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MICRO-SCALE STUDIES OF SURFACE HAILFALL

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Illinois State Water Survey
Urbana, Illinois

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Introduction

The accelerating pace of research on hail prevention in recent years has made imperative the need for deeper knowledge of the variability and nature of surface hailfalls.

It is known that hailstones can be 1) very hard, or very soft (Summers, 1968) and spongy (List, 1961), 2) nearly spherical, spheroidal, or exhibit a wide variety of irregular shapes (irregular, angular, jagged, knobby, lenticular (Gibson, 1863; Volta, 1806), 3) very small or very large (just how large is not known, and not extremely important; the largest reliably reported hailstone weighed 766 grams), and 4) durations of hailfall at a point may vary from a brief instant to over an hour, and 5) the number of stones per unit area can be any where in a wide range from near zero to enough to form a layer of hail over a meter in depth.

It has been known since at least before the time of Gibson (1863) that hail can fall in a disorganized, "patchy" fashion, or in long, almost straight lines over many miles of nearly unbroken coverage by hail. It has become accepted to call these strips of hail "hailswaths". These characteristics were first determined on the basis of subjective observer reports of hailfalls and/or hail insurance loss data. The short-comings of • such.reports are well known and evaluations of their meaningfulness have been attempted.

The development of instruments for measuring or recording hailfall parameters is of rather recent date. The earliest hail instrument reported was an apparatus for measuring the temperature of hail, exhibited by a Swiss investigator, Prof. Colladon, at the Exhibition of the Royal Meteorological Society in London in 1888. The most successful device offered to date for introducing objectivity into descriptions of hailfalls has been the well known "hailpad" (Decker and Calvin, 1961; Schleusener and Jennings, 1960; Wilk, 1961), and the creation of fine-scale networks for the observation of hailstorms and rainfall. Timing of the onset and duration of hail at many points has been facilitated by an adaptation of a conventional weighing raingage, introduced by Changnon (1966). These and other, more elaborate and expensive, hail measurement techniques have been described by Towery and Changnon (1974). Hailpads are excellent yes-no hail indicators and are reasonably good for quantitative estimates of hail parameters if the number of stones per square meter does not exceed some limiting value (probably in excess of 10,000/sq m), and if the stones are not of such size as to destroy or mutilate the pad.

From these rather recent developments and studies related to or deriving from them, it has been established that a single hailswath can be composed of many substructures which have been called "hailstreaks" (Changnon, 1970). In a given hailstorm the individual hailstreaks can be spatially distinct or some of them can partially overlap each other. When overlapping occurs, the existence of these small-scale hailstreaks gives rise to the intermittency of point hailfalls which has been emphasized by Pell (1971) for storms in Alberta. The discovery of hailstreaks has fundamental importance for hail prevention verification (Magaziner and Weickmann, 1973).

The average dimensions of individual Illinois hailstreaks have been determined by Changnon (1970) and Changnon and Towery (1972) as, 1.1 mi wide and 4 to 5 mi long, and these place a minimum requirement on the spacing between observation points which will allow one simply to delineate the areas of hailfall. For field studies on hail prevention it is necessary to become much more quantitative in describing hailfalls. Hailpads are used to estimate such quantities as the number of stones per unit area, the size spectrum, and the total kinetic energy of the fallen hail.

Another quantitative measure, but one which is difficult to interpret, is the damage done to crops. Here a still finer-scale structure to the hailfall becomes apparent. Changnon and Barron (1971), in a study combining photographic and field survey techniques showed large variations in percent crop-damage over distances of only a few hundred feet within a hailstreak. Differences as great as 25% in loss (from 70% loss to 95% loss) over a distance of 600 ft were noted. Whether this variability would also be apparent in the hail parameters themselves, or is primarily due to wind differences cannot be established from that study.

The revelation of such fine-scale structure in the distribution of crop-hail loss makes clear the need for further investigations of the effect of sampling density on quantitative measures of hailfall characteristics, analogous to those conducted on the subject of areal rainfall measurement

(Huff, 1970). To investigate the quantitative small-scale variability of hailfall parameters, a hail network of unprecedented station density was established on a section (1.0 sq mi, 2.56 sq km), of land near Kimball, Nebraska.

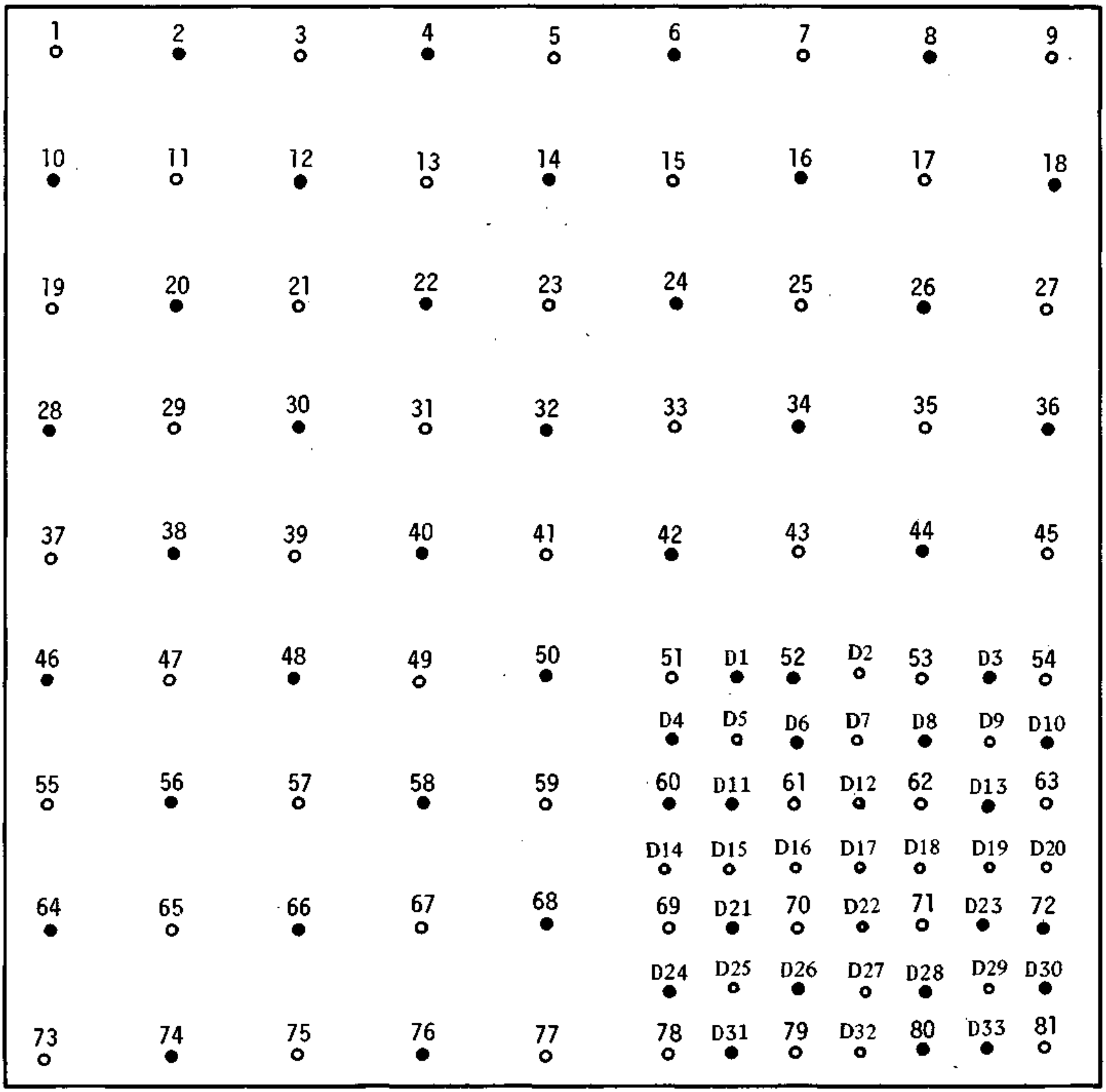
Field Study - Instrument Description and Data Analysis

The network (Fig. 1) consisted of 114 stations set on a grid pattern with a basic separation of 660 ft (200 m). In the southeast corner of the network, stations were set in an ultradense pattern with an average separation of 330 ft (100 m).

The basic instrument employed in this field study is the 12 inch (30 cm) square hailpad (sensing area = 1 ft^2 = .093 m). A new adaptation of the hailpad which has been named the hailcube (Fig. 2), consisting of, in addition to the horizontal pad, four vertically mounted pads has also been employed. This new configuration allows estimates to be made of the horizontal components of hailstone velocity, momentum, energy, and the average wind speed accompanying the hailfall.

The basic idea for the five-sided hail sensor of which the hailcube is an adaptation is due to E. Rosini, Director of the Ufficio Centrale di Ecologia Agraria, (UCEA) Rome, Italy. The UCEA device (Fig. 3) is described by Vento (1972) and has been widely deployed in Italy (Vento and Castaldo, 1972).

Hailcubes were installed at 62 locations in the network, as indicated on the map of Fig. 1, and simple hailpads at the other 52. All hail sensors were mounted on metal fence posts, about 4 ft above ground.



E X P L A N A T I O N

o **HAIL CUBE**

● **SINGLE HAIL PAD**

Figure 1. The Illinois State Water Survey square-mile hail observing network (near Kimball, Nebraska).

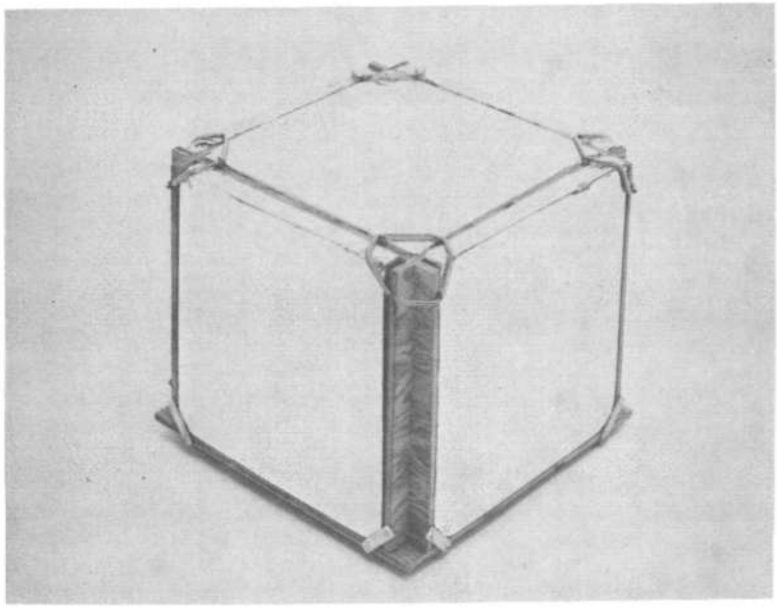


Figure 2. The Illinois State Water Survey hailcube.

