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A study of rainfall in the Roman area in the years 1951–2000(*)

O. Testa, M. Colacino, A. Lavagnini and V. Malvestuto(**)

CNR, Istituto di Scienze dell'Atmosfera e del Clima, Via del Fosso del Cavaliere, 100
00133 Rome, Italy

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Summary. — The daily rainfall data collected in the second half of the last century at 31 climatic stations in Lazio, Italy, have been subjected to statistical analysis in order to describe the pluviometric regime of the whole area on a multi-decadal time scale. The stations, for their geographical distribution within the region under study, are apt to represent different climatic zones, namely, a coastal, a rural, a suburban and an urban zone. The data have been treated both as time series and as geographical statistical variates with the double aim, first, to verify if in the area under study any changes in the yearly precipitation rate, frequency and its distribution over different classes of rain intensity, have occurred in the last 50 years; second, to evidence a possible correlation between the intensity of precipitation and any of some environmental variables such as altitude, distance from the coastline and distance from the urban site. As for the first issue, it can be concluded that the precipitations over the Roman area in the period 1951–2000 show no significant trend; in particular, no trend is visible in any of the single classes of rain intensity, both absolute and percentile-based, considering either their frequency or their percent contribution to the total. As for the second issue, significant correlations have been found in the spatial distribution of rainfall with any of the relevant environmental variables mentioned above. The results of the analysis also show that in the urban area a less amount of rain seem to fall than in the surroundings zones, a result that seems rather anomalous in consideration of the several known factors that favour the intensification of the rainfall in the city with respect to its surroundings. A detailed statistical characterization of all the single 31 stations over the whole period is also given via a separate study of the durations of droughts and of the statistics of rainy days, using best fits based on the Weibull probability distribution.

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(*) The authors of this paper have agreed to not receive the proofs for correction.

(**) E-mail: V.Malvestuto@isac.cnr.it

1. – Introduction

While the existence of a slow but constant increase in the mean yearly temperature of the globe appears to be rather well established, well-definite trends for other climatic parameters, like precipitation, have not been ascertained. In fact, on the base of recent data [1, 2], the global warming seems associated with an increase of severe rain events, which in turn is due to an increment in air temperatures and to the consequent increment of the water vapour content in the troposphere. Moreover, under this respect, the Mediterranean area seems to be rather atypical. In fact, in contrast with what observed in other mid-latitude and high-latitude regions, where an increase in the yearly precipitation totals has been documented [3], in the Mid-Western Mediterranean basin several studies on the regional scale have evidenced a decreasing trend in the mean yearly rainfall. In particular, in Italy and Spain a mean reduction of about 10–20% of the yearly totals in the period 1951–1995 [4,5] has been reported. As for the Eastern Mediterranean, some areas show a decrease, while others show an increase in the precipitation rates, the former case being the more frequent [6-8]. All these works refer to large areas within and around the Mediterranean basin. Therefore, it is of interest to verify whether in a region within the Mediterranean climatic area, though one of limited extension, the existence of a trend of any kind might be revealed either in the total yearly rainfall or in the subtotals of the different rain intensity classes, and, in particular, for those classes referring to the most severe events. As a matter of fact, the trends found in the extreme climatic events for both temperatures and precipitations [9] have proved to be of particular interest as indicators of the global warming. It is a fact that in many parts of the globe where the precipitations tend to increase, the same does the frequency of intense rainfall events. It is true however, that, even in zones where a decrease in the seasonal total rainfall is observed, as reported for North Japan, as well as for the East side of Russia and for some areas of South Africa [10, 9, 2] an increase in the frequency of severe rainfall events has been observed anyway. The same somewhat paradoxical behaviour occurs also in some subtropical areas, for instance in the Mediterranean [11].

In the present work the analysis of long series of data collected in a network of stations, lying within and around the city of Rome, has been undertaken with the aim to analyse whether at district scale (that is, within distances less than 100 km) the above-mentioned general trend is confirmed or not. In addition, it is interesting to verify if and in what extent the presence of a big city, like Rome, is able to modify the rainfall patterns and intensities. The urban effects on the spatial distribution of climatic variables, like temperature and rainfall, have received remarkable attention starting from the seventies [12-18]. These studies led to the concept of "urban heat island", that is the tendency of urban sites to show in the average air temperatures higher than rural areas. The local effect on temperature fields, due to the presence of a city nearby, is well documented in the literature [19-22]. For what concerns rainfall, on the other hand, it must be said that the urban effect , though already considered by some authors (*e.g.*, see [15]), has not received the same attention as the urban effect on temperature. Changnon *et al.* [15] point out three mechanisms through which the urban environment acts on precipitation rates: i) injection of anthropogenic giant nuclei into the clouds and consequent coalescence processes, ii) increase of clouds formation and instability due to convective motions, iii) formation of convergence zones for clouds and precipitation. Oke, in his review on urban climatology [13], lists a variety of conditions which determine an increase of precipitation in zones adjacent to the city. However, other authors dispute his interpretations: in fact, unlike Oke, Huff and Vogel [23] point out that the increment

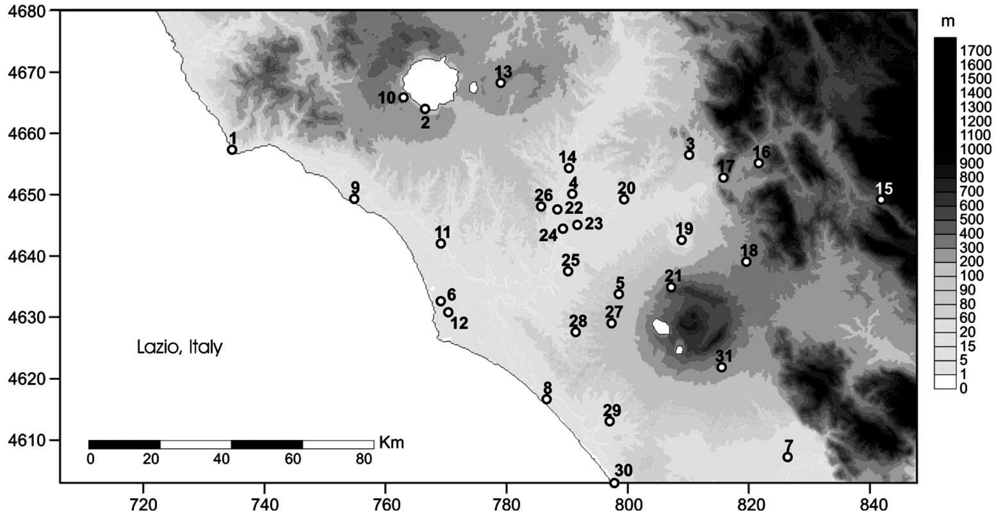

Fig. 1. – The region under study. Geographical distribution of the AM-LP 31 climatic stations within an isohypse map of Lazio, Italy, showing the orography. Longitude and latitude are marked in km on the horizontal and vertical axes, respectively.

in rainfall is observed, rather than within the city itself, in its lee side, within distances of about 30–40 km [24-26, 22].

Since the study of trends in temperature and rainfall is carried out on analysing long historical series, and since the longest available data series are recorded by stations located mainly in urban sites, there always exists the risk to draw biased inferences about the prevailing time trends, when the data analysed exclusively refer to a big urban site, whence the importance of a detailed description of the small-scale spatial variability in the patterns of the basic climatic parameters, when such comprehensive data are available.

2. – Description of the data

The area under study is a wide valley that extends from the Appennini mountain range to the Tyrrhenian sea, having its centre in the city of Rome. In particular, at the northern border, there are Tolfa's mountains (maximum height at about 600 m) extending all the way to the coastline, on the East the range of Monti Sabini, reaching over 1000 m, on the South the Colli Albani, reaching less than 900 m, gently sloping down toward the coast. In order to give a more clear idea of the area under study, an isohypse map has been included (fig. 1), where the 31 stations have been located.

The climatology of the region is characterised, besides the marked influence of the sea, by the other effects due to the complex orography and by the presence of a big city, like Rome, crossed by a conspicuous river and having an extension of about 1285 km^2 and a resident population of over 3 millions.

The data subjected to analysis is a collection of time series apt to describe the pluviometric regime of the whole area under study on a pluri-decadal time scale.

