

Snowfall series of Turin, 1784–1992: climatological analysis and action on structures

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ABSTRACT. The snowfall series of Turin, northwest Italy, is one of the longest available for Europe, with daily observations starting in 1784 and continuous since 1788. The unpublished 207 years data set was carefully obtained from original manuscripts and filed on magnetic media. Mean yearly snowfall amount is 48.9 cm showing a high interannual variability (variation coefficient 79%), with about seven snow days from October through April; the maximum amount was measured in winter 1784–85 (233 cm), followed by 1808–9 with 163 cm. Maximum daily amount was on 4 December 1844 with 64 cm. During the whole period a negative trend is exhibited, increasing in the years following 1890. This pattern is confirmed by the Mann-Kendall test. The change derives from regional climate rather than expansion of the urban area. Return periods of yearly maximum snow loads are calculated in order to contribute to the definition of new values for structural design. A case study of heavy snowfall in January 1987 is examined.

INTRODUCTION

Turin lies at 240 m elevation in the west zone of the Po plain (45°03' N, 7°40' E), 15 km from the alpine reliefs of Susa Valley. The urban area is about 130 km², extending mostly northwest along the Po river. The first descriptive observations concerning snowfall date back to 1675, while daily measurements began in 1784. The numerous manuscripts that have been accumulated during two centuries, at times dispersed in different places, have been carefully analysed; the numerical data have been turned into standard units and filed on computer media, for the first time allowing analysis of the most ancient snow series in Europe.

DATA SOURCES AND PROCESSING

Between 1675 and 1681 the Royal Italian mathematician, Donato Rossetti made a study of the shape of snow crystals, publishing the results in a booklet entitled *La Figura della neve* (The shape of snow), and highlighting the hexagonal structure of crystals. Between 1682 and 1721 sporadic snowfall descriptions are reported in F. L. Sloeri's *Diary* (Rebaudengo, 1969) and later resumed (1753–93) by Count Ignazio Somis. Quantitative measurements of snowfall began with G. D. Beraudo (1785) who founded the first meteorological observatory in the town centre in 1780. Unfortunately some data have been lost and only daily snow data, for the exceptional winter 1784–85, are left. Since 1788 with the foundation of the

Observatory of the Royal Academy of Sciences directed by A. M. Vassalli-Eandi (1808, 1810) daily measurements were regularly handwritten in registers till 1865, when the Observatory moved to Palazzo Madama. There measurements were made till 1919. From then observations were performed at the Physics Institute of the Royal University (1930–43). Since 1928 a thermopluviometric station of Ufficio Idrografico del Po has operated. All of the above meteorological stations are located in the central area of the town, in comparable conditions, so that the whole series of daily snowfall presents only slight inhomogeneities for climatological analysis. When possible, data were checked with newspaper information.

CHARACTERISTICS OF SNOWFALL IN TURIN

Meteorological patterns of snowfall

Meteorological patterns influencing snowfall in the Turin region can be categorised as:

Western and northwestern: characterised by the passage of Atlantic fronts, generally fast and greatly influenced by their passing over the Alps. They produce wet snowfall of light or moderate intensity (1–15 cm),

Northern and eastern: eruptions of cold continental air combined with weak intensity fronts that usually bring a small quantity of light snow (1–5 cm) and

Southern: with respect to snowfalls, the most active

circulation, formed by moist air arriving from the Mediterranean sea during cyclonic events over Genoa Gulf. Produces hard and protracted snowfalls (> 20 cm, 2–5 d) that are wet because of temperatures close to 0°C, showing high values of water equivalent.

