Hail in Southwestern France. I: Hailfall Characteristics and Hailstorm Environment

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(Manuscript received 4 April 1984, in final form 6 July 1985)

ABSTRACT

In the context of an experiment of hail prevention in the Aquitaine region, 12 869 reports of damaging hail have been compiled during 29 years in an area of 88 980 km^2. These observations, together with crop insurance data, have led to a unique hail climatology.

The data presented in this paper concern the geographical distribution of hail damage, the yearly, 5-day and hourly frequencies of hailfall, and the distributions of hailstone size and of hailfall duration. Most of these data are well explained by the fact that hail in the surveyed area is the result of almost any rather severe thunderstorm: large hail, however, is produced by a few isolated long-lived hailstorms traveling downwind of the central part of the Pyrenees with the strong upper level winds. Study of the mean characteristics of 30 of the most severe storms which have damaged the Aquitaine in the last three decades leads to the following description: a typical long-traveling hailstorm moves at 15 m s^{-1} for 1.5 h, dropping a hail strip 86 km long and 6 km wide. The direction of propagation is from the southwest, with an angular deviation of 28° to the right of the mean tropospheric wind. This wind is characterized by an increase in velocity up to 10 km (mean maximum: 32.6 m s^{-1}) without any change in direction above 3 km. In some circumstances, these long-traveling hailstorms produce only hailspots along their path, although the convective and wind conditions are the same as for the major hailstorms.

The insurance data complete the observers reports because they take into account the severity of the hailfalls and also because they give the economical impact of the hail. A decrease in the mean annual percentage of loss is observed during the last two decades in Aquitaine. The significance of this change will be discussed in Part II which is related to a hail prevention project in the same region.

1. Introduction

For the rural population of southwestern France, hail is the main weather related problem. Their crops may be destroyed in "just ten minutes" anytime from April to October.

In 1951, a group of farmers, agronomists, scientists and politicians founded a nonprofit association for the study of hail prevention under the scientific direction of Professor Henri Dessens (Gatheron, 1953). Since then, the Association, now named *Association Nationale d'Etude et de Lutte contre les Fléaux Atmosphériques* (ANELFA), has simultaneously attempted to learn more about the physics of hailstorms, and to design a practical method of seeding these storms with silver iodide. The exceptionally long duration of the project, which is still expanding after a 30-year period of activity, has yielded the results presented in these two papers on the hail climatology presented herein (Part I) and on the economical efficiency of the seeding (Dessens, 1986; hereafter referred to as Part II).

2. Geographical description of the Aquitaine

a. Topography and climate

The area under study is roughly the geographical region of Aquitaine, a sedimentary basin situated between the Atlantic, the Pyrenees and the Massif Central (Fig. 1). The mean latitude is 44°N, and the altitudes do not exceed 300 m MSL except near the Pyrenees which constitute a continuous range 400 km long and 2 or 3 km high. The 88 980 km^2 of the area are administratively composed of 14 departments and 5754 communes. The size of a commune is variable; its mean value is 15.46 km^2 for the whole area, but it changes according to department from 9.48 to 19.75 km^2 and even 28.14 km^2 for the wooded department of the Landes (40). There are similar variations inside a department.

The Atlantic Zone (departments of 16-Charente, 17-Charente-Maritime, 33-Gironde, 40-Landes and 64-Pyrénées-Atlantiques) is essentially flat with only a few hills in the area of the Bordeaux vineyards and in the south, near the Pyrenees. The middle part of this zone is covered by the great pine forest of the Landes. The climate is oceanic; the annual amount of precipitation decreases from 1200 mm at Biarritz, near the Pyrenees, to 800 mm in the Bordeaux area. Rainfalls are lighter in July and August, but periods of droughts are unusual, thanks to the humidity of the air which remains high: on July afternoons, the mean relative humidity is 60% and the mean temperature 25°C (Bessemoulin, 1974).

The Mediterranean Zone (09-Ariège, 11-Aude, 66-Pyrénées-Orientales) is a hilly region crossed by valleys

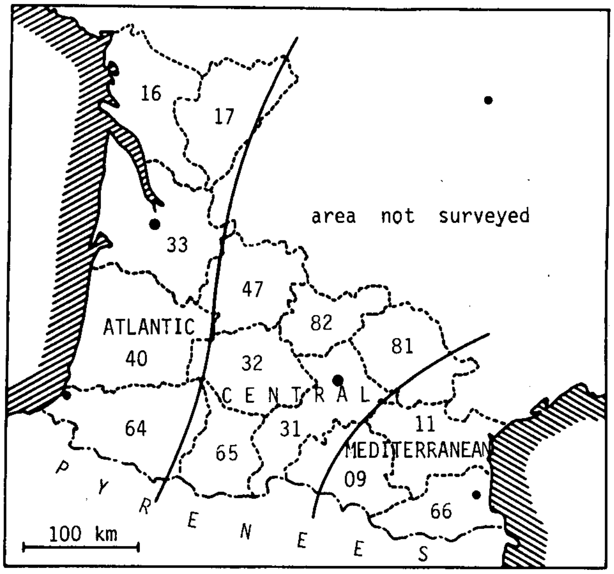

FIG. 1. Climatological areas of Aquitaine.

oriented eastward. The land cover is composed of shrubs or forests near the Pyrenees and the cultivated areas are concentrated in the valleys and near the Mediterranean. The climate of this region is mediterranean, of course, but low-pressure systems coming from the Atlantic are often still active there. The mean annual rainfall is 600 mm along the Mediterranean, and greater near the Pyrenees; a period of drought in July and August is normal. Mean values of afternoon temperature and relative humidity in July are 28°C and 45%, respectively.

The Central Zone (31–Haute-Garonne, 32–Gers, 47–Lot-et-Garonne, 65–Hautes-Pyrénées, 81–Tarn, 82–Tarn-et-Garonne) comprises a variable topography, with a maximum ground roughness in the department of Gers; this roughness is estimated from the numerical maps of the Institut Géographique National. Standard deviations of 25 altitudes in squares of 500 m × 500 m have typical values of 8 to 14 m near Lombez, Gers. The valleys are oriented northward in this area and the ground is covered with about 60% cultivated land and 40% forest. The climate is oceanic, but altered by the Pyrenees in the south and by the Mediterranean in the east. Afternoon mean values of the temperature and the relative humidity are 21°C and 55%, respectively, in July.

b. Atmospheric nucleus content

Although unusual, it is interesting to describe briefly the air quality in the Aquitaine because this property may have a great importance in hail formation.

The Aquitaine is not an industrialized area and contains only two important towns, Bordeaux and Toulouse, and one industrial complex, Lacq (gas refinery and chemical manufactoring); consequently the atmosphere is rather pure when the air comes from the ocean, a situation often associated with hailstorms. In contrast, the visibility is low when the air mass is of continental origin. This influence of the pollution coming from continental Europe is demonstrated by the mean concentration of cloud condensation nuclei (CCN) measured with a thermal diffusion chamber at Lagor, 70 km inland, in both anticyclonic and post-frontal air masses (Fig. 2); it may, however, be noticed that these measures were made only 5 months in winter and spring.

