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The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values

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[1] Earlier reports indicated some specific isolated regions exhibiting a paradoxical increase of extreme rainfall in spite of decrease in the totals. Here, we conduct a coherent study of the full-scale of daily rainfall categories over a relatively large subtropical region- the Mediterranean- in order to assess whether this paradoxical behavior is real and its extent. We show that the torrential rainfall in Italy exceeding 128 mm/d has increased percentage-wise by a factor of 4 during 1951–1995 with strong peaks in El-Nino years. In Spain, extreme categories at both tails of the distribution (light: 0-4 mm/d and heavy/torrential: 64 mm/d and up) increased significantly. No significant trends were found in Israel and Cyprus. The consequent redistribution of the daily rainfall categories -torrential/heavy against the moderate/light intensities - is of utmost interest particularly in the semi-arid sub-tropical regions for purposes of water management, soil erosion and flash floods impacts. *Index Terms:* 1854 Hydrology: Precipitation (3354); 1821 Hydrology: Floods; 1600 Global Change; 1620 Global Change: Climate dynamics (3309)

1. Introduction

[2] Global warming was suggested to be linked with the recent increases of heavy daily rainfall due to the increased atmospheric water vapor and warmer air, [*IPCC*, 1995]. Total annual rainfall also shows increasing trends in many regions, e.g. [*Dai et al.*, 1997]. Contrary to mid- to upper latitude regions of the world in which positive trends in recent rainfall were reported, over the Mediterranean several regional studies show a dominant decreasing trend [*Piervitali et al.*, 1998; *Romero et al.*, 1998; *Ben-Gai et al.*, 1998; *Steinberger and Gazit-Yaari*, 1996; *Xopalki et al.*, 2000; *Steinberger*, 1999]. In particular, over the central-western Mediterranean basin, Italy and Spain, the precipitation trends for 1951–1995 indicate an average reduction of about 10–20% in the total precipitation, which is statistically significant [*Piervitali et al.*, 1998; *Romero et al.*, 1998]. Highest decrease of 26% (157 mm) occurred over the southern belt including S. Italy, S. Spain and Tunisia. In the Eastern Mediterranean, however, mixed rainfall trends are found, but clearly more stations show decreasing trends. These include Jordan stations for the period 1938–1968 [*Steinberger*, 1999], and most stations from Greece, Turkey, Syria, Lebanon and Israel for the period 1951–1990, all showing decreasing trends [*Xopalki et al.*, 2000; *Kadioglu et al.*, 1999; *Paz et al.*, 1998]. An exception to this is a relatively small area over Central and South Israel (N. Negev semi-arid zone), where an increasing trend in the total amounts of rainfall was shown and suggested to be partly associated with large modifications in the land-cover and land-use, [*Ben-Gai et al.*, 1998; *Steinberger and Gazit-Yaari*, 1996; *Alpert and Mandel*, 1986; *Otterman et al.*, 1990; *Ben-Gai et al.*, 1993; *Ben-Gai et al.*, 1994].

[3] This rainfall trend pattern over the Mediterranean is also noticed in globally analyzed maps of long-term precipitation trends observed during 1900–1988 [*Dai et al.*, 1997]. Particularly interesting, as important indicators for global warming are trends of climate extremes such as temperature and rainfall [*Easterling et al.*, 2000; *Groisman et al.*, 1999; *Easterling et al.*, 1997]. In most areas worldwide, the trends in rainfall, either positive or negative, have been observed to have the same sign as the trends in the amounts of 1-day heavy precipitation events. Moreover, in either trend sign, the heavy precipitation trends were disproportionately larger [*Easterling et al.*, 2000]. In a few isolated specific regions, however, although there was a decrease in seasonal total rainfall there was still an increase in the frequency of 1-day heavy precipitation events, as reported for N. Japan, the Asian part of Russia and to some extent also in Natal, S. Africa [*Easterling et al.*, 2000; *Groisman et al.*, 1999; *Iwashima and Yamamoto*, 1993]. These findings may be the result of incidental evidence since the studies were individually conducted and with different thresholds for the heavy rainfall. Here, we show for the first time, in a coherent study that in a relatively large subtropical region, i.e. the Mediterranean, the rainfall indeed behaves in such a paradoxical manner, namely that extreme daily rainfall increases in spite of the fact that total

