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On extreme daily precipitation totals at Athens, Greece

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Abstract. The paper studies changes in daily precipitation records at the National Observatory, Athens, during the period 1891–2004. This is the longest available time series of precipitation for Greece. The results show that both the shape and scale parameter of a fitted two parameter gamma distribution for the last two decades do show a significant difference of these parameters, when compared to any previous period from the 1890s through the 1970s. Also important changes are observed in daily precipitation totals exceeding various thresholds such as 10, 20, 30 and 50 mm. More specifically, a negative trend in the number of wet days (remarkable after 1968) and a positive trend in extreme daily precipitation are evident. The changes of heavy and extreme precipitation events in this part of SE Europe have significant environmental consequences which cause considerable damage and loss of life.

1 Introduction

Significant climatic changes of precipitation in the 20th century reflect in economic, social and ecological implications including droughts, frequency of intense precipitation and of wet days (Karl and Knight, 1998; Folland and Karl, 2001; Zhang et al., 2001). For Europe, the precipitation trend is positive in the north (Forland et al., 1996; Schonwiese and Rapp, 1997) and negative in the south (Schonwiese and Rapp, 1997). Anagnostopoulou et al. (2006) studying the cyclones in the Mediterranean region, found that the Hadley Center atmospheric General Circulation Model (HadAM3P) predicts a future decrease of the frequency of the severe cyclones (<1000 hPa) at the SLP level, but the future cyclones will be more intense, especially at the 500 hPa level.

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Studies regarding long precipitation timeseries and the distribution of precipitation frequency within the Mediterranean Sea and Greece have been carried out by many researchers (Zerefos et al., 1977; Maheras, 1981; Repapis, 1986; Katsoulis and Kambezidis, 1989; Maheras and Kolyva-Mahera, 1990; Flocas et al., 1990; Amanatidis et al., 1993; Nastos, 1993; Mantis et al., 1994; Amanatidis et al., 1997; Metaxas et al., 1999; Brunetti et al., 2001).

The variability of the total precipitation can be explained by a change in the frequency of precipitation events, or in the intensity of precipitation, or both. In contrast with the simulations of extreme temperature by climate models, extreme precipitation is difficult to reproduce, especially for the intensities and patterns of heavy rainfall which are heavily affected by the local scale (IPCC 2001). For this reason, it is necessary to study heavy and extreme precipitation events by analyzing long time series of observed station data.

In this study, we examine the long time series of daily precipitation recorded in the National Observatory of Athens (NOA), for the period 1891–2004, by fitting the gamma distribution to the datasets per decade and by manipulating the exceedances of the daily precipitation over various thresholds, which are indicators for the incidence of extreme rainfall events responsible for social and economical consequences.

2 Data and analysis

Daily precipitation dataset recorded at the meteorological station of the National Observatory of Athens (Longitude: 23°43 E, Latitude: 37°58 N, Altitude: 107 m a.m.s.l.), for the period 1891–2004, was analyzed in this study. This is the longest available and reliable time series of precipitation for Greece. Even in reliable precipitation datasets there is a measurement uncertainty, because of errors due to gauge undercatch mostly depending on wind characteristics during

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Table 1. Parameters of the gamma distribution fitted to daily precipitation data over ten year periods for NOA.

Period	Observed Mean	Observed Variance	Scale Parameter	ShapeParameter
1891–1900	5.12	126.03	7.82	0.66
1901–1910	6.31	72.76	8.65	0.73
1911–1920	6.45	98.62	9.49	0.68
1921–1930	6.35	97.89	9.69	0.66
1931–1940	6.36	78.04	9.58	0.66
1941–1950	5.83	95.75	8.96	0.65
1951–1960	5.81	73.10	8.73	0.66
1961–1970	5.67	65.80	8.18	0.69
1971–1980	6.20	89.16	9.36	0.66
1981–1990	5.99	79.91	8.69	0.69
1991–2000	6.62	125.19	11.40	0.58
2001–2004	9.09	227.41	16.56	0.55

stormy weather (wind–induced turbulence over the orifice of the gauge) and less on evaporation from the gauge.