STATISTICAL CHARACTERISTICS

New snowfall depth

We have analysed the depth of daily new snowfall generally measured around 0800 h or, in the case of brief precipitation, during the day. For the period 1784–1848 French measure units have been converted to cm using the relations: 1 inch = 2.7070 cm and 1 line = 0.2256 cm (Vassalli-Eandi, 1806). The series starts in the last months of 1787 and continues till 1992. Adding the winter of 1784–85 the data set amounts to 207 years. The snowfall for 206 snow seasons (October through April)

Table 1. Turin, 240 m. Yearly (October–April) snowfall amounts (cm). Period 1784–85; 1787–88/1991–92

Mean	48.9	Percentile 0.1	7
Standard deviation	38.7	Percentile 0.2	15
Coefficient of variation	0.79 = 79%	Percentile 0.5	42.5
Minimum value	0	Percentile 0.8	75
Maximum value	233 (1784–85)	Percentile 0.9	98

exhibit parameters shown in Table 1.

Mean yearly snowfall amount shows considerable interannual variability as the high value of the coefficient of variation indicates, one year out of ten exhibiting less than 7 cm or more than 98 cm, while one year out of five exhibits less than 15 cm or more than 75 cm. A few winters were without snow (1.9% of the sample), while the winter of 1784–85, with 233 cm of snow was considered exceptional and for this reason the observer

Table 2. Turin, 240 m. Monthly snowfall amounts (cm). Period 1784–85; 1788/1992

Month	Mean	Std dev	CVar %	Min	Max	P 0.1	P 0.2	P 0.5	P 0.8	P 0.9
Oct	0	*	*	0	6 (1979)	0	0	0	0	0
Nov	2.4	6.6	275	0	53 (1895)	0	0	0	2	8
Dec	11.0	17.4	158	0	129 (1808, 1844)	0	0	5	18	28
Jan	19.0	22.9	121	0	122 (1805)	0	1	10	36	52
Feb	11.8	19.0	161	0	115 (1888)	0	0	4	19	36
Mar	4.0	9.2	230	0	56 (1796)	0	0	0	5	12
Apr	0.7	3.0	429	0	29 (1834)	0	0	0	0	0

* For Mean = 0, STD and CVar cannot be calculated.

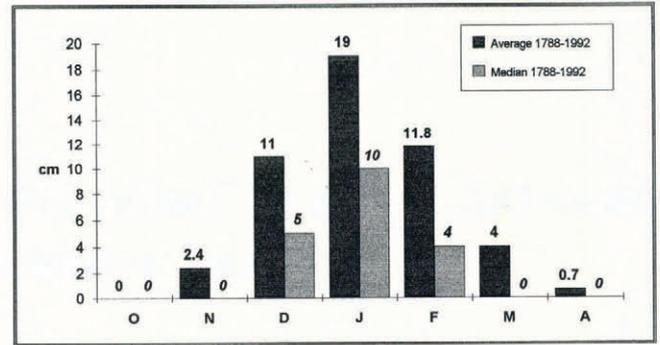


Fig. 1. Turin. Histogram of mean monthly snowfall amounts (cm) (period 1784–85; 1788–1992).

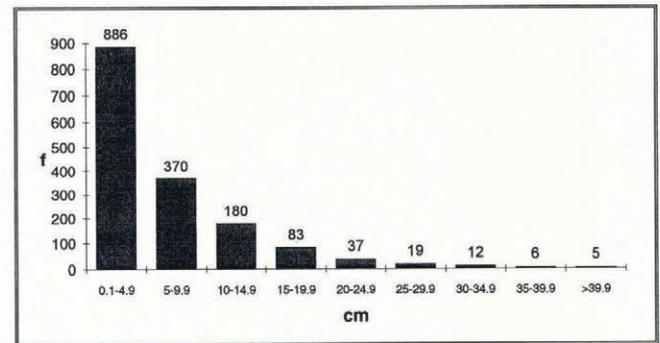


Fig. 2. Turin, 240 m. Histogram of frequencies of daily snowfall amount (cm), period 1788–1992.