The data are the values of daily rainfall in mm, as recorded at 31 climatic stations (some equipped with pluviometers, other with thermopluviometers) spread in the territory of the county of Rome, somewhat more densely packed near the city (see fig. 1

TABLE I. – *The 31 climatic stations with their geographical types, locations and other relevant parameters.*

Type	Station name	Code	Lat. UTM	Lon. UTM	Alt. (m)	Dist. from Rome (km)	Dist. from coast (km)
coastal	Civitavecchia	1	4657444	734548	3	55.5	0.1
rural	Vigna di Valle	2	4664119	766075	262	30	19
suburban	Guidonia	3	4656604	809223	88	24	45.5
urban	Roma Urbe	4	4650234	790121	18	6.5	30.5
suburban	Ciampino	5	4633862	797726	129	13.5	21
coastal	Fiumicino	6	4632707	768642	2	22.5	1.5
rural	Latina	7	4607245	825300	26	52	16
coastal	Pratica di Mare	8	4616695	785927	6	27.5	0.3
coastal	Ladispoli	9	4649423	754500	5	34.5	0.5
rural	Bracciano	10	4665995	762554	290	34	18.5
coastal	Maccarese	11	4642129	768656	7	19	5.5
coastal	Isola Sacra	12	4630900	769866	4	24.5	1.8
rural	Baccano	13	4668365	778428	225	26.5	29
suburban	Castel Giubileo	14	4654445	789580	63	10.5	33.5
rural	Subiaco S.S.	15	4649291	840570	458	52	62.5
rural	Castel Madama	16	4655254	820582	453	34	52.2
suburban	Tivoli	17	4652894	814806	238	27.5	46.5
rural	Zagarolo	18	4639151	818559	318	30	39.5
suburban	Pantano Borghese	19	4642704	807981	52	19.5	43
rural	Settecamini	20	4649349	798579	48	12	34.5
suburban	Frascati	21	4634997	806280	322	14	22.6
urban	Flaminio	22	4647694	787687	15	4	27
urban	Macao	23	4645169	790951	55	2.5	26
urban	Collegio Romano	24	4644548	788599	51	0	24
urban	Eur Tre Fontane	25	4637599	789436	24	6.5	19
urban	M. Mario V. M.R.	26	4648174	785037	110	5.5	26.5
suburban	Castel di Leva	27	4629115	796536	102	17	16.6
coastal	Ostia Idrovore	28	4627669	790672	4	17.5	7
coastal	Ardea	29	4613096	796226	47	31.5	5.5
coastal	Anzio	30	4603000	797000	10	51	0.1
rural	Velletri	31	4621911	814533	332	34	25

and table I). Out of these 31 stations, 8 are run by the Italian Air Force (Aeronautica Militare) and the others by the goverment (former *Servizio Idrografico e Mareografico Nazionale*, *Sezione Idrografica di Roma*, now available at regional level). The period covered by the observations is the second half of the last century, namely the years 1951–2000. These stations, thanks to the variety of their locations, are well representative of the different zones present in the region under study, namely, a coastal zone, a rural zone, a suburban zone and an urban area (see first column in table I). This heterogeneous distribution allows to evaluate how much the precipitation in a given site is influenced by its nearness either to the urban centre, to the sea or to the orographic relief.

Each of these time series will be denoted by $P_s(j)$, where s refers to the station ($s = 1, 2, 3, ..., 31$), while j refers to the day of measurement ($j = 1, 2, ..., D$), the values of $P_s(j)$ being the millimetres of rainfall observed in the given day, a negative value being reserved to indicate absence of data. Note that $D = 18263$ for all stations,

TABLE II. – *The 31 climatic stations with their observational coverage in the half century 1951–2000, and their mean yearly rainfall in such period.*

Code	Station name	Missing years in the period 1951–2000	Meas. days over 18263	%	Mean yearly rain $\left(\text{mm y}^{-1}\right)$
1	Civitavecchia	1951–1960, 1962–1964	12843	70	710.6
2	Vigna di Valle	1951–1954	16312	89	979.0
3	Guidonia	1951–1963, 1986	13097	72	829.4
4	Roma Urbe	1951, 1953, 2000	16138	88	810.7
5	Ciampino		18058	99	838.2
6	Fiumicino	1951–1958, 1997–1998, 2000	13516	74	732.5
7	Latina	1951–1960	14524	80	922.5
8	Pratica di Mare	1960, 1961, 1986	13761	75	830.7
9	Ladispoli	1954, 1964, 1993, 1996–2000	15340	84	769.6
10	Bracciano	1971, 1993, 1998–2000	16437	90	1025.9
11	Maccarese	1993, 1998–2000	16802	92	809.1
12	Isola Sacra	1993, 1998–2000	16802	92	829.5
13	Baccano	1973–1976, 1978–1987, 1993, 1998–2000	11689	64	1196.4
14	Castel Giubileo	1952–1953, 1974, 1976, 1982, 1984, 1993, 1998–2000	14609	80	955.4
15	Subiaco S.S.	1993, 1998–2000	16802	92	1218.3
16	Castel Madama	1953, 1970, 1993, 1998–2000	16072	88	1016.0
17	Tivoli	1964, 1973, 1977–1979, 1998–2000	15341	84	854.3
18	Zagarolo	1964, 1993, 1995–2000	15340	84	1149.5
19	Pantano Borghese	1956, 1959, 1960, 1964, 1984, 1993, 1998–2000	14973	82	793.8
20	Settecamini	1952, 1955–1956, 1958, 1964, 1993, 1998–2000	14609	80	907.6
21	Frascati	1954, 1964, 1998–2000	16436	90	851.4
22	Flaminio	1951–1955, 1964, 1970–1971, 1993, 1998–2000	13880	76	842.1
23	Macao	1951, 1972–1986, 1998–2000	11323	62	804.2
24	Collegio Romano	1964, 1998–2000	16801	92	677.0
25	Eur Tre Fontane	1962–1964, 1993, 1994, 1997–2000	14976	82	810.4
26	M. Mario V. M.R.	1951–1964, 1993, 1998–2000	11688	64	817.1
27	Castel di Leva	1951–1952, 1964, 1993, 1998–2000	15705	86	878.1
28	Ostia Idrovore	1951, 1964, 1993, 1998–2000	16071	88	775.6
29	Ardea	1962–1965, 1993, 1998–2000	15341	84	799.1
30	Anzio	1958, 1960, 1963–1964, 1967–1968, 1970, 1973, 1979, 1993, 1998–2000	13514	74	716.9
31	Velletri	1964, 1970, 1979–1981, 1983–1986, 1993, 1998–2000	13514	74	1205.9

that being the number of days in the considered 50 years, but, due to occasional gaps in the data, the number of good data for a given station is generally less than D, with a minimum of 11323 for the Macao station (see table II).

Starting from the original time series $P_s(j)$, other time series have been formed by space or time averaging. For each of them, when needed, alternative notations will be used in order to make it clear which exactly is the quantity under study. For example,

- $P_s^{(y)}(k)$, with k now indicating the year, will denote the yearly-cumulated time series for a given station, obtained from $P_s(j)$, summing over all the days of a same year.
- $P^{(y)}(k)$ will denote the spatial average of $P_s^{(y)}(k)$, done over all the stations active in the given year k;
- P_s will denote the mean yearly rainfall for a given station, obtained after averaging the time series $P_s^{(y)}(k)$ over the whole period (1951–2000).

3. – Daily data: pure statistical features

3˙1. *Dry days.* – First of all, for each single station, a pure statistical analysis of the daily precipitation values has been carried out, with no regard to either their time order or the presence of data gaps. Two distinct statistics have been formed, one based only on the dry days, the other one based only on the rainy days (> 1 mm day^{-1}). As for the first statistics, we define a “drought” as an uninterrupted run of successive dry days, and the length of a drought as the number of dry days in the run. Then one can investigate the distribution of these lengths. More precisely, each run of dry days is regarded as one realization of an aleatory variable assuming integer values greater than zero. The classes chosen to partition the drought lengths have been defined as follows, with different widths growing in geometric progression:

Class:	0	1	2	3	4	5	6	7	8
Days:	1	2	3-4	5-8	9-16	17-32	33-64	65-128	> 128

droughts lasting more than 128 days being very rare in the region under study.

Results for all the stations are shown in table III. The frequencies have been counted for the whole year or for the summer period alone, summer being here defined as the semester from April 1st to September 30th. All the stations show a maximum located within the first three duration classes (at about a 2-day or a 3-day length). The persistence of the right-hand tails of the observed distributions is responsible for the mean duration of droughts being always lower than their standard deviation, as apparent from table III, where the total number of observed dry days and the maximum duration of a drought in days are also shown for each station, both for the whole year and for summertime only. The comparison with the summertime frequencies confirms the easy supposition that the longer is the duration of a drought, the more likely is that it occurs during the summertime period. The incidence of the first duration class alone oscillates between 22% and 27% with a frequency that is comparable with each of the next two classes. Also, the variability among the stations of means and standard deviations is low as apparent from columns 3 and 4 of table III. On the other hand, the maximum drought duration (column 5) presents wild changes among the stations with a range extending from about 2 months (station n. 15) to more than 9 months (station n. 25: Eur Tre Fontane).