The concentrations of ice-forming nuclei (IFN) have also been measured in several parts of Aquitaine with a mixing-type cloud chamber designed by Soulage (1964a). The mean values are high (Fig. 3), especially inland where they are strongly affected by a few exceptionally high IFN concentrations observed 5 to 10 times a year around the summer months (Soulage and Admirat, 1962; Admirat, 1963). During these events, the IFN concentrations increase progressively for 2 to 5 days in the whole southern part of France, then decrease in the same manner. No reliable explanation was given by Soulage and Admirat 20 years ago, but a biogenic origin for these large summer amounts of IFN may be a possibility (Schnell and Vali, 1976).

3. Characteristics of damaging hailfalls

Since 1952, the ANELFA has attempted to collect any information on hailfalls occurring in the Aquitaine

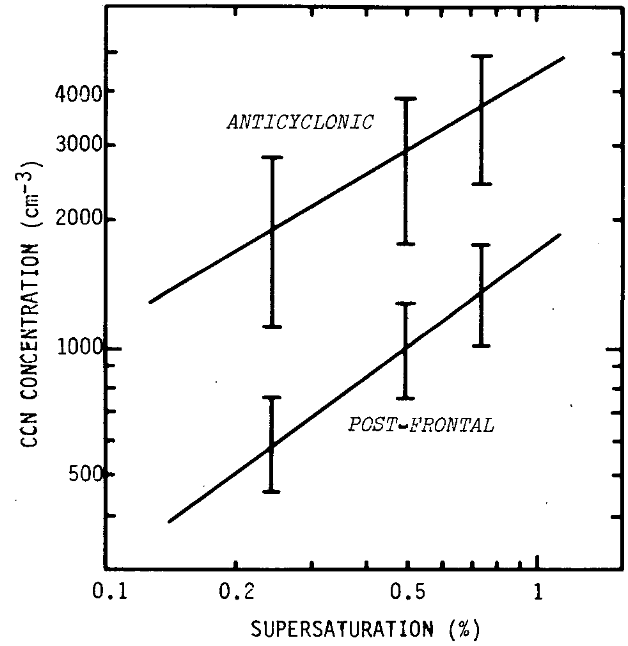

FIG. 2. Concentrations of cloud condensation nuclei at Lagor, December 1980–April 1981 (From Tarrieu *et al.*, 1982); mean daily values and standard deviations.

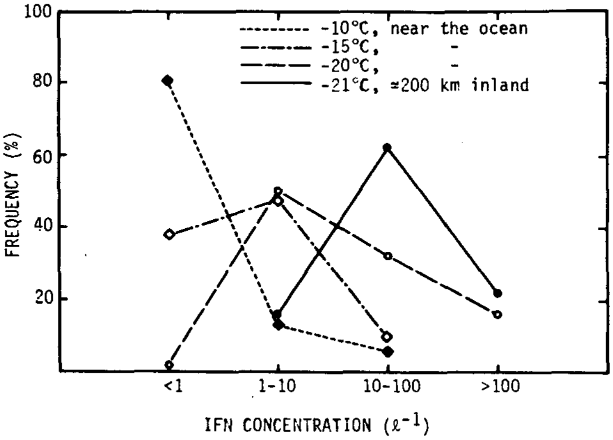

FIG. 3. Frequencies of mean daily values of ice-forming nuclei concentrations near the ocean (Hossegor, June–July 1957, and Biarritz, June 1958) (From Soulage, 1958), and inland (Lannemezan, April 1965–October 1966, and Toulouse, May–September 1963).

from April to October. The main sources of data are the Departmental Hail Prevention Committees and the Departmental Directions of Agriculture. These data are published in annual reports (ANELFA, 1953–1983).

The only hailfalls taken into account for the present study are those with either reported damage to crops, or those with largest hailstone diameter of 15 mm or more. A hail report is defined as the occurrence of hail in one commune; then the unit is not exactly a punctual measure, but a hailfall inside an area of about 15 km^2. The reports have been standardized (using 22 digits) in the following manner: year: 1980; month: 06; day: 14; department: 11; commune: 286; time: 2015 UT; duration: 15 min; diameter: 25 mm; severity index: 4.

The numbers concerning duration, diameter and severity are rough estimates: durations are often rounded off to 5, 10, 15, 20 and 30 min.; diameters of the biggest hailstones are generally estimated from observations of hailstones as peas, cherries, walnuts . . . The index of severity is a number related to the damage at the scale of the commune: 1 = not evaluated, 2 = light, 3 = severe, 4 = complete.

The 12 869 hail reports of the period 1952 to 1980 have then been computerized and used to draft the climatology of damaging hailfall summarized in this section; more detailed data have been published by J. Dessens (1982).

As pointed out by Admirat *et al.* (1980), this climatology will concern the regional climatological characteristics, which are determined by visual observations, and lead to the frequencies of hailfalls, their trajectories, and the geographical scattering of the largest hailstones over large areas. It must not be confused with the microclimatology of hail precipitations in a given area which is now extensively studied by means of hailpads in several places of the world.

a. Geographical distribution

Castet (1974) published a map of the mean annual number of damaging hailfalls per squares of size 30 km × 30 km (Fig. 4). Castet used the reports of the ANELFA for the period 1952–1972, and accepted the hailfall only when at least three communes were damaged in a square. He was then sure that the computed hailfalls were severe. We have not redrawn this map with the data of the last years because the observations since 1972 are not so regularly compiled as before in three departments (n° 32, 47, 82).

All information about the geographical distribution of hailfalls is subject to the problem of the farming bias. For example, the low frequency of reported hailfalls along the Pyrenees and in the Landes forest may be due to the low farming density in this region (dotted areas on Fig. 4). But in any case, the observation of a hail maximum in the middle of 32–Gers is not due to this bias because this department has a farming density comparable to that of the surrounding departments of Lot-et-Garonne, Tarn-et-Garonne and Haute-Garonne (source of data: Atlas d'Aquitaine, planche n°21, and Atlas Midi-Pyrénées, F2). The hail problem is really critical in this department and in the nearest parts of the bordering ones.

b. Yearly fluctuations

Figure 5 gives the yearly number of hail reports in the 14 departments. Many hailfalls occurring by night or in the forests have certainly escaped registration, and the period of observation is also incomplete for some departments (departments n° 16, 17 and 81 have incomplete data until respectively 1967, 1964 and 1963; departments n° 32, 47 and 82 have incomplete

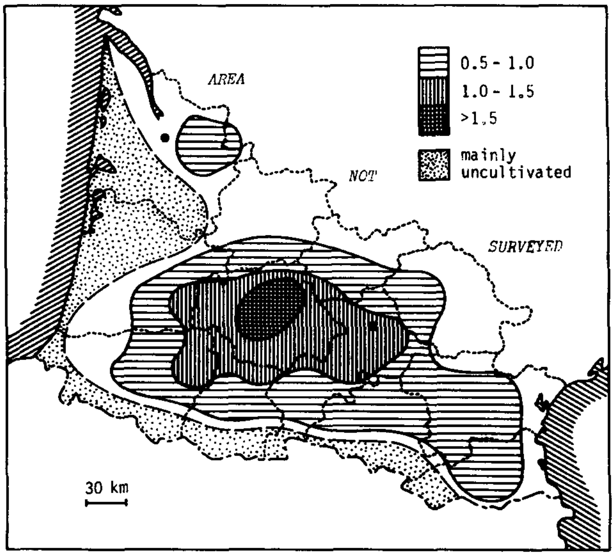

FIG. 4. Geographical distribution of yearly frequencies of severe hailfalls per 900 km^2 (From Castet, 1974).