Beraudo drew up a special table. Such values were never again attained, the value immediately below this being 163 cm in the winter of 1808–9. Statistical parameters of monthly snowfall amount are reported in Table 2. The distribution of snow heights follows the thermic course, with maximum in January coinciding with the mean temperature minimum (Fig. 1). Coefficient of variation of monthly snowfall amounts is in all these months higher than 100%. January and December show greater regularity than autumn and spring months, in which snowfalls are rare. Snow in October is unusual (only two cases, in 1920 and in 1979), while in April it is more frequent because of the continuing winter meteorological

Table 3. Turin, 240 m. Frequencies of daily snowfall amounts. Period 1788–1992

Class interval cm	Frequency	Cumulative frequency	Relative frequency	Relative cumulative frequency
0.1–4.9	886	886	0.554	0.554
5.0–9.9	370	1256	0.232	0.786
10.0–14.9	180	1436	0.113	0.899
15.0–19.9	83	1519	0.052	0.950
20.0–24.9	37	1556	0.023	0.973
25.0–29.9	19	1575	0.012	0.985
30.0–34.9	12	1587	0.008	0.993
35.0–39.9	6	1593	0.004	0.996
> 39.9	5	1598	0.003	1.000

circulation, with 18 cases (8.7% of the sample). There are zero values in every month and in many cases.

The bar graph of frequencies of daily snowfall amounts (1598 d) shows a sharp prevalence (55%) of feeble intensity events up to 5 cm (Table 3, Fig. 2). Daily snowfalls higher than 30 cm (23) are only 1.5% of the total number of events, showing a maximum of 64 cm on 4 December 1844. If we consider consecutive days of snowfall we find a maximum of 85 cm occurred in 1808, from 23 to 25 December.

Table 4. Turin, 240 m. Yearly (October–April) number of snow days. Period 1787–8|1991–92

Average	7.9	Percentile 0.1	2
Standard deviation	5.0	Percentile 0.2	4
Coefficient of variation	0.64 = 64%	Percentile 0.5	7
Minimum value	0	Percentile 0.8	11
Maximum value	30 (1837–38)	Percentile 0.9	14

Snow days

In this work we have considered snow days as those with at least 1 cm of new snowfall, excluding days showing a lower value of snow on the ground. The series of snow days in Turin during the period 1788–1992 exhibits the statistical parameters of Table 4.

Like snowfall amounts, the number of snow days is also subject to considerable interannual variability (coefficient of variation 64%), with a median value of 7. One year out of ten may have less than two or more than 14 snowfall days. For agricultural implications it is interesting to analyse the main cases of early or late snowfalls (Table 5).

Table 5. Turin, 240 m

Late snowfalls		Early snowfalls	
Date	Depth cm	Date	Depth cm
25 April 1972	3	27 October 1979	6
24 April 1883	2	31 October 1920	2
21 April 1838	7	1 November 1920	12
20 April 1838	1	2 November 1920	30
20 April 1954	12	2 November 1919	2
18 April 1991	2	3 November 1880	2
17 April 1991	6	7 November 1858	15

The extreme dates with at least 1 cm snowfall recorded in a 207 yr period range from 25 April 1972 to 27 October 1979. The latest date in which a snow event has been reported for Turin was 1 May 1714, when Soleri reported a snowfall from 2000 to 2400 h. The same observer reported a snowfall on 27 April 1713.

Damage due to autumn snowfalls is rare. Effects of spring snowfalls are greater because mechanical damage on arboreal vegetation already covered with leaves combines with physiological damage of vegetative organs caused by the low temperature around 0°C. The event of 17–18 April 1991 was particularly hard as the total snowfall amount reached 8 cm in the town and over 20 cm in the hilly neighbourhood.

