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A detailed study of rainfall in the Roman area in the decade 1992–2001(*)

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Summary. — A study of the rainfall regime in the Roman area over the decade 1992-2001 has been undertaken on using tipping pluviometers data, coming from 23 climatic stations located in Rome and in its surroundings. The time response of the instruments and the automatic acquisition system ensure a resolution of less than 1 minute, thus offering the possibility of an accurate evaluation of intense and extreme events. The mean yearly rainfall over the whole decade has been determined for each station, obtaining values between 682 and 870 mm/year, with a geographical average of 771 and a standard deviation of 47. A study of the rainfall distribution within the 48 half-hours of the day has been carried out in order to ascertain whether preferred times for rain events exist. The analysis has evidenced that this is the case, with high rainfall rates mostly occurring in the late morning and low rates in the late night. Typical values of the maximum 30-min rainfall ever recorded at any given station oscillate between 25 and almost 60 mm. A separate analysis of rainy and dry days has been carried out on studying the statistics of the time delays between two successive tips of the pluviometer. This allowed a characterization of the intense rains as well as of the droughts: the resulting histograms show the existence of a bimodal distribution explained in terms of two kinds of rain events, intense summer showers and drizzles distributed over the rest of the year. As for the droughts, the longest durations appear to range from one to about seven months. On confining the analysis to the rainy days only, the rain intensity data for each station has been plotted and fitted with a Weibull distribution. The corresponding Weibull parameters, while gathering around common mean values, do not show any recognizable pattern when regressed, for instance, *versus* the altitude of the station or the distance from the coastline. Last, the likelihood that a day of the year, taken at random, be a rainy day or not has been computed for each station yielding probability values ranging from 0.18 to 0.22.

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1. – Introduction

In the last few years several climatic studies have been dedicated to the variability of weather and, in particular, to climate extreme events, pointing out the existence of significant changes in their statistical features, their amount, distribution and frequency [1-9]. The increasing attention to these topics is due not only to the fact that, when extreme events occur, they often cause large losses of human lives and costly damages to the property, but also to the fact that, even when the extreme events are not the primary concern, it is easier to detect a climatic change by restricting the analysis to the tails of a statistical distribution, rather than by analysing the whole distribution itself.

The concept of "extreme event" has received strong attention from all the components of the geophysical scientific community: Meteorologists, Hydrologists, Geologists and Oceanographers. A purely qualitative notion of extreme event is obviously too generic, since several ways to define it are possible, with the risk of producing confusion. In fact, the expression "extreme event" can be used in many scientific fields with different means, but always carrying the meaning of a highly improbable event, *e.g.*, an extreme daily or monthly temperature, or a very high daily rainfall, or even storm events such as hurricanes [10]. At the same time, an extreme event is sometimes defined by the impact that it has on society [7]. In the following only extreme events of hourly or daily precipitation are considered.

Nowadays, because of a persisting thoughtless landscape use and too fast changes in social infrastructures which favour an increase of vulnerability of the habitat, catastrophes, as a result of climatic extremes such as river floods and landslides, have become more likely. Examples are the huge damages caused by Hurricane Floyd, described in Easterling *et al.* [7] and the recent impact of Hurricane Rita on the city of New Orleans (September 2005).

In cases like these ones, the preliminary study of both frequency and intensity of extreme events, such as the heavy and torrential precipitations, along with their spatial distribution, becomes fundamental to plan, build and maintain adequate infrastructures (such as an apt network of sewerages and embankments) either to prevent injuries and damages, or at least to decrease their amounts in the short and long period.

Furthermore, on the base of recent data [7, 11], the global warming, which is directly connected to the increase of the Greenhouse gases, seems also associated with an increase of extreme events. This association might depend on the fact that in some areas the mean temperature rise would seem to modify the hydrogeological cycle causing a higher incidence of extreme climatic events, such as either heavy precipitations or drought durations [1, 12].

As for the present work, the treatment of the data is carried out also in order to extract important information for the government organizations that have the task of planning and executing interventions on the territory. Under this respect, the statistical characterization of the intense rains as well as of the droughts is an important issue.

The database analysed in this work is so dense and detailed, and the climatic stations are so uniformly distributed within the city of Rome, that a fairly accurate characterization and description of the pluviometric regime of the urban and surrounding area seems possible. This is done by first computing the mean rainfall distribution along the day with the aim to show how rain events are distributed throughout the day and in particular whether preferred times exist for them. Then, a separate analysis of dry and rainy days is carried out in order to evidence the extreme events of both types.

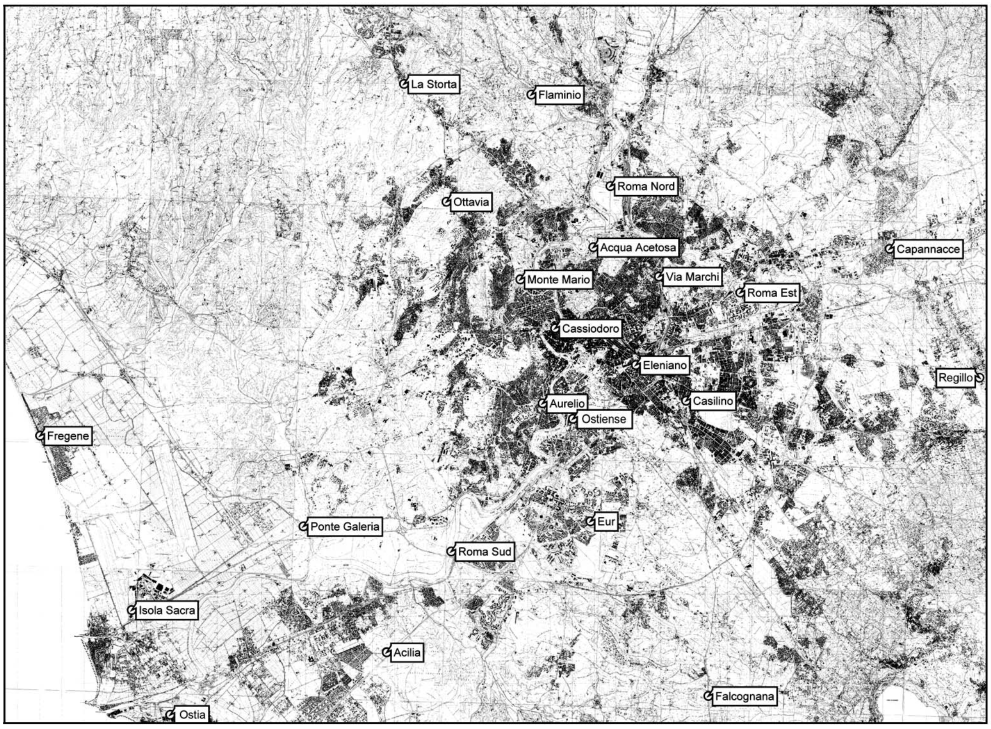

Fig. 1. – Geographical distribution of the ACEA 23 climatic stations within a map of Rome and its surroundings.