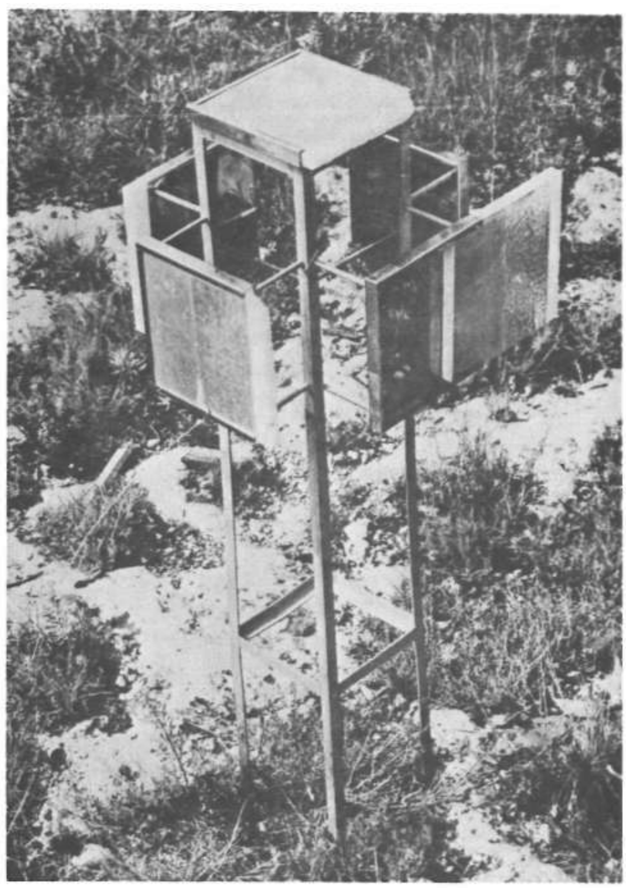


Figure 3. The five-sided passive hail sensor developed by the Ufficio Centrale di Ecologia Agraria, Rome, Italy.

The basic principles for analyzing hailpads have been expressed elsewhere in the literature, (Schleusener and Jennings, 1960). Measurement of the dents on the pads allows determination of the time integrated size spectrum of the hailfall, and derived quantities such as mass, kinetic energy and momentum.

The estimation of hailstone sizes from the dents on the hailpads is accomplished through a calibration. Several ways exist for performing this calibration. The calibration performed by a method due to Rinehart (1969) has been found best and is the one used in this study (see Appendix).

Under the assumptions' that all hailstones fall at their terminal fall speeds and move horizontally at the speed and in the direction of the wind, the vertical faces of the hailcubes allow, in addition, estimates of the net horizontal fluxes of these quantities. This is accomplished as follows:

1) the size spectrum N(D) is determined from the top pad in the conventional way,

2) the time integrated volume size spectrum in the air in the vicinity of the cube, N*(D), is determined by dividing the concentration in each size category by its terminal fall velocity, $V_t(D)$

$$N^*(D) = \frac{N(D)}{V_t(D)} \quad ,$$

3) the number of stones hitting a vertical face, a measured quantity, is

$$N_H(D) = V_n N^*(D)$$

where V_n is the wind speed normal to the face. Since V_n is not a function of D, the same relation holds if we sum over the entire spectrum $N_H = V_n N^*$. This means that for routine use it is only necessary to count the total number of hail dents on the vertical faces, without regard to size,

4) the wind speed component is estimated as

$$V_n = \frac{N_H}{N^*} .$$

In general two such components are determined and vectorically summed to give the horizontal wind vector V_H.

In calculating the average wind from the cubes it is assumed that there is no correlation between fluctuations of the wind and changes in the spectrum of hail diameters during the hailfall.

Random wind fluctuations should have no effect on the estimate of the average wind. However, it would be strictly necessary to know the ' distribution of the wind fluctuations in order to calculate the true total accumulated kinetic energy of the hailfall, due to the dependence of the energy on the square of the wind speed. It might be possible to estimate the gust characteristics from the standard deviation of the arrival directions measured from the top pad, but this has not been attempted as yet and the effect of gustiness on the energy will be ignored here.

5) The wind direction is determined from the relative number of stones hitting the adjacent vertical faces. Wind direction can also be estimated by measuring and averaging the orientations of the oblong dents on the top pad of the hailcubes or on simple hailpads. The direction determined in this way agrees very closely with that based on the data from the vertical cube faces.

6) Adding the square of (V_H) to the square of the fall velocity, v_t, yields an estimate of the total kinetic energy of each hailstone

$$K.E. = \frac{\pi}{12}\rho_i D^3 \left(v_t^2 + |\vec{V}_H|^2\right)$$

Results

The square-mile network was operated through the months of May, June, and July, 1973, the operational season of the National Hail Research Experiment.

Considering the rather low hail frequency which was experienced in northeast Colorado and southwestern Nebraska in 1973, it was very fortunate that three hailstorms occurred over the network. The first occurred on 21 May with all the observing sites being struck by hail which was several cm in maximum diameter, with a relatively small number of stones per square meter. The second case was on the 29th of June and only about half of the observing sites were struck by a very few stones per site (this hailfall was so weak that only a very cursory analysis of it will be presented). The third occurred on 22 July, all sites being struck by stones of up to 2.6 cm diameter but with many small stones. The number of stones per square meter was in the thousands. The stones struck the instruments from the southwest and part of the network was struck by a minor second hailfall on 24 July. It is noteworthy that the two major hailfalls were of such different character; one a fall of a few fairly large stones and the other a fall of very numerous, mostly small, stones. An example of a hailcube from the 22 July hailfall is shown in Fig. 4. In both of the major hailfalls a few dents were found on many sensors which could only be attributed to soft or slushy hail.

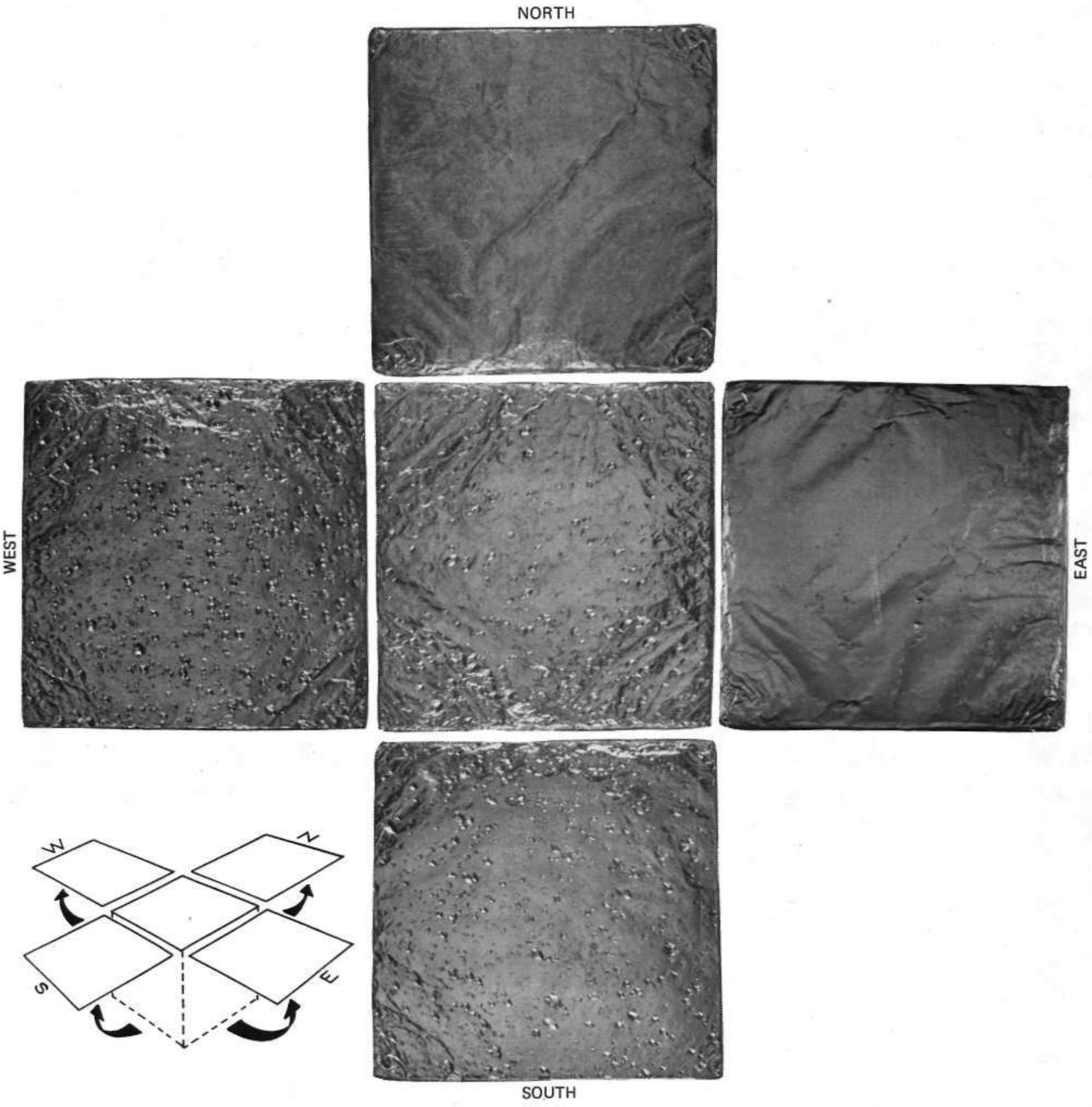


Figure 4. An example of a hailcube from the hailstorm of 22 July 1973.

The initial plan was for crop hail insurance adjusters, retained by the Environmental Assessment Group of NHRE, to make detailed estimates of damage for comparison with the hailpad and hailcube measurements. However, the two major hailfalls fell at such times that very little or no crop damage resulted; the first fell when the wheat was immature and not vulnerable and the second while it was being harvested.

Hailfall of 21 May 1973

The storm from which hail fell in several streaks on and around the square-mile network and the adjacent NHRE operational area, was a large storm which was not seeded. It passed over the square-mile network around 1540 MDT. From the map of total number of stones per square meter (Fig. 5) it would appear that the network was on the northern edge of the hailstreak which affected it.

The stones struck the instruments from the northwest, blown by winds of up to 40 mps. The number of stones on either of the vertical faces was less than the number on the top on only 9 out of the 62 hailcubes. Figures 6 and 7 show wind directions determined from dent orientation for all sites and speeds deduced from the hailcubes. Speeds are shown only for those cubes having more than 200 stones per sq m on the top pad since it was found that for cases with very few stones the wind estimates were erratic, and could in some cases be unreasonably high.