SNOWFALL BEHAVIOUR THROUGH TWO CENTURIES

Inhomogeneities introduced by urbanisation

Analysis of the snowfall amount time series of Turin cannot leave aside considerations of possible inhomogeneities introduced by the increase of urbanisation during the last two centuries. Turin's population has grown from 43.87×10^3 in 1702 to 1.115×10^6 in 1981. For most towns, due to heat-island effects in winter, temperature is higher inside than out. This fact may have influenced the evolution of snowfall amount, causing a reduction in the period following 1950. This variation, strictly connected with urban climate, is negligible in the context of the climatological analysis, for the following reasons:

— The geographical conformation of the town of Turin, bounded to southeast by the River Po and by the hilly ground (up to 700 m) has stopped urban expansion in those directions. The meteorological observatories are placed in this zone, coinciding with the historical centre of the town. Therefore they have undergone little change (as time passed) of their microclimate. They have also always been in an urban situation.

— Comparing the snowfall series of Turin with those of

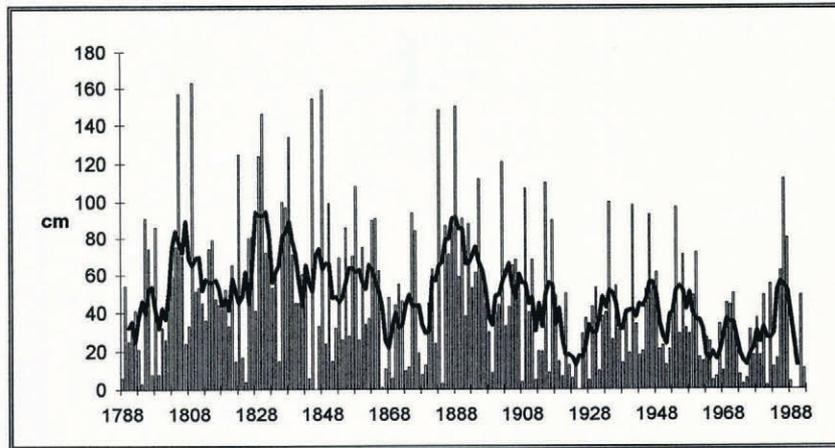


Fig. 3. Turin, 240 m. Yearly (October–April) snowfall amount and 5 yr moving mean, period 1787–88|1991–92. Series maximum value is 233 cm (1784–85), here not indicated as separated from continued measurements.

the town of Bra (290 m, period 1862–1991 (Brizio and Mercalli, 1991)) and Cuneo (530 m, period 1877–1990 (Biancotti and others, 1991)) indicates that the snowfall amount decrease is a common characteristic after 1915, not depending on local conditions. Both are small towns with no considerable urbanisation.

Snowfall amount time-series analysis

We applied a 5 yr moving mean to the graph in Figure 3 of winter snowfall amount (October through April), to smooth interannual variations. The graph shows a period of high snowfall from 1800 to 1860. A decrease followed around 1870, and then an increase between 1880 and 1890. After 1900 a decrease phase began, with a minimum in the decade 1920 to 1930, a weak increase between 1940 and 1950, a new lower-than-normal period between 1960 and 1975, then a higher-than-normal period between 1981 and 1987. The last years of the series show low values with the only case of two consecutive years without snow (1988–89 and 1989–90). A negative trend is confirmed for this data by the non-parametric Mann-Kendall test (Giuffrida and Conte, 1989).

Figure 4 plots the number of snow days for the record period. The 5 yr moving mean is plotted. The number of days measuring at least 1 cm snowfall shows a decrease through two centuries, with maximum from 1800 to 1860 and minimum in the decade 1920 to 1930. A weak negative trend is confirmed for these data also, by the Mann-Kendall test.

Interesting historic data also confirm that there was more snow (duration and amount) during the 19th century. The Savoy Royal Family moved by sledge from the Royal Palace to Valentino park, as noticed by Soleri in January 1718 and 1719. Soleri also reported snow piles remaining in shady yards on 22 May 1716.