2. – The area under study and its climatology

The area under study is a wide valley that extends from the mountain range of Appennini to the Tyrrhenian sea and is crossed by the river Tevere. The area has its centre in the city of Rome. The northern border is marked by Tolfa's mountains (maximum height about 600 m), extending near the coastline, the eastern border by the range of Monti Sabini (reaching over 1000 m), and the southern border by Colli Albani (reaching less than 900 m), that gently slope down toward the coast (fig. 1).

The climatology of the region is characterised, besides the nearness of the sea, by the interaction between the seaside and the surrounding orography and by the metropolitan area of Rome with its large urban heat island. Such region, that is located in a relatively flat area within the basin of Tevere river, about 25 km inland from the shoreline, has an extension of about 1285 km^2 and a resident population of near 3.5 millions, corresponding to an average density of about 2000 inhabitants per km^2.

As for the climatology of the site, previous works, both observational and modeling, have shown that, when synoptic winds are light, the atmospheric circulation is dominated by local effects. In particular, daily long-term observations have shown that, specially during the summer, the prevailing winds are nocturnal land (westward) breezes and daytime sea (eastward) breezes, which develop across a layer 1 or 2 km thick. The vertical motion associated with these breezes is generally modest due to the flatness of the region and to the strong air stratification, but the breezes present pronounced drops in intensity at early morning and late afternoon with enhancement of the vertical convective motion [13-15]. Also, slope winds originating at the neighbouring mountains can often modify the breeze regime by coupling with them and so giving rise to a large variety of flow patterns [16]. The interaction between breezes and slope wind has been investigated using a prognostic mesoscale model [17]: the simulations, which compare favourably with observations, shows that the two kinds of winds play roles of comparable importance. Interactions of these winds with the urban heat island have been recently evidenced by a model-aided investigation based on data collected during a winter campaign deploying sodars, tethered balloons and standard surface instrumentation [18]. A very detailed investigation of the intensity and direction of the winds prevailing in the amospheric circulation in the Roman area is presented in a recent work by G. Mastrantonio and co-workers [19]. On the other hand, it is difficult to find studies on the correlations between the wind regime and the precipitation events in the available literature.

3. – Description of the data

The data analysed are time series, taken from of an array of 23 pluviometric stations, recorded within the decade 1992-2001. The data allow to determine the number of tips per minutes recorded in each station, whence the features of the precipitation distribution on a few-year time scale can be assessed. The very short minimum sampling time (a few seconds, contrasted with many hours, used for data collection in ordinary databases) allows for a fine assessment of extreme events, such as severe but very short rainfalls, as well as of long droughts.

The 23 pluviometric stations are run by ACEA (the city agency for the management and the distribution of electricity and water) and are located within the city of Rome and in its surroundings (see fig. 1 and table I). Table I reports for each station the period of measurements along with the total number of days, hours and tips recorded, the yearly averages, and some statistical distribution parameters to be explained later.

Thus, the database consists of 23 ASCII data files, one for each station. The raw data are the hour and minute of the day at which the pluviometer tips occurred throughout the decade 1992 to 2001 (a tip corresponding to 0.2 mm of rainfall), but for some stations the observation period was shorter (see table I). Each of these series represents a "point process" [20, 21], and will be denoted by $M_s(k)$, where the index s refers to the station, the integer k is a serial index labelling the tip, and M_s gives the minutes elapsed from January 1, 1992, hour 00:00. For example, $M_3(12) = 1441$ means that the 12th tip recorded at station 3 occurred within the first minute after the midnight between January 1 and 2, 1992. Thus, the index k ranges from 1 to T_s, that is the total number of tips recorded at the given station during the whole decade, which is order of $3 \cdot 10^4$ for most stations (but at Fregene it does not exceed 10000). The instants $M_s(k)$ form a long monotone non-decreasing sequence of non-negative integers, each one not greater than $N_M \cong 5.256 \cdot 10^6$ (the number of minutes in 10 years), that are not necessarily distinct, since during severe events up to 32 tips have occurred within the same minute. At each station there may however be several data gaps, each lasting one or more hours, up to a maximum of many months (belonging to the same year), so that two distant successive values of the sequence $M_s(k)$ occasionally subtend a long period of missing observations, not of drought. Moreover, the data for 4 stations (Acqua Acetosa, Roma Est, Regillo, Fregene) cover the years 1998-2001 alone, and another station (Roma Sud) the years 1992-1995 and 2001, gaps being however possible in the middle here and there (see table I). Note also that the unit data block is the day-hour, in the sense that a

TABLE I. – *Pluviometric stations with their Acea code and some statistical parameters characterizing the precipitation regime.*

