The recent abrupt increase in the precipitation rate, as seen in an ultra-centennial series of precipitation

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Summary. — The authors analyse the ultra-centennial series (1833-1995) of daily total amounts of precipitation recorded in the Genoa University's Meteorological Observatory and the precipitation annual rates, investigating any relationship with the recent occurrences of exceptional rainfall. Among the principal results there is a constant decrease in the number of rainy days since the first records and a significative jump of precipitation rate since 1950. The application of the Gumbel method to the Return Time of the Annual Maximum (AM) series, owing to the recent anomalous variations of Annual Maximum daily precipitation (mm/24 h), has revealed an increase of heavy rainfall in the last thirty years. Moreover, the return times of these events are remarkably shortened.

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1. – Introduction

The purpose of this research is to show any possible connection between variability and increase in intensity of precipitation in the Genoa area and, therefore, to relate its results to the studies of other meteorological observatories throughout the world as general signs of possible ongoing climatic changes. It is worth pointing out an increase in the greenhouse effect originated by the unrestrained discharge of gaseous pollutants released by the combustion of fossil fuels (Yatagai and Yasunari, 1994).

Important evidence of this effect may reside in the global warming rate of the atmosphere of the Earth, increased from 0.3 to 0.6 °C in about 100 years (IPCC, 1992). The use of global forecast models has enabled the data processing of all possible climate evolution and weather state variations. An estimate of regional climate change is offered by the most important study in this sector, by the IPCC scientific assessment (Intergovernmental Panel on Climate Change). The scenario for the estimates of regional change from pre-industrial times to 2030 shows in southern Europe (35–50 °N, 10 °W–45 °E) an amplitude of atmosphere warming estimated to be about 2 °C in winter and 2-3 °C in summer, associated to an increase of precipitation in winter and a

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decrease of 15% in summer (IPCC, 1991). In this work we approached the hydrologic frequency analysis of an ultra-centennial climatological station, to point out a possible signal of change in the distribution of precipitations in a long time series.

The climatological series of the Observatory of Genoa University begins in 1833; at that time the actions of humans upon the environment were certainly less notable than nowadays. The series can therefore be regarded as an authoritative survey on the subject. The Genoa city has not suffered from the consequence of an intensive urbanisation which usually causes meaningful local climatic modifications, because the ancient city had been growing around the climatological station since 1921. Now the town is confined between the mountains and the sea which both prevent a further development of the neighbourhood.

With respect to the historical series of precipitation recorded in the Genoa area, all main statistical data up to 1980 have been processed (Flocchini *et al.*, 1981 and many more authors); in particular the principal evidences of the series are presented. The annual average of precipitation until 1995 is 1293 mm and its extremes were recorded as follows:

– the highest total amount of annual rainfall occurred in 1872 with 2764.5 mm;

– the lowest one occurred in 1921 with only 524.5 mm.

These peaks of annual total amounts occurred 125 and 75 years ago, respectively, and were exceptional events, unsurpassed up to the present. Similar events happened in the same years in other Mediterranean towns: Milan (Italy) and Marseilles (France) witnessed the highest record of all times in 1872, whereas the lowest recorded rainfall was in Pisa, Livorno and Florence (Italy) in the year 1921 (Flocchini *et al.*, 1981). In this survey it is also important to verify the connection between the total annual precipitation and the daily annual maximum recorded in this series, and to estimate the relation between climate and weather variation.

Excesses in the Annual Maximum (AM) values of daily precipitation recorded in Genoa have occurred almost exclusively in the last twenty years, as shown in fig. 1, in which the standardised time series of the AM values recorded points out the accumulation of

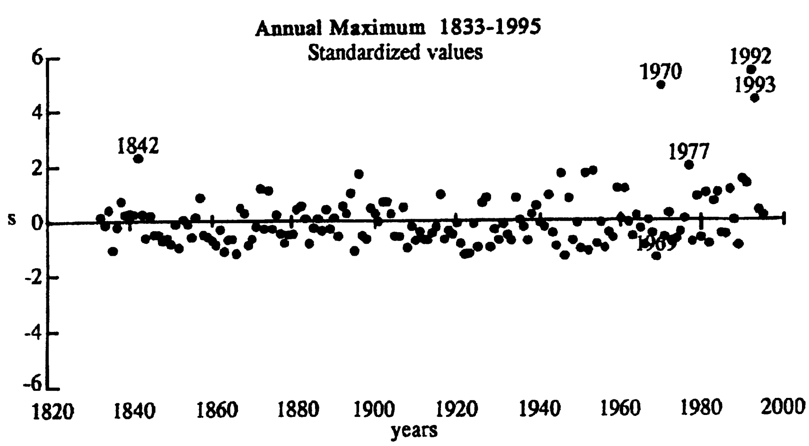

Fig. 1. – Standardized temporal series of Annual Maximum; the labels betoken the peak values and the lowest value for the whole series.