3˙2. *Rainy days.* – Table IV presents the corresponding statistics for rainy days, columns 2 to 7 referring to wintertime only, and the successive six columns referring to summertime only. In both cases the first of the six columns contain the number of

Table III. – *Statistical parameters of dry days for each of the 31 stations. The left section of the table refers to the statistics over the whole year, while the right section refers to summertime alone.*

Length of droughts (1951–2000)								
Period	Over the whole year				Summer only			
Stat. code	Number of dry days	Mean (day)	St. dev. (day)	Max (day)	Number of dry days	Mean (day)	St. dev. (day)	Max (day)
1	11074	7.8	10.8	122	5979	10.3	14.3	122
2	13011	6.4	7.6	77	7020	7.8	9.2	77
3	10529	6.1	7.2	72	5550	6.4	7.6	55
4	13443	6.5	7.9	86	7249	8.1	9.9	86
5	14258	6.5	8.2	85	7676	7.9	10.2	85
6	11675	6.8	9.4	112	6399	9.2	12.6	112
7	11150	6.4	8.3	74	6043	8.0	10.4	74
8	11857	7.6	11.5	144	6441	9.8	13.9	144
9	12439	7.9	11.7	193	6748	10.8	15.4	155
10	12673	6.5	8.4	94	6867	7.9	10.6	94
11	13512	7.7	10.6	112	7355	10.5	13.7	112
12	13540	7.6	10.8	113	7432	10.9	14.7	113
13	9053	6.6	10.5	197	4879	7.9	12.0	139
14	11392	6.8	8.7	83	6144	8.5	10.7	83
15	12074	5.4	6.4	61	6352	5.6	6.7	60
16	11928	5.7	6.9	82	6305	6.3	8.0	82
17	11815	6.3	8.0	102	6260	7.2	9.2	94
18	12159	6.8	8.5	68	6394	7.8	9.8	68
19	12210	7.4	8.9	66	6424	8.6	10.4	66
20	11458	6.6	8.7	89	6125	7.9	10.4	89
21	12934	6.8	8.9	91	6924	8.2	10.9	91
22	10799	6.6	8.6	91	5790	8.0	10.4	91
23	8853	6.6	9.2	115	4784	8.2	11.5	115
24	13425	7.3	9.8	123	7231	9.2	12.4	123
25	11735	6.9	11.0	272	6366	8.9	13.2	180
26	9185	6.8	8.7	82	4926	8.3	10.6	82
27	12515	7.2	9.8	102	6748	9.4	12.6	102
28	12799	7.4	10.2	111	6996	10.0	13.7	111
29	12332	7.7	11.8	233	6700	10.0	14.0	127
30	11241	8.3	12.5	128	6104	12.4	17.6	127
31	10004	6.1	8.7	91	5431	7.2	10.1	88

rainy days observed in that season during the whole period 1951–2000. The successive columns contain, respectively, expressed in millimetres, the mean daily rainfall (computed over the rainy days only), its standard deviation (which results always greater than the corresponding mean) and the maximum daily rainfall observed for either season. The mean daily rainfalls are rather uniform over all the stations with a range comprised between about 10 and 14 mm day^{-1} in winter and between 9.5 and 12 mm day^{-1} in summer, with the only exception of station n. 18 (Zagarolo) that is located at an altitude over 300 m. Even more uniform are the corresponding standard deviations lying in the interval 11–15 mm day^{-1}. On the other hand, much more variable appear to be the maxima, whose range of variation is from 90 to about 200 mm day^{-1}, except for two

TABLE IV. – *Statistical parameters of rainy days for each of the 31 stations. The left section of the table refers to the statistics over wintertime, while the right section refers to summertime. In each case the best-fit Weibull parameters are also listed.*

	Rainy days (1951–2000)											
	Winter						Summer					
Stat. code	Tot. num. days	Mean (mm)	St. dev. (mm)	Max (mm)	Weibull parameters		Tot. num. days	Mean (mm)	St. dev. (mm)	Max (mm)	Weibull parameters	
					c	k					c	k
1	1519	10.8	12.3	113.8	9.047	0.863	722	10.9	13.6	121.4	8.734	0.810
2	2295	12.4	14.3	198.0	10.540	0.867	1296	10.9	12.9	117.6	8.865	0.832
3	1711	10.3	11.0	105.0	8.642	0.876	1190	9.8	10.3	93.0	8.397	0.915
4	2131	10.7	11.9	200.0	9.037	0.879	1210	10.0	10.9	89.0	8.418	0.874
5	2398	10.0	11.4	213.0	8.333	0.869	1405	9.6	11.0	131.6	7.805	0.839
6	1817	10.8	12.5	120.4	9.096	0.865	827	10.5	14.4	129.8	7.861	0.757
7	2113	11.4	12.7	135.6	9.650	0.872	1208	9.9	11.5	94.6	8.077	0.841
8	1875	11.4	12.8	113.8	9.497	0.853	885	10.6	14.2	200.0	8.440	0.807
9	1915	11.2	12.0	110.4	9.646	0.893	909	10.7	14.1	232.2	8.673	0.832
10	2333	13.8	15.8	180.0	12.040	0.887	1325	11.6	13.7	172.2	9.811	0.869
11	2129	11.4	13.2	154.6	9.561	0.863	1014	10.5	13.2	124.8	8.467	0.829
12	2204	11.8	13.3	165.0	10.254	0.905	960	11.3	14.5	196.8	9.323	0.843
13	1631	13.4	14.8	140.7	11.272	0.843	953	12.1	17.6	347.4	9.615	0.789
14	1954	11.6	12.3	125.0	9.955	0.891	1109	10.5	12.6	180.0	8.593	0.835
15	2593	13.6	14.9	145.0	11.700	0.866	2002	10.2	11.1	153.6	8.604	0.884
16	2300	12.6	13.0	114.0	11.187	0.927	1656	11.4	12.9	147.0	9.778	0.887
17	2033	10.5	11.3	106.4	9.030	0.901	1363	10.2	11.4	144.6	8.667	0.884
18	1837	17.6	19.0	332.5	16.152	0.946	1250	13.7	14.0	136.0	12.470	0.963
19	1654	12.4	12.6	115.0	10.913	0.906	1056	11.2	11.9	111.0	9.578	0.885
20	1825	12.4	12.6	153.0	11.356	0.984	1101	12.1	13.8	146.7	10.676	0.927
21	2138	11.5	12.6	129.0	9.823	0.882	1272	10.4	11.2	132.7	8.885	0.888
22	1843	11.1	12.4	120.4	9.235	0.854	1108	10.0	12.7	130.6	7.900	0.805
23	1518	10.8	11.2	91.8	9.197	0.886	849	9.6	11.9	129.2	7.632	0.815
24	2117	9.7	11.2	180.4	8.135	0.882	1132	9.7	11.9	114.4	7.772	0.824
25	2003	10.5	11.7	121.5	8.848	0.879	1095	10.2	12.8	144.6	8.144	0.814
26	1517	10.8	11.8	93.8	9.232	0.887	888	10.5	13.1	169.4	8.552	0.836
27	2025	12.6	13.0	144.3	11.436	0.967	1087	11.1	11.6	100.4	9.663	0.920
28	2139	10.8	12.7	198.0	9.161	0.875	999	10.5	12.8	115.0	8.386	0.814
29	1902	11.8	12.2	100.0	10.415	0.933	905	11.1	12.6	95.0	9.511	0.891
30	1551	12.1	12.7	100.7	10.707	0.925	637	11.9	13.8	90.5	9.909	0.848
31	2105	13.8	14.8	112.6	11.986	0.881	1295	11.7	12.8	115.6	9.799	0.852

outliers, the Zagarolo station again, with its winter maximum of 332 mm in one day, and another mountain station (station n. 13: Baccano) with its summer maximum of about 350 mm in one day, the latter values corresponding to exceptional torrential events discharging within 24 hours a quantity of rain equal to the one falling on the average during a whole semester. In each case the observed histograms, all strongly peaked at the first bin, have been fitted with a Weibull distribution

$$W_{c,k}(x) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} \exp\left[-\left(\frac{x}{c}\right)^{k}\right], \qquad \text{for } x \geq 0 \tag{1}$$

thus obtaining four optimal parameters for each station, (k_w, c_w) for wintertime, and (k_s, c_s) for summertime. Note that the parameter c is a scale factor sharing the dimension of the variable under study (herein, mm day^{-1}), whereas the other parameter k is a dimensionless exponent. The estimated values of c and k are shown in table IV.