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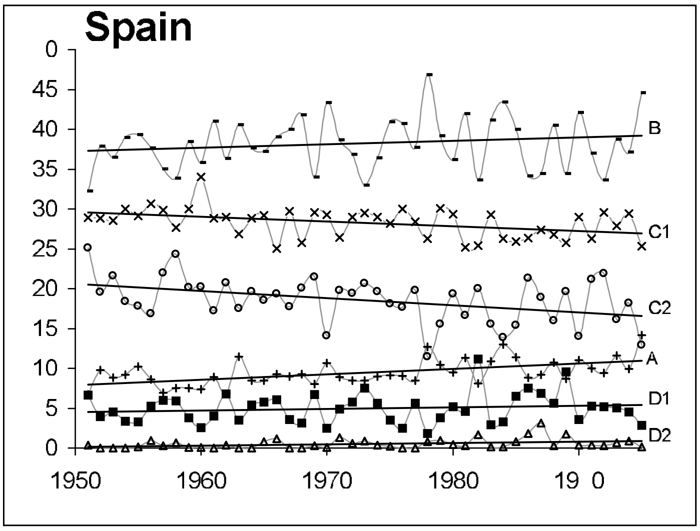
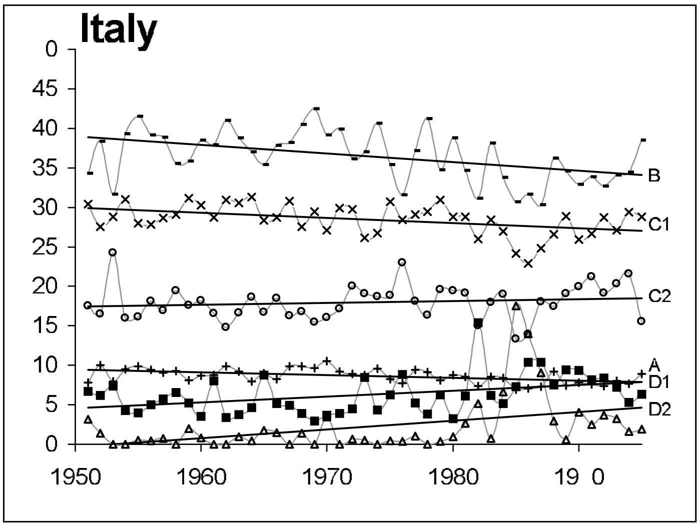
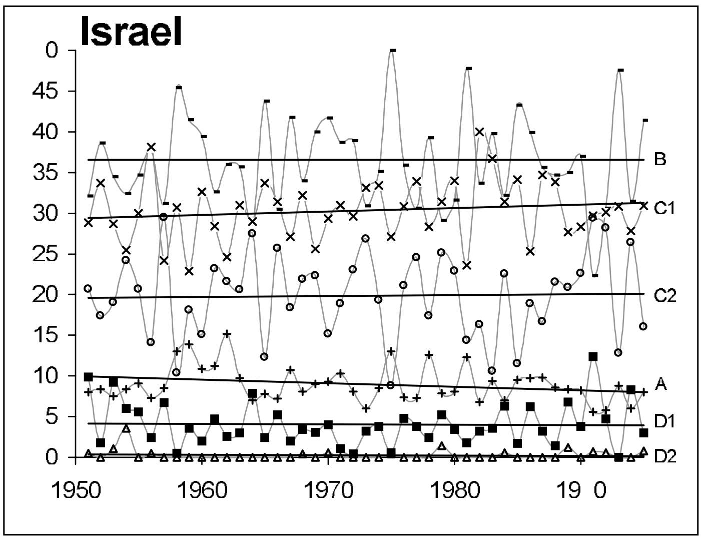


CATEGORY	RAINFAL (m /day)		TREND (SIG.)	SIGNIFICANCE OF MONOTONE TIME TREND
B	4-16	●	+0.04 (0.253)	(0.3)
C1	6-32	↓	-0.059 (0.0 3)	(0.019)
C2	32-64	↓	-0.089 (0.0 4)	(0.021)
A	0-4	↑	+0.068 (0.0)	(0.0 6)
D1	64-128	●	+0.019 (0.367)	(0.74)
D2	128-UP	↑	+0.017 (0.017)	(0.0125)



CATEGORY	RAINFAL (m /day)		TREND (SIG.)	SIGNIFICANCE OF MONOTONE TIME TREND
B	4-16	↓	-0.1 (0.0 2)	(0.0 27)
C1	6-32	↓	-0.06 (0.0 1)	(0.0 93)
C2	32-64	●	+0.025 (0.3 5)	(0.101)
A	0-4	↓	-0.035 (0.0)	(0.0 8)
D1	64-128	↑	+0.07 (0.0 6)	(0.0 86)
D2	128-UP	↑	+0.1 (0.0 5)	(0.0 13)



CATEGORY	RAINFAL (m /day)		TREND (SIG.)	SIGNIFICANCE OF MONOTONE TIME TREND
B	4-16	●	-0.0 4 (0.9)	(+)(0.984)
C1	6-32	●	+0.043 (0.318)	(0.3 6)
C2	32-64	●	+0.01 (0.857)	(0.793)
A	0-4	●	-0.04 (0.076)	(0.161)
D1	64-128	●	-0.0 5 (0.861)	(0.8 3)
D2	128-UP	●	-0.0 5 (0.501)	(+)(0.763)

rainfall generally decreases. We shall describe this large increase in the rainfall upper extreme by analyzing six rainfall categories over Spain, Italy, Cyprus and Israel for 1951–1995.