Table I. – *Exceptional* AM *values referred to the highest event and the lowest one. All events occurred in this century, except one which occurred in the mid-1800* (1842): *the same event occurred* 130 *years later* (1970).

Year	mm	σ	Hierarchy	Time lag in *years* from 1992	Epoch
1842	247.4	2.3	4th	− 150	1800: middle
1970	389.2	4.9	2nd	− 22	1900: last 30 years
1977	228	2	5th	− 15	1900: last 20 years
1992	417.8	5.4	1st	0	1900: current years
1993	360.8	4.4	3rd	+ 1	1900: current years
1969	41.6	− 1.3	lowest	—	1900: last 30 years

all-time maximum values. The peak values singled out satisfy the relation

$$*x_i \geqslant \mu + 2\sigma\,, \quad i = 1833,\ 1834\ \ldots,\ 1995\,; \quad \mu = \text{average}\,; \quad \sigma = \text{standard deviation}\,.$$

The variation of occurrence of these extremes, when considered on a probability-distributive scale of the kind $F = Fx_i$, is lower than 2 percent of the total. Its effects upon the hydrologic conditions on the ground were devastating. Each case in the Genoa area resulted in river floods taking lives and causing huge property damage (Russo and Sacchini, 1994).

In the AM series (fig. 1) the year 1969 is to be noted, during which the minimum value was recorded; furthermore, it is worth noticing how this event was observed only one year before the beginning of a period of exceptionally heavy daily precipitation.

The absolute values of the AM series are given in table I. The paroxysm of the year 1992 is perhaps the climax of a succession of extremely severe events, both statistically ($x_p \cong \mu + 3\sigma$, where x_p = most probable value of x_i) and for its effects on the ground.

2. – Working methodology

The series of climatological data collected between 1833 and 1995 was analysed by taking into account:

*P: annual-precipitation total values;

*d: number of rainy days with precipitation > 0.2 mm;

*AM: Annual Maximum values of daily precipitation.

Hence the series was broken down into four 40-year intervals, in order to carry out the following stages:

– comparing data relating average values upon same-length time intervals;

– working out the data comparison in long series > 30 years, thus satisfying the WMO's climatological recommendations; *e.g.*, usually from 1930 to 1960;

– identifying several data strings—relating to different periods—for use in forecasting;

– identifying cycles and return periods of the examined events.

The data have been compared by graphic representations showing their long-term climatologic characteristics, and subsequently by tables for a more detailed analysis. Smoothed trends obtained with the centred moving average technique have been given for the temporal series, to underline any possible variation at the lowest frequencies.

3. – Data analysis

After the description of AM distribution, the single annual-precipitation values were considered. The diagram in fig. 2a shows the trend of the precipitation across the whole series. Figure 2b depicts the curve resulting from the application to the previous