The goodness of the fit done via the best Weibull distribution has been measured using a chi-square test which takes into account only those classes of the histogram where at least one event is predicted. If a 95% significance level is adopted, the chi-square acceptance threshold for the null hypothesis ranges between 12 (for only 5 classes) and 17 (for 10 classes). The comparison of these thresholds with the actual chi-square values indicates that, despite the optimisation of the parameters c and k, only one station out of three exhibits a data histogram that can be adequately represented with a Weibull probability density, the discrepancy being mostly due to the relatively high values in the right-hand tail of each histogram. This persistence of the tails in the histograms is

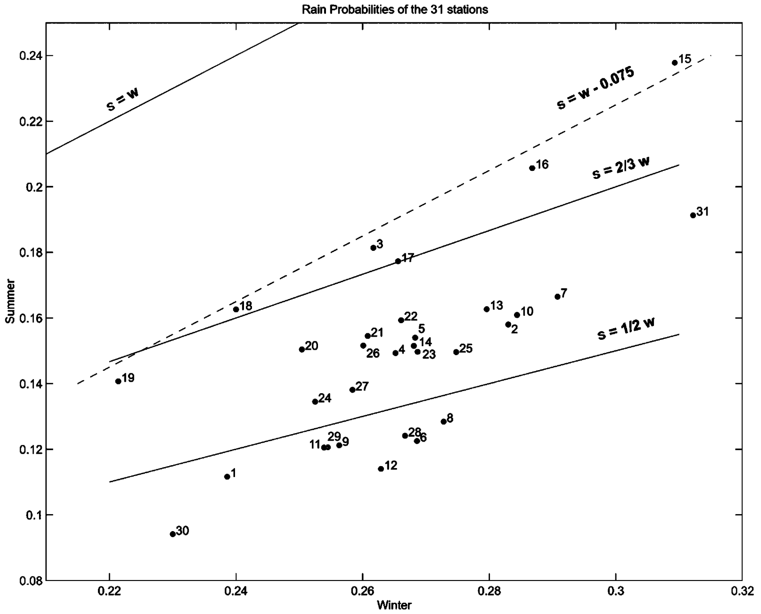

Fig. 2. – Rain probabilities of the 31 stations: summer values are drawn *vs.* winter values. Most points cluster around the straight line $s = w/2$, for which the summer rain probability, s, is the half of the rain winter probability, w. Mountain stations appear to stay above the line $s = 2/3w$, and somewhat to be aligned along the line $s = w - 0.075$, while coastline stations tend to stay below the straight line $s = w/2$.

linked with the fact that the standard deviations systematically exceed the corresponding means.

3˙3. *Variability among the stations.* – The similarities and the differences among the stations are evident from tables III and IV and from fig. 2, where the rain probabilities for winter and summer, respectively w and s, are presented *vs.* each other.

As for the values of the optimised Weibull parameters c and k, listed in table IV, columns 6–7 and 12–13, they are all comprised in rather narrow ranges even making no distinction between the two seasons. However, on a k-c plane, the summer station-points would appear rather neatly separated from the winter station-points, the mountain stations showing, as expected, the higher values of the Weibull scale factor c, that is directly proportional to the average precipitation. Moreover, there are few stations, mostly suburban stations, which in winter show a Weibull exponent k near to 1, which corresponds to a more distinct maximum in the distribution.

Other aspects of variability of rainfall among stations, when the mean precipitation over the whole period 1951–2000 is concerned, are discussed in sect. **8**.

4. – The treatment of the data gaps and the validation of the yearly series

While analysing the 31 time series of daily rainfall data, for each station the percentages of useful and lacking data have been calculated, and only the years with at least 2/3 of daily measurements have been considered for further processing. Such years, that will be briefly called “good years”, generally have lacking data occurring as long sequences rather than as single or short gaps in the database. Such gaps have been previously filled with the aim to have, for each station, full data for each good year. The filling procedure is based on a Monte Carlo method in which proper consideration is given to the time location of the data gaps. For each day of a good year, where the data was missing, it was first decided whether it was a rainy day or not on the base of the pertinent (wintertime or summertime) rain probability; then, if the day was rainy, the gap was filled by randomly drawing a number of millimetres from the pertinent theoretical Weibull distribution depending on the specific station and season; otherwise, no rain was assumed to have occurred. For what concerns the non-good years, note that no consideration of the data collected therein was given in the subsequent data treatment. Thus, for any given year in the period 1951–2000 only a fraction of the 31 stations contribute to form the geographical average of any relevant quantity. Fortunately, in our database the bad years for the various stations appear to be distributed randomly, with no evident preference towards any specific category of stations. Moreover, for most years (excluded 1964, 1993 and 1998–2000) the number of stations contributing to form a yearly value exceeds the two thirds of the total.

Before using the original time series for any purpose, it is also necessary to perform various controls testing their reliability. In fact, it is known that most long-term meteorological time series suffer by inhomogeneities due to various sources. This is especially true for precipitation, since progressive improvements of instrumentation can introduce artificial systematic drifts with time. In order to ensure that precipitations trends be not spurious, it is important that the inhomogeneities be evidenced and that inhomogeneous series be either adjusted or discarded. Therefore, it has been decided to perform a homogeneity test on each of the 31 yearly series. In the absence of metadata recording the historical relevant facts regarding the single stations, several statistical tests, have been recommended [27-30]. The test used here is an indirect homogeneity test based on the analysis of the time series formed with the ratios between the rainfall at a station in a given year and the corresponding one taken from a reference time series. This test, called the Standard Normal Homogeneity Test (SNH-Test), was developed by Alexandersson [28]. Its basic assumption is that the ratio q of a suitably defined normalized precipitation at the test station and the corresponding quantity taken from the reference series is fairly constant in time (usually not far from one), so that an inhomogeneity is revealed by a systematic change in this ratio. In our case the yearly series of normalized precipitations at any station was defined as the yearly rainfall divided by the station average over the whole observation period, that is

$$Q_s(k) \equiv \frac{P_s^{(y)}(k)}{P_s}. \tag{2}$$

The reference series was then built as a weighted mean of all the remaining stations:

$$Q_s^{ref}(k) \equiv \frac{\sum_{j=1,N}^{j\neq s} w_{j,s} Q_j(k)}{\sum_{j=1,N}^{j\neq s} w_{j,s}}\,, \tag{3}$$

where the weights $w_{j,s}$ are the squared Bravais correlation coefficients between the test station s and any other station j. The time series of the ratios q when testing the station

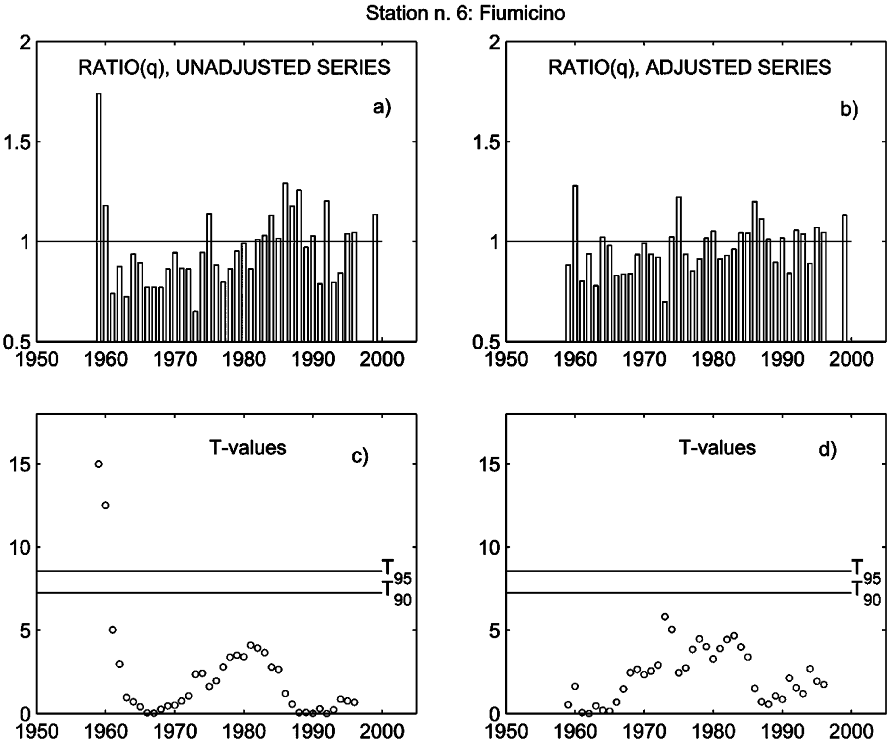

Fig. 3. – Performance of the SNH-Test on the annual precipitation series from the station Fiumicino. Q-ratios before (a) and after (b) the adjustment, and T-values before (c) and after (d) the adjustment.

s is then defined as

$$q_s(k) \equiv \frac{Q_s(k)}{Q_s^{ref}(k)} \,. \tag{4}$$

This q-series is now standardized by defining the new series:

$$z(k) \equiv \frac{q_s(k) - \overline{q}_s}{s_s} \,, \tag{5}$$

where $\overline{q}_s$ is the sample mean value and s_s is the sample standard deviation of the $q_s(k)$. From this z-series a test parameter $T_{\max}$ is computed as the maximum value of a new time series defined as

$$T(k) \equiv k\overline{z}_1^2 + (N-k)\overline{z}_2^2, \qquad \text{for } k = 1, 2, \ldots, N-1 \,, \tag{6}$$

where now k represents the year, and $\overline{z}_i$ is the mean value over each of the two segments in which the z-series is divided by the year k, the latter being included in the first of the two segments. Significant thresholds at the 90% and 95% levels for the $T_{\max}$ statistic are available in the literature [28], which can be used as critical levels for the acceptance or

