On the Role of Strong Winds in Damage to Crops by Hail and Its Estimation with a Simple Instrument[1]

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ABSTRACT

Surface winds which accompany the fall of hail have a profound effect on crop damage. Quantitative estimates of the horizontal and total flux of hailstone kinetic energy can be made with simple theoretical considerations using data obtained from a hailcube. A hailcube is a box with aluminum foil wrapped styrofoam pads on four sides and the top. The analytical procedure for obtaining the energy estimates from cubes is described. Results show that the total kinetic energy, which includes the effect of the wind speed, can be up to five times greater than the vertical kinetic energy—the energy imparted without the effect of the wind.

1. 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. Much of the objective hailfall data have been accrued following introduction of hail instruments and their employment in extensive networks.

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 m^{-2}), and if the stones are not of such size to destroy or mutilate the pad. Their use has led to the discovery of small-scale hailswath substructures called hailstreaks (Changnon, 1970), which in Illinois have characteristic dimensions of 8 km in length and 1÷2 km in width.

Most recently, hailpad networks of extremely fine scale have been employed in determining the variability of various hailfall parameters over distances much smaller than the dimensions of hailstreaks (Morgan and Towery, 1975).

A serious lack of information exists concerning the importance of the wind occurring at the time of hail in the damaging of crops. This lack is due to the great difficulty of assessing the effect. Wind measurements are rarely available at the scene of serious hail damage.

Wind is perhaps as important in the hail damage problem as the hail itself. More or less clear statements of this fact can be found in the literature going well back into the last century. Pini (1885), for example, cited in his summary of the hailstorms of Northern Italy in 1879 at least three cases of notable hailfalls which produced minor or no damage to crops, and specifically attributed this to the lack of wind at the time of the hail.

2. The instrument

To gain data for the study of the role of wind in producing crop damage, a new adaptation of the hailpad, which has been named the "hailcube," has been developed. In addition to the conventional horizontal

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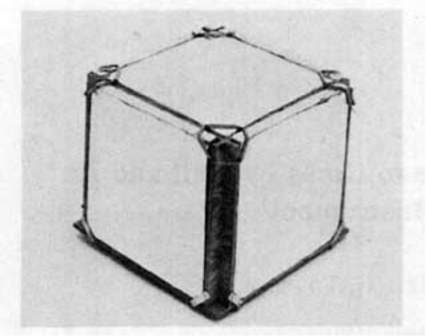

FIG. 1. The Illinois State Water Survey hailcube.

hailpad, it consists of four vertically mounted hailpads arranged with the other to form the five sides of a cube (Fig. 1). This new configuration allows estimates to be made of the horizontal components of hailstone velocity, momentum, kinetic energy, and the average wind speed accompanying the hailfall. It is mounted on a metal fence post, about 1.5 m above the ground, with the vertical faces oriented N–S and E–W and so labelled.

The basic idea for the five-sided hail sensor, of which the hailcube is an adaptation, is attributed to Prof. E. Rosini, Director of the Ufficio Centrale di Ecologia Agraria (UCEA), Rome, Italy. The UCEA device (Fig. 2) is described in Vento (1972) and has been widely deployed in Italy (Castaldo and Vento, 1974).

3. Analysis of the hail impressions

An example of a hailcube which has experienced a hailstorm is shown in Fig. 3.

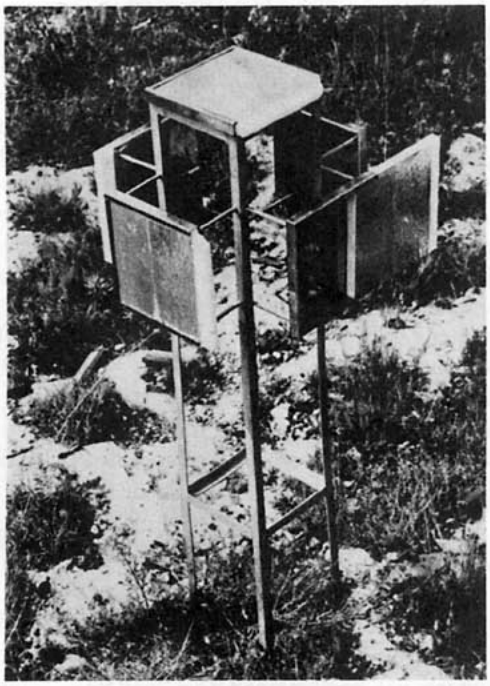

FIG. 2. The five-sided passive hail sensor developed by the Ufficio Centrale di Ecologia Agraria, Rome, Italy.