Code ACEA	Station	Altitude (m)	Years	days	hours	%	Max tip/min	n. tips	Rainfall mm/year	Probability of rain	Weibull $N = 600$	
											c	k
01	La Storta	144	1992-2001	3077	73461	84	32	35376	844.3	0.205	0.090	1.525
02	Flaminio	85	1992-2001	3351	80406	92	15	34862	760.1	0.195	0.096	1.479
03	Roma Nord	18	1992-2001	3160	75796	86	19	35631	824.2	0.219	0.109	1.344
04	Ottavia	134	1992-2001	3374	80954	92	20	37592	814.1	0.205	0.087	1.482
05	Capannacce	68	1992-2001	3137	75050	86	25	33866	791.1	0.214	0.088	1.549
06	Acqua Acetosa	21	1998-2001	1415	33923	97	14	14710	760.2	0.207	0.080	1.491
07	Monte Mario	130	1992-2001	3047	73070	83	29	31188	748.3	0.196	0.091	1.457
08	Roma Est	28	1998-2001	1435	34437	98	13	14279	726.9	0.212	0.086	1.500
09	Via Marchi	38	1992-2001	2876	68909	79	23	34165	869.2	0.221	0.085	1.551
10	Cassiodoro	35	1992-2001	3119	74823	85	16	33093	775.4	0.211	0.082	1.463
11	Eleniano	76	1992-2001	3084	73968	84	17	33807	801.3	0.211	0.081	1.413
12	Aurelio	86	1992-2001	3340	80123	91	19	34538	755.7	0.209	0.106	1.198
13	Regillo	82	1998-2001	1435	34437	98	23	15531	790.7	0.210	0.081	1.650
14	Ostiense	27	1992-2001	3307	78408	89	19	35125	785.4	0.203	0.083	1.459
15	Fregene	3	1998-2001	1149	27162	77	15	10573	682.4	0.177	0.093	1.624
16	Casilino	38	1992-2000	2744	65814	83	17	29439	784.2	0.209	0.095	1.358
17	Eur	53	1992-2001	3051	71443	81	19	29924	734.3	0.205	0.102	1.287
18	Ponte Galeria	64	1992-2001	3105	74359	85	20	32510	766.5	0.204	0.089	1.538
19	Roma Sud	10	’92-’95; 2001	1355	32445	74	18	13583	734.0	0.200	0.101	1.360
20	Isola Sacra	10	1992-2001	3085	73942	84	16	31550	748.1	0.199	0.088	1.629
21	Acilia	70	1992-2001	3374	80880	92	27	32415	702.6	0.192	0.090	1.425
22	Falcognana	108	1992-2001	2897	69404	79	15	32772	827.8	0.216	0.101	1.399
23	Ostia	9	1992-2001	3143	74641	85	24	30017	705.1	0.194	0.085	1.455
									$\mu = 771.1$			
									$\sigma = 46.8$			

day-hour either is entirely included in the measurements, or it is completely absent. The gaps are present in every year, but never is their number so high as to compromise the derivation of sound statistical conclusions, which can anyway rely on thousands of data.

This data can be converted into a time series giving the number of tips that occurred in each minute within the assigned period. Such number is a small non-negative integer, not higher than 32, a negative value being reserved to indicate absence of observation. This time series, which carries the same amount of information as the raw data $M_s(k)$, has the form of a series of increments between instants distributed as in a Poisson point process (with non-uniform density), and will be denoted by $B_s(j)$, where s refers again to the station and j refers to the serial minute ($j = 1, 2, \ldots, N_M$). Thus, for example, $B_3(2882) = 5$ means that at station 3 five tips were recorded within the second minute after the midnight between January 2 and 3, 1992. In this form, the virtual number of data for all the stations is the same, but the actual number of data, namely the non-negative elements of the sequence $B_s(j)$, may be well lower than $5.256 \cdot 10^6$, as occurs for the few stations with only a 4-year coverage.

Starting from the time series $B_s(j)$, other time series have been generated via time or space averaging and denoted with obvious notation: for example, $B_s^{(d)}$ denote the series obtained from $B_s(j)$ cumulating over a whole day, while $B(j)$ denote the geographical average of $B_s(j)$, done over all the stations under examination.

4. – Data processing

First we define a suitable threshold (0.8 mm/day) for the precipitation rate discriminating a rainy day from a non-rainy, or dry day. This threshold corresponds on the average to at least one tip occurring within 6 hours of one same day. Also, on considering the time series $B_s(j)$, since we have a reading every minute, we define a minute to be of type P if at least one tip occurred within the successive 6 hours, otherwise the minute is defined to be of type N.

The 23 time series $B_s(j)$ have been processed to extract the following information:

1) The average yearly rainfall for each station.

2) The distribution of rainfall over the day for the entire period of observation, having partitioned the day in its 48 half-hours. This is done for each single station, but only the most interesting histograms are presented. All the histograms have been tested against the null hypothesis of an underlying uniform distribution.

3) The frequency distribution of the time delay between two successive tips of the pluviometer for each station in the whole period of observation.

4) The whole period of observation has been partitioned in time segments each consisting of a sequel of minutes all of the same type, either P or N, that is, time segments where there is rain, and others where there is not. In both cases a statistical study has been carried out. In the first case for each station a histogram has been derived giving the distribution of the rain intensity, measured in term of the time occurring for a fixed number of millimetres to fall. In the second case, the same statistical analysis, done over the whole database at point 2 above, has been repeated on limiting the time delays to those exceeding the threshold of four hours. The latter analysis is intended to offer a statistical description of the "droughts", while the former is mostly intended to describe the incidence of the episodes of severe rainfall.

For the case of rain intensities, to each histogram a Weibull distribution function has

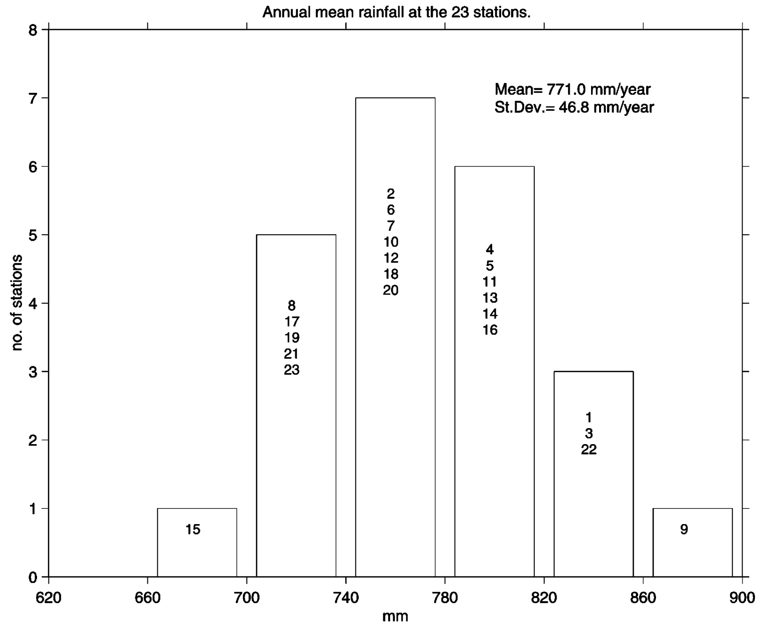

Fig. 2. – Frequency distribution of the annual mean rainfalls observed at the 23 stations.

been fitted using a maximum-likelihood optimisation to find its two parameters, c and k:

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

where x is meant to be rain intensity in mm/day, c is a scale factor for x and k is a dimensionless shape factor controlling the location of the distribution maximum.