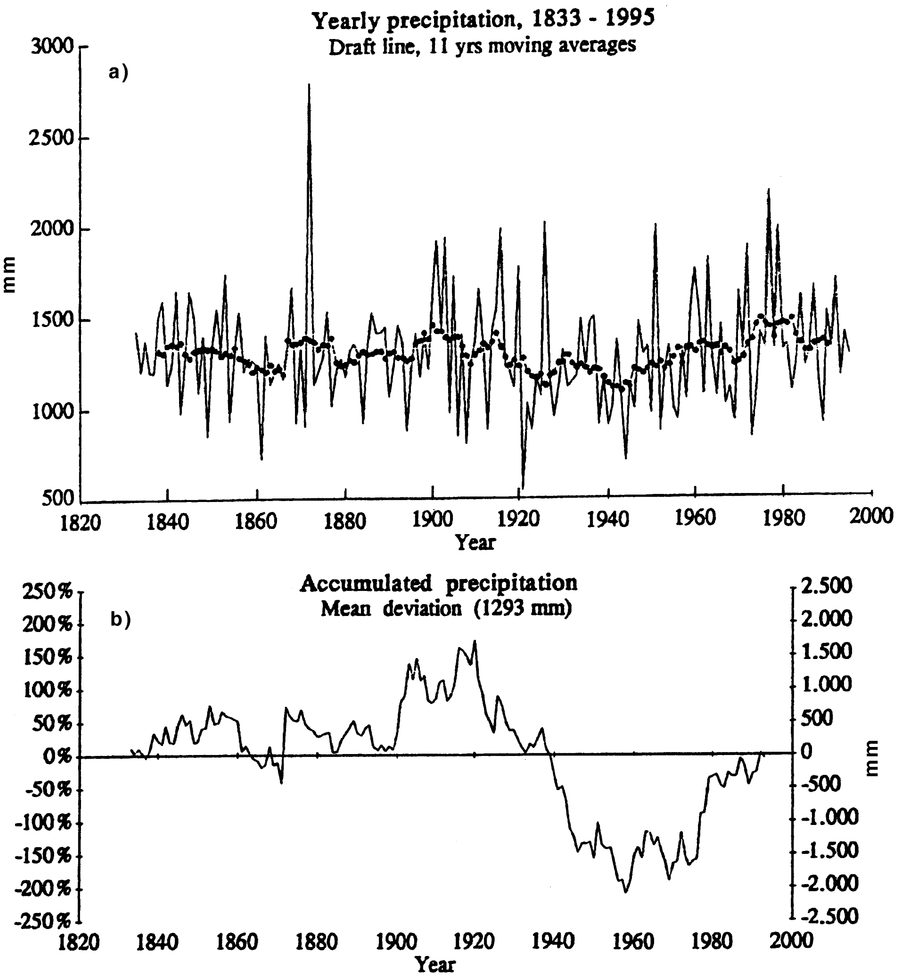

Fig. 2. – a) Trend of accumulated values of precipitation for Genoa (I), from 1833 to 1995. The asymmetric distribution of the signal, with remarkable variation from about 1910 to 1970, is to be noted. b) Accumulated values of precipitation in Genoa (I), for subperiods of forty years. The surplus or deficit of precipitation for each interval is marked.

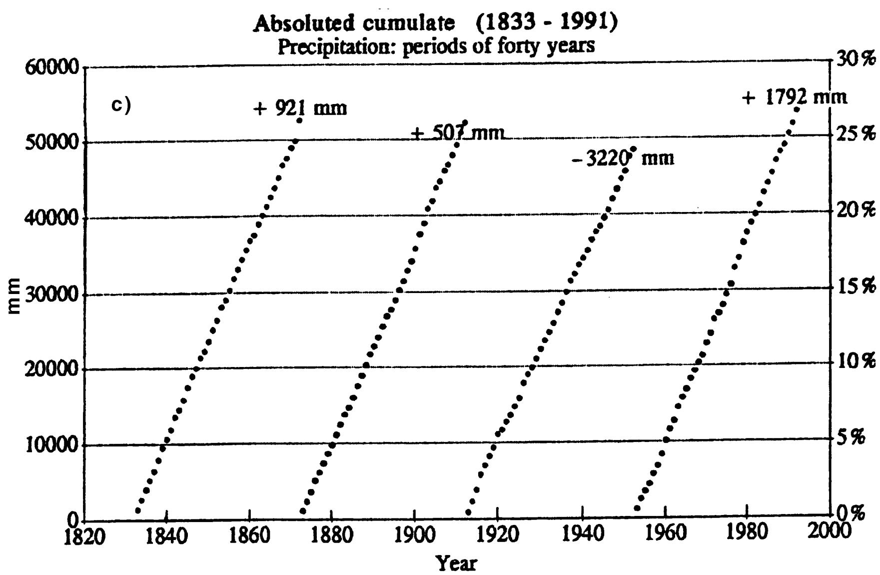

Fig. 2. – (*Continued*) c) Trend of the rainy days in Genoa (I), from 1833 to 1995. The unvarying negative tendency of this signal is distinguishable.

data of the cumulative sum of deviations from the average value. Using the same statistical property for 40-year periods, the hydrological variations are suggested in fig. 2c.

Figure 2a shows a remarkable variation in the annual increase of precipitation in the Genoa area without any particular trend. Comparison between figs. 2a and 1 outlines the singularity of the 1872 event.