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. Although several ways exist for performing this calibration, a method by Rinehart (see Morgan and Towery, 1974) has been found best and is the one used in this study.

The analysis adopted here is the simplest of several possible approaches. It has been chosen primarily because it does not require any calibration beyond that already available (based on spheres at terminal fallspeed) for determining the size spectrum on the top (horizontal) pad.

It is not possible without a very complex calibration to measure the size spectrum of the stones striking the vertical faces of the cube, because their speeds normal to the face are more nearly the wind speed component normal to each face, and not the terminal fallspeed. This is not a serious drawback.

Under the assumptions that all hailstones fall at their terminal fallspeeds and move horizontally at the speed and in the direction of the wind, the vertical faces of the hail cubes also allow 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, $V_t(D)=1.4\times10^3 D^{\frac{1}{2}}$ [m s^{-1}, D in cm], i.e.,

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

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

$$N_H(D)=V_nN^*(D),$$

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 $N_H=V_nN^*$. 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 vectorially summed to give the horizontal wind vector

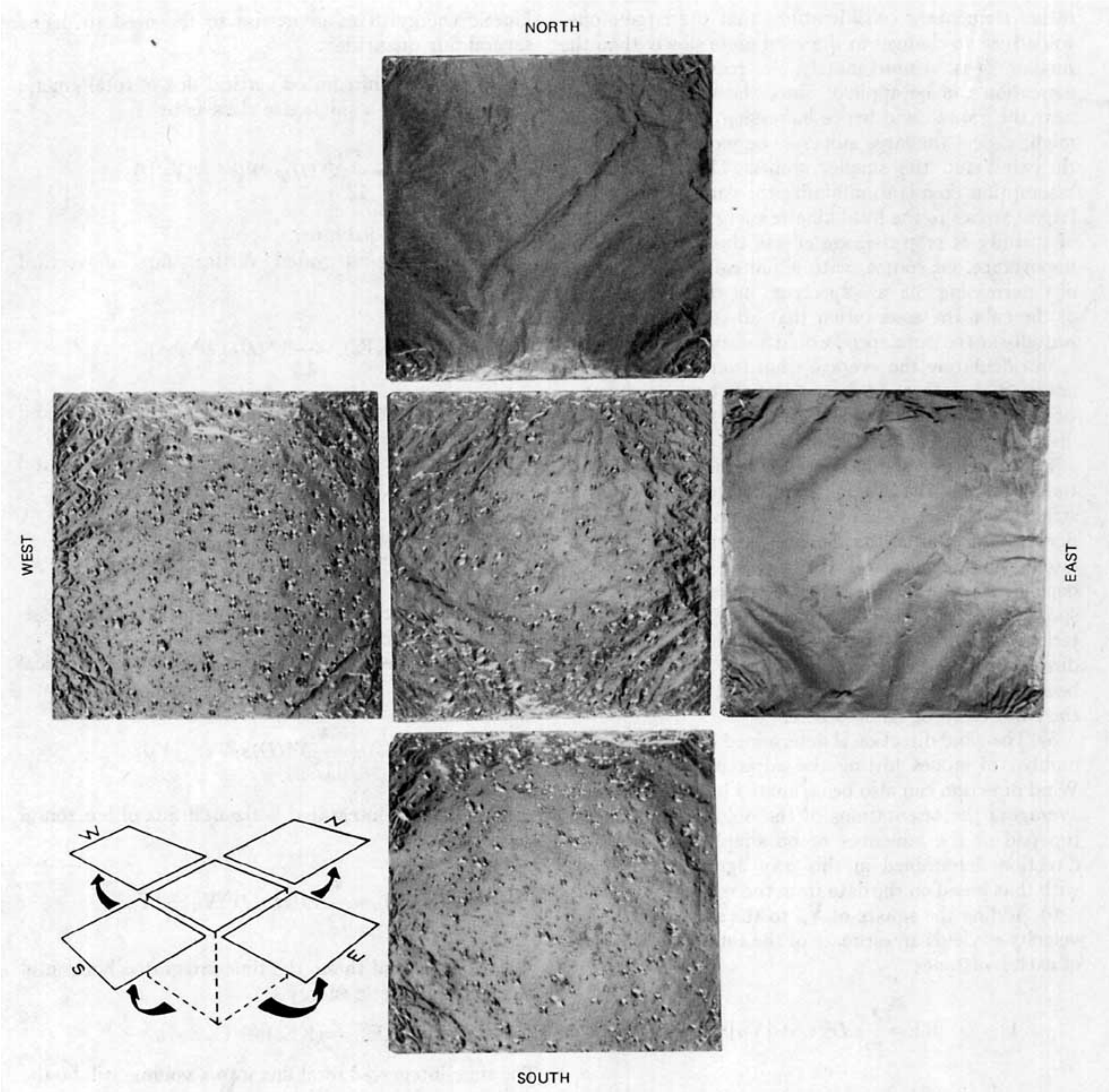

Fig. 3. An example of a hailcube from the hailstorm of 22 July 1973.