As for point 1) above, the average yearly rainfalls of the single stations are listed in column 10 of table I and plotted in the histogram of fig. 2. Their values range from a minimum of 682.4 mm/year, recorded at Fregene (a coastal station), to a maximum of 869.2 mm/year, recorded at Via Marchi in the East side of the city of Rome. The corresponding geographical average, computed over all the stations, is 771.0 mm/year with a standard deviation of 46.8 mm/year. The Fregene, Ostia and Acilia stations, with their minimum precipitation rates, are somewhat anomalous, since all the others show values above 725 mm/year, the difference being due to the nearness of the above-mentioned three stations to the coastline and, consequently, to the efficiency of the breeze regime in removing the clouds in correspondence with the sea-land interface.

5. – The rain distribution over the 48 half-hours of the day

The information that has a remarkable importance from a practical viewpoint is surely the possible tendency for rain events to concentrate in some hours of the day rather than in others. If this is not the case, when the average percentage of rain fallen within each half-hour of the day (the average being performed over the whole observation period) is plotted against the 48 distinct half-hours, one should observe a histogram which does not significantly differ from a uniform distribution, what can be easily assessed via a χ^2-test.

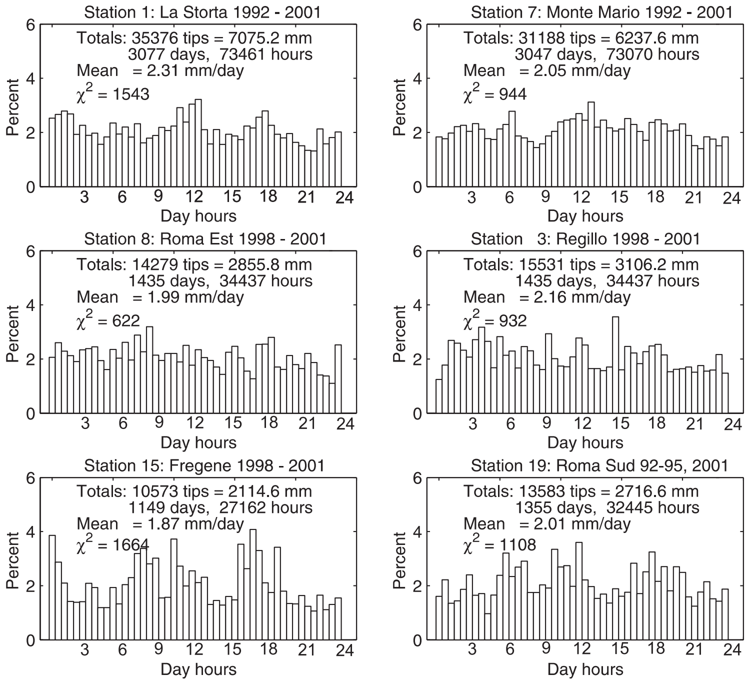

Fig. 3. – Distribution of rainfall over the 48 half-hours of the day for 6 selected stations out of the 23 ACEA stations presented in table I. For each half-hour, the rain fallen within it throughout the observation period was cumulated and finally expressed in percent. It is seen that for all the stations the χ^2-test strongly refuses the null hypothesis of an underlying uniform distribution.

As a matter of fact, for each station a so high χ^2 value was obtained, as to imply rejection of the null hypothesis even adopting a 95% significance level, the χ^2 critical level for 48 degrees of freedom being about 65. Some of the histograms, obtained for 6 of the 23 stations, are shown in fig. 3. These six stations have been selected for their maximum variability or their greater departure from a uniform distribution as evident from their high χ^2 value. The inadequacy of a uniform distribution to represent the histograms for all the stations suggested to evidence the hours preferred, or avoided, by the precipitation events.

In particular, figs. 4 and 5 display the distribution histograms for all the stations, with bars stacked over each other, each segment of a bar reporting the corresponding ACEA station code. The maxima range from 2.69 mm/day (Stat.16, Casilino) to 3.73 (Stat.9, Via Marchi), while the minima range from 0.94 mm/day (Stat.19, Roma Sud) to 1.62 (Stat.22, Falcognana), the minima being typically 2 to 3 times lower than the corresponding maxima. For example, at station 9, the highest contribution to the total rainfall comes from the half-hour 12:30–13:00, where the rainfall intensity, averaged over the decade, is 3.73 mm/day, whereas the minimum contribution comes from the half-hour 8:30–9:00 in the morning, where the rainfall intensity, averaged over the decade, is only 1.47 mm/day.

On the other hand, fig. 6 shows the distribution along the hours of the day of the maximum 30-minute rainfall ever registered during the whole observation period at each given station.

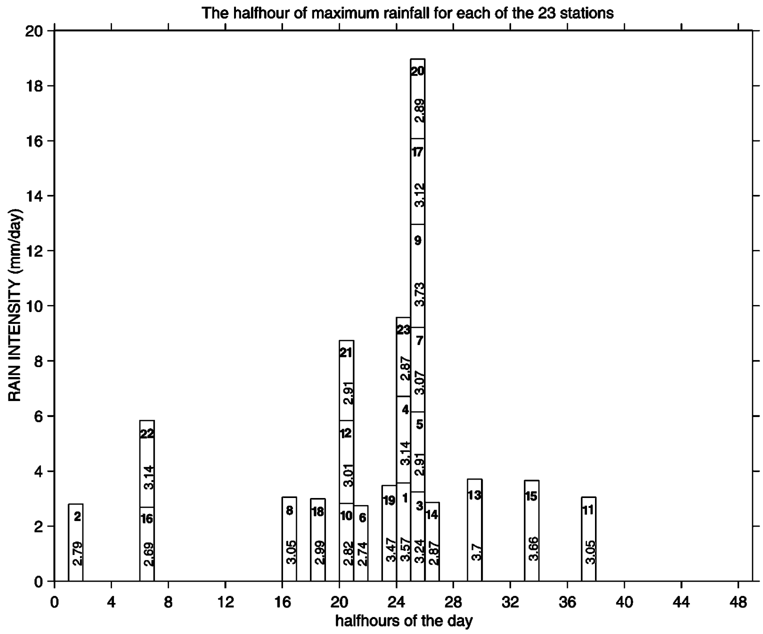

Fig. 4. – Distribution of the maxima of mean half-hour precipitation rates observed at the 23 ACEA stations, the mean being done over the decade and the maximum over the 48 half-hours of the day. Each segment of a bar contains the code number of the station and the corresponding maximum value in mm/day.