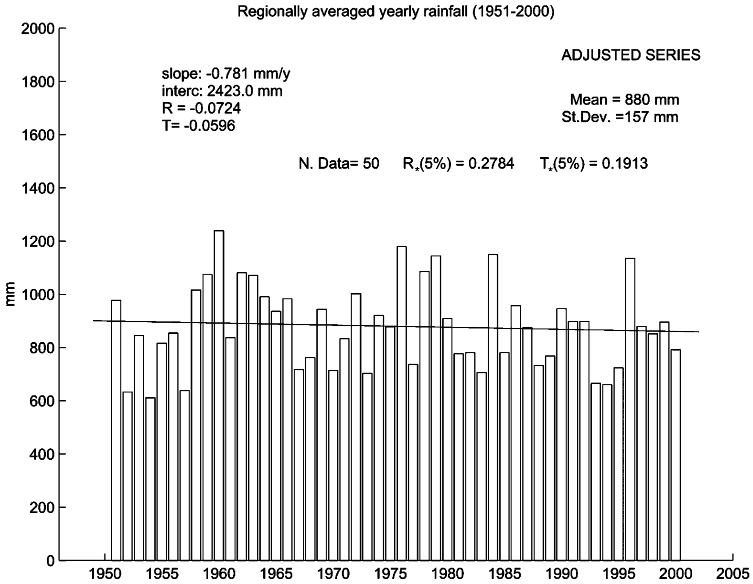

Fig. 4. – Regionally-averaged yearly total rainfall *vs.* time (1951–2000), built using the adjusted series. No significant trend is visible from both viewpoints of the correlation coefficient R and of Mann-Kendall's tau-test T, at the adopted significance level of 95%.

rejection of a null hypothesis consisting in the statement that the original time series at the test station is homogeneous. When the null hypothesis is rejected, the T_{max} statistic also pinpoints the year at which it is most likely that a sudden discontinuity occurred. This allows the adjustment of the original time series $P_s^{(y)}(k)$ which is done as follows. First, one computes the two means of the yearly rainfalls at the test station both before and after the critical year, say $P_{s,1}$ and $P_{s,2}$; then one multiplies either the past values by the factor $P_{s,2}/P_{s,1}$ or the successive values by the inverse factor $P_{s,1}/P_{s,2}$, depending on whether the metadata make us prefer the past or the successive values as the more reliable ones. In the absence of metadata, our choice was always to consider more reliable the longer data segment.

Following this procedure, 9 out of the 31 stations were found to be affected by an inhomogeneity significant at the 95% level (the corresponding critical value of T_{max} for about 50 degrees of freedom is 8.55). In all cases the precipitations values in the shortest segment were adjusted. Then the test was repeated and the precipitation series readjusted until a check with the SNH-Test detected no more inhomogeneities. Figure 3 illustrates the results before and after the performance of the SNH-Test for one of the 31 stations. It can be seen that after the adjustments, while the T_{max} value gets drastically reduced, the time series is only lightly reshaped and it can be anticipated that the whole ensemble of adjustments has very little influence on all the subsequent data processing.

5. – Yearly series: collective time behaviour

When the data are regarded as time series, the first issue to undertake is obviously the search of trends. Unfortunately, the frequency and ubiquity of data gaps for each

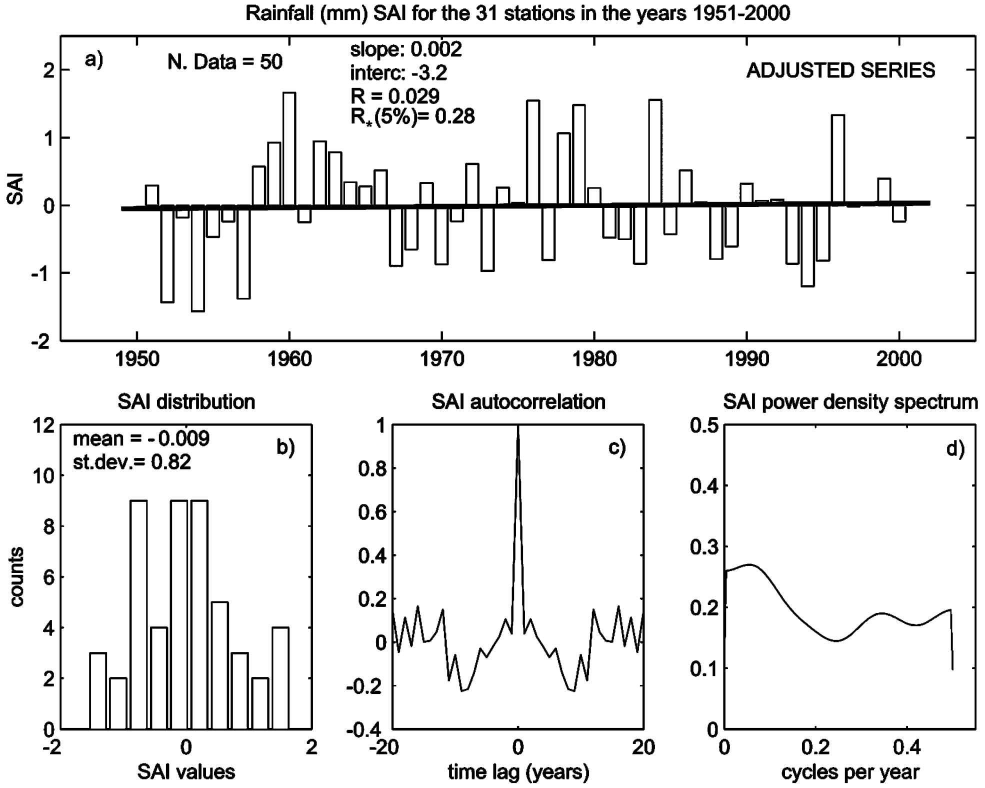

Fig. 5. – Standardized Anomaly Index (SAI) defined on the 31 stations from year to year (1951–2000): (a) behaviour *vs.* time; (b) statistical distribution of SAI values; (c) autocorrelation function, and (d) power spectrum of the SAI time series presented in (a).

of the single stations made it impossible to study the specific time evolution of yearly rainfall for any of them. Only after building a suitable geographical average, it is possible to obtain an uninterrupted time series for the entire period 1951–2000, consisting of the yearly rainfalls averaged over the whole region. This suitable average, defined above as $P^{(y)}(k)$, has been computed as an arithmetic mean of all the $P_s^{(y)}(k)$ values available for the given year k, and plotted in fig. 4. The corresponding regression line *vs.* time has been evaluated and drawn, together with the correlation coefficient and Kendall's Tau in order to allow the detection of a possible trend.

The time average over the period 1951–2000 of the geographically averaged rainfall $P^{(y)}(k)$ is 880 mm y^{-1} with a standard deviation of 157 mm y^{-1}, but no significant trend appears to be present in this period. In fact, the regression line describing the time behaviour of $P^{(y)}(k)$ shows a slope too low (according to the 95% significance level) in order to conclude in favour of any correlation between rainfall and time. This is confirmed by the execution of the non-parametric test based on the Kendall's Tau (*e.g.*, see [31]), which also returns a value well inside the no-rejection zone for the null hypothesis (in this case, the assumption of no correlation). In other words, in the Roman area the total yearly rainfall in the period under study (1951–2000) does not show any substantial trend. This result is independent of the adjustments described in the preceding section since the non-adjusted yearly data, when spatially averaged, show negligible differences with respect to the adjusted ones.

An alternative way to analyse the spatially averaged yearly rainfalls of a region is the construction of a dimensionless time series known as Standardized Anomaly Index (SAI), which is presented in fig. 5. This index is defined on the 31 stations year by year as the arithmetic mean of the standardized anomalies computed with respect to the long-term station mean [32]:

$$I(k) = \frac{1}{N_k} \sum_{s=1}^{N_k} \frac{P_s^y(k) - \mu_s}{\sigma_s}, \qquad \text{for } k = 1, 2, \ldots, 50\,, \tag{7}$$

where μ_s and σ_s are, respectively, the mean and the standard deviation of the time series $P_s^{(y)}(k)$ in the whole period ($k = 1, 2, \ldots, 50$), and N_k is the number of the stations with available data in the k-th year. The analysis of the SAI adds further evidence to the above-mentioned negative statement under several respects. First, the corresponding regression line shows an even lower correlation degree with time. On the other hand, it must be said that a similar treatment of the same data, restricted to shorter periods (say, two decades), would yield spurious trends of both signs. Second, the variance of the SAI distribution suggests that the average correlation between two randomly chosen stations is around 65%, a result that might be anticipated given the relatively short distances among the 31 stations with respect to the cloud systems; so high a correlation between any two stations, in the presence of a trend, would certainly facilitate its detection, so that the negative result is somewhat reinforced. Third, the SAI time series shows (figs. 5c-d) a negligible short-term autocorrelation and only some degree of long-term memory, with most of the variability concentrated at periodical oscillations with periods of 20 years and 3 years with a neat preference for the 20-year cycle. The presence of such a long cycle suggests caution in the search of trends when only short data segments of the series are available.