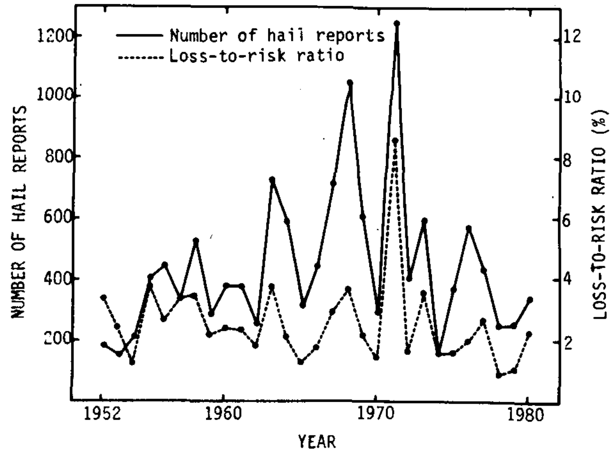

FIG. 5. Yearly number of hail reports compared with annual loss-to-risk ratios from insurance data.

data from respectively 1973, 1967 and 1967); the graph gives, however, a correct evaluation of the yearly fluctuations of hail. Hail reports were more numerous around the middle of the period, with three years of particularly heavy hail: 1963, 1968, 1971. On the average, the total number of 12,869 hail reports in 29 years results in the following evaluation of the time/space frequency: hailfall in one commune per year in an area of 200 km^2, or 1 hailfall per commune in 13 years.

c. *5-Day frequency*

The dates of damaging hailfalls on a commune are high quality data with a percentage of error certainly lower than one. With several thousand observations, it is then possible to consider the hail frequency for periods as short as five days (Fig. 6). Thirty-one May has been added to the 26–30 May period, then the total has been multiplied by 5/6; the same correction has been made for 31 July and 31 August.

In order to avoid any random distortion, a smoothed curve has been drawn with five-value running means, the terms of each series having the following weights: 1, 4, 6, 4, 1. The results show several irregularities; since hail reports are not independent events, the variations in Fig. 6 probably reflect only the random occurrence of the few large hailstorms. However, the minimum of the end of June is independently observed in the three zones of Aquitaine (J. Dessens, 1982).

d. *Hourly frequency*

The 9954 hail reports onset time, from April to October, give a very regular diurnal distribution with a maximum at 1600 LST (time UT is also Local Solar Time since the 0° Meridian goes through the exact middle of the area). But it is interesting to present the diurnal distribution for two periods: April to June, 5121 reports and July to October, 4833 reports, because there is a significant difference in the two distributions (Fig. 7). In summer, the diurnal activity decays more slowly, and there is a second distinct maximum at night, between 0000 and 0100; this is most apparent along the Atlantic.

e. *Size distributions of the largest hailstones*

The diameters of the largest hailstones have been observed in 5091 cases. Figure 8 shows the distributions for the three subareas of Aquitaine. The curves indicate that large hailstones are more frequent in the Central zone area, and rare in the Mediterranean one. Figure 9 compares the mean distribution for the whole area of Aquitaine with some distributions in other parts of the world. The data are as follows:

Location	Area (km^2)	Period (yr)	Method	Number and type
Transvaal	2,600	4	Observers	4333 reports
Oklahoma	8,100	4	Observers	299 reports
Alberta	52,000	5	Observers	10311 reports
Colorado	1,600	3	Hailpads	33 hail days
Aquitaine	89,000	29	Observers	5091 reports

The width of the observation area and the high number of hail seasons that contribute to the Aquitaine curve explain the regular shape of this curve. The frequency of large hailstones is higher in Aquitaine than in the four other areas but this may be partly due to

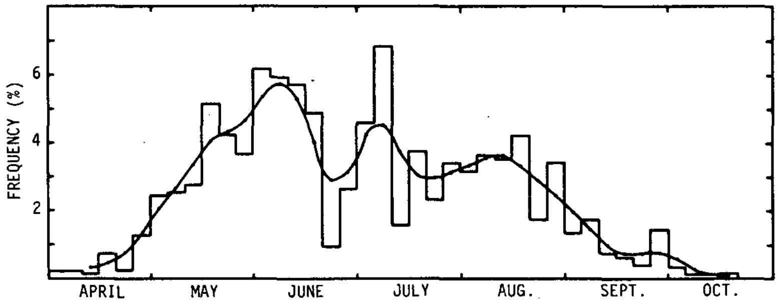

FIG. 6. Five-day frequencies of hailfall. The smoothed curve is drawn using a binomial filter (see text).

the fact that the reports in Aquitaine concern only damaging hailfalls.

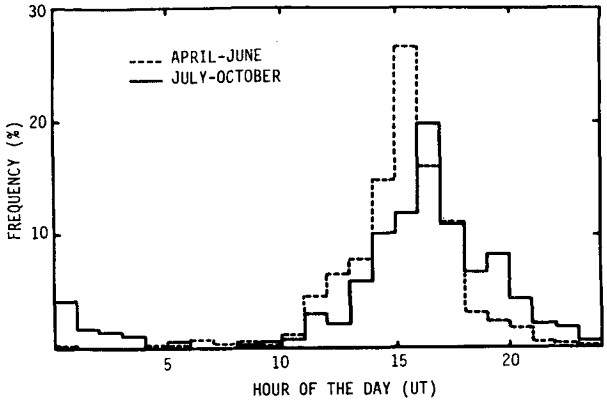

FIG. 7. Diurnal frequency of damaging hailfalls.

f. Duration of hailfalls

The duration of point hailfalls has been estimated in 2524 cases. Figure 10 shows that the hailfalls are briefer in the Central Zone than in the two maritime ones and, as in the case of the size distributions, the greater contrast in these duration distributions is between the Central Zone (mean duration: 11.6 min) and the Mediterranean one (14.7 min). The comparison of the mean distribution for the whole area of Aquitaine with distributions in other parts of the world is presented on Fig. 11: The data can be summarized as follows:

Location	Area (km^2)	Period (yr)	Method	Number and type
Transvaal	2,600	8	Observers	7803 reports
Alberta	57,000	10	Observers	30000 reports
Colorado	1,600	2	Recording system	70 cases
Aquitaine	89,000	29	Observers	2524 reports
France			Observers	1100 reports

The distribution for France was established from a series of reports of the observing network of the *Météorologie Nationale* for a "part of the country" not stated in the Genève (1961) paper. But the distribution is in keeping with that of the Aquitaine area.

g. Hailstone size versus hailfall duration

The maximum hailstone size and the point hailfall duration have been reported together in 1915 cases for the whole area of Aquitaine. Table 1 shows the mean point hailfall duration for different size classes so arranged in order to have a sufficient number of cases in each class. Table 2 shows the mean largest hailstone diameters for different hailfall durations arranged in the same manner.

The shortest point hailfalls have the smallest maximum hailstone sizes, but the longest hailfalls do not

TABLE 1. Mean point hailfall durations.