The same data used to build the histograms in fig. 3 were also processed in order to compute for each station the percentiles referring to the distribution of the mean half-hour rainfalls, having now no regard for the daytime they occurred. The relevance of this data processing is due to the fact that rain events lasting less than half an hour hardly play a role when planning aid interventions in favour of population struck by floods, landslides and similar natural calamities due to heavy precipitations. At each station the percentiles were computed for percent values running from 0 to 100 with a uniform step of 10, thus obtaining 11 values of rain intensity, expressed in mm/day. Figure 7 plots these rain intensity values *versus* the corresponding percent values for all the stations.

6. – The distribution of time lags between successive pluviometer tips

Another important issue to be addressed is the statistical distribution of the intensity of rain events. First of all, the time delays (in minutes) between any two successive tips have been computed as the differences of the original time series $M_s(k)$, and denoted by $\tau_s(k)$. Of course, when two successive pluviometer tips occur within the same minute, that is $M_s(k) = M_s(k+1)$, one gets $\tau_s(k) = 0$. In all these cases, however, when exactly n tips occur within the same minute with $n > 1$, it is reasonable to put the further $n-1$ lags equal to $1/n$ instead of zero, since it is unlikely the rain intensity to change significantly within one minute. These values of time lags for each station form another data set which can be regarded as one sample of an aleatory variable δ which, if the time instants were randomly thrown over the whole time period with a uniform mean

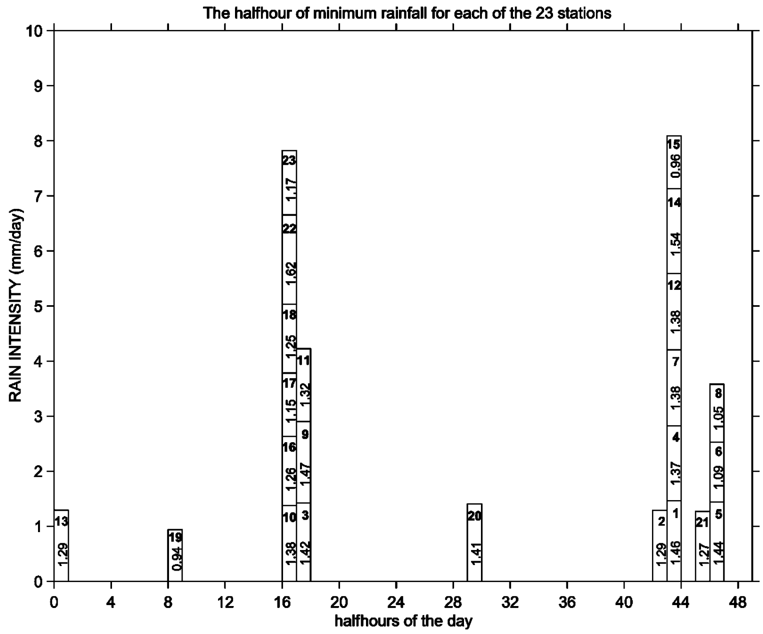

Fig. 5. – Distribution of the minimum of mean half-hour precipitation rates observed at the 23 ACEA stations, the mean being done over the decade and the minimum over the 48 half-hours of the day. Each segment of a bar contains the code number of the station and the corresponding minimum value in mm/day.

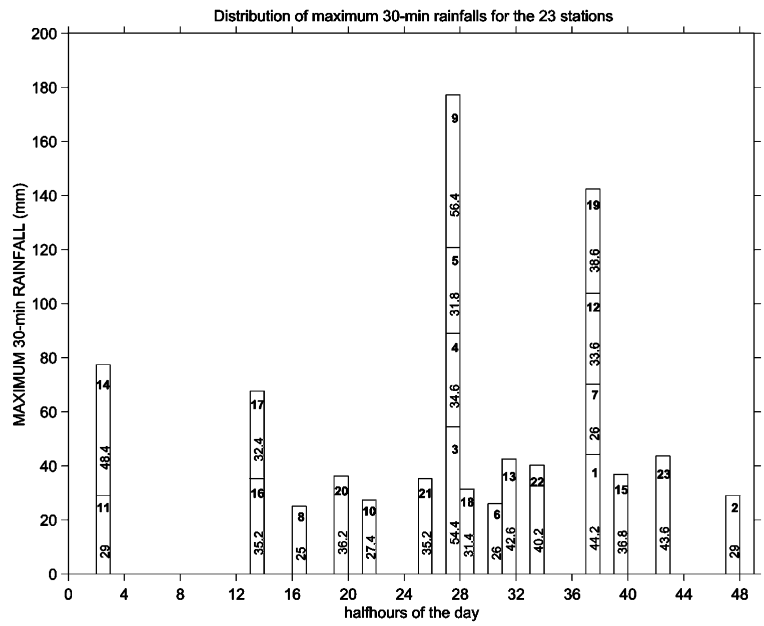

Fig. 6. – Distribution of the maximum 30-min precipitation rates observed at the 23 ACEA stations, the maximum being done over the decade. Each segment of a bar contains the code number of the station and the corresponding maximum value in mm.