2. Methodology

[4] We suggest 6 daily rainfall categories as powers of 2 in analyzing the 1951–1995 trends for 265 Mediterranean stations, located as follows: in Mediterranean-Spain(182 stations), Italy(42), Cyprus(3) and Israel(38). The analysis in each location followed the same exact methodology. The selected daily rainfall categories in mm/d are: Light(A) 0–4, Light-Moderate (B) 4–16; Moderate-Heavy (C1) 16–32; Heavy (C2) 32–64; Heavy-Torrential (D1) 64–128; and Torrential (D2) 128-up. Daily rain values in powers of 2, i.e., 2^n as indicated above, allow the analysis of the contributions of several rainfall categories to the rainfall totals and how these contributions change with time. Earlier studies have generally adopted a number of different but single thresholds in order to define heavy rain which made it difficult to compare among these studies. In a recent review [*Easterling et al.*, 2000], for instance, five different thresholds were listed for heavy rain, i.e. 20, 25.4, 50, 50.8 and 100 mm/d. These threshold values and others found in the literature, can be well fitted to our suggested 2^n definitions of heavy rainfall, i.e. 20 to 16, 50 to 64 and 100 to 128. The necessity for a thorough analysis of all categories is obvious and becomes more so in light of findings that annual rainfall increases may also be due to increases in the Light category - the other end of the rainfall distribution frequently ignored. For instance, in the Canadian prairie, the Light (≤ 5 *mm*) daily rainfall was reported to cause the annual rainfall increase [*Akinremi et al.*, 1999]. A different non-discrete approach would be the use of gamma distribution and the analysis of changes in the shape and scale parameters [*Ben-Gai et al.*, 1998; *Groisman et al.*, 1999].

3. Results

[5] Figure 1 shows the contributions (as percentage from the total annual amounts) of each of the aforementioned defined daily rainfall categories for the period 1951–1995. The monotonous non-linear time trends were tested for significance using Spearman's rank correlation. A natural separation among the categories contributions for all 3 countries (the results for three stations in Cyprus not presented), is evident, as follows. Class B (Light-Moderate) is the number one contributor with about 34–39% immediately followed by the Heavy categories C1(27–31%) and C2 (16–20%). The Light category A(7–11%) is next, and closing the list are the Torrential categories, D1(4–8%) and D2(1–4%). In Spain and Italy, the D-categories increased, while the central C-categories decreased. In Spain, moreover, the lower extremes increased as well, indicating a very strong increase of the daily rainfall variability. No significant trends were evident in Israel and Cyprus. The slopes of the trends (in %/y) along with their statistically significance levels, are shown in Figure 1.

[6] Following are some of the most interesting findings

1. **In Spain:** The categories at both distribution extremes, i.e. Light (A), Light-Moderate (B) and Torrential D (D2 significant) increased their contributions to the total annual rainfall. This increase in both tails of the distribution is accompanied by an even more significant decrease of the central heavy categories, C1 and C2, which contribute about half the totals, dropping from about *49% in the early 1950s to only about 43% in the 1990s*. The actual annual 1951–1995 average for the 182 rain-gauge stations was about *530 mm/y*. The mean trend of annual rainfall was *−1.52 mm/y/y* (−0.88 mm/y/y for the 5-y running mean).
2. **In Italy:** There is a clear dividing line between the Heavy-Torrential categories (C2,D1 and D2) which show an increasing trend, and the weaker categories (A,B,C1) which show a highly significant decreasing trend. The Heavy to Torrential contribution (C2 + D1 + D2), *increases from 23% in the 1950s to about 31% from the total annual rainfall in the 1990s*.
3. **In Israel and Cyprus:** No significant trends were found. There are, however, as in the W. Mediterranean, Heavy categories (C1, C2 in Israel;C2, D1 in Cyprus) that increase and Lighter categories (A in Israel; B, C1 in Cyprus) that show a decreasing trend.
4. **Relation to El-Nino:** It is interesting to note that Torrential rainfall categories D1 and D2 tend to peak in El-Nino years [*Trenberth*, 1997], particularly noticed for Italy non-smoothed Figure 1, for the El-Nino years 1953,1965,1982/3,1986/7. In 1983 and 1986, for instance, the D2 category alone contributed over 15% compared to an annual average of only 1–4%. The link between Torrential rainfall and El-Nino seems to strengthen in recent last decades as suggested also for rainfall over N. Israel [*Price et al.*, 1998] and Turkey [*Kadioglu et al.*, 1999].