	Hailstone size (mm)					
	<6	6–10	11–20	21–25	26–70	Total
Number of reports	590	373	457	249	246	1915
Hailfall duration (min)	7	9	15	15	13	11*

* Average.

TABLE 2. Mean largest hailstone sizes.

	Hailfall duration (min)					
	<5	5–6	7–10	11–20	21–47	Total
Number of cases	324	457	431	429	274	1915
Hailstone sizes (mm)	9.5	10.4	16.1	18.7	17.4	14.4*

* Average.

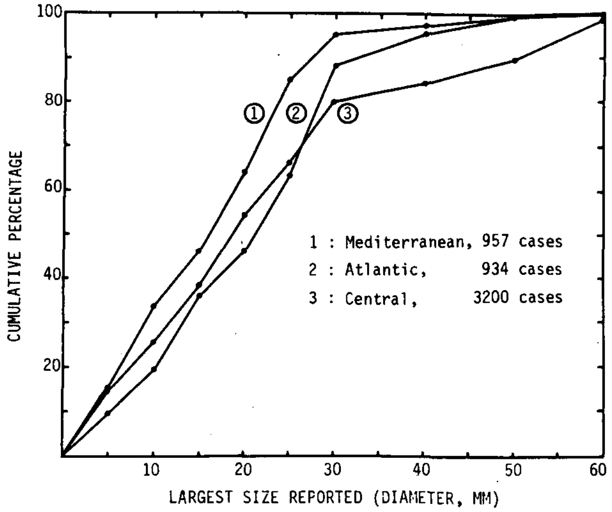

FIG. 8. Cumulative frequency distribution of largest hailstone diameter for the three zones of Aquitaine.

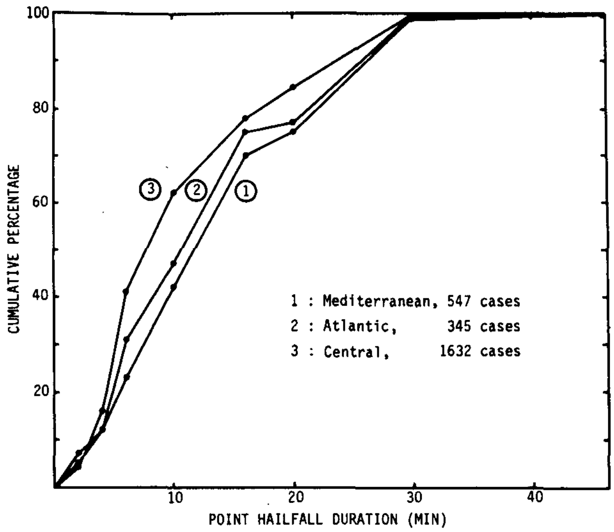

FIG. 10. Cumulative frequency distribution of hailfall durations for the three zones of Aquitaine.

have the largest. A physical interpretation of these results will be presented in section 6.

4. Hail insurance data

Hail insurance in France is offered by about 50 insurance companies gathered in a dozen hail sections. The most important of these sections is the Caisse Centrale des Mutuelles Agricoles, a mutual insurance company which now handles 42% of the total amount of insured crop values in southwestern France. The data of all the companies are collected by the hail section of the *Assemblée Plénière des Sociétés d'Assurances.* A summary of the data is published every two years by J. Moreau at the Congress of the *Association Internationale des Assureurs contre la Grêle* (Moreau, 1983). For Aquitaine, this summary provides the yearly amount of the insured crop values since 1944 in a group of 13 departments (plotted on Fig. 1 except for Nos. 16 and 17, but with 46, north of 82, in addition) and the corresponding annual loss-to-risk ratios *R*; the departmental values of *R* are also published, and we know from Moreau (personal communication, 1984) the departmental distribution of the insured values.

The ability of the insurance data to represent the hail severity is first a function of the relationship between crop losses and hail characteristics. The establishment of such a relationship has been made for some types of crops using impact energy of the hailfall or

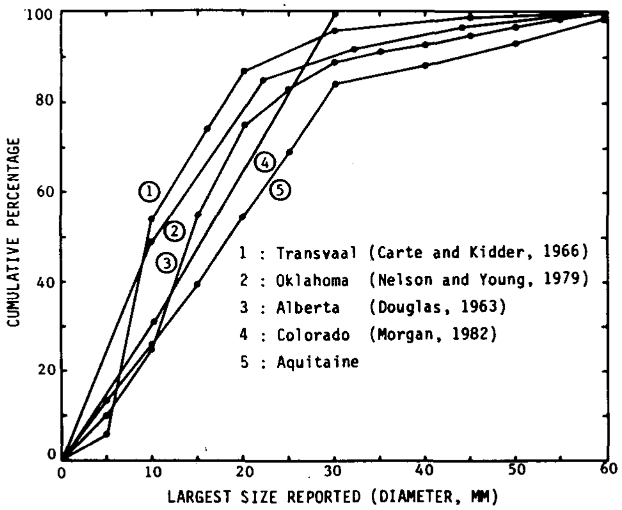

FIG. 9. As in Fig. 8 for different parts of the world.

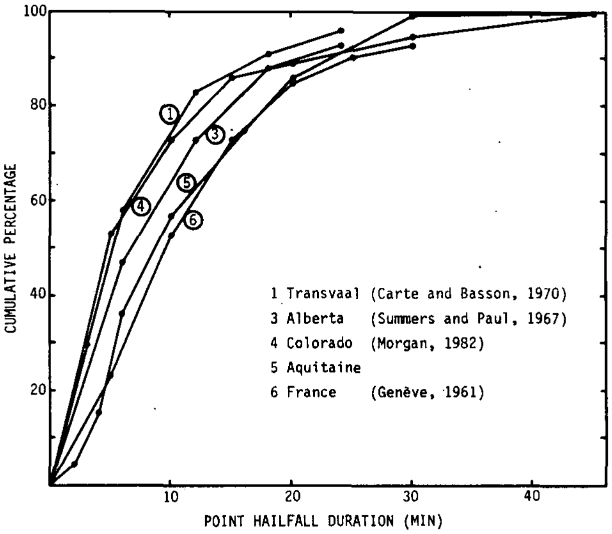

FIG. 11. As in Fig. 10 for different parts of the world.

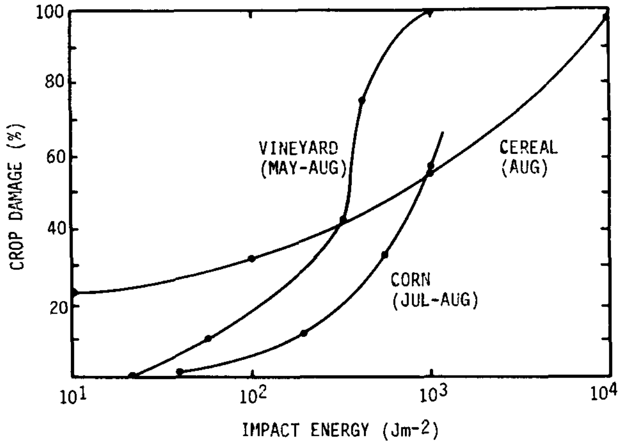

FIG. 12. Examples of crop damage vs impact energy for corn (Changnon, 1971), cereal (Wojtiw and Renick, 1973) and vineyards (Ginouvès and Jean, 1980).

hailstone diameters as measured by hailpads (Changnon, 1971; Wojtiw and Renick, 1973; Ginouvès and Jean, 1980). For a given type of crop at a given period in the hail season, losses are found to be related to the number of stones with diameters over 6 mm, and to the impact energy. Figure 12 gives examples of crop damage versus impact energy for the most usual crops in Aquitaine: wine, 44% of the total crop value; wheat and corn, 24%; the other crops are vegetables, 12%, fruits, 12%, meadow and tobacco, 8% (Ginouvès, 1978). The problem is that, while the losses in a piece of land with a given type of crop are accurately settled (Moreau, 1933, 1968), the annual mean value of R results from individual values of R covering several types of crops at different vegetative stages.