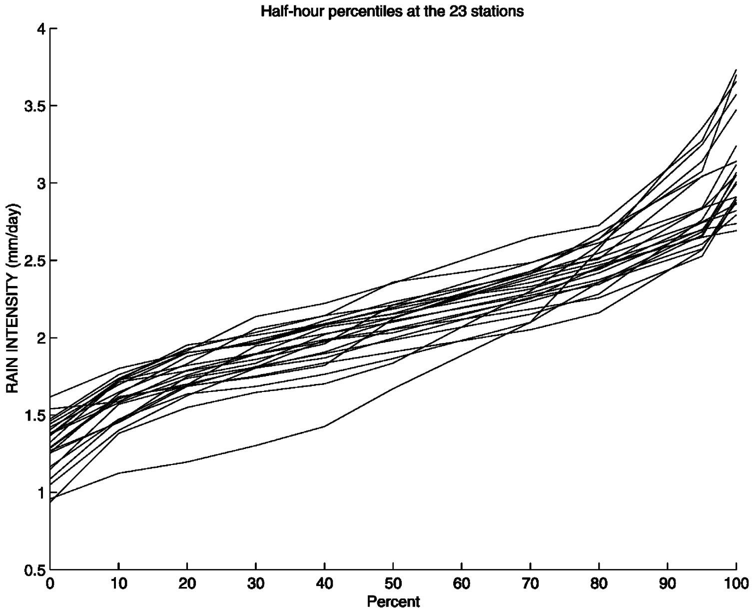

Fig. 7. – Percentiles of rain intensity at the 23 ACEA stations. The anomalous station is Fregene, a coastal one.

density λ, would be distributed according to the following probability density:

$$f(x, \lambda) = \lambda e^{-\lambda x} \qquad (x \geq 0), \tag{2}$$

x being the lag between two successive time instants (corresponding in our case to the tips of the pluviometer bucket). This distribution for any value of λ would be monotonically decreasing with a maximum in $x = 0$ and an expected value equal to $1/\lambda$.

The computed frequency histograms of the delays $\tau_s(k)$, built on partitioning the time range for the delays (0 minutes to 1 year) in 21 classes having widths increasing nearly in geometric progression, have been presented in fig. 8 simultaneously for all the stations (first panel) and, separately, for five of them selected so as to represent different locations within the urban area. Almost all stations exhibit the typical double maximum corresponding to the separation of the precipitation events in two categories, the intense rains typical of the summer season and the milder rains typical of the fall-winter season. Under this respect the Fregene station is again rather atypical since the first maximum occurs at the minimum time delay, indicating an excess in the incidence of very severe rainfall events with respect to the other stations.

The discrepancy between the shape of the theoretical distribution given by (2) and the obtained histogram is not surprising at all. Indeed, for no station can the density λ be assumed constant through all the seasons of the year.

The systematic presence of the two maxima in the histograms confirms the opportunity, mentioned in sect. **4**, point 4), to perform two distinct analyses for the rainy and the non-rainy time segments. This lead to carry out separate statistical treatments of the delays greater or lower than a fixed conventional threshold (0.8 mm in 24 hours) marking

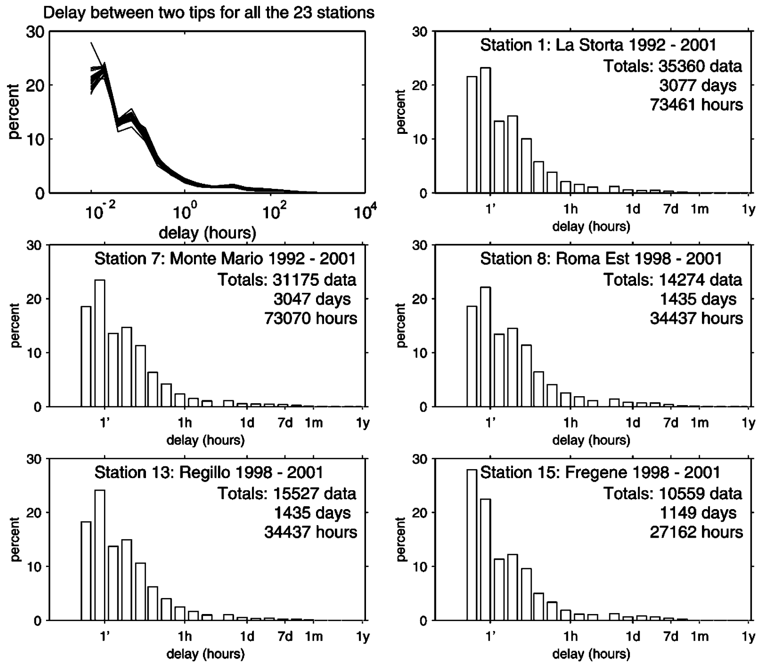

Fig. 8. – Frequency distribution of time delays between 2 successive tips for five of the 23 ACEA stations. In the first panel the distributions of all the stations are shown. Note the definition of the histogram classes whose widths normally increase by a constant ratio of 2. Note also that the frequency bar pertaining to zero time lag, not representable on a logarithmic axis, has been drawn in corrispondence to a conventional time lag equal to half a minute.

the border between a rainy day and a dry day. On the one hand, the histograms representing rainy segments alone, as illustrated in the next section, will be fitted with some apt probability distribution function. On the other hand, in order to evidence the statistical distribution of runs of dry days (their sequences being briefly dubbed "droughts" hereafter), the above-mentioned histograms were simply truncated in correspondence with a minimum threshold of a 4-hour delay between successive tips, what brings to the new histograms presented in fig. 9 for the same five stations above.