V_H. This "wind" should not be confused with the true wind accompanying the hail. It is a function of the wind and the hail and might be called an "effective wind" or "hail-averaged wind." In analyzing data from the field it has been calculated and examined by itself only to see how it varied from point to point and to compare it to observed winds for reasonableness.

The assumption that the hailstones move with the wind in the horizontal really amounts to assuming no variation of the wind vertically to a height sufficient for the largest stone to have adjusted to a sharp change in horizontal wind speed. Some relaxation of this rather unrealistic condition is possible when one considers the minimal contribution to the horizontal fluxes due to the largest stones which are few in number. The analysis given here places the overwhelming weight on the smaller more numerous stones. This is clear from the low numbers of large stones striking a unit horizontal surface and considering the effect of dividing this by the terminal fallspeed to arrive at the time-integrated concentration in the air.

Any attempt to improve on this assumption would require detailed knowledge of the wind structure to a height of many tens of meters. One understands from rather elementary considerations that the large stones will adjust to changes in the wind more slowly than the smaller ones. Unfortunately no reasonable average correction can be applied. Since the wind is retarded near the ground and hence increasing with height, one might expect the large stones to be moving faster than the wind and the smaller stones. The effect of the assumption then is to minimize the contribution of the largest stones to the total kinetic energy. In the context of a study of crop damage effects this will be of little importance. Of course, with a full calibration capable of determining the size spectrum on the vertical faces of the cube the assumption that all stones move horizontally at the same speed would no longer be necessary.

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, because of 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 $\mathbf{V}_H$ to the square of the fall velocity v_t yields an estimate of the total kinetic energy of each hailstone:

$$\mathrm{KE}=\frac{\pi}{12}\rho_i D^3(v_t^2+|\mathbf{V}_H|^2),$$

where ρ_i is the density of pure ice.

4. Some factors relating to damage

The following simple statements regarding damage by windblown hail are offered primarily as an introduction to this complex problem.

As a first approximation we do not consider modification of wind flow by the plants or objects, nor change in configuration of the plants due to the wind, and we assume that the presence of a horizontal wind has no effect on the vertical flux of stones, or their vertical components of energy, momentum or the flux of mass (hail precipitation rate or accumulation). As noted above, each stone will have a horizontal component of kinetic energy. This gives rise to the need to define several flux quantities:

(a) The time-integrated vertical flux of total kinetic energy given for a single size class as by

$$(\mathrm{KE})_v=\frac{\pi}{12}N^*(D)\rho_i D^3(v_t^2+|\mathbf{V}_H|^2)\cdot v_t.$$

This can be divided into:

(b) The time-integrated vertical flux of vertical kinetic energy

$$(\mathrm{KE}_v)_v=\frac{\pi}{12}N^*(D)\rho_i D^3 v_t^2\cdot v_t$$

which can be measured from the top pad alone and could be called the no-wind energy, and

(c) The time-integrated vertical flux of horizontal kinetic energy

$$(\mathrm{KE}_H)_v=\frac{\pi}{12}N^*(D)\rho_i D^3|\mathbf{V}_H|^2\cdot v_t.$$

It is clear that $(\mathrm{KE})_v=(\mathrm{KE}_H)_v+(\mathrm{KE}_v)_v$. The horizontal fluxes are:

(d) The time-integrated horizontal flux of vertical kinetic energy

$$(\mathrm{KE}_v)_H=\frac{\pi}{12}N^*(D)\rho_i D^3 v_t^2\cdot|\mathbf{V}_H|$$

(e) The time-integrated horizontal flux of horizontal kinetic energy

$$(\mathrm{KE}_H)_H=\frac{\pi}{12}N^*(D)\rho_i D^3|\mathbf{V}_H|^2\cdot|\mathbf{V}_H|$$