There was no wind instrument at the site for comparison with the winds estimated from the cubes, but a nearby wind recorder agreed at least in order of magnitude. The recording pen on the wind instrument at the

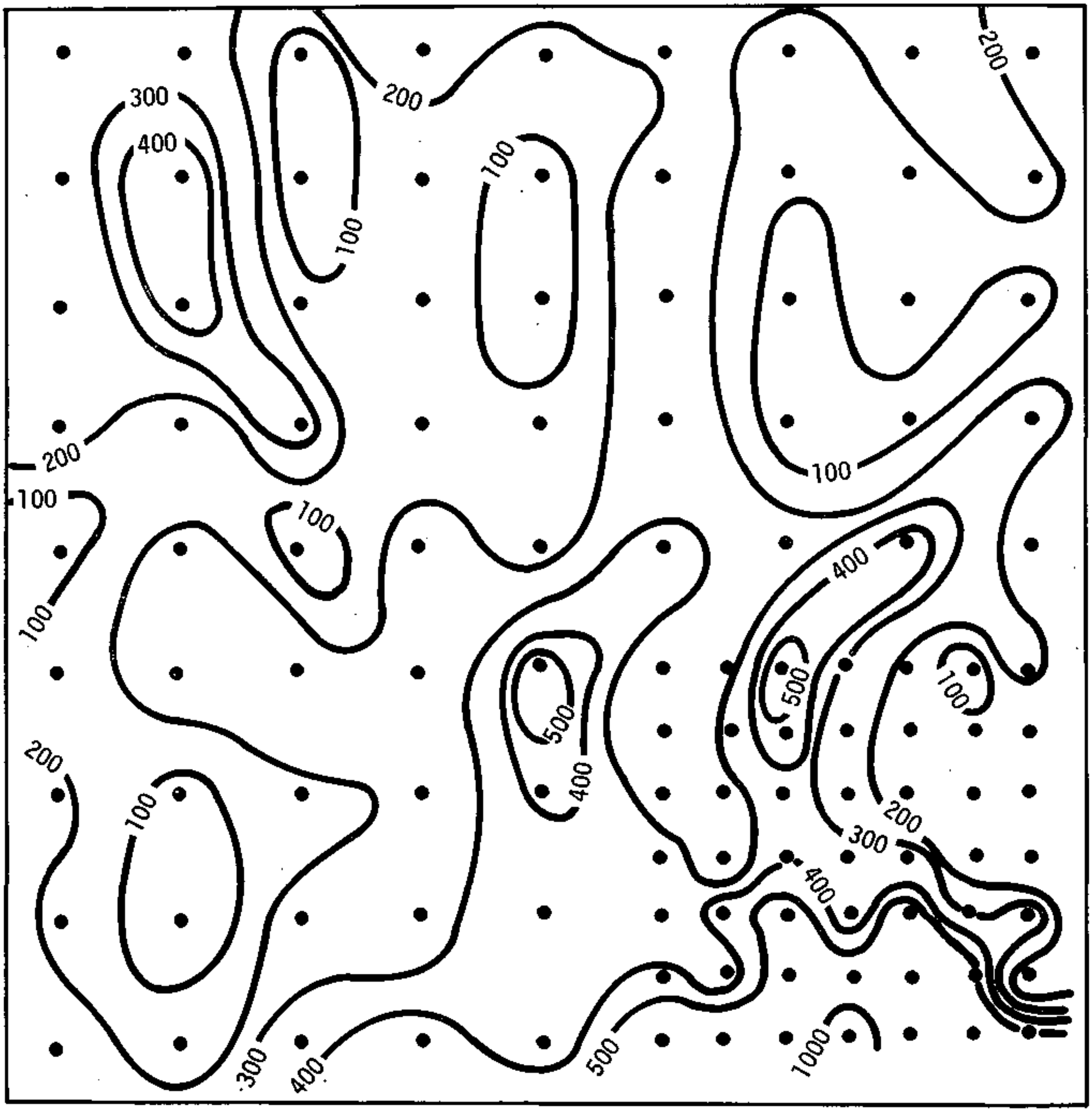


Figure 5. Distribution of the total number of hailstones per square meter; storm of 21 May 1973.

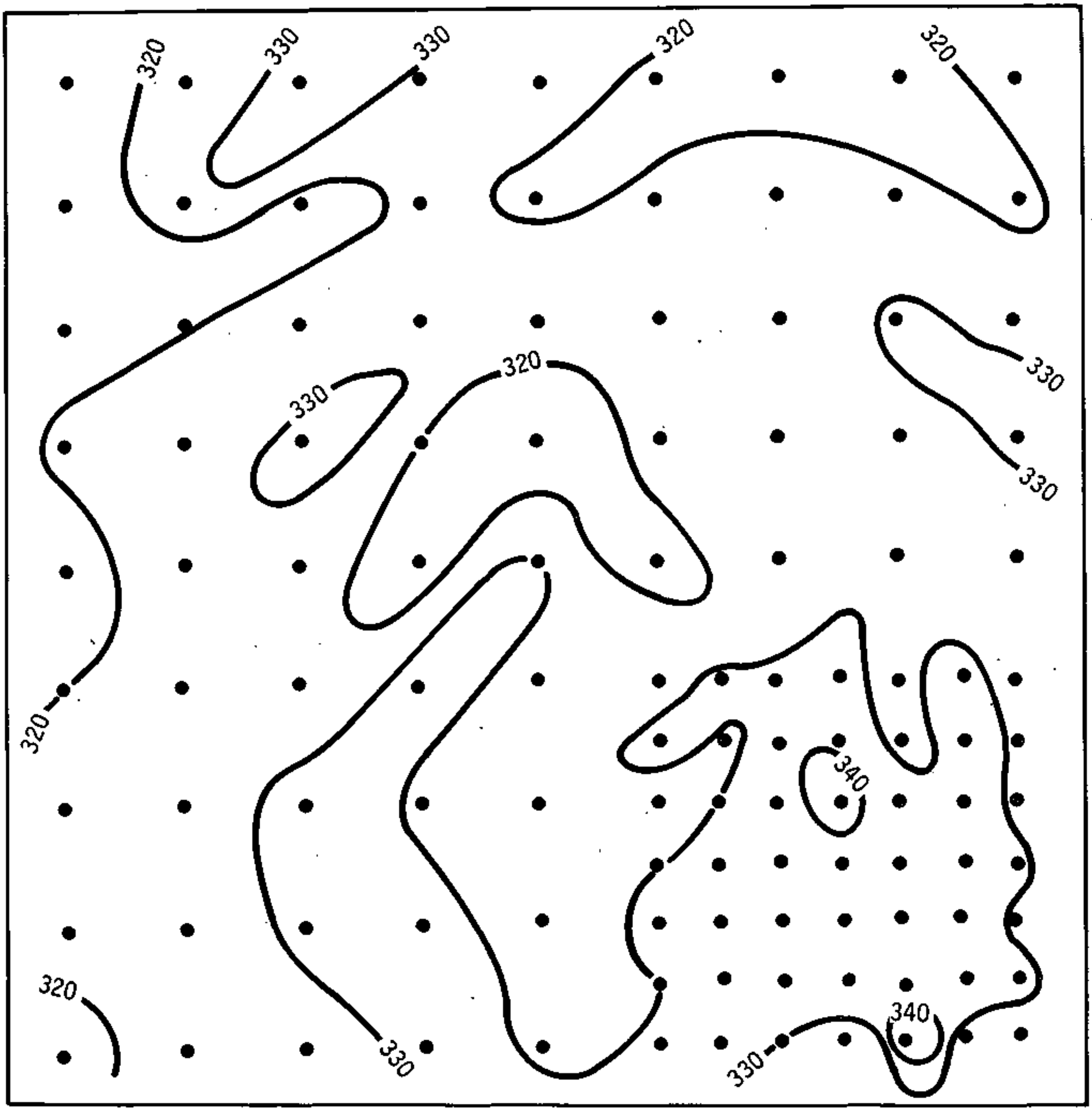


Figure 6. Distribution of deduced direction of wind accompanying hail (degrees, meteorological convention); storm of 21 May 1973.

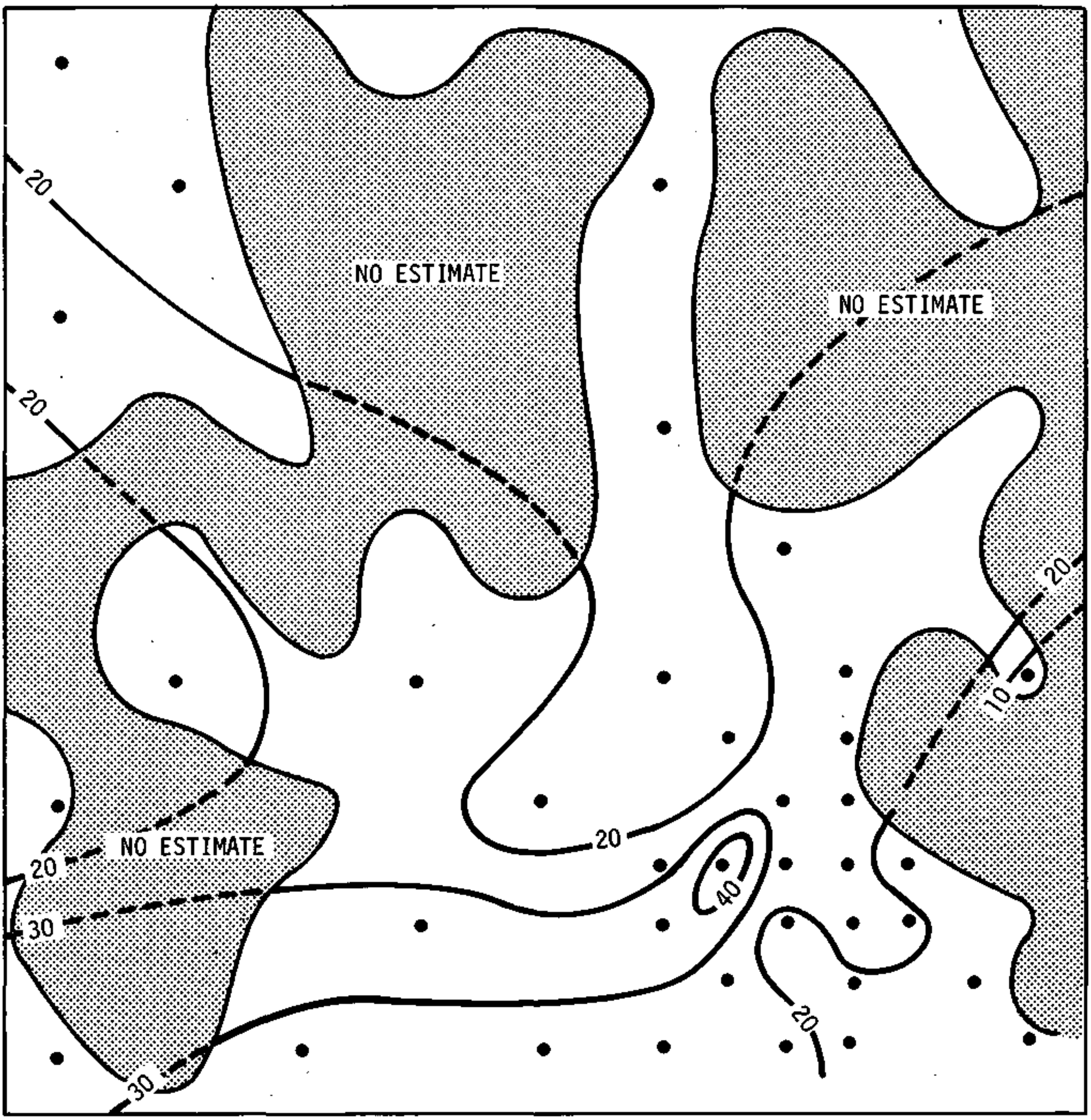


Figure 7. Distribution of speed of wind (m/sec) accompanying hail; storm of 21 May 1973.

nearest NHRE mesometeorological surface network station, located about 1.0 mi (1.6 km) to the south of the square-mile network, stopped functioning (the pen jumped off the chart) after recording a peak wind of 23.5 mps at 1540 MDT.