The annual maximum precipitation peak is not related to a maximum of daily value. The exceptional amount of precipitations in 1872 cannot be considered the result of a single episode, but rather of a continuous rainfall lasting the whole autumn. The peak value of 1848 mm in October, November and December 1872, compared with the general autumnal average (498 mm), represents a real historical seasonal record (Dagnino *et al.*, 1992).

The cumulative sum of deviations from the average in the ultra-centennial series (1833-1995), illustrated in fig. 2b, outlines the difference between periods of greater stability and others characterised by variability, in which accumulating phases alternate with deficit phases. In this century a non-stationary accumulation (addition, accretion) greater than the average amount is followed by a period of hydrologic deficit, lasting up to fifty years.

Figure 2c shows the balance of the annual rainy increase, related to equal periods of forty years; the analysis makes evident the variation of the single series, whose differences were calculated with respect to the total average (51716 mm = 25% of total). The whole series shows only one period of big oscillation in the years 1910-1950: this interval shows a deficit, 3220 mm, with a negative lapse rate of about 80 mm/year.

Moreover, an accumulation of about 1400 mm (on the average) occurred in the first two 40-year series from 1833 to 1912, equal to 44.4% of the total variation. In the last

TABLE II. – *Assessment of precipitation modifications for intervals of* 40 *years. Departure of single periods from the average of the whole series. Note the oscillation of precipitation gradient* (1913-1952), *after a long period of moderate variations.*

Precipitation	Mean mm	Standard deviation σ	Coefficient of variation %	Relative mean annual gradient %	Absolute mean annual gradient mm
1833-1992 series	1219.9	305.4	23.6	—	—
I period 1833-1872	1315.2	328.1	24.9	+ 1.8	+ 23.3
II period 1873-1912	1304.8	250.3	19.2	+ 1	+ 12.9
III period 1913-1952	1211.6	324.1	26.7	− 6.3	− 80.2
IV period 1953-1992	1336.9	307.9	23.0	+ 3.5	+ 45.1

40 years (1953-1992) an accumulation of 1792 mm (55.6% of the total variation) represents the utmost recovery of the rainy debt, on the whole period.

Table II underlines the instability of these historical series, just in the last 80 years, with two periods of 40 years, showing opposite sign rate.

The comparison between the rainy days distribution (fig. 3) and the precipitation rate (fig. 4) shows that the number of rainy days decreases with a constant share. This does not seem to be related to the rain intensity variation (fig. 4).

The absolute minimum of the series (fig. 3) took place in 1921 with only 67 rainy days in a year, and the maximum in the 1972 with 170 rainy days; the precipitation rate had got its minimum in 1887 with 7.4 mm/day while a maximum of 19.6 mm/day was recorded in 1970.

So the average precipitation intensity (mm/day) increases, in particular from the 2nd half of the current century on. Table III underlines the variations of both

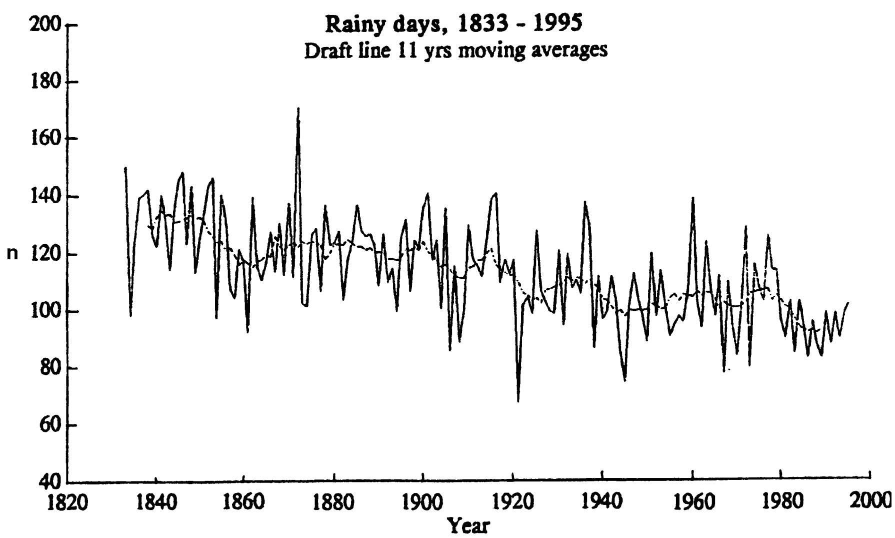

Fig. 3. – Temporal series of yearly precipitation in Genoa (I), from 1833 to 1995. Notice the extreme values of 1872 (2764.5 mm) and 1921 (524.5 mm).

