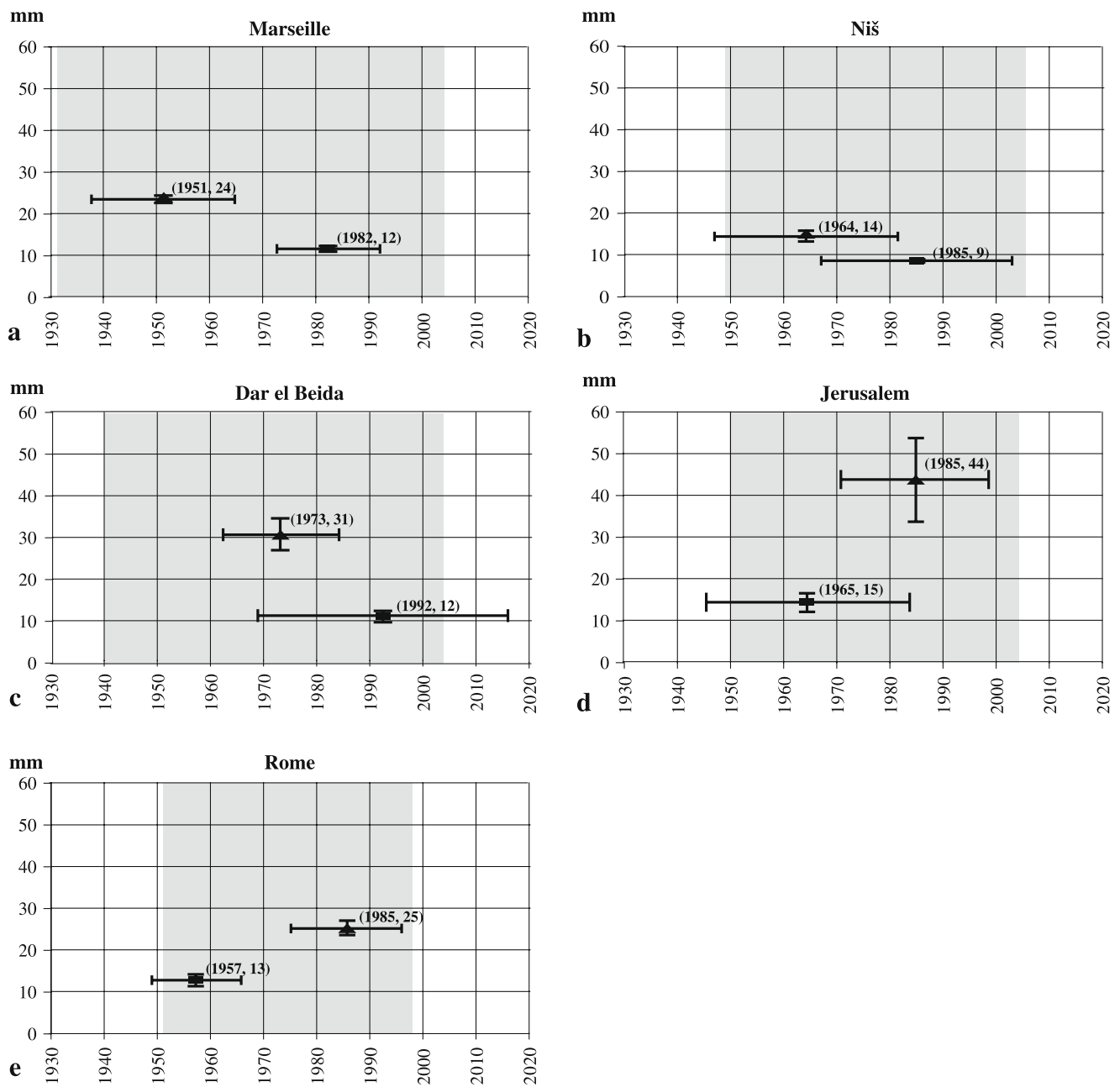


Fig. 7 Same as Fig. 5, but for the RSY, in **a** Marseille, **b** Niš, **c** Dar el Beida, **d** Jerusalem, and **e** Rome

analysis of the trends was limited. Figure 9 illustrates the significant spatial trends that were found in isolated areas. Four trends can be identified, mainly in southern Italy, Greek mainland, and the island of Rodos:

1. An increase in the RSY was found in Argostoli, Corfu, Brindisi, and Rodos.
2. An increase in the Δ NRS was found in Larisa, Ankara, Brindisi, and Rodos.
3. An increase in the Δ RSL was found in Argostoli, Larnaca, Athens, and Rodos.

4. An increase of the combined uncertainty index (UI) was detected in several stations in the south-eastern basin (Tirana, Argostoli, Athens, Rodos, and Larnaca).

These results and especially, the last one, reinforce the conclusions presented in several previous studies regarding the isolated region of Greece that presents significant trends and uncertainties (Douguédroit and Norrant 2003; Maheras and Anagnostopoulou 2003; Norrant and Douguédroit 2005; Feidas et al. 2007).