SNOW LOADS ON STRUCTURES

Intensity and distribution of snow loads on roofs, q^* , depends on geographical, physical and geometrical parameters. Among these are latitude, climate, altitude, type of building, pitch slope and roofings, roof structure, temperature and wind. To obtain the load, q^* , on the roof of a building, one multiplies the load, q , acting on the ground (and here experimentally determinable) by the

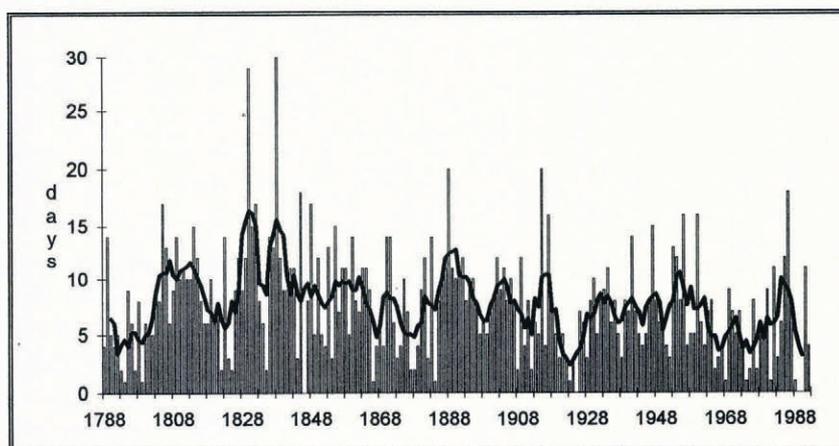


Fig. 4. Turin. Yearly (October–April) number of snowy days (with at least 1 cm) and 5 yr moving mean (period 1787–88|1991–92).

shape coefficient μ by the exposure coefficient C_e and by the thermic coefficient C_t as follows:

$$q^* = \mu \cdot C_e \cdot C_t \cdot q \tag{1}$$

Values of these coefficients are reported in the national technical rules and in international notices. Values of q are generally stated for geographical areas as a function of elevation of the location. Italian technical regulations at present in force (Ministero dei Lavori Pubblici, 1982a, b) provide a snow load at the ground, q for the Piedmont district (with Turin as the regional capital) and for other districts in northern Italy, of:

$$q = 0.90 \text{ kN m}^{-2} \quad \text{for } A \leq 300\text{m}$$

$$q = \left[0.90 + \frac{1.5}{1000}(A - 300) \right] \text{ kN m}^{-2}$$

$$\text{for } A > 300\text{m} \tag{2}$$

A is the elevation a.s.l. expressed in m. Particularly, as Turin lies at 240 m, $q = 0.9 \text{ kN m}^{-2}$. These rules are unfavourable for safety as is confirmed almost every year by damage to roofs, large industrial sheds and other structures. At present the Comitato di Studio per i Carichi e Sovraccarichi del Ministero dei Lavori Pubblici — 1a Sezione, is preparing new proposals for snow loads, deduced by several studies carried out at different Italian locations with observation periods of about 50 yr. These proposals appear much safer than rules currently in force. For instance, in the Piedmont area, load values on the ground for return period $T_0 = 200$ yr are given by the following relations:

$$q_{T_0=200} = 1.60 \text{ kN m}^{-2}$$

$$\text{for } A < 200\text{m} \tag{3}$$

$$q_{T_0=200} = 1.60 + 3(A - 200)/1000 \text{ kN m}^{-2}$$

$$\text{for } 200\text{m} < A < 750\text{m} \tag{4}$$

$$q_{T_0=200} = 3.25 + 8.5(A - 750)/1000 \text{ kN m}^{-2}$$

$$\text{for } A > 750\text{m} \tag{5}$$

Data obtained for this work cover over 200 yr of observations, the longest we have found in specific references, can contribute to check Equation (3) for the Turin area. Note that Equation (3) gives a value of $q = 1.720 \text{ kN m}^{-2}$ for $A = 240$ m, the elevation of Turin.