[7] In Italy, the Torrential contributions D1 and D2 exhibit the largest inter-annual fluctuations, compared to the other categories. In Israel, however, all categories have high inter-annual variability, probably related to the increased semi-aridity at the more southern sub-tropical latitudes of Israel. Over this semi-arid region, tropical and sub-tropical systems like the Red-Sea trough with high inter-annual variability, contribute in some years a good portion of the rainfall which increases toward the south [*Krichak et al.*, 1997; *Alpert et al.*, 1990]. This is also reflected in the large span of the rainfall normals over the 38 Israeli stations from maximum of 776 mm/y in the north to a minimum of 105 mm/y only 220 km to the south.

Figure 1. (opposite) Rainfall contributions, as percentage from the total annual amounts, for each of the daily rainfall categories A, B, C1, C2, D1, D2, for the period 1951–1995. Upper panel-Mediterranean Spain 182 stations, [*Romero et al.*, 1998], Central panel- Italy 42 stations, [*Piervitali et al.*, 1998], Lower panel- Israel 38 stations, [*Ben-Gai et al.*, 1998]. The chosen daily rainfall categories in mm/d are: Light(A) 0–4, Light-Moderate (B) 4–16; Moderate-Heavy (C1) 16–32; Heavy (C2) 32–64; Heavy-Torrential (D1) 64–128; and Torrential (D2) 128-up. The corresponding symbols for the points in the 6 lines from up the panels downward are: B 'minus' (−), C1 'multiplication sign' (×), C2 'circle' (○), A 'plus' (+), D1 'square', D2 'triangle'. To the right, the calculated trends (in %/y) based on best-line fit and the respective statistical individual significance level (in parentheses) both for linear trend and for the monotone (Spearman's) non-linear time tests are given. Since 18 such observed significance levels are reported, there is an increased probability for a false statistical discovery if the individual 0.05 is considered significant. Using a statistical procedure to control the false discovery rate at the 0.05 level [*Benjamini and Hochberg*, 1995; *Yekutieli and Benjamini*, 1999], an individual value below 0.022 (0.018 for the linear trends) is considered statistically significant. The linear trend significance level should be viewed with caution as the percentage data at the extreme categories are far from satisfying the normality or linearity assumptions underlying the reported significances of the linear slopes. In two cases, where the results were not significant, signs even changed and remain non significant; the changed sign in the monotone time trend for these two cases (in Israel B and D2), is indicated in parentheses. Arrows on the right indicate the trends' direction up/down. Circles indicate non-significant trends. The issues of quality control, homogeneity, and completeness were considered in much detail in several earlier studies [*Piervitali et al.*, 1998; *Romero et al.*, 1998; *Ben-Gai et al.*, 1998] for Italy, Spain, and Israel, respectively.

4. Summary

[8] Global warming was suggested to be linked with the recent increases of heavy daily rainfall due to the increased atmospheric water vapor and warmer air. Total annual rainfall also shows increasing trends in many regions. Contrary to many mid- to upper latitude regions of the world in which positive trends in recent rainfall were reported, over the Mediterranean several regional studies show a dominant decreasing trend.

[9] In the present analysis we examined six daily rainfall categories for 265 stations in Mediterranean-Spain, Italy, Cyprus and Israel for 1951–1995. We showed that extreme daily rainfall increases in spite of the fact that total rainfall generally decreases. For instance, torrential rainfall exceeding 128 mm/d contributes 4–5% of the total Italy rainfall in the 1990s compared to only 1% in the 1950s; an increase by a factor of 4. Furthermore, heavy to torrential categories above 32 mm/d contributed in the 1950s only 23% of Italy rainfall and this share increased to 32% in the 1990s. Italy stations during 1880–1996 have shown similar trends for heavy rainfall contributed mostly by the rainfall in summer and in the transition seasons [*Brunetti et al.*, 1999]. Similar analyses are presented here for Spain and Israel. In Spain, the categories at both extremes, i.e. Light (A), Light-Moderate (B) and Torrential D (D2 significant) increased their contributions to the total annual rainfall. This increase in both tails of the distribution is accompanied by an even more significant decrease of the central heavy categories, C1 and C2, which contribute about half the totals, and have dropped from about *49% in the early 1950s to only about 43% in the 1990s*.

[10] Such a scenario illustrates the existence of a substantial change in the rainfall distribution over a relatively large subtropical region, the Mediterranean, in which the "increase in variance" overcomes the "reduction in the mean" [*Meehl et al.*, 2000]. These results strongly illustrate the trends suggested due to global greenhouse gas warming. Both modeling [*Hennessy et al.*, 1997], and observational studies [*Brunetti et al.*, 1999], show that this reduction is associated with fewer rainy days. The latter is explained by the increase in the frequency and persistence of sub-tropical anticyclones, particularly over the Mediterranean.

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