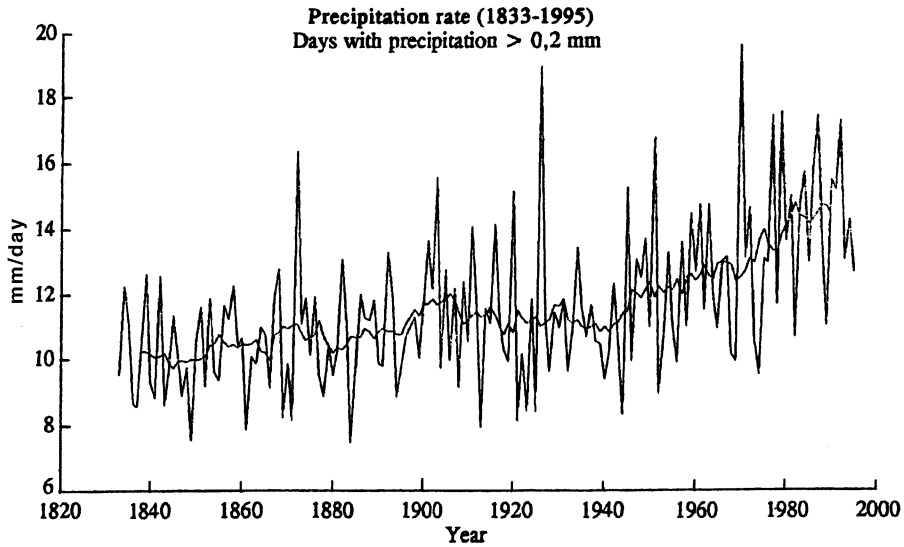

Fig. 4. – Trend of precipitation rate in Genoa (I), from 1833 to 1995. After the 1950s, the tendency takes a positive course.

TABLE III. – *Assessment of rainy days and precipitation rate, for intervals of* 40 *years. In evidence* (*bold*) *are the highest deviations for the whole series. The incessant breakdown of the gradient in rainy days is very important too. It is remarkable how the change of precipitation rate occurred only in the last few years. This effect is probably originated by a massive increment of precipitation, in the same periods* (*cf. table* II).

Rainy days (days with rainfall > 0.2 mm)	Mean mm/d	Standard deviation σ	Coefficient of variation %	Relative mean annual gradient %	Absolute mean annual gradient mm/d
1833-1992 series	112.5	18.0	16.0	—	—
I period 1833-1872	126.7	16.6	13.1	+ **12.3**	+ 13.8
II period 1873-1912	117.8	13.2	11.2	+ 4.4	+ 5.0
III period 1913-1952	106.7	15.6	14.6	− 5.4	− 6.1
IV period 1953-1992	100.2	13.6	13.6	− **11.3**	− 12.7

Precipitation rate	Mean mm/d	Standard deviation σ	Coefficient of variation %	Relative mean annual gradient %	Absolute mean annual gradient mm/d
1833-1992 series	11.5	2.3	20.3	—	—
I period 1833-1872	10.3	1.7	16.5	− **10.3**	− 1.2
II period 1873-1912	11.1	1.6	14.4	− 3.9	− 0.5
III period 1913-1952	11.3	2.3	20.6	− 1.8	− 0.2
IV period 1953-1992	13.3	2.4	18.3	+ **16**	+ 1.8

TABLE IV. – *Differences between periods of* 40 *years, from the first one* (1833-1872) *on. The progressive variation of the gradient, especially in the last period, is evident.*

Precipitation Departure from I period 1833-1872: 1315.2 mm	Mean (mm)	Gradient in 40 years relative %	 absolute mm
II period 1873-1912	1304.8	0.8	− 10.3
III period 1913-1952	1211.6	7.9	− 103.5
IV period 1953-1992	1336.9	1.7	+ 21.8

Rainy days Departure from I period 1833-1872: 126.7 days	Mean (d)	Gradient in 40 years relative %	 absolute d
II period 1873-1912	117.8	− 7	− 8.8
III period 1913-1952	106.7	− 15.7	− 20
IV period 1953-1992	100.2	− 20.9	− 26.5

Precipitation rate Departure from I period 1833-1872: 10.3 mm/d	Mean (mm/d)	Gradient in 40 years relative %	 absolute mm/d
II period 1873-1912	11.1	7	0.7
III period 1913-1952	11.3	9.5	1
IV period 1953-1992	13.3	29.3	3

variables. A comparison between the first and last series shows that during an interval of 150 years almost 25 rainy days went lost. It is a very important variation for Genoa, a sub-Mediterranean climatic area, where the number of rainy days is 112.5 (that is about one third of the days in one year).