Maximum snowfall depth in Turin

Yearly maximum new snowfall depths, h_1 , occurring during one or more consecutive days, (or rather, for the years in which it happens, the snowfall amount of consecutive days with at least 1 cm of new snow), have been ranked in order of magnitude, so that

$$(h_1)_1 \leq (h_1)_2 \leq \dots (h_1)_m \leq \dots (h_1)_h.$$

Each variate $(h_1)_m$ is assigned the Weibull probability index equal to:

$$P_m = \frac{m}{n + 1} \tag{6}$$

and single points, coordinate $[P_m, (h_1)_m]$ were plotted on a Gumbel diagram (Fig. 5). This graph shows that yearly maximum new snowfall depths fit an extreme value type 1 distribution (E1), with the following statistical parameters:

average	$\bar{h}_1 = 0.213 \text{ m}$
standard deviation	$\sigma_{h_1} = 0.173 \text{ m}$
coefficient of variation	$c_{h_1} = 0.812 = 81.2\%$
minimum	$(h_1)_{\min} = 0 \text{ m}$ (years 1866, 1923, 1989)
maximum	$(h_1)_{\max} = 0.850 \text{ m}$ (year 1808)
fractile 0.95	$(h_1)_{0.95} = 0.536 \text{ m}$

For an E1 distribution, argumental values associated with return periods T_0 (years) are determinable following the relations (Leporati, 1983):

$$h_{T_0} = \bar{h}_1(1 + K_{T_0}c_{q_1})$$

$$K_{T_0} = \frac{-\ln \left[-\ln \left(1 - \frac{1}{T_0} \right) \right] - 0.5772}{1.2825} \tag{7}$$

Thus, argumental values of snowfall depth for return periods of 50, 175, 200 and 1000 yr, are:

$$h_{T_0=50} = 0.661 \text{ m}$$

$$h_{T_0=175} = 0.831 \text{ m} \tag{8}$$

$$h_{T_0=200} = 0.849 \text{ m}$$

$$h_{T_0=1000} = 1.067 \text{ m}$$

Snow density

The density of each yearly maximum snowfall depth was obtained from the water equivalent volume as recorded every 24 h in the rain gauge. Mean, standard deviation and coefficient of variation of the 207 new snow density values were:

$$\bar{\gamma} = 1.132 \text{ kN m}^{-3}$$

$$\sigma_\gamma = 0.439 \text{ kN m}^{-3} \tag{9}$$

$$C_\gamma = 0.388 = 38.8\%$$

In windy areas, 10% further doubt may be assumed, considering the underestimate associated with the measurement of snow water equivalent by normal rain gauges (Mercalli and Viarengo, 1989; Navarre, 1992).

The new snow density depends above all on air temperature and on the presence of wind during precipitation, while the density of snow cover on the ground tends to increase due to metamorphism phases during the accumulation of new snowfall (U.S. Department of Agriculture, 1980). At Turin (station at low altitude, $A = 240$ m) the presence of snow cover is not continuous, but is characterized by one or more separated events, with intermittent snow layer on the ground, often for not longer than 10 consecutive days. In these conditions density variation in time may be neglected (Sanpaolesi and others, 1983) and a constant value may be taken for this parameter for specifically structural purposes. It is obvious that this value cannot be taken equal to the new snow density values (Equation (9)),