Spatial variations in the wind speeds and directions inferred from hailfall measurements can be due to 1) real spatial variations in the wind, and 2) variations in the time of fall of hail in the presence of a time varying wind field. The two causes are undoubtedly both present and are not separable with the measurements available.

An interesting pattern was noted in the spectrum of hail sizes over the network. The area in the SE corner where the hail diameters are largest exhibits a bi-modal spectrum while the others show one with a single peak. This suggests that the hailstreak structure consists of a broad "skirt" of smaller stone sizes with a distinct "core" of larger stones overlain on it. Nevertheless, the patterns of total number of stones and maximum stone diameter are such as to suggest that even on this small scale, there is approximate validity to Admirat's (1972) relation which says that in natural hailstorms the two parameters vary from point-to-point with positive correlation.

Figure 8 shows the distribution of the mass of hail per sq m. The values range from 4.8 to 2,382 g/m . The average value of 252.1 is equivalent to 0.25 mm. of precipitation and yields an estimate of 630 tons as the total mass of hail that fell on the square mile.

The distribution of maximum hailstone diameters (Fig. 9) displays a range of values from 0.83 to 3.20 cm.

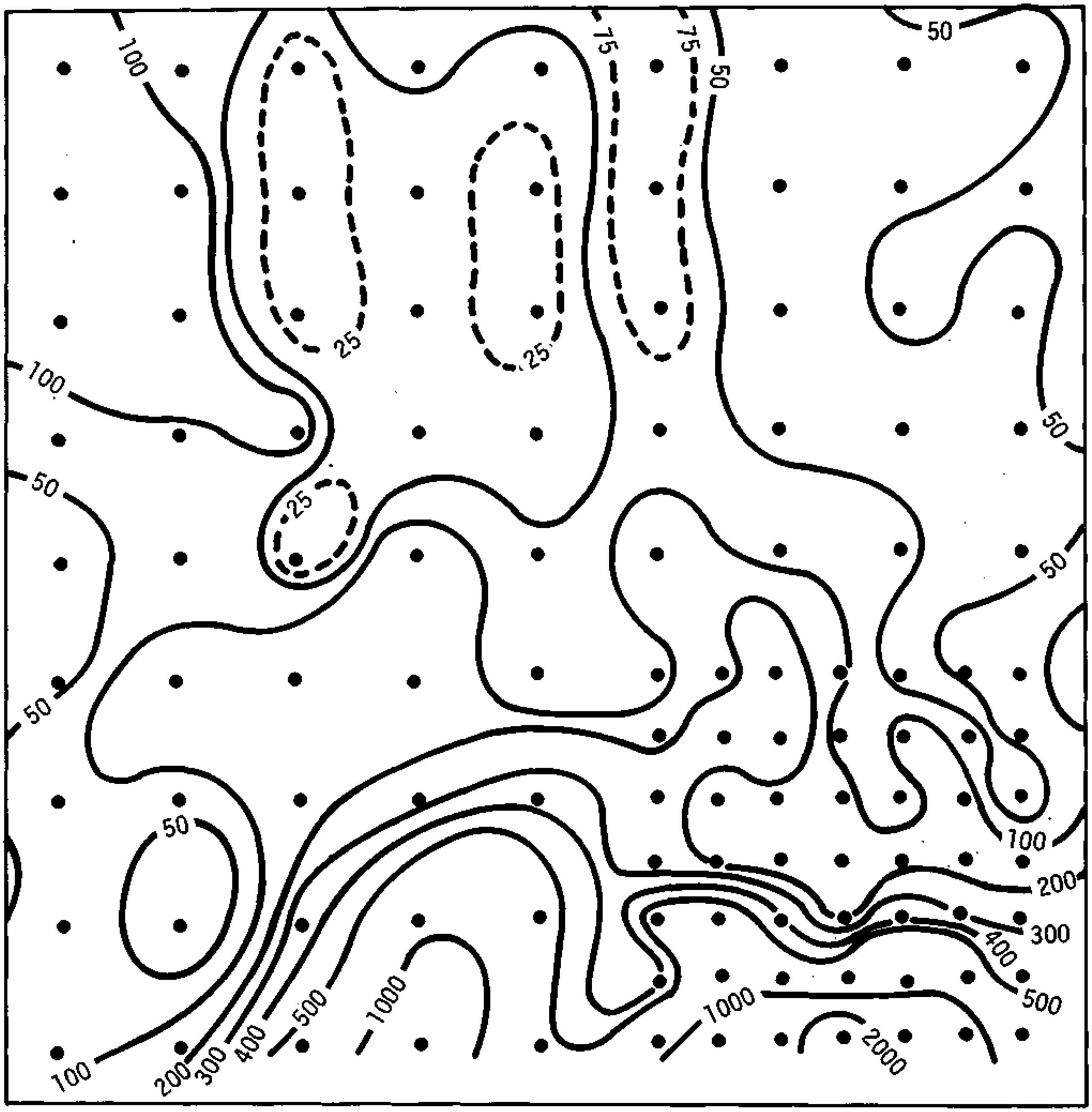


Figure 8. Distribution of mass of hail (g/m^2); storm of 21 May 1973.

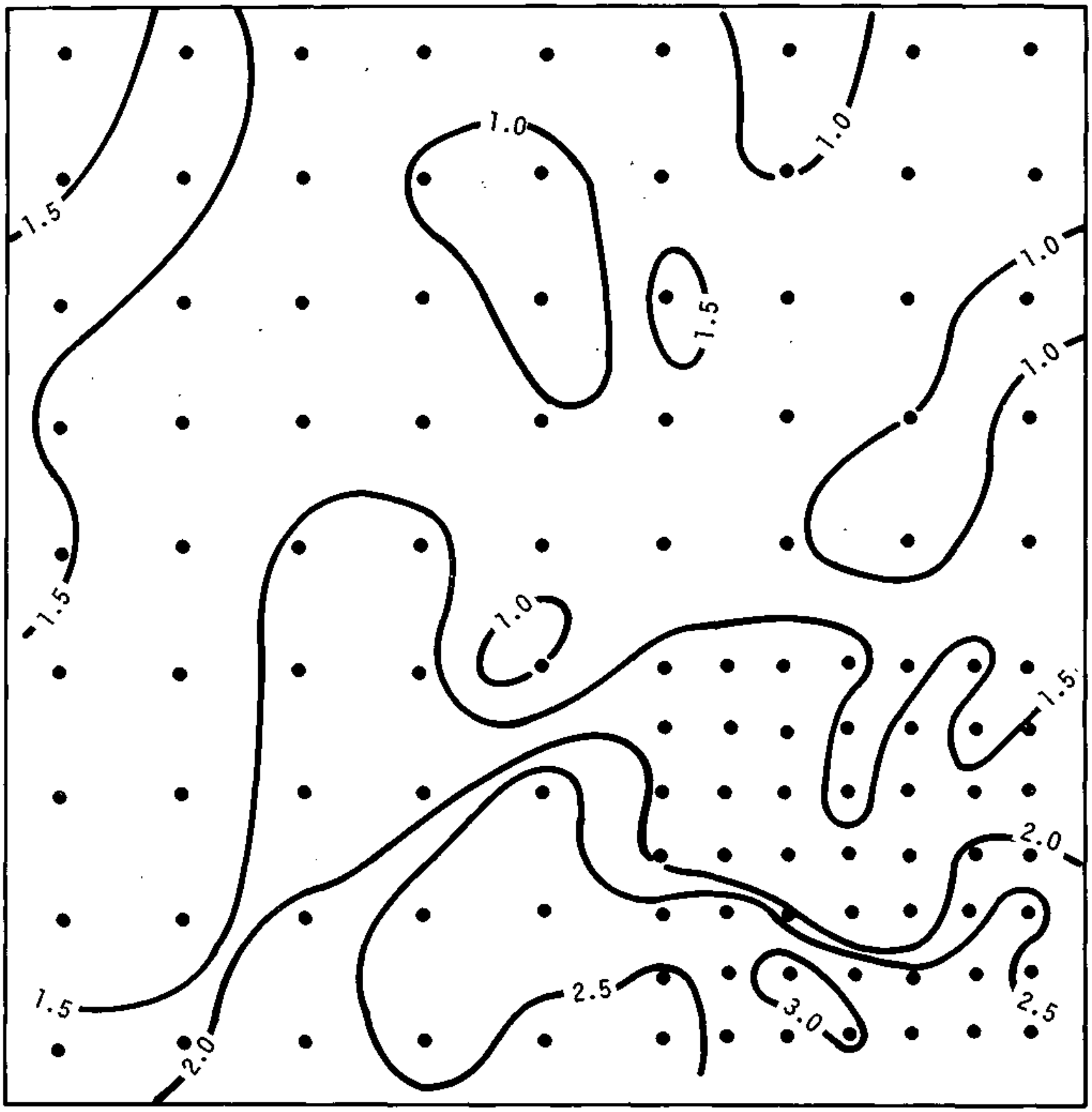


Figure 9. Distribution of maximum hailstone diameter (cm); storm of 21 May 1973.

Vertical kinetic energy (in joules/m^2) is shown in Fig. 10; the range is from 0.4 to 550 joules/m , with an average of 32.8 joules per sq m. The total vertical kinetic energy which fell on the square mile in the form of hail was 8.4×10^7 joules.

Total kinetic energy, which includes the effect of wind speed is shown in Fig. 11, for those hailcubes for which speeds are displayed in Fig. 7. The range of values is quite large, from 13.2 to 901.2 joules/m^2 . Due to the high estimated wind speeds in the southern part of the network, the total energy is much greater than the vertical energy.

Hailfall of 29 June 1973

The second hailfall on the square-mile network was a limiting case to the point that an observer at the site might not have noticed it, or might have chosen to ignore the few small stones which fell. The importance of such a hailfall lies less in what it can teach us about small-scale variability than in what it means, for example, for the interpretation of radar echo values. The few stones arriving at the ground may be the survivors of many which have melted during fall. The map of Fig. 12 shows the rather ragged hail pattern. The numbers are the number of stones per sq ft on the top pads only. Zero's within the hail envelope are due to cases in which clear and unmistakable hail dents were noted on the vertical faces of cubes, but not on the tops.