Another peculiar aspect is that the yearly precipitation rate (fig. 4) underwent an anomalous rising during the period 1953-1992, as reported in table IV. If we consider the oscillations with respect to the mean of the first period (1833-1872), the intensity variation is greater than 29%. It must be observed that the exceptional values of AM (cf. figs. 1 and 4) occurred during the last period (after 1950). It is worth noting that an abrupt change of the precipitation rate corresponds to a clear increase of daily rainfall amount. The forcing of a meteorological signal (AM) can be detected through another climatological variable. This result induced us to examine more particularly the recurrences of AM as significant index of hydrological variations.

3·1. *Return time analysis of Annual Maximum.* – In order to investigate the AM oscillation observed during 163 years of the Genoa series, the probability of occurrence has been calculated by the Gumbel distributive forecasting function (Gumbel, 1958). The Gumbel extreme-values law fits the empirical distribution of rainy frequency with good agreement (Kite, 1978). This method permits a comparison between climatic series of different areas, as demonstrated by some authors (Flocchini *et al.*, 1982; Vilar

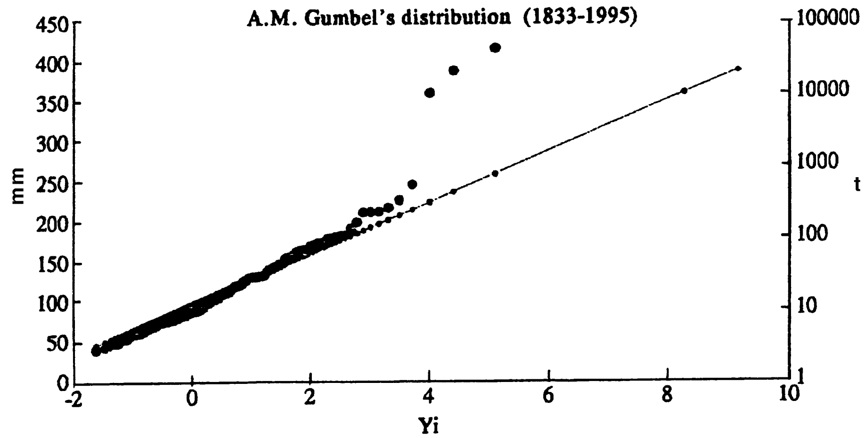

Fig. 5. – Straight line of Gumbel, related to the AM values of precipitation in Genoa (mm/24 h). The values x_i are related to the parameters of distribution, Y_i. The second ordinate (on the right) reports the return times in logarithmic scale. The fit is good under the value of 190 mm; besides this threshold exceptional values for probability of occurrence are found.

and Burgueño, 1995) who analysed the data of Genoa and the ones of the other Mediterranean stations.

In order to apply the Gumbel method, we have applied the algorithm proposed by Ven Te Chow (Ven Te Chow, 1951), a method simplified for practical uses, at the whole AM series that was subdivided into four periods of forty years each. The differences between the calculated and observed values for a given return period were considered in order to identify exceptional values of flood events in the Genoa series. The plot of the results represents in the abscissa the K frequency factor expressed in terms of T or return time and related with the millimetres of precipitation.

The Gumbel model in fig. 5 presents the exceptional values of AM which exceed the 95.45% of the statistical cumulative distribution (precipitation in 24 hours $>$ 190 mm); the *décollement* line between the data and the extrapolated values is exactly above the 196 mm of precipitation. Figures 6a, b, c, d show the different behaviour for periods of 40 years. The thresholds above 95.45% for these four periods are reproduced in table V: these data strengthen the hypothesis of a temporal interconnection between a jump of precipitation rate and AM series (figs. 1 and 4).