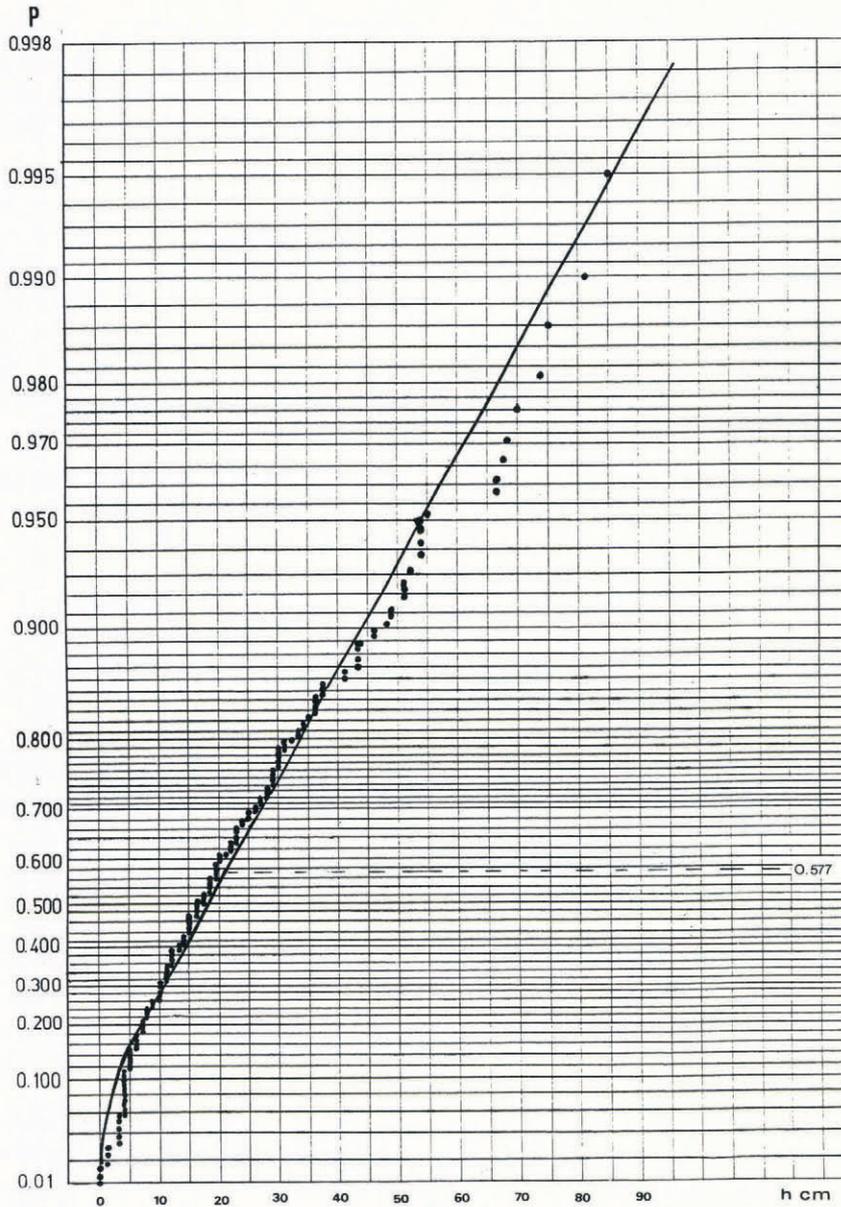


Fig. 5. Gumbel diagram. Distribution of yearly maximum new snowfall depths in Turin.

because it increases with continued snow precipitation, as evidenced by some researchers (Martinec, 1977), both experimentally and analytically. In particular, for snow some hours to days old, minimum values of density are 2.0 kN m^{-3} (Schweizer Norm. SIA 160, 1989; ISO/DIS 4355, 1978).

Snow load at the ground in Turin

Yearly maximum snow loads on the ground, $q_1 (\text{kN m}^{-2})$ can be deduced from yearly maximum snowfall depths, $h_1 (\text{m})$, following:

$$q_1 = 2h_1 . \tag{10}$$

Assuming constant density the statistical distribution of the load on the ground is of the same kind as for snowfall depths. Statistical parameters of yearly maximum snow loads and argumental values combined with return periods generally considered in technical rules, appear in Table 6.

Consideration of snow loads

From Table 6 it appears that, on the basis of the analysis of this work the argumental value of snow load in Turin for a return period of 200 yr, is equal to 1.698 kN m^{-2} . This is in good accord with Equation (3) which give a value of 1.720 kN m^{-2} for $A = 240 \text{ m}$.

Equation (2), properly extended to other areas of the country, also represents the Italian proposals for snow-load technical rules to be included in the “Eurocode 1: Basis of design and actions on structures — Part 2.5: Snow loads”.