The first step of the analysis was to divide the dataset in 10-year groups and fit the gamma distribution on each of the 11 daily precipitation timeseries (1891–1900, ..., 1991–2000) in order to find out the change of the distribution parameters extracted. Furthermore, this analysis was applied to the data in 30-year groups. The gamma distribution, which in addition is recommended by the World Meteorological Organization (Thom, 1971; Neyers, 1990), is the most appropriate for studies relative to precipitation distributions due to its moderately skewed profile (Thom, 1958; Ding, 1992; Guttman et al., 1993; Wilks, 1995; Groisman et al., 1999). This distribution has been used for the study of the distribution of the precipitation frequencies in Greece (Katsoulis and Pappas, 2000), as well as for the spatial and temporal analysis of the extreme precipitation in Cyprus (Tymbios and Michailidis, 2002). The benefit of the gamma distribution is the better fitting to the frequency distribution of the precipitation as compared to other theoretical statistical distributions, which either underestimate or overestimate the frequency distribution of the daily precipitation. Furthermore, the increase in the scale parameter β (appeared in the formula for the probability density function) results in stretching out the probability density distribution and therefore can be used in the determination of the probability of extreme events. The general formula for the probability density function of the gamma distribution is:

$$f(x) = \frac{\left(\frac{x-\mu}{\beta}\right)^{\gamma-1} \exp\left(-\frac{x-\mu}{\beta}\right)}{\beta\Gamma(\gamma)} \quad x \geq \mu, \gamma, \beta > 0 \tag{1}$$

where γ is the shape parameter, μ is the location parameter, β is the scale parameter, which characterizes the scale of the intensity of the daily precipitation (the higher β is, the higher the intensity is), and Γ is the gamma function which has the formula:

$$\Gamma(a) = \int_0^\infty t^{a-1} e^{-t} dt \tag{2}$$

The case where μ=0 and β=1 is called the standard gamma distribution. The equation for the standard gamma distribution reduces to

$$f(x) = \frac{x^{\gamma-1} e^{-x}}{\Gamma(\gamma)} \quad x \geq 0; \ \gamma > 0 \tag{3}$$

The second step was to examine the temporal variability and trends of the timeseries of the number of precipitation days exceeding various thresholds such as 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 mm. Especially the threshold of 50 mm is considered representative of heavy and extreme rainfalls, by many researchers (Karl et al., 1995; Karl and Knight, 1998; Brunetti et al., 2001, 2004).

3 Results and discussion

It has been mentioned previously that the gamma distribution represents daily precipitation satisfactorily. In order to reveal changes in the precipitation variability through time, we constructed the histograms of daily precipitation for 10-year and 30-year periods, along with the gamma distribution, from 1891 to 2004. The statistics of each 10-year distribution are presented in Table 1 and the respective statistics of each 30-year distribution are presented in Table 2. Although the variance is about the same for 1891–1900 and 1991–2000, the scale parameter is widely different. Regarding the 30-year distributions, similar results are extracted indicating a significant differentiation of the statistics for the last period 1981–2004, compared to earlier periods. The increase in the variance and the scale parameter, as well as the shift of the

Table 2. Parameters of the gamma distribution fitted to daily precipitation data over thirty year periods for NOA.

Period	Observed Mean	Observed Variance	Scale Parameter	Shape Parameter
1891–1920	5.98	98.87	8.74	0.68
1921–1950	6.19	89.89	9.42	0.66
1951–1980	5.89	75.86	8.76	0.67
1981–2004	6.73	122.71	11.04	0.61

mean towards higher values reveal the incidence of extreme daily precipitation values since 1980s. This is in agreement with the findings of Groisman et al. (1999) who studied the relationship between the increase in total precipitation and the frequency of heavy rain events, over a wide area comprising Canada and Norway (for the period 1900–1995), the USA and Australia (1910–1996), the former Soviet Union (1936–1994), Mexico, China, Alaska and Polland (available data for the post-World War II period). They found that the shape parameter of the precipitation gamma distributions remains rather stable, independent of total precipitation, while the scale parameter is most variable and they also insist that a disproportionate increase in heavy precipitation is expected, as total precipitation increases in the future.