Hailfall of 22 July 1973

The storm of this day was also not seeded. It passed over the square mile just after 1800 MDT with the stones being windblown from the SW. The

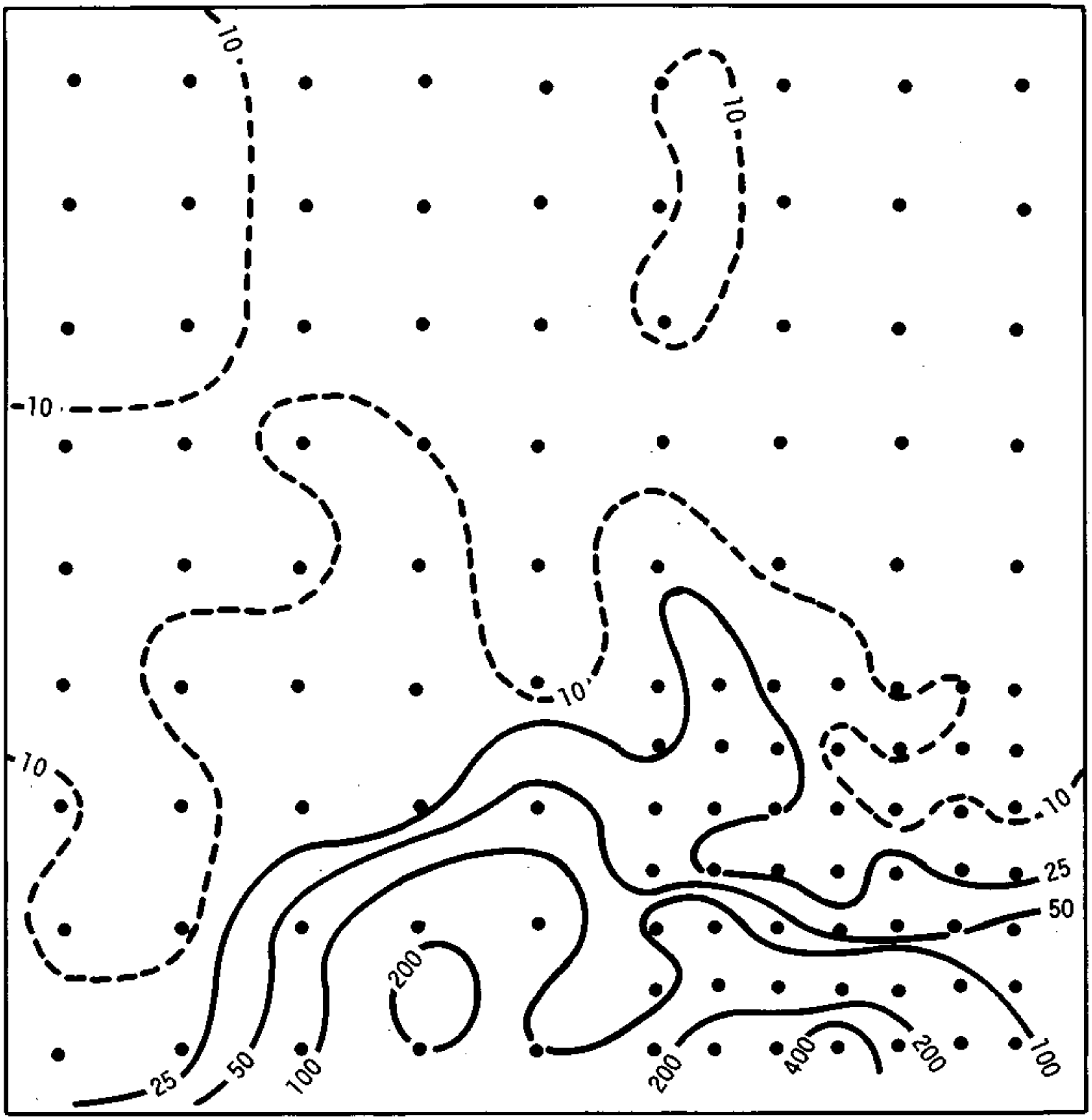


Figure 10. Distribution of vertical kinetic energy ($joules/m^2$); storm of 21 May 1973.

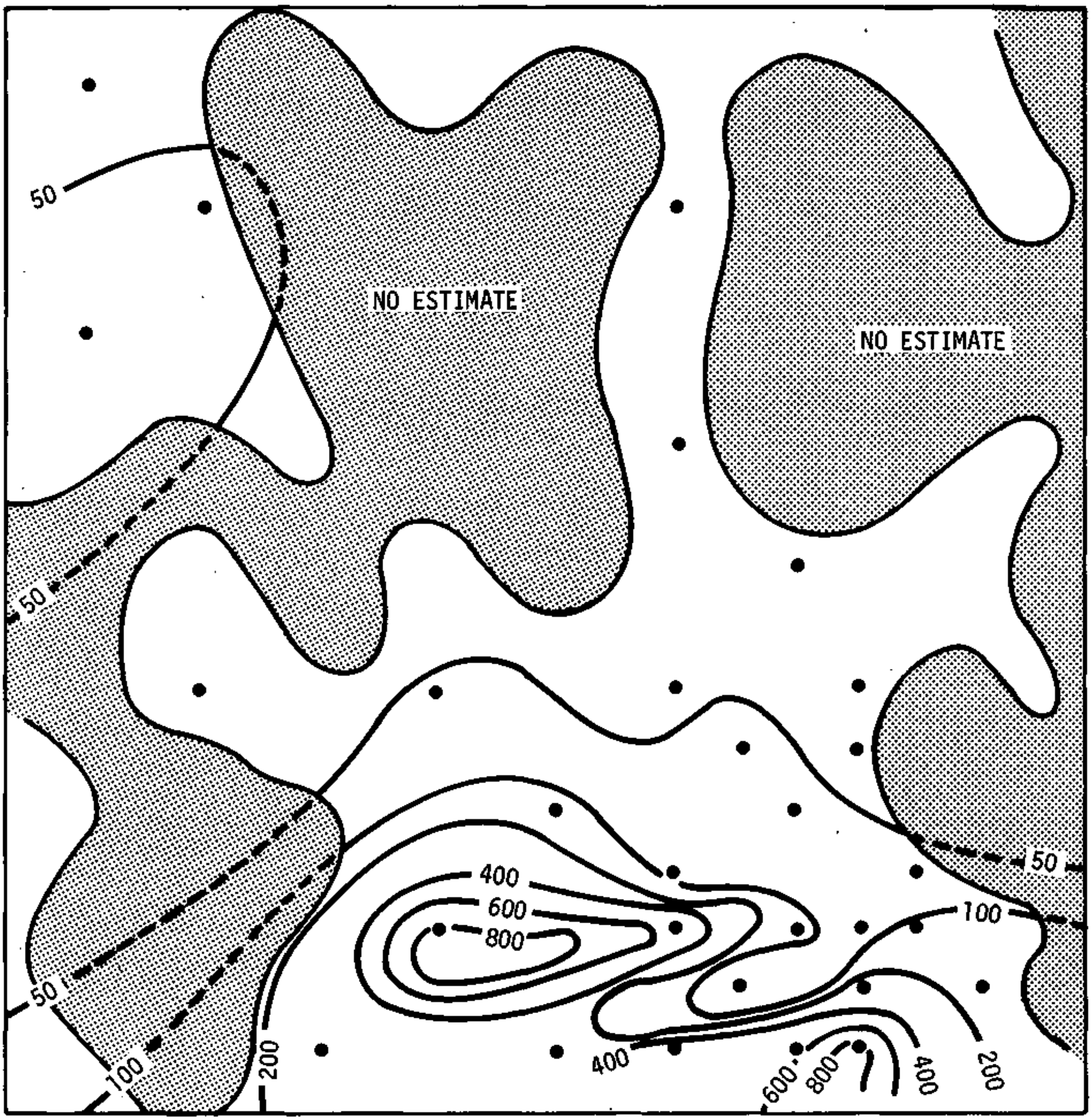


Figure 11. Distribution of total kinetic energy (including effect of winds) (joules/m^2); storm of 21 May 1973.

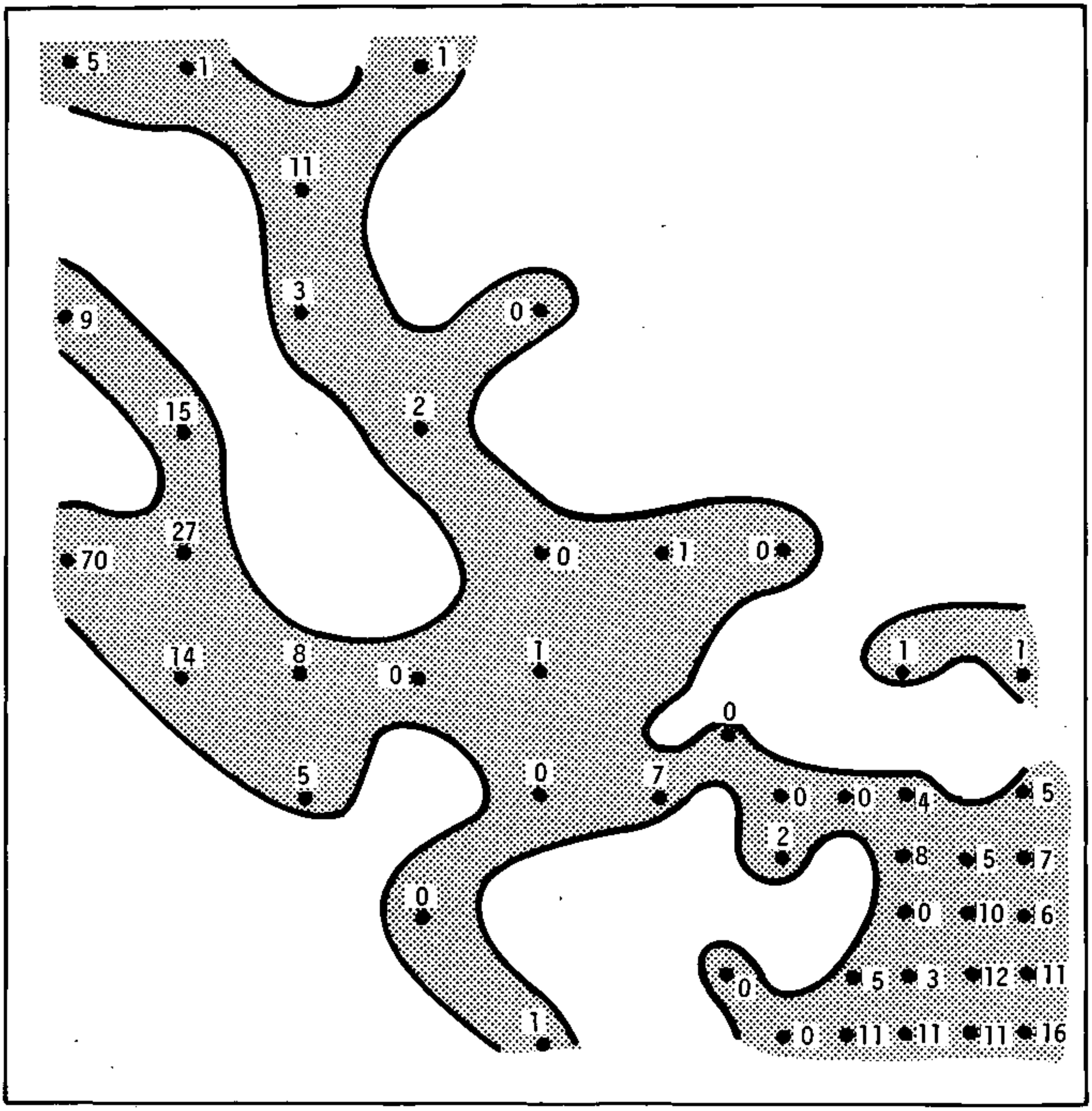


Figure 12. Storm of 29 June 1973; number of stones per square foot.

numbers of stones (Fig. 13) are much higher than in the May storm, from less than 1500 to over 7,000 per sq m.