January 1987 snowstorm

The period 1985 to 1987 included several heavy snowfalls in Turin, resulting in 112 cm of snowfall in the winter of 1985–86. This had not been reached since winter 1901–02 (121 cm). In winter 1986–87 snowfall amount reached 80 cm. In 1986 precipitation was widely distributed in time, limiting damage only to the fall of snow from roofs.

Table 6. Turin, 240 m. Argumental values for return periods of snow load

Parameter	Symbol	Value
Average of yearly maximum snow loads	\bar{q}_1	0.426 kN m ⁻²
Standard deviation of yearly maxima	σ_{q_1}	0.346 kN m ⁻²
Coefficient of variation	c_{q_1}	0.812 = 81.2%
Fractile 0.95 of yearly maxima distribution	$(q_1)_{0.95}$	1.072 kN m ⁻²
Argumental value for return period $T_0 = 50$ yr	$q_{T_0=50}$	1.322 kN m ⁻²
Argumental value for return period $T_0 = 175$ yr	$q_{T_0=175}$	1.662 kN m ⁻²
Argumental value for return period $T_0 = 200$ yr	$q_{T_0=200}$	1.698 kN m ⁻²
Argumental value for return period $T_0 = 1000$ yr	$q_{T_0=1000}$	2.134 kN m ⁻²

In 1987 the greater intensity of snowfalls caused record structural breakages. In fact between 13 and 16 January, 67 cm of snow fell, the eighth highest amount in the series of maximum amounts since 1784. The highest, on 23 to 25 December 1808, was 85 cm. The January 1987 snowstorm began at 0600 h (UTC + 1) on 13 January, due to the intervention of a warm front coming from the southwest, activated by a cyclonic area placed between Corsica and the Gulf of Genoa. The presence of a cold air layer on the Po plain (in Turin, $T_{\min} = -7^\circ\text{C}$) caused a light and dry snowfall till 1500 h on 14 January, when the snow depth was 30 cm. Because of the continuous inflow of warm air from the Mediterranean Sea, the temperature approached 0°C , with wet and heavy snow that at 2000 h became rain. During the night between 14 and 15 January the precipitation continued with a new amount of wet snow (12 cm) added to the depth on the ground (36 cm). In the evening of 15 January, temperature reached $+1^\circ\text{C}$ and precipitation became intermittent. The cyclonic circulation caused new wet snowfalls at the dawn of 16 January (temperature always near 0°C). At 1800 h snow depth was 43 cm, corresponding to a new snowfall amount of 67 cm and with water equivalent equal to 71.6 mm recorded (probably underestimated) by rain gauge. At 2200 h on 16 January the precipitation became rain, stopping in the night. During the same day most damage occurred. Tree branches broke in the town avenues, gutters and cornices caved in and plane roofs (in particular glass greenhouses, industrial sheds and steelworks sheltering fuel stations) collapsed. The damage caused by the snow sliding off roofs was enormous, with many parked cars damaged by wet snow masses.

CONCLUSIONS

Statistical analyses are carried out for the first time on the Turin daily snowfall series, one of the longest in Europe spanning over two centuries of continuous measurement. The time-series analysis of snowfall amount over the 200 yr shows a decreasing trend, and allows detailed description of the characteristics of snow phenomenon in the Piedmont plain. This provides operational guidelines for the evaluation of the probability of events affecting

many activities. For instance, the frequency of daily snowfall depths provides indications for public removal planning: in 95 cases out of a hundred the organisation will face daily snowfalls lower than 20 cm; to take the extreme snowfalls of 1986 and 1987 as a model would overestimate the removal service with costs in the long periods of inactivity. On the other hand, the objective evaluation of the risk thresholds is decisive to size the works for which the safety limits must be strictly respected as in the case of structural loads analysed in this paper. Another field of interest is the estimate of the risk of late and early snowfalls with respect to agriculture. In October snowfalls can be considered exceptional. In April we may expect a snowfall every 11 yr.

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