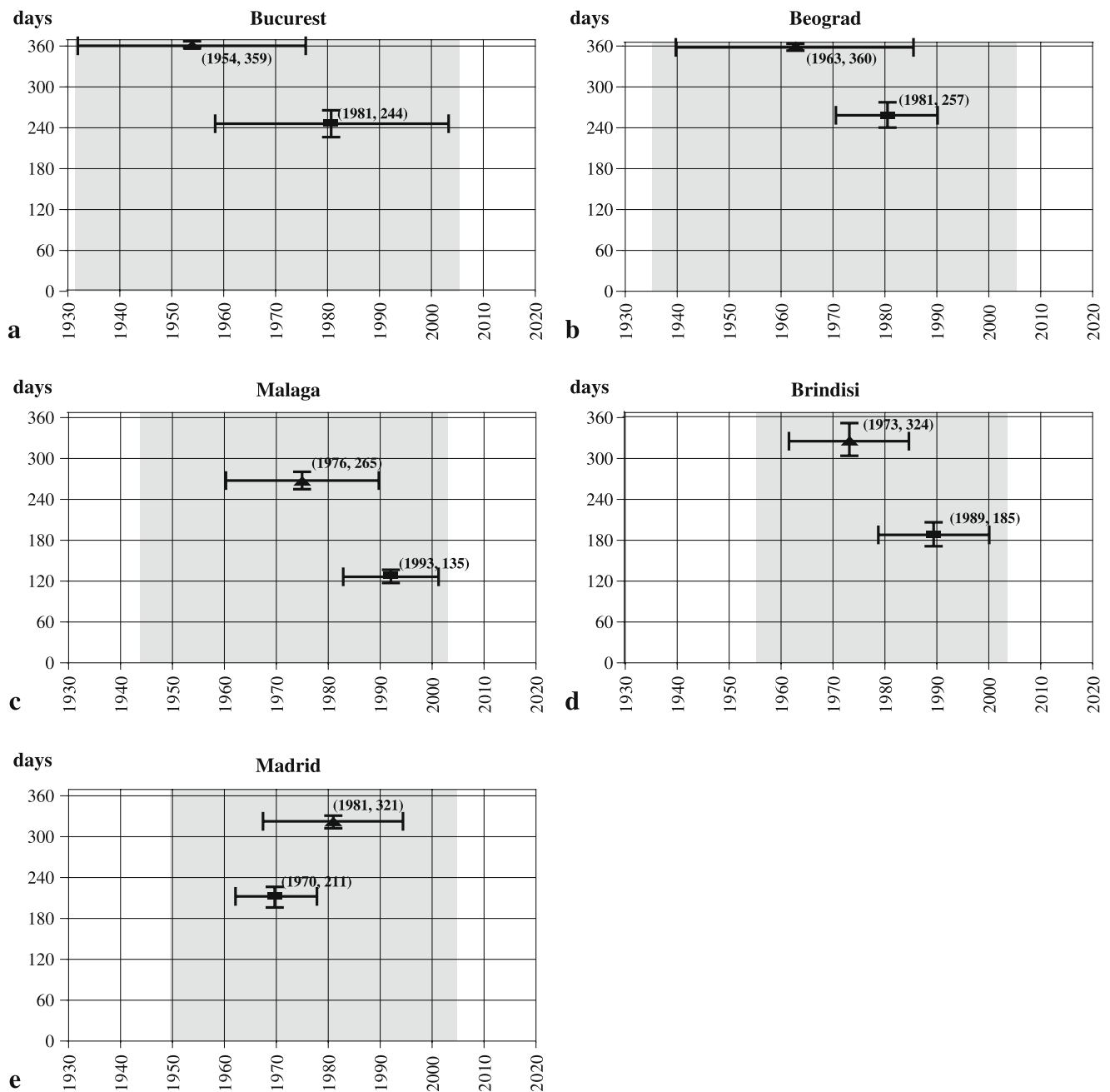


Fig. 8 Same as Fig. 5, but for the RSL, in **a** Bucurest, **b** Beograd, **c** Malaga, **d** Brindisi, and **e** Madrid

Furthermore, an attempt to detect a spatial distribution of the shifting years either of the temporal trends or their uncertainty was made. Due to their very limited number (Tables 2 and 3), no spatial pattern could be identified.

5 Conclusions

Several methodologies were used in the present study in order to analyze temporal trends, uncertainty trends, and

extreme events of four parameters. The following conclusions were recognized:

1. Despite the general rumors of tremendous changes in the rainfall regime, no significant temporal trends or uncertainty trends were found in most of the stations, neither in their annual totals, their number of rain spells, their rain-spell yields, or their rainy season length.
2. In most of the few significant trends which were found, former years tended to be wetter, longer, and with more abundant rain spells, and the opposite in later years.