Most of the hail was windblown from the southwest, but in the southern part of the network, where there was less hail, there were two distinct phases to the fall of hail, a major one from the southwest and a lesser one from a northwesterly direction which fell on the morning of the 24th while the sensors were being changed. This was apparent from the presence of hailstone dents on the south, west and north faces of hailcubes in that region. On the tops of most cubes in the southern portion the dents were oriented mostly from the southwest, and a second group of dents from the northwest could be detected. If all dents had a length to width ratio such as to make orientation measurements possible, it would be a simple matter to separate the two phases and make an estimate of the wind speed, direction and other wind dependent quantities for each phase, but many dents are of indeterminate orientation and this is not possible. No wind estimates were made for cubes with numbers of stones on the north vertical face greater than ten percent of the number of either of the other two "damaged" faces. All quantities not dependent on a wind estimate, such as number of stones per sq m and vertical kinetic energy were estimated from the top pads, as in conventional hailpad applications.

The nearest complete surface wind history which could be obtained near the time of this storm came from the NHRE mesometeorological station located 8 mi (13 km) north of the network. There the wind had been south easterly until about 1740 MDT. It then swung smoothly around to north until there was an abrupt shift to the southwest at 1821 followed by a gradual swing to just north of west by 1840. The shift from north to southwest was accompanied at that station by an abrupt increase of windspeed from less than 2.5 mps to

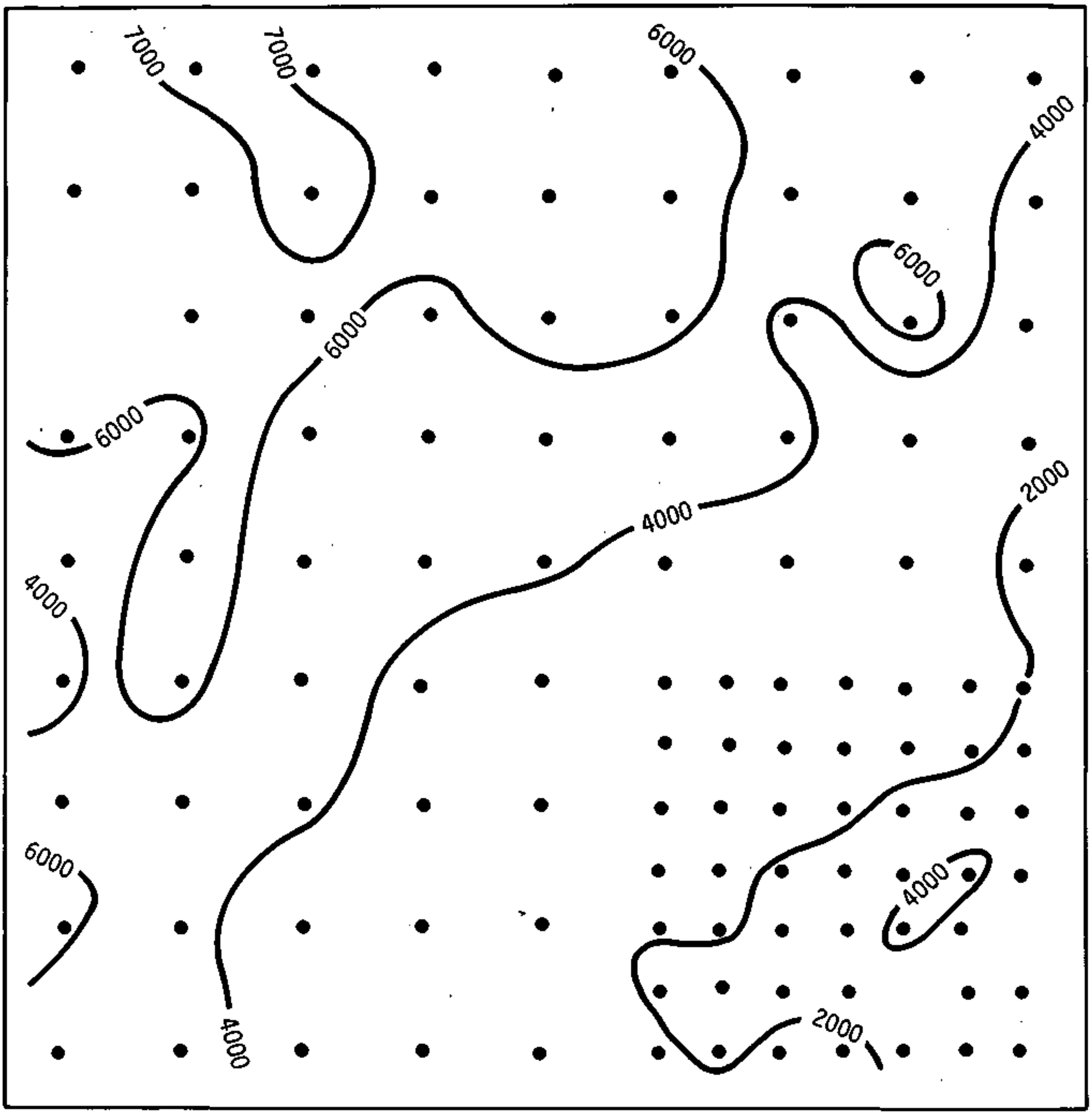


Figure 13. Total number of stones per square meter; storm of 22 July 1973.

about 7 mps with gusts to over 10 mps. The speed continued to increase as the wind continued to swing toward the west with peak gusts of 27 mps as it became just north of west at 1841. At the wind measuring site nearest the network (about 1 mile to the south) the abrupt gust arrival was stronger, the wind increasing from less that 2.5 to over 10.0 with peak gusts to over 14 mps at 1804 MDT. The highest gust, of over 18 mps occurred at 1822, and the winds remained above 10 mps until 1852. No wind direction record was available from this closer station. The wind records described do not allow precise timing of the hail event, but it would at least appear reasonable to conclude that the hailfall from a southwesterly direction came with or just following the gust front, shortly after 1800. The minor hailfall from the northwest came on the morning of 24 July. Figures 13 through 16 show the number of stones per square meter, maximum diameter, mass of hail, and vertical kinetic energy for the July 22 (24) hailfall.

The range of values of the number of stones per sq m, from 838 to 7471, is slightly smaller than it would have been without the second hailfall having occurred. Nevertheless it is nearly a 9 to 1 variation. Gradients of over 1000 stones/sq m per 660 ft occur at many places. The maximum stone diameter and total number of stones are distributed in a manner which suggests reasonable validity of Admirat's relationship. The range of maximum diameters is from 0.83 to 2.61 cm. The mass of hail ranged from 50 to 1720 g/m^2. The average mass was 530.5 g/m^2 giving a total of 1,358 tons of hail on the square mile. Vertical kinetic energy extremes were 2 and 229 joules per m^2 with an average of 60.5 joules/m^2 and a total of $1.5 \times 10^{\circ}$ joules over the square mile. Wind direction as estimated from the hail dents on the horizontal pads varied

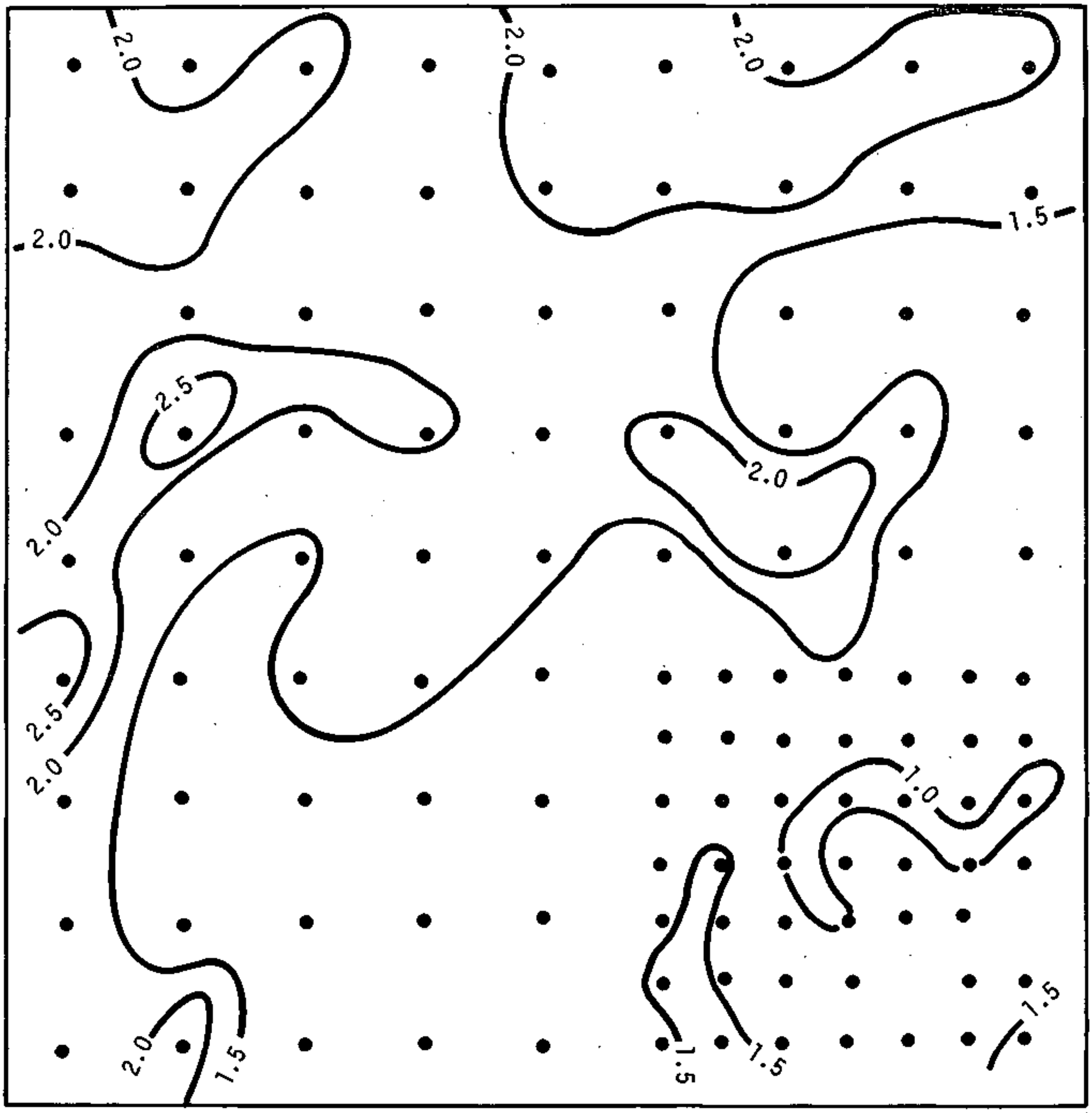


Figure 14. Distribution of maximum hailstone diameters (cm); storm of 22 July 1973.