6. – Analysis of the yearly rainfall per intensity classes

In certain sites an increase of the incidence of extreme events has been reported while the total yearly rainfall remained constant or even decreased [11]. Therefore, it is important to separately analyse the yearly rainfall series per intensity classes when searching for specific long-term trends in some class of extreme events only. The classes into which to partition the rain intensity may been taken in two different ways:

- *absolute classes*, with bounds in mm, common to all the stations;
- *classes based on fixed percentiles*, where the percentiles are to be computed for each station from its data taken in a reference period (typically, a period covering a few decades).

Absolute classes. A criterion of partitioning rainfall events into classes with widths growing according nearly to the powers of 2 has been adopted (see table V) following preceding work on the subject [11]. Note that Class A_0 is the class of dry days, while the last class, G, includes the torrential rains (over 256 mm day^{-1}). The introduction of a specific no-rain class, while not necessary when studying the contribution of the different intensity classes to the annual total of rainfall, becomes mandatory when studying the

TABLE V. – *Definition of the different absolute classes of rain intensity (note the separate class A_0 of dry days) and of the percentile-based classes, as used in this work.*

Absolute classes			Percentile-based classes		
Definition	Code	mm day^{-1}	Definition	Code	Range
Dry day	A_0	0–1	Dry day	A_0	0–1 mm
Tiny	A	1–4	Tiny	A	1 mm–20th
Light-Mild	B	4–16	Light	B	20th–40th
Moderate	C	16–32	Mild	C	40th–60th
Heavy	D	32–64	Moderate	D	60th–80th
Violent	E	64–128	Heavy	E	80th–95th
Torrential	F	128–256	Violent	F	95th–99th
Exceptional	G	256–600	Torrential	G	99th–100th
Note: Classes include their lower bound only.			Exceptional	H	$\geq$ 100th

frequency distribution of rain events over their different possible intensities. In fact, in the latter case lumping the events of no rain and light rains together would make it impossible to separately evaluate the possible trend of the light rain events alone, whose frequency is normally obscured by the overwhelming proportion of the no-rain events.

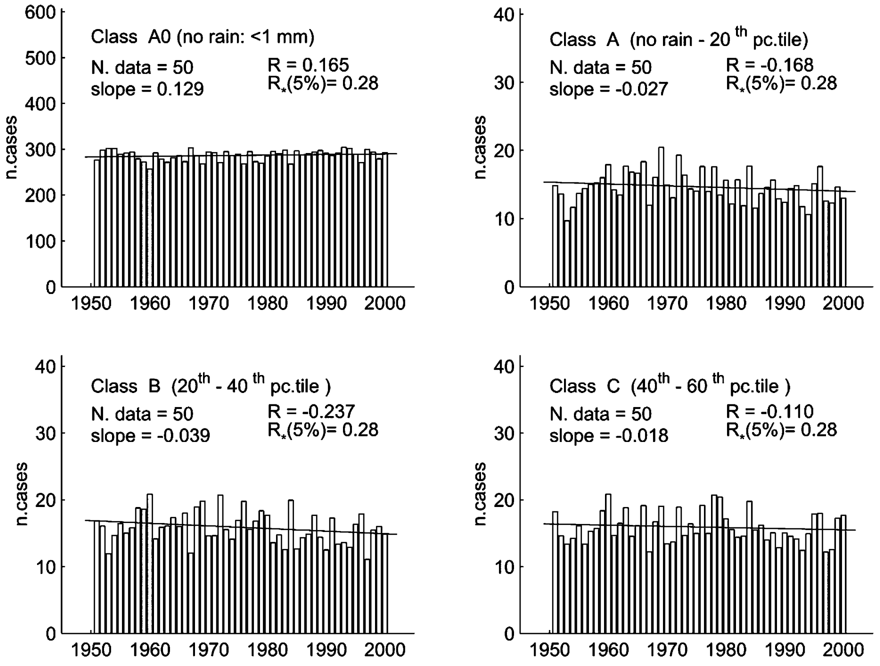

Fig. 6. – Regionally-averaged specific contributions to the yearly rainfalls, coming from the first four percentile-based (A_0 to C) intensity classes, *vs.* time. All the trends appear to be not significant at the 95% level. The contribution due to each class is expressed as number of cases or days.

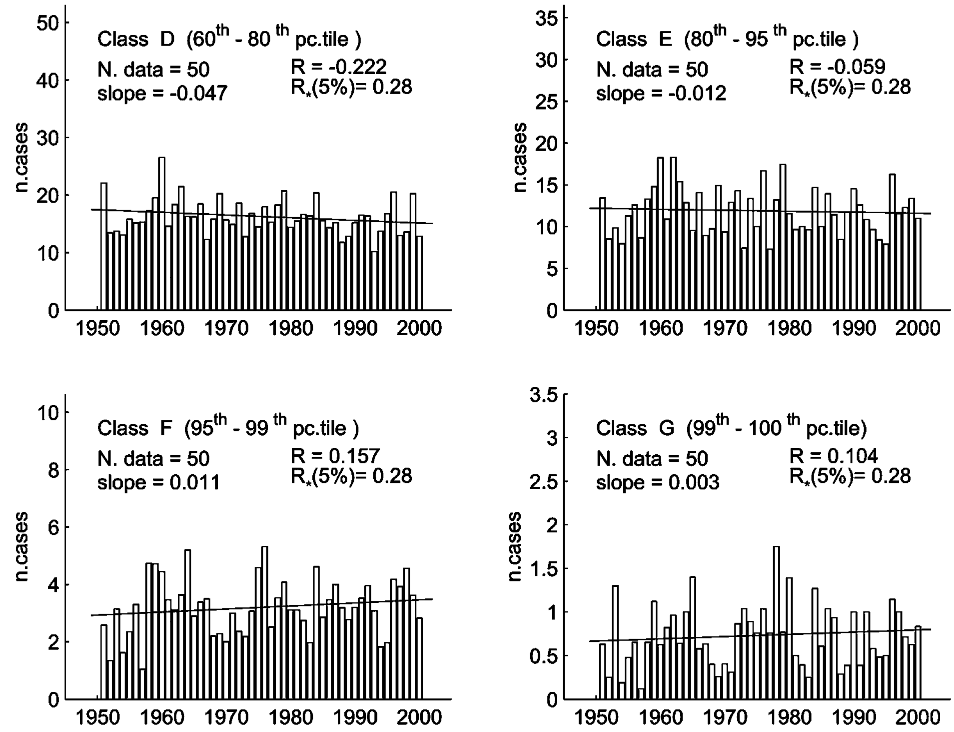

Fig. 7. – Same as fig. 6, but for the successive four non-zero percentile-based intensity classes. Here, also, all the trends appear to be not significant at the 95% level.

Percentile-based classes. An event of 50 mm day^{-1} could be an extreme event at a low-altitude station but not at a mountain station, so that absolute bounds are suitable to define rain intensity classes only for limited areas with a regular orography. In alternative, one can adopt classes, different for each station when expressed in mm day^{-1}, but representing the same group of percentiles. The set of common percentiles thresholds adopted was: 20, 40, 60, 80, 95, 99 and 100. The reference period adopted for the identification of the corresponding thresholds in mm, station by station, was the 30-year window 1961–1990. These standard thresholds allow us to define nine classes, the first being again the class of dry days, A_0, the second the class of events between 1 mm day^{-1} and the local 20th percentile standard threshold, and so on, till the last class including events above the local standard maximum. Note that, also with this partition, the classes' widths increase approximately as a geometric progression.

Whether absolute or percentile-based classes are used, the daily data must be reprocessed station by station and cumulated on a yearly base. This can give rise, for each station, to four different class statistics:

- number of days that in the given year the daily rainfall falls within a given intensity class;
- percentage of the days that in the given year belong to the given class;
- total in mm obtained summing all the daily data of a given year belonging to a

given class;

- percentage of the yearly rainfall (mm) due to the daily data belonging to a given class.

The second option is just a variant of the first, since the number of days in a year is a constant.

In the following we considered all these statistics but chose to present results only for the first (briefly, the class yearly frequencies), since the results obtained for the others do not appear to add any further information. Moreover, it must be said that the presence of data gaps (non-good years exist for all stations, except one) forced us to analyse only the geographical averages of the above-mentioned class statistics. Thus, for each statistic, all the values coming in a given year from the single stations (those active in that year) were combined into one regional yearly datum. This leaves us, for each class statistics under study, with one yearly time series for the whole region, which is submitted to further processing. Particularly interesting is the search for trends in the class yearly frequencies in view of the fact that some authors, as Alpert *et al.* [11] for the Mediterranean area, report paradoxical trends in the time behaviour of the absolute class of highest intensity, despite the presence of an antithetic trend in the yearly totals in the period 1951–1995.