TABLE V. – *Thresholds of daily precipitation, for which it is possible to consider the exceptional values of the experimental distribution. These values* (mm/24 h) *are representative for each interval of forty years. The stability of the central period 1873-1952 is outstanding, contrary to the highest value towards the end of the century.*

Periods	1833-1872	1873-1912	1913-1952	1953-1995
Gumbel's distribution: boundary of the 95.45% ($\mu \pm 2\sigma$ of standardized distribution)	174 mm	100 mm	118 mm	311 mm

TABLE VI. – *Return time for each exceptional value of precipitation, calculated by Gumbel's function* (*central column*). *The periods which are much longer than the AM series* (163 *years*) *are written in italics. The different weights of the* α *coefficient are important for the return time estimation.*

AM series	Gumbel's function $x^* = m(\beta + 1/\alpha y_l)$	Exceptional value Year	mm	T-years
1833-1872	$x^* = 107.01\ (0.8659 + 0.2468\ y_l)$	1842	247.4	**351**
1873-1912	$x^* = 114.01\ (0.8802 + 0.2203\ y_l)$	1896	212.5	87
1913-1952	$x^* = 105.56\ (0.8498 + 0.2763\ y_l)$	1945	213.2	41
		1951	213.8	71
1953-1995	$x^* = 138.09\ (0.8392 + 0.4608\ y_l)$	1990	200.2	4
		1953	218.0	6
		1977	228.0	6
		1994	360.8	47
		1970	389.2	74
		1992	417.8	115
1833-1995	$x^* = 116.57\ (0.8462 + 0.2719\ y_l)$	1990	200.2	25
		1896	212.5	37
		1945	213.2	38
		1951	213.8	38
		1953	218.0	44
		1977	228.0	60
		1842	247.4	110
		1994	360.8	*3905*
		1970	389.2	*9565*
		1992	417.8	*23570*

TABLE VII. – *Return time in years, for fixed values of precipitation. In italics are the periods which are much longer than the AM series* (163 *years*). *The first four records refer to AM periods of 40 years. The record listed in the last line refers to the nonsubdivided series. Notice the intensity of precipitations in corresponding intervals: for example, in the last period 1953-1995, the intensity is doubled for a return time of almost 50 years.*

AM periods	150 mm	200 mm	250 mm	300 mm	350 mm	400 mm
1833-1872	9	59	*388*	*2573*	*17087*	*113502*
1873-1912	8	53	*287*	*2828*	*20693*	*151429*
1913-1952	8	44	*244*	*1355*	*7520*	*41763*
1953-1995	2	4	8	19	40	87
1833-1995	6	25	119	*574*	*2778*	*13448*

Accordingly, the return times T for each exceptional value were calculated, estimated by the Gumbel function (table VI).

The results in table VI show the respective characteristic equations as well.