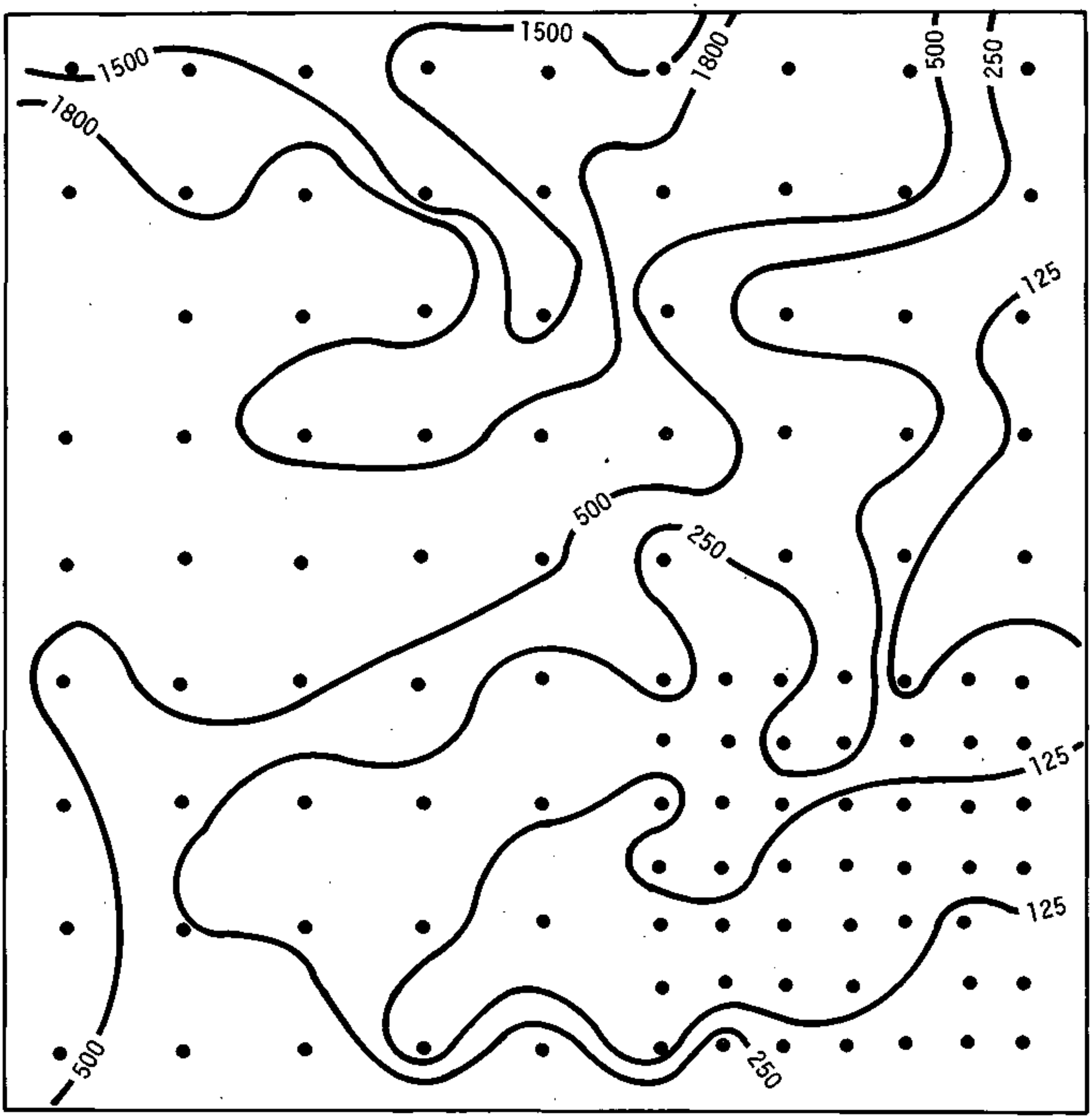


Figure 15. Distribution of mass of hail (g/m^2); storm of 22 July 1973.

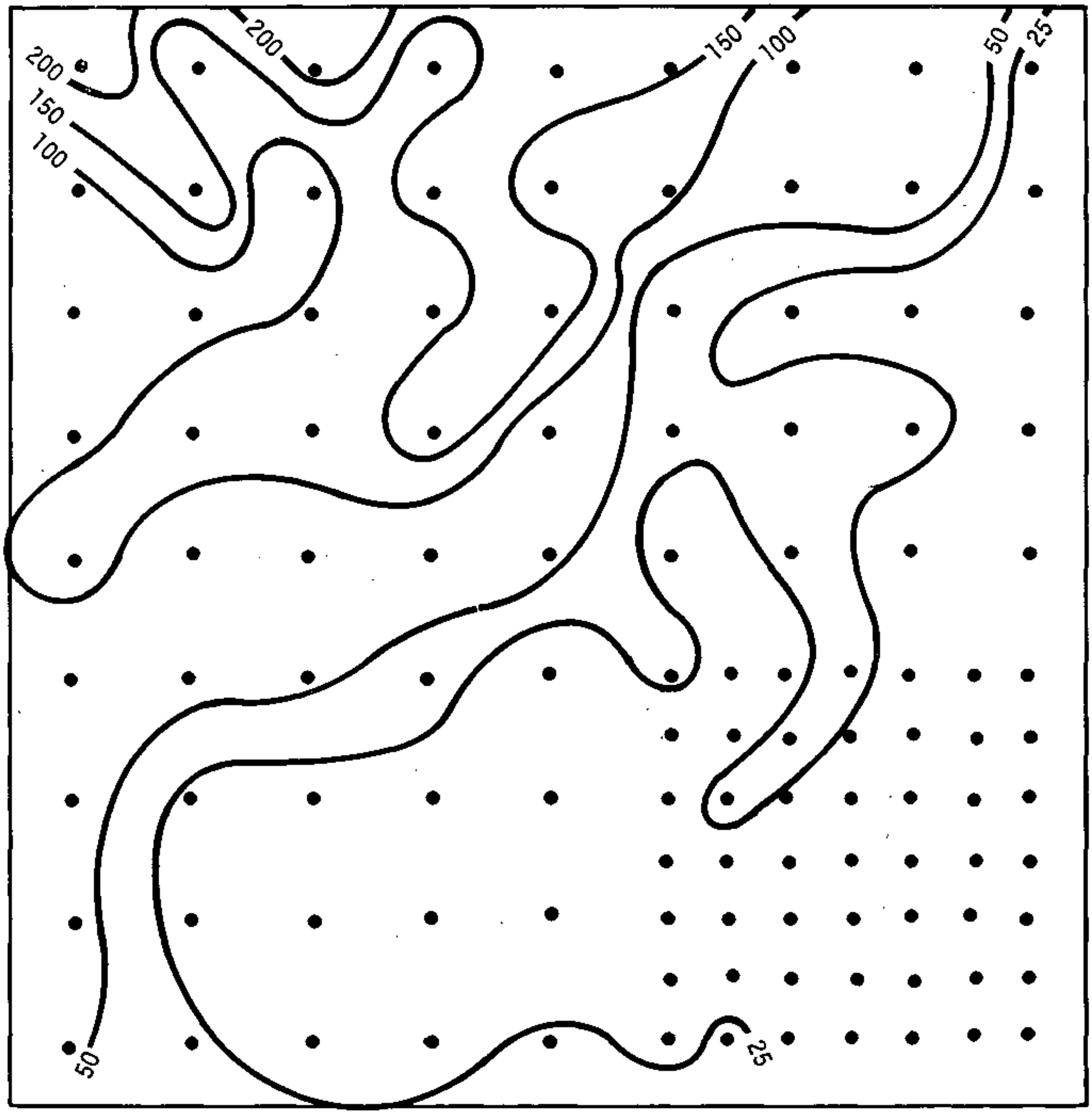


Figure 16. Distribution of vertical kinetic energy (joules/m^2); storm of 22 July 1973.

from 196 to 288 degrees. These were isolated extremes and the overall distribution of directions is more uniform than they would imply.

The estimated winds and total kinetic energy are shown in Figs. 17, 18, and 19. The highest speed estimate is 23.4 mps and the lowest 10.2, both reasonable in the light of the wind instrument records described above. The total kinetic energy ranged from a low of 11.5 joules/m^2 to a high of 516, which, compared to the vertical energy values is indicative of the importance the wind has in hail damage to crops.

Summary and Conclusions

The experience of one summer's operations of a very dense hail network has shown that hail parameters vary greatly over very small distances.

Parameters derived from hailpads exhibited coherent patterns over the network, indicating that instrumental inaccuracies are not a limiting factor to the study of variability at this scale. Windspeeds estimated from the hailcubes appear to be reasonable and also form coherent patterns. These new instruments should in the future prove of great value in studies on the relationship between objectively measured hailfall parameters and crop damage.

Acknowledgments

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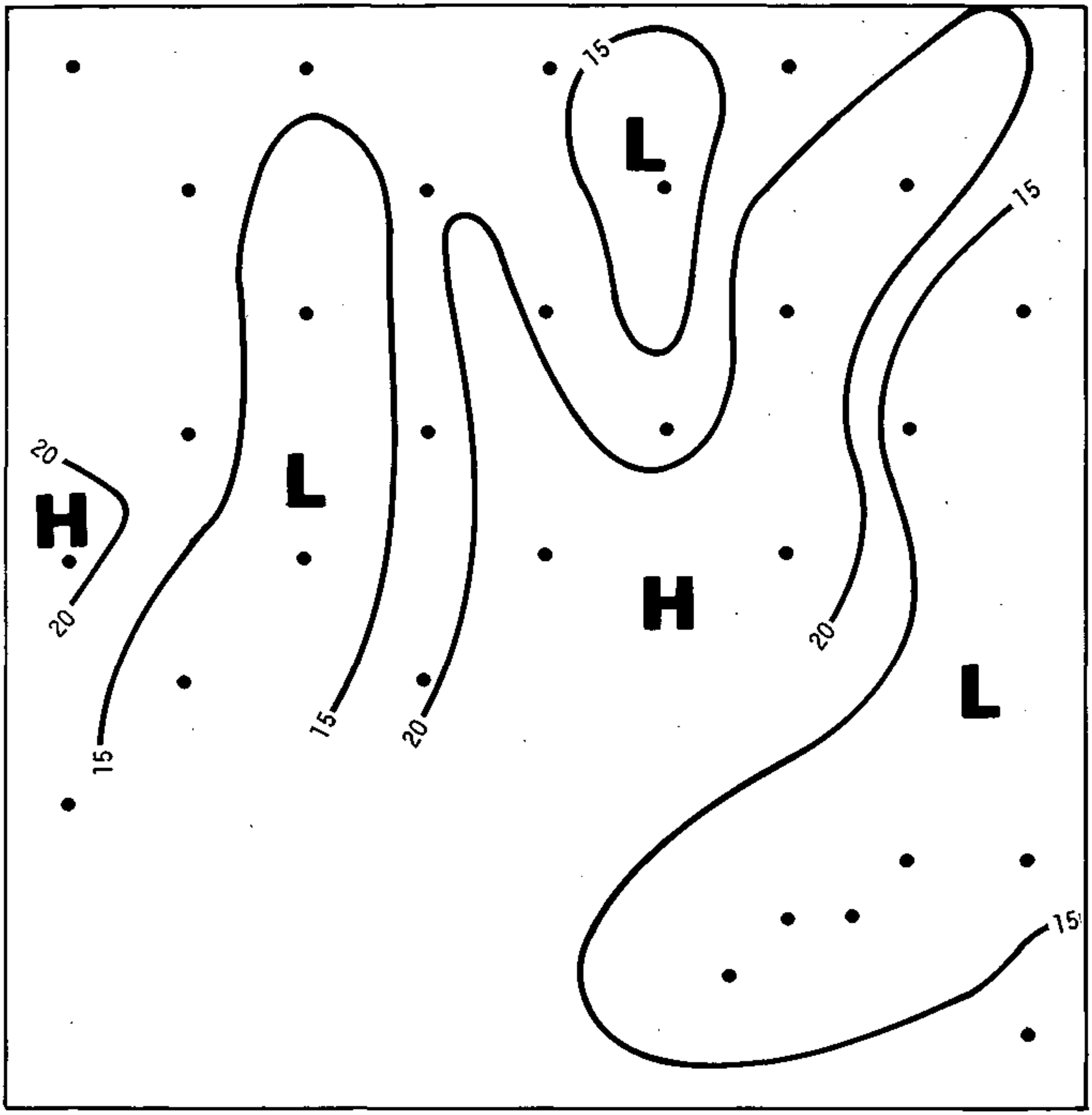