The meaning of the insurance data is also a function of the percentage of the area covered by the insurance. Table 3 shows, in the second column, the percentage of the departmental areas covered by cultivated land (excluding grassland) and, in the fourth column, the percentage of the crop production covered by hail insurance (*Service Régional de Statistique Agricole*, 1981). The product of these two numbers, divided by 10^2, gives approximately the percentage of the area which is covered by the insurers. In some departments, mainly Nos. 09 and 66, this percentage is very low and the representativeness of the insurance data is questionable; for the whole Aquitaine, the insured area represents 11% of the total area ($32.4 \times 34.3 \times 10^{-2}$). One should examine whether this sample is sufficient or not; at the First International Workshop on Hail Measurements held in Banff, Alberta, 22–26 October 1977, the conclusion of the panel discussions (Sterling, 1978) was that "more use should be made of loss-to-risk data, particularly in areas where insurance coverage is adequate as in both Alberta and France".

Another important conjecture when using a series of annual mean values of R is that the insurance coverage varies with time. First the total amount of the insured value in Aquitaine has increased (even after the inflation has been corrected by a factor of about 8), at a nearly constant rate during the period 1952–72 (Fig. 13); this is due to a great improvement of farming yields during this period, to a refitting of the agricultural profit, and finally to an extension of the insurance coverage. Secondly, the crop partition has suffered variations throughout the period: mainly, corn and fruits have increased more than others, the former until 1960 and the latter since 1950.

In conclusion, to use insurance data in a climatological study is certainly not perfectly correct, but it still is the only way to assess (by a number) the severity of hailfalls in a large area during several years.

TABLE 3. Summary of the hail insurance data.

Department	Area ($\times 10^3$ ha)	Percentage of land area cultivated, (1981)	Crop value (10^6 F) (1981)	Percentage of the crop value insured (1981)	Percentage of loss, yearly mean and standard deviation (1944–1981)
09–Ariège	491	12.5	150	28.9	$\bar{R} = 2.96 \pm 2.49$
11–Aude	634	36.1	1658	47.3	2.46 ± 2.13
31–Haute-Garonne	636	52.0	1218	40.5	1.90 ± 1.60
32–Gers	630	66.6	1639	38.1	3.18 ± 3.29
33–Gironde	1020	19.9	2219	30.0	2.76 ± 2.16
40–Landes	935	19.6	898	58.0	1.72 ± 1.72
46–Lot	522	22.7	277	33.1	3.78 ± 2.90
47–Lot-et-Garonne	539	50.9	1811	34.0	2.57 ± 2.25
64–Pyrénées-Atlantiques	768	23.0	689	53.2	2.01 ± 1.83
65–Hautes-Pyrénées	452	17.3	223	28.2	2.35 ± 2.07
66–Pyrénées-Orientales	414	19.3	1743	8.6	2.34 ± 2.62
81–Tarn	578	39.3	593	35.9	1.94 ± 1.80
82–Tarn-et-Garonne	373	56.0	1350	24.0	3.55 ± 2.25
All departments	7992	32.4	14468	34.3	2.57 ± 1.41

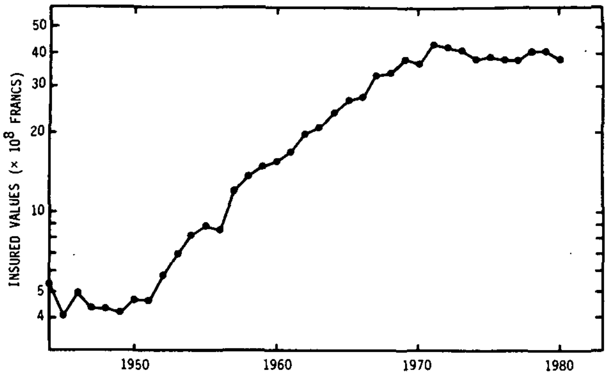

FIG. 13. Yearly fluctuations of the amount of insured crops in 1980 (adapted from Ginouvès, 1978).

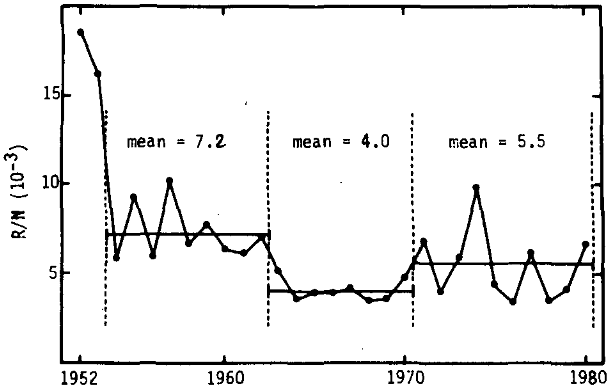

FIG. 15. Yearly ratio of the loss-to-risk ratio R to the number of hail reports N.

a. Spatial distribution of hail loss

The right-hand column of Table 3 gives the mean yearly values and the standard deviations of R in the 13 departments of Aquitaine; these values are calculated with the 38 annual loss-to-risk ratios. The departments which are partly in the area of maximum hail frequency in Fig. 4 have, in general, the highest values of R. But since not only the hail frequency but also the severity and the type of crops have a bearing on R, the correspondence between Fig. 4 and Table 3 is not sharp; for example, R in Haute-Garonne is not so high as would be suggested by Fig. 4.

The mean annual economic impact of hail may be evaluated by multiplying the vegetal production by 10^2 R; for the whole Aquitaine the yearly loss can then be estimated to about *F.* 370 million for the 8 million hectares.

b. Yearly fluctuations

The main interest of crop insurance data for hail climatological studies is probably their ability to provide information on the variability and the fluctuations of the phenomenon. In a large area such as Aquitaine, the crop distribution changes very slowly, and the yearly fluctuations of R are related to the severity as well as to the frequency of hailstorms.

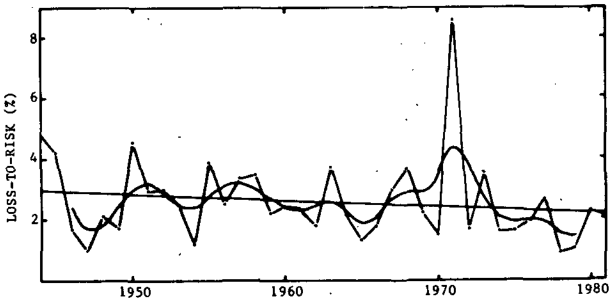

FIG. 14. Original data series, smoothed curve and regression line of the loss-to-risk ratio in Aquitaine (13 departments).