7. – The distribution of rain intensities and the probability of rain

As for the rainy days, in order to derive statistical distributions of rain intensity, the following procedure has been adopted. Starting from the secondary time series $B_s(j)$, as anticipated in sect. **4**, each minute j has been labelled as a P-minute if at least one tip occurred in the next 6 hours, namely, more precisely, if the total number of tips, occurred within the 6-hour time span comprising the minutes from j to $j + 359$, exceeds zero, provided that the possible negative values of $B_s(j)$ (indicating a lack of observation) be assimilated to zero. Conversely, it has been labelled as an N-minute. After that, the time series $B_s(j)$ results decomposed in two types of frequently mingled sequences made of either P-minutes only or N-minutes only, any P-sequence being obviously not shorter than 360 elements. Now, on limiting the statistics within the P-sequences alone, we cumulated the amount of rainfall minute after minute until at least 20 tips are collected,

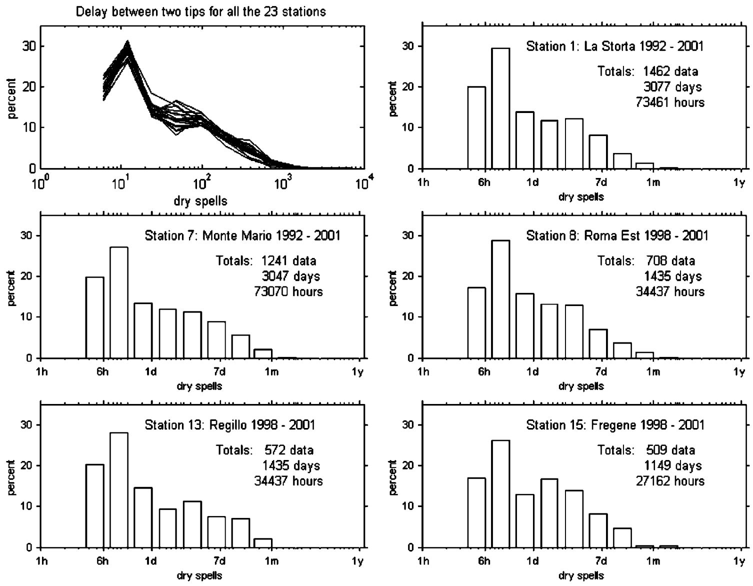

Fig. 9. – Same as fig. 8, after the truncation of the histogram in correspondence to a minimum threshold delay of 4 hours. This allows to appreciate the details in the long right tail (representing the "droughts") of the histograms in fig. 8, details there masked by the too wide extent of the vertical scale.

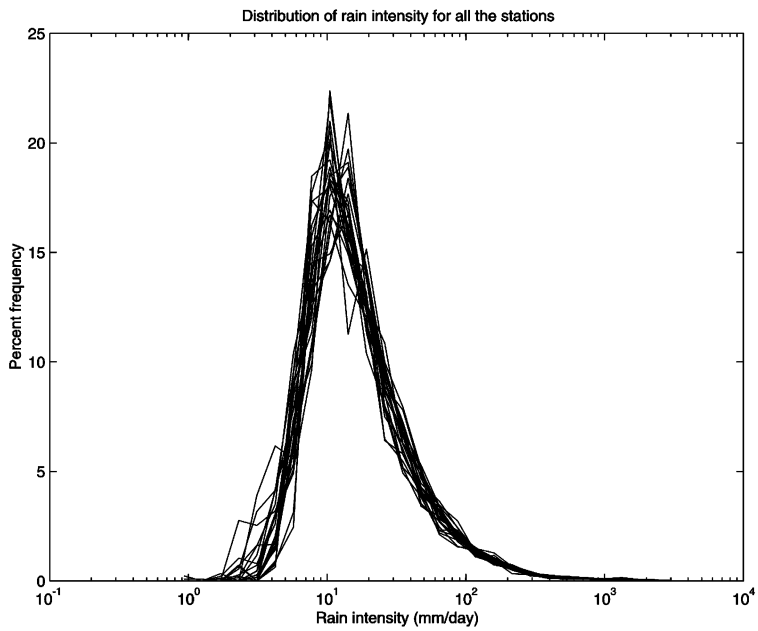

Fig. 10. – The distribution of rain intensities for the 23 stations. Note that the distribution mode is about 10 mm/day for all stations, while values larger than 300 mm/day are highly unlikely.

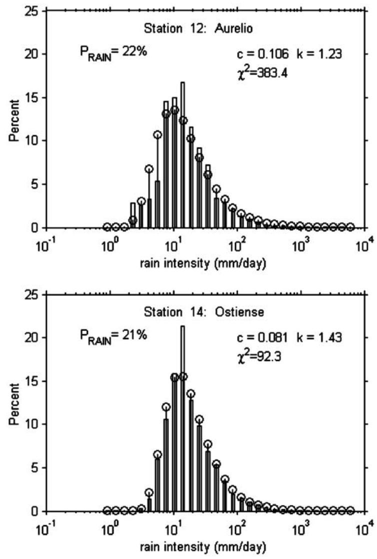

Fig. 11. – A Weibull distribution has been fitted for each station to N data drawn via Monte Carlo method from the corresponding database. Here only four stations are shown.

and divided such amount of rainfall by the time occurred, assigning to the thus obtained rain intensity a statistical weight proportional to the occurred time. It must be noted that the counting process was aborted each time it was not possible to file a total of at least 20 tips before the end of a P-segment. This usually happens near the end of a P-segment or when a long data gap is encountered. In all these cases the counting process is resumed from zero at the beginning of the next P-segment, the effect of this treatment of the data being a slight underestimation of the incidence of light rain intensities. In this way it is possible to obtain for each station a histogram of rain intensity, thirty classes for rain intensity having been adopted spanning in geometric progression the interval between 0.8 and 7000 mm/day. The results are shown in fig. 10 for all the stations.

Next, separately for each station the rain intensity histogram has been fitted with a Weibull distribution using the following procedure. First, from the database of a single station a sample of $N = 3000$ data has been drawn using the Monte Carlo method, so that, no matter which the station was, a sample with the same number of data was made available. Then the reciprocals of these 3000 values were regarded as a sample of a Weibull variate x with probability density given by eq. (1).

The parameters c and k were estimated through the maximum-likelihood method, as implemented by MATLAB, and the predictions based on the fitted theoretical distribution were compared with the observed bars of the histogram, the agreement being measured via a chi-square test. The agreement is quite good for most stations. The results are shown in fig. 11 for four stations. Figure 12 shows the scatter plot of the 23 pairs of Weibull parameters, each pair (c, k) representing one station in the two-dimensional parameter space (see table I, columns 12-13, for the complete list of their values). The resulting distribution of points is characterized by a strong negative correlation measured by a correlation coefficient close to -0.75; the corresponding regression line is shown in fig. 12 superimposed to the scatter plot.