Figure 17. Distribution of wind speeds accompanying hail (m/sec); storm of 22 July 1973.

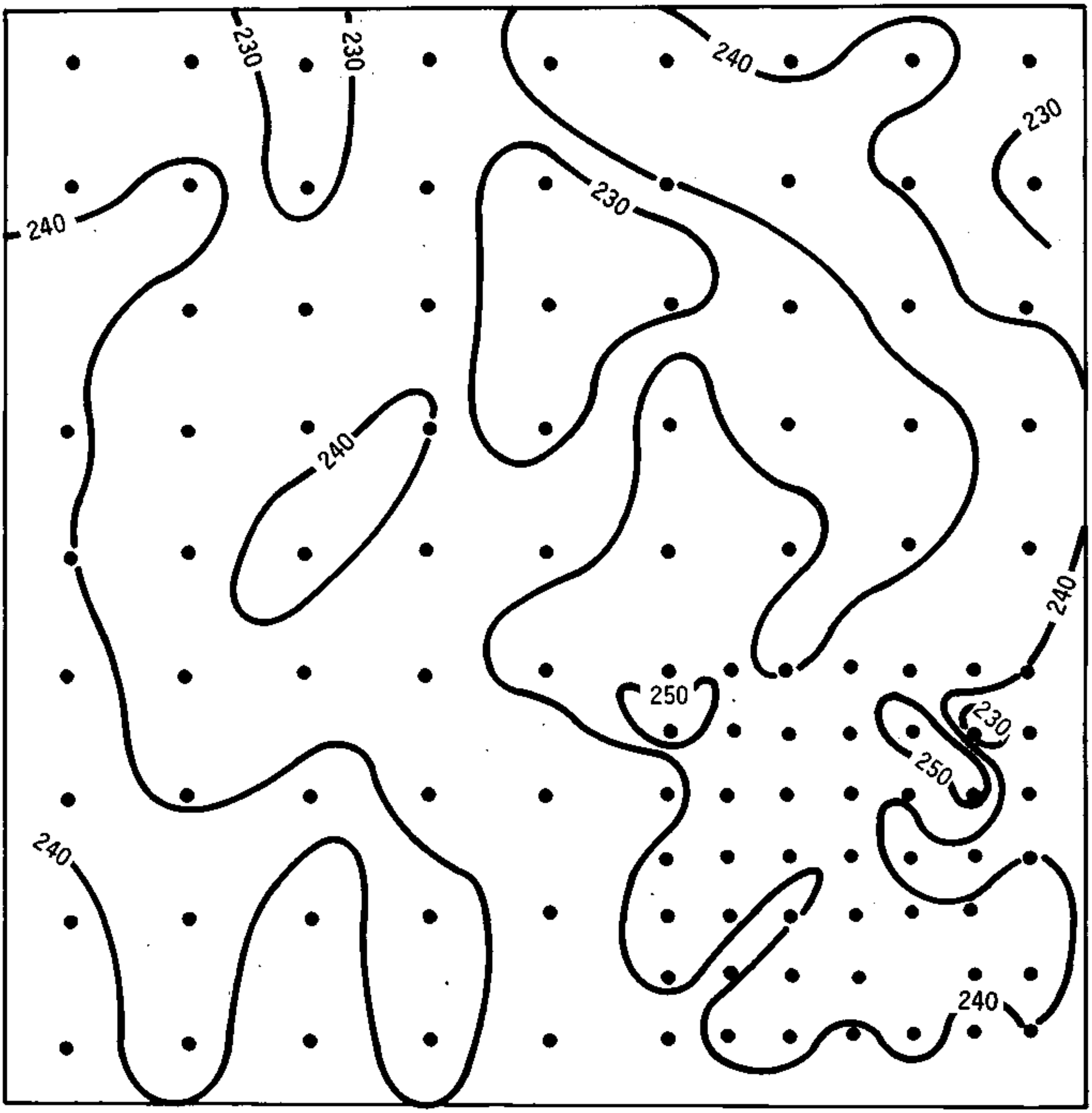

Figure 18. Distribution of wind directions (degrees, meteorological convention); storm of 22 July 1973.

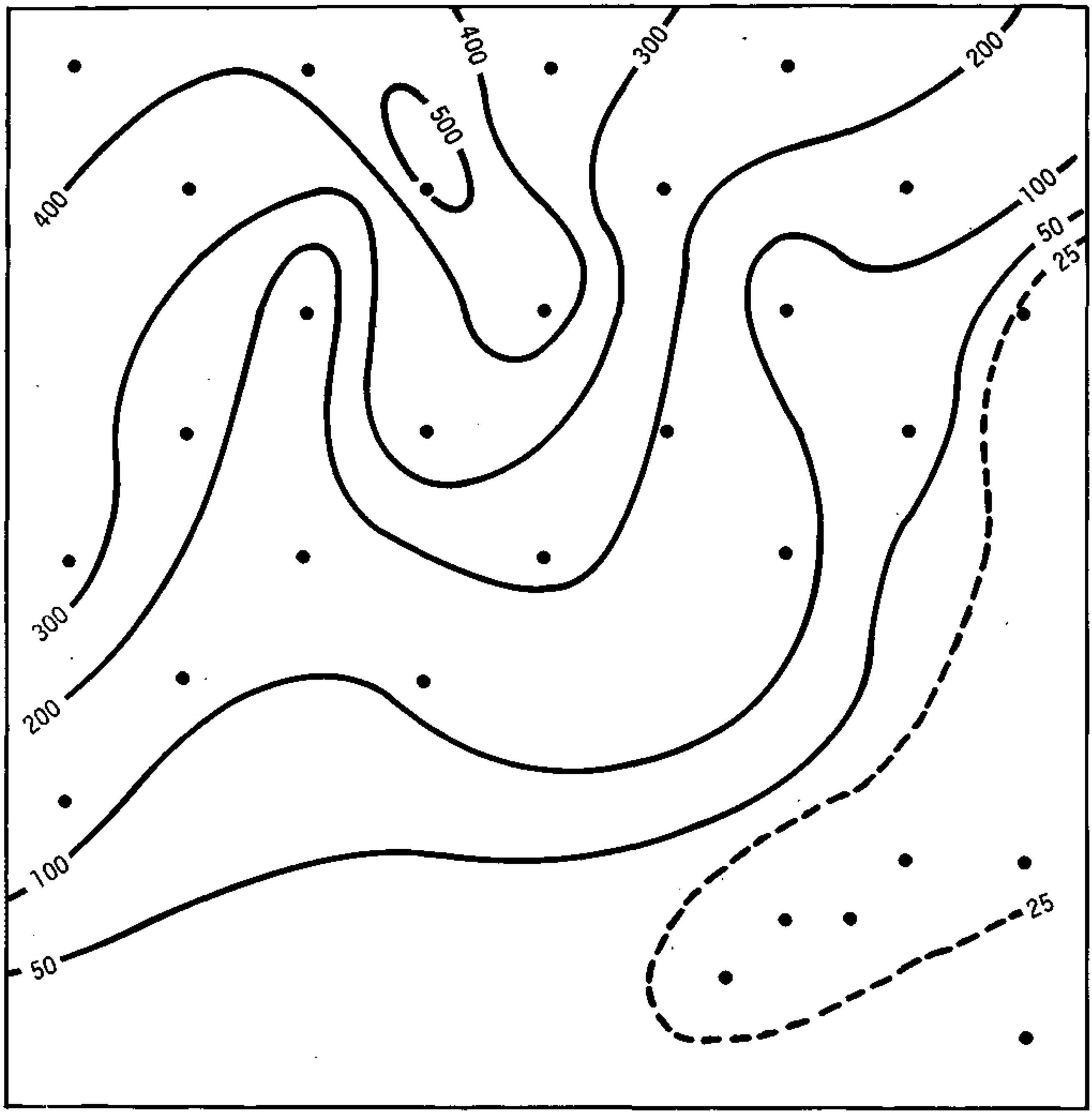

Figure 19. Distribution of total kinetic energy (joules/m^2); storm of 22 July 1973.

The servicing of the instruments in the field was the responsibility of Mr. Robert Thorns. The assistance of Dr. E. Mueller, Mr. E. Silha, Mr. R. Reitz, Mr. J. Eynke, Mr. J. Mueller and Mr. G. Fetter in this task deserves special thanks.

The prototype of the ISWS hailcube was built by Mr. 0. Anderson.

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APPENDIX

A brief description of the hailpad calibration

In an internally circulated memorandum on file at the ISWS since 1969, R. Rinehart (presently with Colorado State University) described a hailpad calibration scheme which has since been employed in the analysis of hailpads at the ISWS. The scheme is not only unique and original, but is well thought out and gives realistic results.

The calibration consists in measuring both the minor dimension and curvature of dents made by real hailstones and finding the regression between the two. The applicability of this approach rests on the following readily-verified assumptions:

1) A hard sphere impacting on the hailpad causes a dent whose curvature corresponds to the curvature of the sphere.
2) Dents on hailpads do not change with time.

To accomplish the calibration, paper circles of various diameters were inserted into dents and the diameter of the circle most closely fitting the dent was recorded as D_C, the hailstone and circle diameter. The minor dimension of the same dent was recorded as D_D. The regression between these, based on 173 dents, was

$D_D = -0.0455 + 0.599\ D_c$ (correlation coefficient = 0.901), or

$D_c = 1.67\ D_D + 0.0761$

The latter of these is the properly expressed calibration equation, where D_c is interpreted as the hailstone diameter.

Only clear, clean dents were used in determining this regression, and dents which were greatly elongated were not used.