Figure 14 shows the yearly values of the loss-to-risk ratio R for the 13 departments. A relationship between R and the number N of hail reports can be investigated for the years 1952–80 (Fig. 5); the year-to-year correlation is 0.8, and a detailed analysis of the variations of the ratio R/N (Fig. 15) suggests the following discussion:

1) In 1952 and 1953, the hail observation network was notoriously insufficient; the low value of N is due to a lack of hail reports.

2) After 1953, the correlation improves, with a mean decrease of the ratio R/N until 1970: this may be explained by a regular increase of the observation network, the whole area being progressively surveyed.

3) Since 1970, a mean increase of the ratio R/N is observed, with an important discrepancy between R and N in 1974. One may remember (section 3b) that three departments have left the ANELFA in 1967 and 1973; hail reports are still received from these departments, but many are missing, mainly those which were previously sent by the seeding operators. In fact, 1974 was a very high-frequency hail year in one of these departments (Gers); the same explanation can work for 1971 and 1977. In 1980 the reason is different: there were not too many hailfalls, but they were exceptionally severe during one day (14 June). In conclusion, the two sets of data (loss-to-risk ratio, number of hail reports) have been compatible, but the insurance data are completed for a long period, and they take into account the severity of hailfalls.

The regression line of the R values shows a decrease in the long-term trend of the loss-to-risk ratio from 2.97 in 1944 to 2.17 in 1981. This trend may be due to agricultural or economic factors, but perhaps also to climatological changes either natural or due to the hail prevention experiment (see Part II).

The short-term trends of R are shown in Fig. 14 by the smoothed values calculated with 5 years running means in the same way as the smoothed values of the

TABLE 4. Percentage and cumulative percentage of the total damage in the year for the worst six hail days. Mean values for a 14 year period in the Haute-Garonne.

	Rank of day					
	1	2	3	4	5	6
Percentage of losses	45.5	21.3	11.6	7.1	4.1	3.1
Cumulative percentage	45.5	66.8	78.4	85.5	89.6	92.7

5-day frequency. Fluctuations of approximately six years are visible in spite of the disturbance due to 1971.

d. Daily fluctuations of the hail damage

The annual variability of the loss-to-risk ratio at the scale of one department has been highlighted by the standard deviations of the mean values for a period of 38 years (Table 3). As will be shown now, this variability is due to the fact that the annual value of the loss-to-risk ratio in one department depends on very few major hail days.

Hail insurance data per day are available from the *Caisse Départementale des Mutuelles Agricoles* in some departments. In the Haute-Garonne, this mutual insurance company covers half of the total amount of insured crop value, which constitutes a representative sample for the hail damage. For each year from 1968 to 1981, the percentage of the annual loss (in francs) is calculated for the worst six days, then averaged for the whole period (Table 4).

The concentration of the annual damage in a very few days, which is a well-known general characteristic of hailfall (Knight *et al.,* 1979), is clearly visible; if, for any reason, the worst day in a year is suppressed, the annual damage is nearly reduced by half. A major problem in the design of hail suppression experiments is in this distribution.

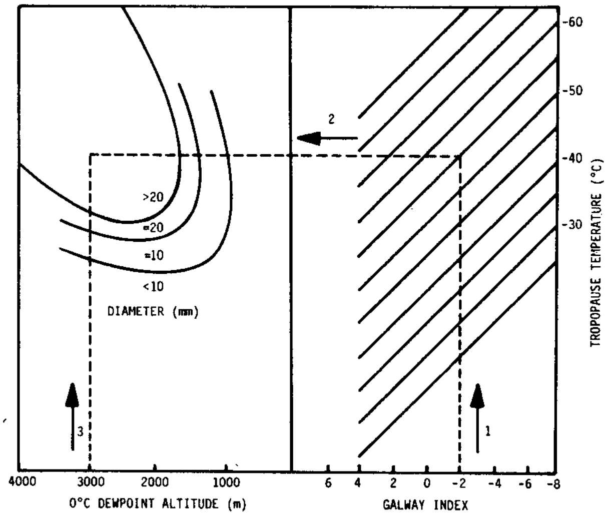

FIG. 16. Determination of the maximum hailstone diameter (After Molénat, 1975). Example: Galway index = −2, tropopause temperature = −55°C; follow line 1 then line 2: 0°C dew-point altitude = 3000 m; follow line 3: intersection of lines 2 and 3 gives a probability of maximum hailstone diameter of more than 20 mm.

5. Hail days meteorological conditions and hailstorm types

a. Mean meteorological conditions

The most usual meteorological conditions leading to damaging hailfalls are frontal or postfrontal. In the Haute-Garonne, where hail insurance data are available daily, 65% of the occurrences of severe hail damage are associated with a cold front arriving in the second half of the day; this percentage is larger along the Atlantic where even a front coming at night may induce hailstorms. When the time of arrival of the surface cold front is well identified, the hailstorm is generally observed within 4 hours after the passage of the front.

Other conditions of hailstorm formation are a low pressure area with some air mass discontinuity generally not apparent on the large-scale meteorological maps, and severe thermal convection within an air mass producing the well-known intramass thunderstorms. The orographic thunderstorms which form in the afternoon above the Pyrenees and then move over the plains in the evening are typically intramass thunderstorms; they usually cause more damage because of rain (flash floods) than because of hail.

Molénat (1975) showed that it is possible to forecast the most probable maximum hailstone diameter with the sounding data. Using the hailfall observations, collected within 150 km around Bordeaux for 16 years, and the soundings taken twice a day at Bordeaux, he has drawn a three-entry graph where the largest hailstones are classified according to their diameters. The three entries are the lifted index (Galway, 1956), the temperature of the tropopause and the 0°C dew-point altitude. The maximum hailstone diameters plotted on the graph are clearly separated in four zones (Fig. 16). The graph, which was initially established on a 16-year observation period, is used on an operational basis since 1975 in the Atlantic Zone, and also more recently in the Central Zone with an additional sounding operated at Toulouse during the hail season. During the period of utilization (from 1975 to the present), no observed diameter has been greater than the diameter forecasted by the graph. On the other hand, the graph often in-

TABLE 5. Typical major hailstorms.