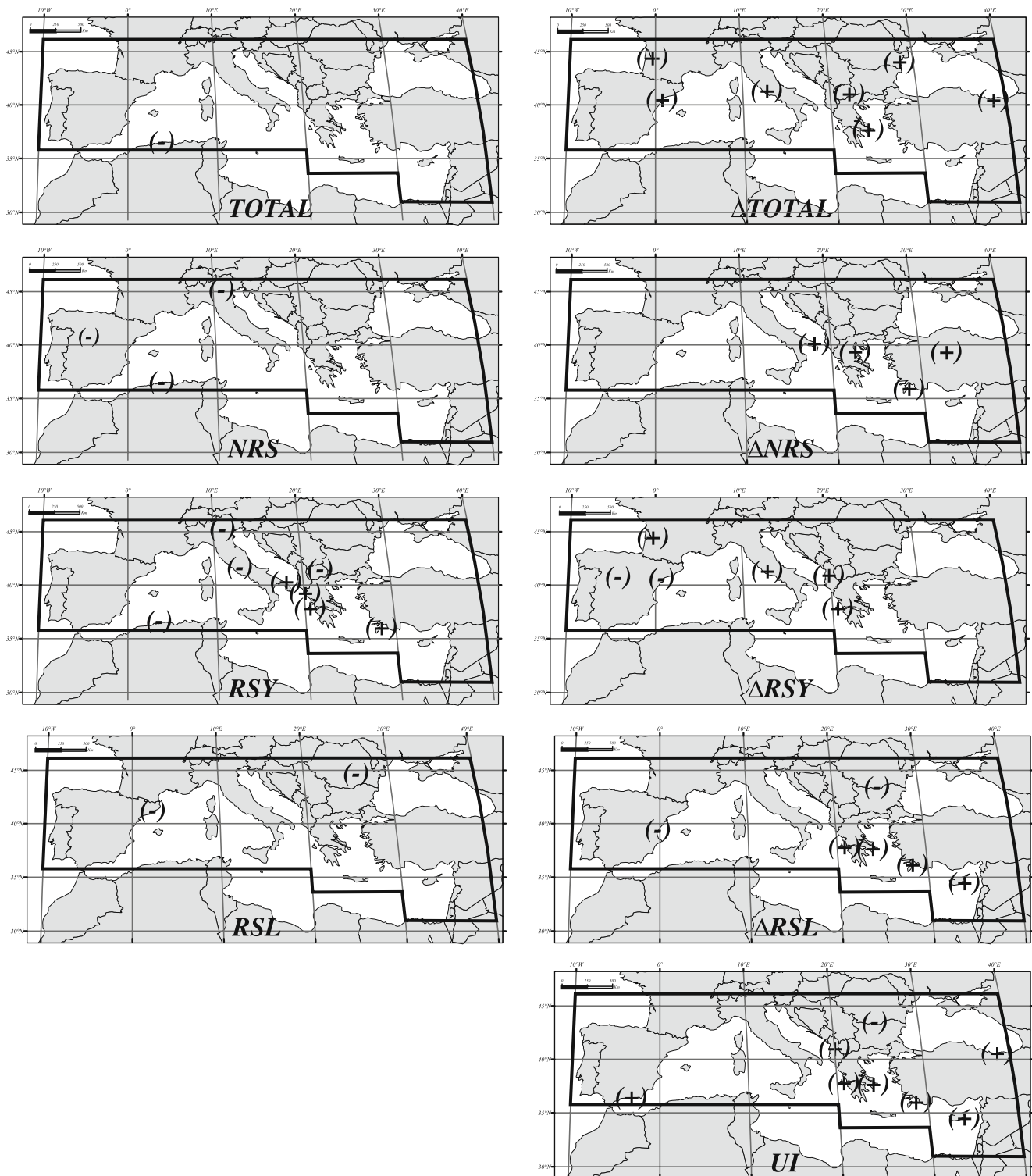


Fig. 9 Location of stations with significant trends both the parameters (*left*) and their uncertainties (*right*)

3. In the few cases that a significant trend was detected, uncertainty tends to increase more than it tends to decrease.
4. In Dar el Beida, there are significant decreases in TOTAL, NRS, and RSY, without any change in their uncertainty.
5. In Dar el Beida and in Argostoli, the 1960s were a decade of extreme abundant TOTAL and NRS. On the other hand, the early 1990s (TOTAL) and late 1980s (NRS) were periods of extreme low values of these two parameters.

6. The shifting periods were generally within the stations which did present significant temporal trends mainly in the 1960s or in the 1980s. However, no clear spatial pattern could be identified.
7. It is possible to talk about significant trends in one of the parameters or their uncertainty, only in limited or specific locations within the Mediterranean basin (mainly in the region of Greece). However, it is impossible to delimitate major regions in the Mediterranean basin, with significant trends.

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