Figures 6 and 7 show the corresponding frequencies for percentile-based classes. The absence of a trend is visible in any case (absolute classes and percentile-based classes) from the comparison between the absolute values of the obtained correlation coefficients and the threshold for the 95% significance level above which the rejection of the null hypothesis would be allowed. As a matter of fact, all rainfall classes appear to evolve in time without showing significant trends or any other definite pattern.

7. – Classes *vs.* totals

A possible correlation between the percent incidence of each rain intensity classes at a station and the corresponding annual amount of rainfall has been investigated in order to check whether large yearly totals of rainfall are accompanied by an increase in the frequency of some specific type of rain events, for example, of the torrential precipitations. Thus, all the 1275 available data points (one point representing a given station in one of its good years) have been used to form the eight scatter plots shown in fig. 8, where the results for the eight percentile-based classes are shown. The corresponding regression lines show significant correlations for all the intensity classes. Such correlations are negative for the classes of no-rain and lower rain intensity, positive for the classes of higher intensity (over 16 mm day^{-1} for absolute classes, over the 80th percentile for percentile-based classes). This implies that an increase in total rainfall is accompanied by an increase in the number of rainy days per year, as well as in the number of the non-light rain events. This result is not so obvious. In fact, a high annual rainfall might only be due to a large number of rainy days, or, alternatively, to an unusually high incidence of torrential episodes alone. Here both things concur to make high yearly rainfalls. More in detail, on the average, the bigger contributions to the yearly total come from two absolute classes, the B and C classes (4–32 mm day^{-1}) with, respectively, 35% and 30%. Class D (32–64 mm day^{-1}) rates about 20%, so that three intermediate absolute classes explain alone over 85% of the total precipitation observed at a station in this area. As for the percentile-based classes, when the precipitation is expressed in mm, 85% of the total rainfall falls between the 40th and the 99th standard percentile, with 50% falling in classes C and D, or between the 40th and the 60th standard percentile.

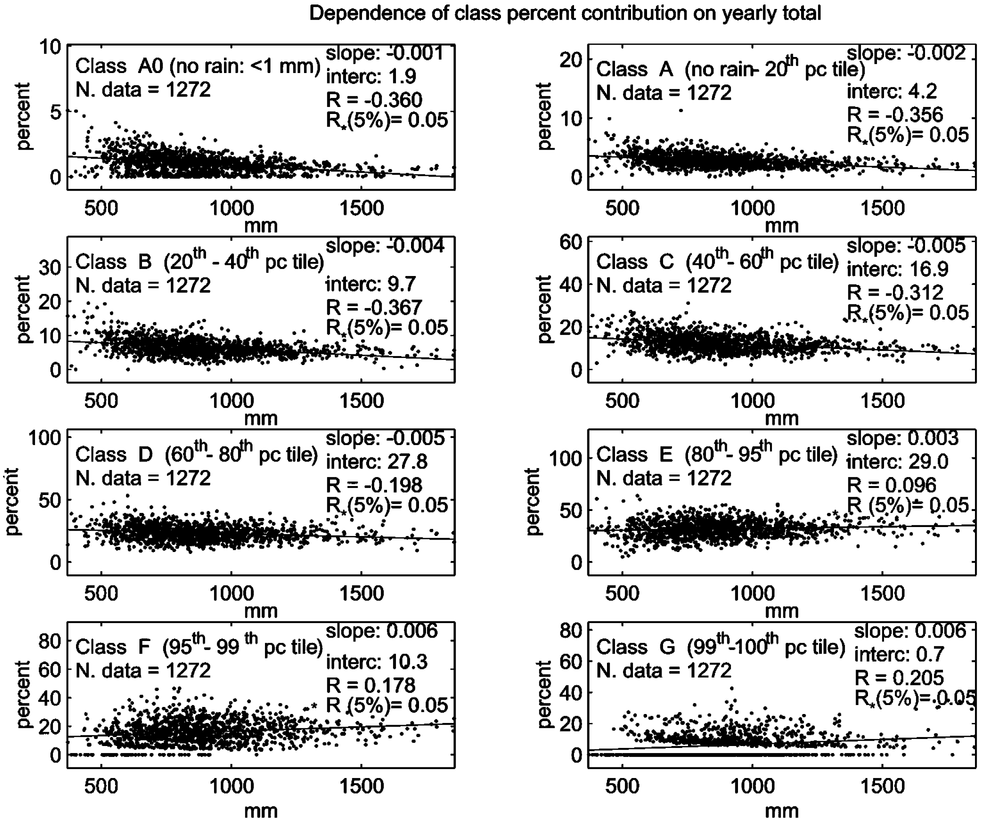

Fig. 8. – Correlations between the yearly total rainfalls and the specific contributions to them by the eight percentile-based intensity classes (each point comes from the rainfall at a station in a given year). As expected, the observed correlations are negative for all classes below the 80th percentile, and positive above.

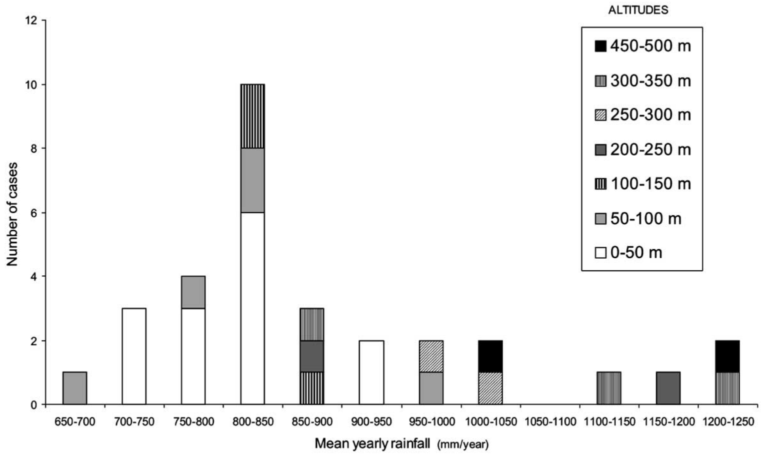

Fig. 9. – Influence of the altitude of the stations on their mean yearly rainfall.

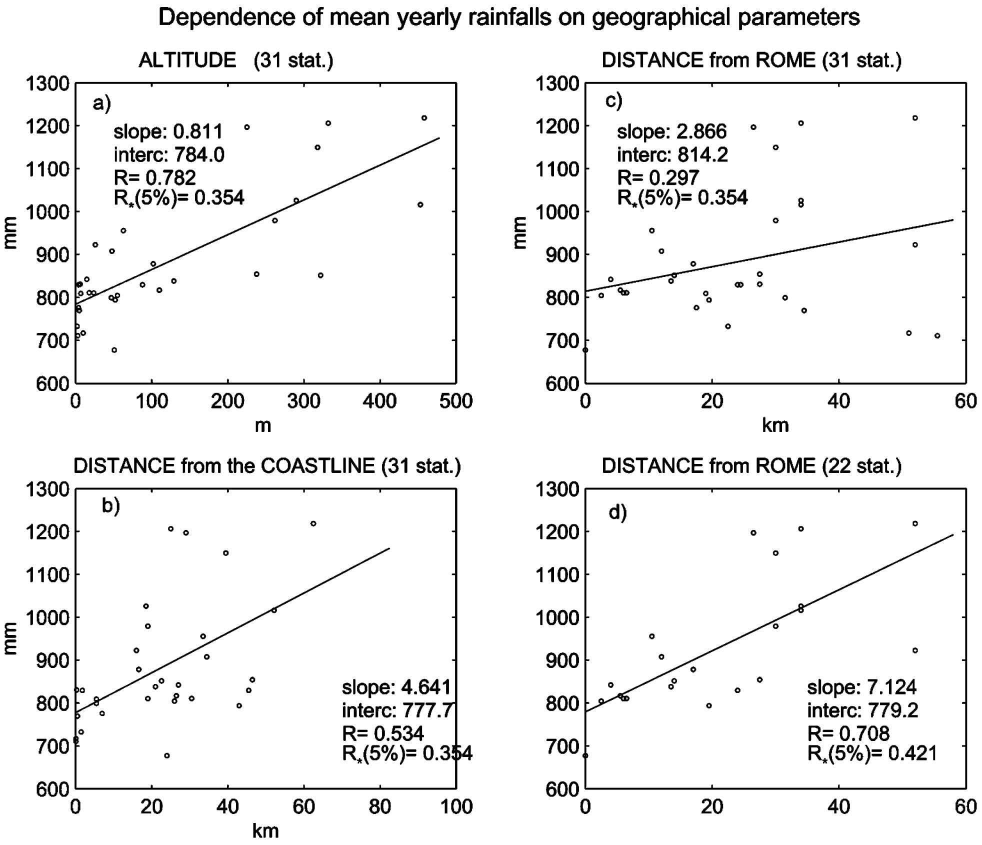

Fig. 10. – Dependence of yearly rainfall on various geographical parameters. In each plot a point represents the mean yearly rainfall of a given station, the mean having been computed on averaging over the whole period 1951–2000: (a) correlation with the altitude of the 31 stations; (b) correlation with the distance from the coastline; (c) correlation with the distance from the city (*i.e.* from the station Collegio Romano) ; (d) same as (c), after removal of the nine coastal stations.