No.	Day	Time (UT)	Hailpath Length (km)	Hailpath Width (km)	Maximum hailstone diam (mm)	Storm propagation Direction (deg)	Storm propagation Velocity (m s^{-1})	Mean tropospheric wind Direction (deg)	Mean tropospheric wind Velocity (m s^{-1})
1	7 May 1952		150			212	9	215	21
2	18 Jul 1955	1800	80		50	242		217	26
3	9 Sep 1956	2000	150	5		239		220	26
4	18 Aug 1958	1600	90		60	243		213	20
5	31 May 1961	1600	130		40	243	14	188	19
6	10 Jul 1962	1800	110		30	260	26	231	31
7	1 Jun 1964	1400	120		25	242		187	22
8	5 Jul 1964	1500	45	6		267		247	16
9	26 Jul 1964	1600	75	2	60	203		223	11
10	30 Sep 1964	1800	60	3	20	238	11	215	10
11	26 Sep 1965	1600	100		60	278		220	15
12	27 Sep 1965	1500	80		15	264		233	21
13	4 Jul 1966	2000	50	8	30	262	14	229	23
14	12 May 1967	1600	55	7	50	248	15	203	22
15	6 Jul 1967	1800	90		80	271		246	15
16	10 Jul 1968	1800	120		60	239		226	23
17	13 Aug 1969	2100	70		60	246	14	216	23
18	14 Jun 1970	2000	65	8	30	265		224	16
19	16 May 1971	1700	85	9	50	205	11	199	26
20	19 Aug 1971	1600	120	6	30	223	17	201	20
21	19 Aug 1971	1700	140	8	30	241	17	205	25
22	10 Aug 1972	2100	27		50	244	14	222	25
23	2 May 1973	1330	55	6	60	246		227	20
24	31 May 1973	1800	55	5	30	223		214	16
25	27 Jun 1973	1730	140	10	70	246	17	189	20
26	17 May 1975	1500	60	6	30	223		213	21
27	6 Sep 1975	1400	25	5	30	267		232	23
28	11 Jun 1980	1800	90		20	245		235	26
29	14 Jun 1980	1800	100	5	40	261	14	195	26
30	8 May 1981	1530	40	8	30	240		202	19
	Average	1640	86	6.3	42	244	15	216	21

dicates diameters larger than those reported, but larger hailstones may have fallen in the country. In conclusion, provided the forecast is limited to the air mass represented by the soundings, the graph is a practical complement to the classical tools and methods used by the French Meteorological Service: surface and upper level network, radars, satellite imagery and numerical models.

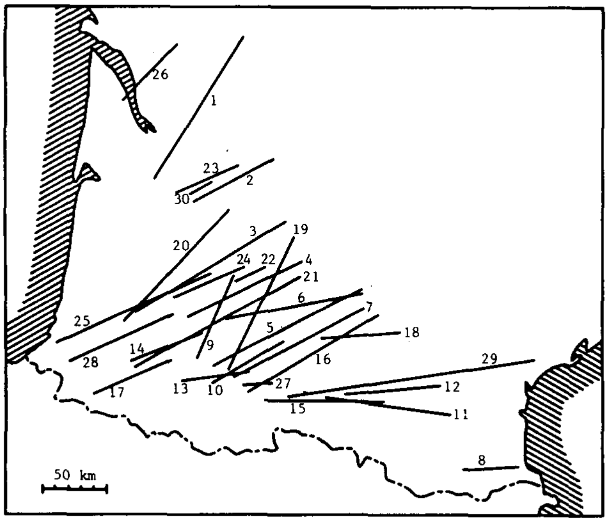

FIG. 17. Hailswaths of 30 among the most severe traveling hailstorms occurring during the period 1952–81 (see Table 5).

b. Ordinary storms producing discrete hailfalls

As pointed out by H. Dessens (1967), any summer thunderstorm is capable of dropping damaging hail on

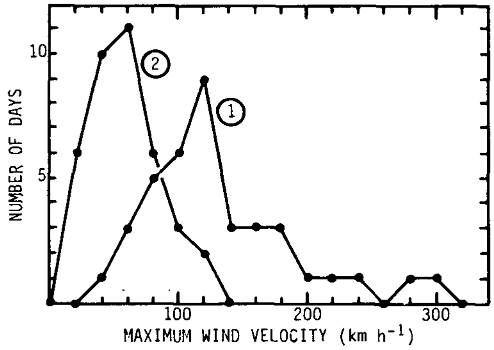

FIG. 18. Frequency distribution of wind speeds at high levels from 38 days with destructive hailstorms (1) and 38 days with thunderstorms but without significant damage by hail (2). (After H. Dessens, 1960.)

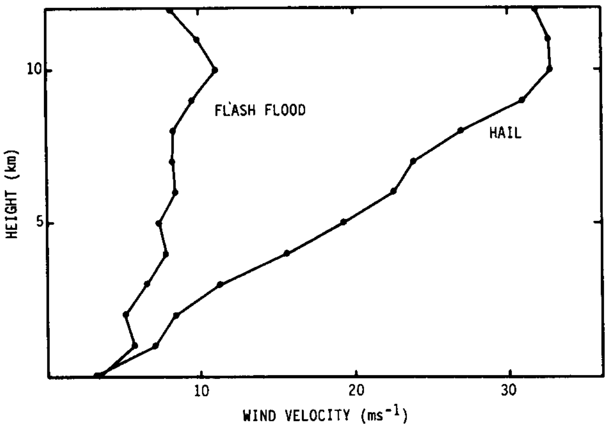

FIG. 19. Mean values of the wind velocity for 22 soundings in the environment of severe hailstorms.

a small area during the first stage of its life. The most usual type of thunderstorm in Aquitaine, as probably in many other parts of the world, is the multicellular storm whose propagation is more controlled by the birth of new cells than by the environmental winds. Hail production by this type of storm may be considered as incidental; however, as there are numerous cells in a storm and numerous storms in a region, many scattered hailfalls are observed in a day which produce some economic impact. We may consider that these common hailstorms produce a background hailfall.

c. *Steady state hail producers and their wind environment*

The important hailstorms are the long traveling ones producing large hailstones on an extended area. These hailstorms are rare because the yearly number of days of occurrence is very small, and on those days, their number does not exceed two or three in Aquitaine, but each produces severe damage to a great number of communes.

The more severe a hailstorm, the simpler is its history. Table 5 presents the main characteristics of 30 of the most memorable storms of the last three decades in Aquitaine. In each case, the identification of the path (Fig. 17), some days after the storm, was simple because the damage was generally complete. With a mean path of 86 km × 6 km = 516 km^2, about 8% of the area of one middle-sized department, or 0.6% of the total surveyed area is damaged. The economic impact of only one such storm is evident. This is illustrated by storm case 29 (14 June 1980): the yearly values of R (loss-to-risk ratio) in the departments of 09–Ariège and 11–Aude reached, respectively, 10.5 and 5.5% on account of this storm alone.

All paths shown in Fig. 17 originate from the left and move towards the right, the origin of most being at some tens of kilometers downwind from the Pyrenees divide; the main hailstorm source is in front of the central part of the mountain range where the altitudes are highest. The lack of paths in some areas may be due to a lack of observations such as in the Landes forest near the Atlantic, in the rough and hilly country in Lauragais and in Corbières near the Mediterranean.

These traveling hailstorms are distinctive when they are seen in profile. Downwind from the active part of the storm, which breaks through the tropopause (mean altitude: 11,400 m), the anvil extends hundred of kilometers; this observation has led H. Dessens (1960) to conclude that there is a close association between severe hailstorms and very strong winds between 6 and 12 km. The frequency distributions of the maximum wind velocity in the troposphere for days with thunderstorms, but without significant hail damage, are quite different (Fig. 18). Considering the wind data in the neighborhood of the 30 hailstorms of Table 5, we note that the typical wind profile for these long-traveling storms is as follows:

- Surface winds are light, often from the southeast at Bordeaux and from any direction at Toulouse;
- As the height increases from 1 to 3 km, the wind veers from the southwest; the veering to the right is clearly visible at Bordeaux, but not so regular at Toulouse, probably because of the proximity of the Pyrenees. The wind velocity increases (Fig. 19);
- The direction of the wind is nearly constant at all altitudes from 3 to 12 km; the mean value of the wind direction changes only from 209° at 3 km to 218° at 12 km. The wind velocity increases up to 10 km where its mean value is maximum (32.6 m s^{-1}).