A physical explanation of the enhanced precipitation, mainly in mid-latitude cities, is the urban heat island (UHI). With respect to the National Observatory of Athens (NOA), the urbanization effect is attributed to the extensive building of Athens around NOA after the Second World War and the rapid increase of the population and the number of vehicles mainly after 1970. The urbanization effect in NOA refers mainly to maximum air temperature (an increase $\sim 2°C$) and to the warmer seasons of the year (Philandras et al., 1999). The possible main factors, which cause urban induced changes in precipitation, are the mechanical turbulence resulting from increased surface roughness, the addition of sensible heat from the urban warm air and the anthropogenic condensation nuclei floating in the urban air (Chandler, 1965). These factors are responsible for heavy storms of convective nature in the developed mega-cities. A lot of studies have been carried out providing evidence that UHI is associated with convective precipitation in Atlanta (Bornstein and Lin, 2000), in Mexico city (Jauregui and Romales, 1996), in Tel Aviv (Goldreich and Manes, 1979), in Beijing City (Guo et al., 2006), in Tokyo (Yonetani, 1982) in London (Atkinson, 1971) and in Ankara (Cicek and Turkoglu, 2005).

Moreover, the pronounced increase in heavy precipitation could be attributed to the global warming during the recent decades. Warming relates to higher water content in the atmosphere (Douville et al., 2002; Trenberth et al., 2003) and this has been evident in many regions (Sun et al., 2000; Ross and Elliott, 2001). This phenomenon results in an increase in the probability of severe convective weather.

In the process, a statistical analysis of heavy and extreme events was performed to study their variability and trends. Figure 1 depicts the course of the annual precipitation timeseries (upper graph) and the number of days with precipitation >0.1 mm (lower graph), herewith wet days, along with linear and loess fitting.

Annual precipitation has no statistically significant trend (p=0.24) in the 1891–2004 period (the peak in the annual timeseries corresponds to the year 2002, and exceeds the average precipitation by over two standard deviations). On the other hand, the wet days series shows a slight negative trend, which is not statistically significant (p=0.47), during the examined period. However, this trend becomes statistically significant (p=0.03) during the last thirty seven years (1968–2004). The absence of a significant trend in annual precipitation and the negative trend in wet days, especially in the last three decades, indicate an increase in the extreme daily precipitation. This temporal pattern is appeared over the northeastern quadrant of the contiguous United States, where during the last 30 years (exactly at the time when most of increase in very heavy precipitation started) a decrease in the number of wet days was observed (Groisman et al., 2005). Additionally, in several regions such as South Africa, Siberia, the Eastern Mediterranean Sea, central Mexico, and northern Japan, rainy days are becoming less frequent and an increase only in heavy precipitation is observed while total precipitation and/or the frequency of days with an appreciable amount of precipitation are not changing and/or are decreasing (Easterling et al., 2000; Alpert et al., 2002; Fauchereau et al., 2003; Groisman et al., 2005). Besides, this is in agreement with the results of Brunetti et al. (2001, 2004), who find a negative significant trend in the number of wet days all over Italy, and a positive trend in precipitation intensity, which is significant only in the northern regions.

In order to verify more systematically the increase in the intensity of the rainfall events, we applied various thresholds (10 mm to 100 mm) to daily precipitation timeseries and our findings show a clear increasing trend of the number of days exceeding the examined thresholds, especially 50 mm (Fig. 2). This is particularly important as these events ($>$50 mm per day) cause considerable damage and loss of life.