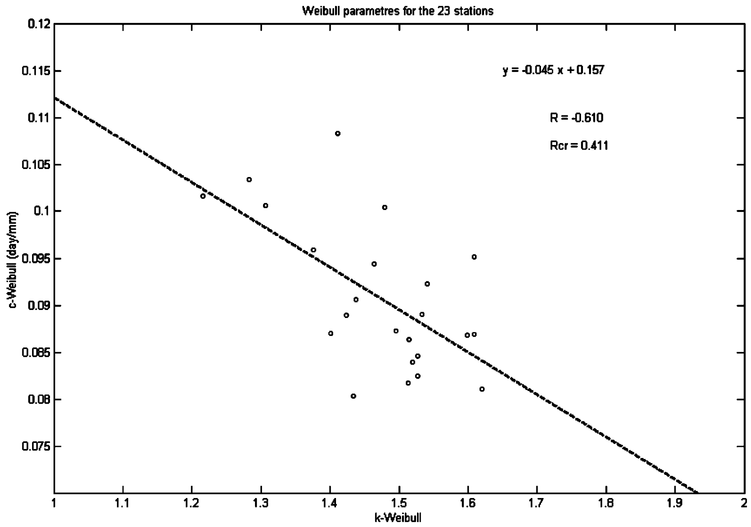

Fig. 12. – The scatterogram of the 23 pairs of Weibull's coefficients (c, k) is plotted in the (c, k)-plane, each point representing a station.

Last, for each station the rain probability, that is the probability that a day taken at random be rainy or not has been computed and listed in table I column 10. This probability has been estimated as the ratio between the number of rainy days and the total number of days having at least 16 hours of observation.

8. – Conclusions

The analysis of the our data has allowed for an exceptionally detailed assessment of the features characterizing the overall rainfall regime of the area under study and, in particular, for an accurate description of extreme events, whose duration is usually limited to at most few hours and sometimes is confined to just few minutes. This result became possible thanks to the concurrence of two favourable circumstances: i) the abundance of data and their high density, ensured by the fast time response of the instrument (the tipping bucket pluviometer can record even some dozens of events per minute), and ii) the relatively low percentage of missing data. On the other hand, the relatively short time span of the measurements (at most 10 years for each station) precluded us from drawing any significant conclusions about possible time trends on the long time scale.

The practical usefulness of these results mainly consist of the informational support offered to civil protection agencies in setting up effective alert systems and in planning, for example, emergency timely interventions in favour of the population exposed to risks or damages coming from violent storms and their consequences such as landslides and flash floods or from shortage of water due to persistent droughts.

A marked preference for the rain events to occur in certain hours of the day has been evidenced in each station. On the other hand, others hours appear to be significantly lacking in rain events with respect to the local mean value. The maximum mean precipitation rates within the day (the rates being calculated for each half-hour of the day as means over the whole decade, and the maximum being then calculated among all the half-hours) generally tend to occur in the late morning, in concurrence with the well-known peaks in sea breeze intensity, while the corresponding minima tend to occur in the early morning and in the early night, when the breezes tend to present sharp drops in intensity. This is not surprising in the light of the enhancement of convective motion due to the solar heating, responsible for the formation of cumulus clouds in the late morning, and, on the other hand, in the light of the prominence of a low inversion layer and strong stability air conditions in the early morning and in the evening. In particular, when the precipitation rates are expressed in mm/day, the maxima range from 2.69 (Stat. 16—Casilino) to 3.73 (Stat. 9—Via Marchi), while the minima range from 0.94 (Stat.19—Roma Sud) to 1.62 (Stat. 22—Falcognana), the minima being typically 2 to 3 times lower than the corresponding maxima. Note that a high contribution to the total rainfall coming from a given half-hour only implies that there must occur a good combination of rain frequency and intensity.

As for the most intense rain events, the quantity used here in order to evaluate their strength was the maximum rain discharge within an interval of 30 minutes, the maximum being now calculated among all the many thousands of values available at each station for each half-hour over the whole decade. The most intense rain event of all was observed at station 9 (Via Marchi), where a total rainfall of 56.4 mm occurred once between 13:30 and 14:00, a really extreme event with an intensity more than 700 times greater than the corresponding mean maximum rainfall.

Also, the highest rain discharge at any station within a period of 24 hours has been computed, taking again the maximum among all the thousands of daily values available over the whole decade. These maximum values have been listed in the table below together with the year when the maximum occurred.

The range of these values, together with the common shape of the histograms in fig. 10, seem to indicate that daily rainfalls larger than 100 mm/day are rare in the region under study, so that one should be very suspicious with daily data higher than, say, 300 mm/day, values that, when recorded by automatic acquisition systems, are likely to be due to malfunctioning of either the measuring equipment or the acquisition program rather than due to true extreme events. This is confirmed also by independent work done on the calibration and validation of precipitation gauges [22], whence it appears that exceptionally severe rain events, occurring typically less than once in a century, do not exceed 400 mm/day, even though such exceptional daily rain discharges are often confined within a few hours.

At each station the percentiles of rain intensity, computed for percent values from 0 to 100 with a step of 10, do not show significant differences among stations (see fig. 7), except for the Fregene station where light rainfalls seem more frequent than elsewhere and heavy rainfalls appear to form an unusually long tail.

The statistics of the time delays between two successive tips allowed a characterization of the intense rains as well as of the droughts. As for the droughts, the longest durations appear to range from 1 to 7 months. As for rain events, almost all stations exhibit a bimodal distribution, corresponding to the separation of the precipitations events in two categories, the intense rains typical of the summer seasons, and the milder rains typical of the fall-winter season.

Last, it has been shown that the likelihood that a day of the year, taken at random, be a rainy day or not at each station yields a probability value comprised in the narrow range from 0.18 to 0.22 with a very small variance and with only one outlier, namely station 15 (Fregene), having the least probability value.

Station	Rain discharge (mm/day)	Year
1	86.4	1998
2	77.4	1992
3	87.2	1996
4	75.4	1992
5	70.2	1997
6	64.6	1998
7	87.4	1992
8	59.0	2001
9	99.4	1996
10	84.0	1993
11	95.0	1993
12	94.2	1998
13	54.4	1998
14	120.2	1993
15	84.6	2000
16	66.8	1993
17	99.6	1993
18	81.8	1996
19	116.4	1993
20	105.4	1993
21	89.0	1993
22	98.8	1997
23	89.2	1996

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