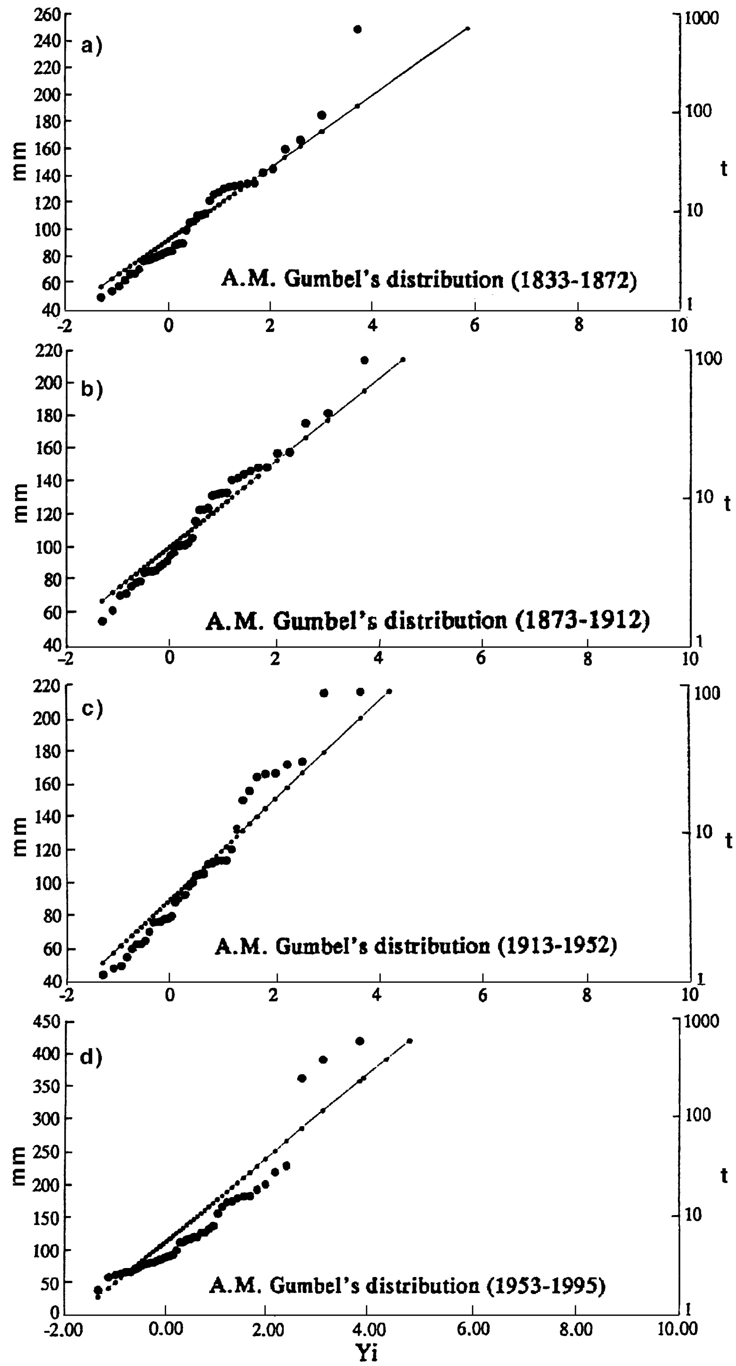

Fig. 6. – Straight lines of Gumbel, related to the AM values of precipitation in Genoa (mm/24 h), series of 163 years, subdivided into intervals of forty years. Notice the different performance of each signal: as pointed out in fig. 4, there is a good agreement between the increase of the precipitation rate and the AM in the last forty years.

Afterwards, the equations are solved for assigned fixed values of precipitation; table VII reproduces the resulted return time T. The periods written in italics, twice longer than the whole sample series, are without signification.

4. – Discussion and conclusions

The evidences about the irregularity and instability of the weather since the end of the last century till today, with particular reference to the number of rainy days, are evident and suggest some considerations.

The ultra-centennial series of Genoa is characterised by wide variations about the average value which is not considerably changed during the course of time (fig. 2a). A remarkable behaviour was the relative short dry period from 1910 to 1950, which failed to contribute to the mean precipitation value (fig. 2b).

As we previously mentioned, the number of rainy days is a not yet stabilised parameter (fig. 3) and it is interesting to observe that the decrease trend started before the beginning of the Genoa series.

The decrease of rainy days can be considered a binary signal as a possible recorder of the climatic conditions which, according to our investigation, seem to have started to change a long time ago. The annual precipitation rate makes the present century a rather complex and changing period.

This composite signal shows a constant increase and becomes stronger particularly about the 1940s, lasting till today. It follows that the present Genoa area is concerned with an oscillation of its climate: from a sub-Mediterranean marine kind towards typical conditions of more southern Mediterranean areas, characterised by extreme variations of the precipitation rate.

With similar behaviours, the maximum annual precipitation rate value was recorded in the period 1970-1993, corresponding to highest values of daily precipitation (AM). By the computation mentioned in table VI the return time for AM values is remarkably shortened. The forecast of extremes by the Gumbel method provides two different conclusions. The first 130 years show hydrological events without change. In the last 30 years, on the contrary, for equal return times daily precipitation occurred with very high intensity (cf. table V). This abrupt climatic oscillation, after a long period of stability, makes the classic periods of 30 years not long enough for hydrologic forecasting (as far as planning of hydraulic works is concerned).

The same conclusions were obtained in climatic subtropical and African tropical stations, where the instability of the rainfall rate was particularly remarkable (Demarée, 1990).

Today it is impossible to understand whether this apparent climatic variation is related to the rise of the average precipitation rate or to the reduction of the rainy days number. Now it seems that there is not an opposite tendency able to reverse the phenomenon which comes out with the return of the same atmospheric manifestations (fig. 1). The forecasting extrapolations about the maximum extremes, produced by Gumbel's model (fig. 5), feel deeply the effects of these climatic variations. From 1975 to 1995 the intensity-return period ratio has risen in a considerable way; the return time has decreased from 1000 years to 100 years or less!

It is interesting to observe that the number of rainy days is the only element of climate permanent changing. This parameter has begun to show a negative trend for the whole period, which excludes a feedback by anthropic effects and so it seems the result of a still unfinished climatic ultrasecular oscillation.

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