8. – Dependence of the mean yearly rainfall on geographical parameters

As a last step in the analysis of data, we examine the spatial variability among the stations on using only the station time averages of the precipitation data, P_s, done on the whole period of 50 years. This spatial variability is evident from table II, column 6, where the mean yearly rainfalls of the 31 stations are listed. Since the degree of the variability is noticeable, possible correlations have then been searched between the mean yearly rainfalls P_s of the 31 stations and some environmental variables. The first of these variable is obviously the altitude. The histogram in fig. 9 yields the frequency distribution of P_s within its range (700–1230 mm y^{-1}), at the same time evidencing the altitudes of the stations by means of a grey-tone colouring of the bars, so as to help perceive the strong influence of altitude. In fact, it appears that the stations with a remarkable annual average rainfall (from 1000 up to 1300 mm y^{-1}) are located at heights well above the sea level (over 200 m); on the other hand, rainfalls from 600 up to 1000 mm y^{-1} are

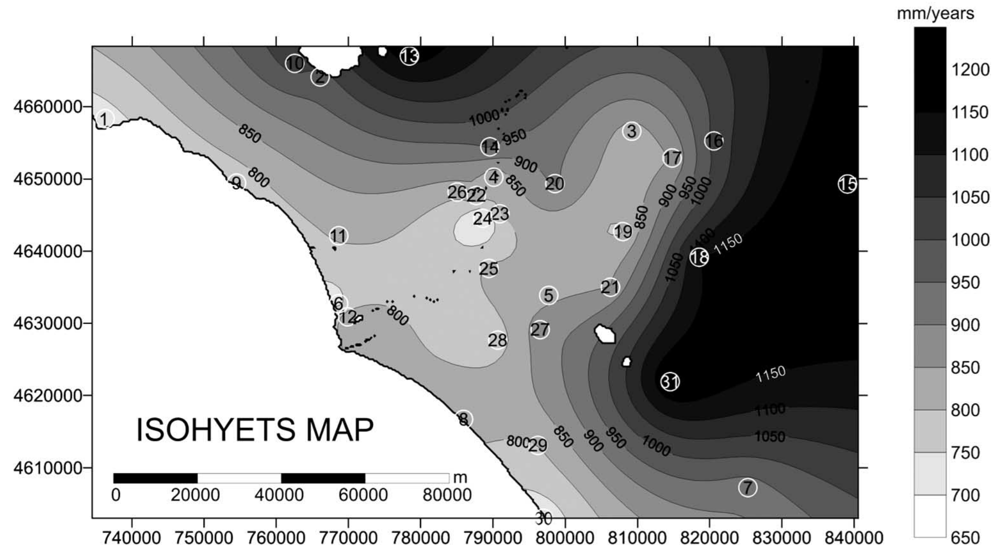

Fig. 11. – A map of isohyets of the region under study, built with standard graphic methods for surface reconstruction, starting from the 31 values of the mean yearly rainfalls of the stations and their locations. Longitude and latitude are marked in metres on the horizontal and vertical axes, respectively. Higher rainfall rates are indicated by darker regions.

more frequent at lesser altitudes.

The dependence of the mean yearly rainfalls P_s on altitude, distance from the coastline, and distance from the city is shown in fig. 10. Each of the regression lines drawn (the one in the last panel redrawn, indeed, after removal of the 9 coastline stations) indicates the existence of a significant and positive correlation between each of the above-mentioned parameters and the mean yearly rainfall P_s. In particular, the slope of the regression line in fig. 10a indicates that for each metre of altitude the mean yearly rainfall increases of 0.8 mm, while the regression line in fig. 10b indicates that, for each km of distance from the coastline, the mean yearly rainfall increases of 4.6 mm. As for the distance from the city, the correlation with the annual rainfall seems to be not significant in a first analysis (fig. 10c), but, on taking into account the strong influence of the proximity to the sea on the rainfall in the coastal stations, the sample of stations has been previously purged of the latter ones, thus leading to a reduced new sample of 22 data points. From this new sample a significant and positive correlation emerges (fig. 10d), the slope of the regression line indicating that for each km of distance from the city the mean yearly rainfall increases of 7.1 mm. However, non-coastal stations far from Rome often are stations located at high altitude, too, so that the correlation of rainfall with the distance from the city may be regarded only as a reiteration of the correlation with the altitude.

Finally, an isohyet map (fig. 11), interpolating the mean yearly rainfalls over the whole area under study, has been prepared using standard graphic software (SURFER and CORELDRAW). From this map, as well as from the mean yearly rainfalls of the 31 stations reported in table II column 6, it appears that the mean yearly rainfall is very variable over the area under examination. In fact, it more than doubles passing from a minimum of 677 mm y^{-1} (at Collegio Romano) to a maximum of 1218 mm y^{-1} (at

Subiaco S. Scolastica). The yearly rainfall appears to rise on moving from the coastal area to the rural one. The observed values of yearly rainfall seem to split the area under study in three zones. First, a coastal zone, where low precipitation totals are observed, second, an urban zone with intermediate precipitation values, third, a rural zone featuring the highest precipitation rates. The distinction of these three zones is confirmed from the fact that the isohyet map closely resembles the isohypse map, presented in fig. 1. This in turn confirms that the altitude, more than the other environmental variables, is the geographical factor that strongly influences the rainfall.

9. – Conclusions

The mean yearly rainfall does not seem to have changed significantly in the last fifty years (1951–2000) in the Roman county. This is reinforced by the fact that also the frequencies of events belonging to different intensity classes (both absolute and percentile-based), as well as their contributions in millimetres or in percent to the annual rainfall, do not show any significant long-term increase or decrease. These negative findings appear *prima facie* to be in contrast with some recent works on precipitations over the Mediterranean and, specifically, over Italy, which conclude in favour of the existence of trends for extreme events [33-37, 11].

It must be noted, however, that the results found by us in this reduced region cannot be compared directly with the results reached by other colleagues for larger areas, the spatial scales being completely different. As a matter of fact, all the above cited works take into account data referring to the whole Italian peninsula, if not to larger areas, so that even the complete absence of a local trend in a given small region may be missed in the geographical averaging that must be done to extract the mean information over the larger scales. As an example, the work by Brunetti *et al.* [33] analyses 67 Italian stations, only three of which (Ciampino, Roma Urbe and Vigna di Valle) fall in the same area under examination in the present paper. Moreover, in their work these three stations are merged with other nine to form a sample representing the so-called CE sub-region (Central-Eastern Italy). For this sub-region the authors conclude in favour of the existence of a (negative) trend, but only when the winter precipitations are considered, while no significant trend is proved for the yearly totals, what implies that in the other seasons an opposite compensating trend must have been at work. Besides, a complete absence of significant trends in yearly totals is reported by these authors not only for the CE sub-region, but also for seven of the eight different districts whereby Italy is subdivided, the only exception being the so-called SO sub-region (South-Western Italy).

As another example, when we consider the intense or torrential events, it is evident that the results obtained by us notably differ from those published by Alpert *et al.* [11]. But these authors analyse the data coming from 42 stations scattered over the whole Italian peninsula, while, as already said, our 31 observatories are concentrated near Rome. So, it may be well that in the second half of the last century there has been a trend in the extreme events when Italy as a whole is concerned, even though no trend at all can be observed in a much more limited area. Moreover, the paper of Alpert *et al.* [11] is based on precipitation data up to 1995 only, and, given the peculiar nature of their time series exhibiting a rather abrupt and isolated peak in the mid eighties, it is possible that the addition of few ordinary values of rainfall, recorded in the following years, may bring to a substantial revision of the positive trend found in the shorter period.

On the other hand, we do find significant correlations between the yearly rainfall and the contribution to it coming from any of the intensity classes (see fig. 8). But this is a rather obvious result. Also, significant and positive, but expected, correlations are found by us between the mean annual rainfalls of the 31 stations (the average being done over the whole period of 50 years) and environmental variables like altitude, distance from the coastline and distance from the city.

Our results also show that in the urban area a less amount of rain seems to fall than in the surrounding zones. Therefore, in the controversy outlined in the introduction between Oke [13], on one side, and Huff and Vogel [23], on the other side, our results lend evidence in favour of the views of the latter authors, taking account also of the fact that the prevailing winds in this region are westerly.

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