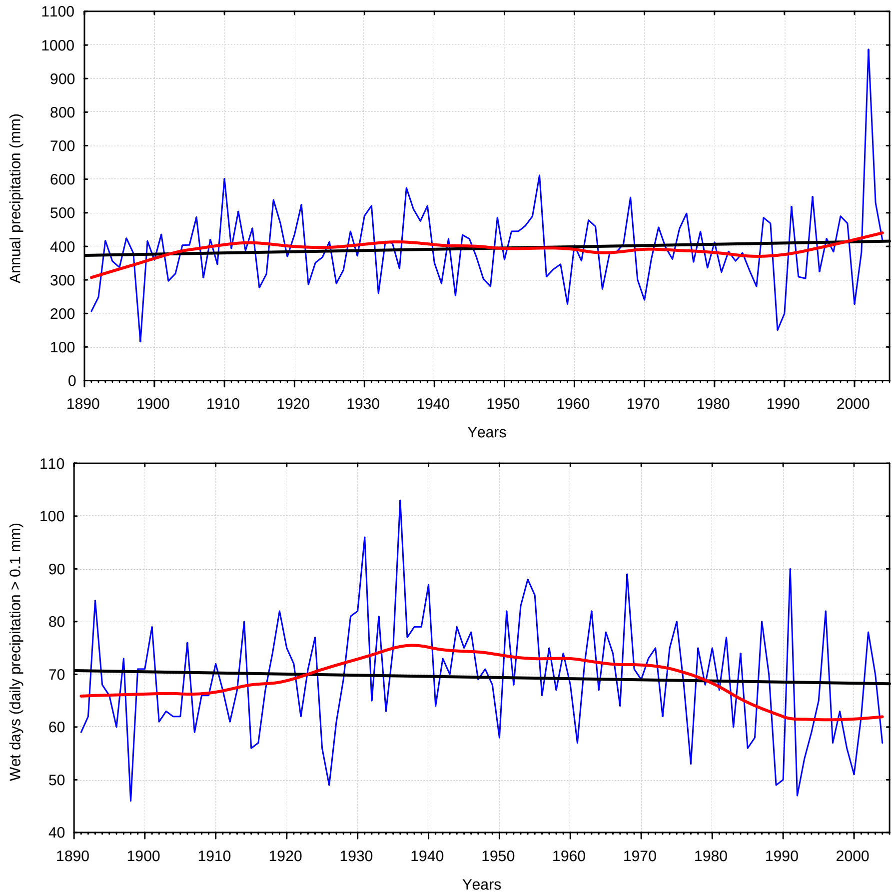

Fig. 1. Time series of annual precipitation (upper graph) and number of days with precipitation >0.1 mm (lower graph), along with linear and loess fitting.

More specifically, the increasing trends in the percentages of the number of wet days exceeding specified thresholds are more evident and statistically significant ($p<0.05$) since the decade of 1970 to present. Figure 2 depicts only the exceedances of the wet days over 10, 20, 30 and 50 mm per day, but the same pattern is appeared regarding the thresholds of 60, 70, 80, 90, 100 mm, however these events are more infrequent to happen, and their timeseries show a lot of gaps. It should be noted here, the extreme precipitation events during summer-autumn of the year 2002, which are the most intense all over the examined period 1891–2004, causing many disastrous floods and considerable damages all over Greece. Groisman et al. (2005) found out that changes in heavy precipitation frequencies are always higher than changes in precipitation totals and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed. Relative studies have been performed for USA by Karl et al. (1995) and Karl and Knight (1998), who remarked a significant positive trend in the frequency of extreme rainfalls (greater than 50 mm per day) over the last few decades in the USA. Besides, concerning Australia, Suppiah and Hennessy (1998) found a significant increase in the 90th and 95th percentiles of rainfall, while in Japan, Iwashima and Yamamoto (1993) revealed that, the highest precipitation events were recorded in recent decades.

In the process, wavelet analysis (Torrence and Compo, 1998) is used to identify variations in temporal cycles in the annual precipitation in NOA and furthermore to find relationships between annual precipitation and the dominant modes of the climate variability. The wavelet power spectrum and the global wavelet power spectrum are depicted in Fig. 3. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 5% significance level, using a red-noise (autoregressive lag1) background spectrum. The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in left graph. Wavelet analysis shows that multidecadal cycles (~25 years) are dominated at the beginning and the end of the twentieth century. Moreover 2–10 year period is exhibited at the recent years while 4–8 year period is appeared at the end of the nineteenth century.