In summary, the wind in the neighborhood of the most severe hailstorms, which are of the traveling type, has a constant direction above 3 km, increasing at a mean rate of 3.3 m s^{-1} km^{-1} from 3 to 9 km. This mean profile is typical of a frontal synoptic situation, in contrast with the intramass wind profile related to flash flood thunderstorms; there, the wind direction often changes above 3 km while the wind speed is nearly constant, as shown in Fig. 19 (Dessens and Godard, 1982).

The direction and the velocity of storm propagation have been compared to the direction and the velocity of the mean wind in the troposphere calculated as the vectorial mean of the wind at 1, 2, 3, . . . , 12 km (Dessens and Godard, 1982). The mean angular deviation of the 30 storms is 28° to the right of the wind, with only one case of perceptible deviation to the left. In the eastern part of the area, paths 8, 11, 12, 15, 18, 27 and 29 are oriented more eastwardly partly because the mean wind direction for these cases is 228° instead of an average of 213° for the 15 other cases, and partly because the mean angular deviation is 39° to the right instead of 24° as for the other cases. The first effect is probably related to the general atmospheric circulation, and the second to the topography of the ground, the valleys being oriented eastwardly in the direction of the Mediterranean. The storm velocity has been estimated in 13 cases, resulting in a mean value of 15 m

s^{-1} which is to be compared with the mean velocity of the mean wind around the same storms, 21 m s^{-1}. It may be noticed here that, as a rule, the storm velocity is directly related to its severity; storms 20, 21 and 25 are, for example, among the most severe of the series of Table 5.

Considering a 30-year period, we have shown in detail the main characteristics of 30 major hailstorms. It would have been possible to do so for approximately 60 additional hailstorms of nearly the same severity that have also damaged Aquitaine during this period. Nevertheless, the mean characteristics would not change significantly and Fig. 17 would be cluttered with many hailswaths being almost coincident. Between these 30 annual major storms and the background storms already described, often, long-traveling storms are observed that occur under the same meteorological conditions as the major hailstorms; i.e., with strong winds at the upper levels. They also have long paths, but the hailstones are smaller than 15 mm and/or the hailfall is not continuous along the path.

6. Physical climatological relations

We may now return to the climatological characteristics of hailfalls in order to explain some of them by the physical nature of hailstorms, and mainly by the effect of strong upper winds on the hailfall severity.

a. Geographical distribution

The geographical distribution of hail reports is well explained by the superimposition of Figs. 4 and 17. The core in the Central Zone is produced by the long-traveling hailstorms which are more frequent downwind of the central part of the Pyrenees; this is the result of the thermal convection which is more vigorous when the heat sources are at a high level, and probably also of a dynamical effect which produces stronger winds at an upper level downwind of the barrier. The distance of the hail core from the divide is about 120 km, a situation quite similar to that observed in Central Alberta (Summers and Paul, 1967).

b. Yearly fluctuations

The yearly fluctuations of R (Fig. 14) must be produced primarily by the fluctuations in the very small number of hail days with long-traveling hailstorms. This number itself appears to be related to the number of cold fronts moving during daytime in conjunction with a jet stream at an upper level. Another effect has been suggested by Soulage (1964b) who has observed that when the annual mean ice forming nucleus concentration is high in a region, the hail damage is low, and vice versa.

As is the case with Fig. 6, the fluctuations are due to a small number of severe storms, and they may have no statistical meaning.

c. Size distribution of hailstones

The size distribution of hailstones is different in the three zones of Aquitaine (Fig. 8) because the long-traveling hailstorms with large hailstones are frequent in the Central Zone and rare in the Mediterranean one. On the three curves of Fig. 8, and consequently on the Aquitaine curve of Fig. 9, the break in the slope at 30 mm may then be due to a bimodal distribution: the hailstones produced by the background hailstorms are smaller than 30 mm, whereas the hailstones produced by the long-traveling hailstorms are often larger than 30 mm.

d. Duration of hailfalls

In the same way, we can explain the shorter duration of hailfalls (Fig. 10) in the central part of Aquitaine by the greater frequency of fast moving storms in this area. The mean values given in Table 5 for a hailshaft of 6 km diameter moving at 15 m s^{-1}, yield a point hailfall duration of 7 min. In fact, Table 1 indicates that the observed mean duration of hailfalls with hailstones of 26–70 mm is 13 min. The difference may be explained by the ellipsoidal shape of the hailfall elongated in the direction of travel.[1] If, for example, the hailshaft is 6 km large and 12 km long, then the point hailfall duration is 14 instead of 7 min.

7. Conclusions

The climatology of damaging hailfalls in Aquitaine, presented in this paper, has been established during a 29-year period with a network of 5,754 communes covering an area of 88,980 km^2. The 12,869 reports received are reliable with respect to the date and the time of day. They are, in general, suitable for hailfall durations and largest hailstones dimensions, but the index used for the severity is only a rough estimate of the damage. In order to make up for the lack of severity measurements, hail insurance data have also been used.

The distribution of the 5-day frequencies of hail reports is not regular in spite of the large number of observations. In contrast, the distribution of hourly frequencies is symmetrical with a peak at 1600 (solar time), which confirms the main effect of the surface temperature on hailstorm formation.

In the middle of the area where the hail frequency is the greatest, the mean point hailfall duration is shorter and the largest hailstones are bigger than in the Atlantic and Mediterranean areas. This is due to the major, long-traveling hailstorms which are more frequent downwind of the central part of the Pyrenees. On the average, these hailstorms are moving at 15 m s^{-1} over a distance of 86 km with an angular deviation

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[1] See, for example, the radar pictures of the two storms of 19 August 1971 on the cover of *J. Rech. Atmos.*, **5**, 1971, n°4.

of 28° to the right of the mean tropospheric wind. These storms occur when the wind increases with altitude without any change in direction above 3 km, a situation often observed behind a cold front. If there is no long-traveling major hailstorm in a year, hail losses are produced only by the background hailstorms; if there are several major hailstorms in one year it is called a "hail year", as in 1963, 1968, 1971 and 1973.

A final remark concerns the long-term evolution of the mean annual percentage of loss which has decreased from 3 to 2% during the last three decades. The significance and the origin of this change will be discussed in Part II which is related to the hail prevention project operated by the ANELFA in southwestern France.

Acknowledgments. Nearly every person living in Aquitaine is concerned by the hail problem, and the ANELFA has gained the complete cooperation of a great number of individuals and organizations: the Departmental Hail Prevention Committees, the Departmental Directions of the Agriculture and the National Hail Insurance Group. The hailfall reports have been computed at the Prefecture of the Haute-Garonne, and the meteorological data have been supplied by the weather stations of Bordeaux and Toulouse.

Finally, I should like to express my gratitude to the three anonymous reviewers of this paper whose comments and recommendations have been extremely helpful.

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