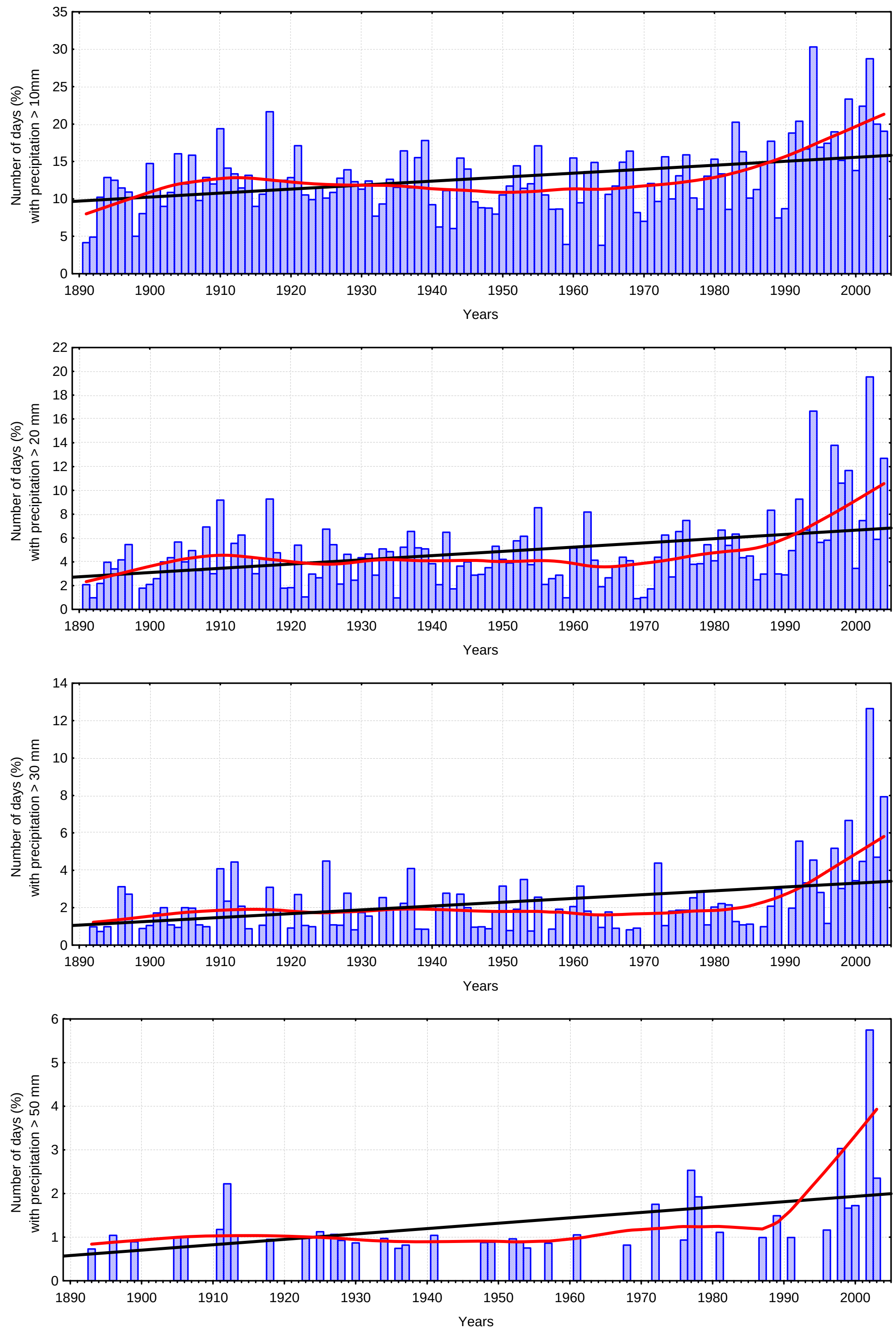

Fig. 2. Time series of the annual percentages of the number of days with precipitation greater than 10 mm, 20 mm, 30 mm and 50 mm (annual number of days exceeding specified thresholds divided by the number of wet days of the year), along with linear and loess fitting.

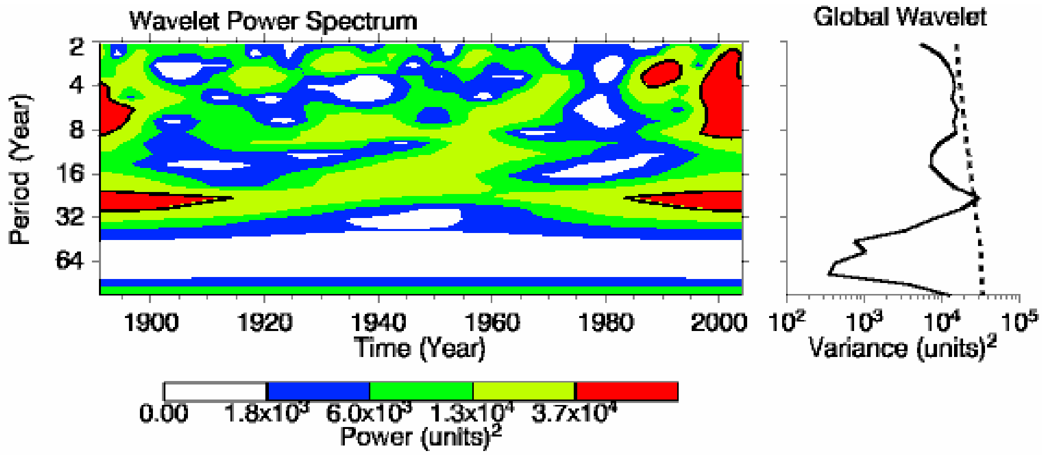

Fig. 3. The wavelet power spectrum (left graph) and the global wavelet power spectrum (right graph).

The quasi biennial and quasi decadal variability could be attributed to North Atlantic Oscillation Index (NAOI) due to conclusions of Hurrell (1995) and Hurrell and Van Loon (1997), who showed that over the past 130 years the NAOI has presented considerable variability at quasi-biennial and quasi-decadal time scales, and the latter have become especially pronounced the second half of this century. Since 1980, NAOI remained in one extreme phase resulting in anomalies in the precipitation, including dry wintertime conditions over southern Europe and the Mediterranean Sea. Xoplaki et al. (2004) studying the influence of large scale dynamics and trends in the wet Mediterranean precipitation variability, found out that inderdecadal change in the first CCA mode (Canonical Correlation Analysis between large scale circulation at different levels and the precipitation) are related to variations in the NAOI and responsible for time scale variations of the Mediterranean precipitation, throughout the twentieth century. Moreover, multidecadal variations characterize the ENSO Euro-Mediterranean relationship during the 20th century (Mariotti et al., 2002).

4 Conclusions

The analysis of the daily precipitation timeseries for the National Observatory of Athens gives the following results:

(i) the increase in the variance and the scale parameter of the fitted gamma distribution, as well as the shift of the mean towards higher values reveal the incidence of extreme daily precipitation values within the last examined fifteen years.

(ii) the annual precipitation timeseries has no statistically significant trend in the 1891–2004 period while the wet days appear a slight negative trend, which is not statistically significant, during the examined period and becomes statistically significant during the last thirty seven years and this drives in more extreme daily precipitation.

(iii) the increasing trends in the percentages of the number of wet days exceeding specified thresholds are more evident and statistically significant since the decade of 1970 to present.

(iv) the wavelet analysis applied to the annual precipitation revealed inter annual, decadal and multidecadal cycles, which dominant modes of variability vary in time.

The information extracted by similar studies of heavy and extreme precipitation events analyzing long timeseries of observed stations datasets will help policy makers, and the community in general, to find ways of protection and limitation of damages by floods and loss of life.

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