(f) The sum of these, the time-integrated horizontal flux of total kinetic energy

$$(\mathrm{KE})_H=(\mathrm{KE}_v)_H+(\mathrm{KE}_H)_H.$$

The time-integrated total flux into a volume will be the grand sum of these:

$$\text{(g)}\quad \mathrm{KE}=(\mathrm{KE})_H+(\mathrm{KE})_v=\text{(a)}+\text{(f)}$$
$$=\text{(b)}+\text{(c)}+\text{(d)}+\text{(e)}.$$

Now, not all of these energy flux quantities will be relevant to damage of specific crops or structures. A limiting case to be considered would be the vertical wall of a house normal to the wind. Some crops, such as fruit trees and vines, are trained upward to grow in a way that begins to approach this situation. Clearly, the damage to the wall depends totally on the wind-created horizontal components. In fact only (e) above would determine the damage. Another limit case would be a flat, horizontal roof, the damage to which could only derive from (b). It is difficult to envision a crop approaching this case. An extended, close planted crop such as wheat or alfalfa would undoubtedly be sensitive primarily to (a), the vertical flux of total energy, though at the edges of fields the horizontal flux (d) would be important. The limit case crop would be an isolated tree, envisioned as an elevated sphere or cloud filled uniformly with leaves and fruit. The damage to such a crop would be the effect of all the subterms, or the grand total given by (g).

5. Some illustrative results

The hailcubes were used in the field as part of the National Hail Research Experiment in 1973. Sixty-two hailcubes were deployed in a single section (2.56 km^2) of land near Kimball, Neb. The network also contained a large number of simple hailpads for the purpose of determining small-scale variability of hail parameters (Morgan and Towery, 1974).

Two significant hailstorms occurred over the network. The first was on 21 May with all the observing sites being struck by hail, several centimeters in maximum diameter, with a relatively small number of stones per square meter. The second 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 and they struck the instruments from the southwest. 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. 3. In both of the major hailfalls, a few dents were found on many sensors which could only be attributed to soft or slushy hail.

These two major hailfalls were 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.

a. Hailfall of 21 May 1973

This storm from which hail fell in several streaks on and around the hailpad and hailcube network and the adjacent NHRE operational area, was a large storm which was not seeded. It passed over the network around 1540 MDT. From the pattern of the total number of stones per square meter it appeared 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 m s^{-1}. 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. Fig. 4 shows the wind speeds calculated from the hailcube analyses. Speeds are shown only for those cubes having more than 200 stones m^{-2} on the top pad since it was found that for cases with very few stones, the wind estimates were erratic, and were in some cases unreasonably high.

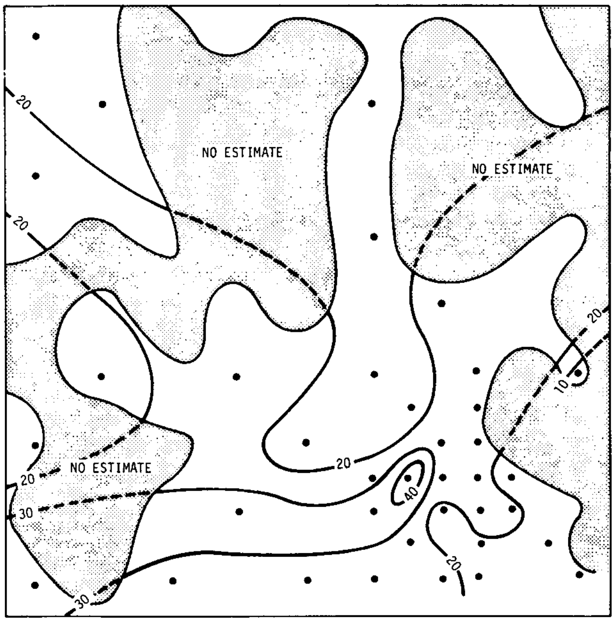

FIG. 4. Distribution of speed of wind speed (m s^{-1}) accompanying hail from storm of 21 May 1973.

There was no wind instrument at the site for comparison with the winds estimated from the cubes, but a nearby wind recorder agreed reasonably well with the hailcube estimates. The recording pen on the wind instruments at the nearest NHRE mesometeorological surface network station, located about 1.0 mi (1.6 km) to the south of the network, stopped functioning (the pen jumped off the chart) after recording a peak wind of 23.5 m s^{-1} at 1540 MDT.

Vertical kinetic energy (J m^{-2}) is shown in Fig. 5; the range is from 0.4 to 550 J m^{-2}, with an average of 32.8 J m^{-2}. The total vertical kinetic energy which fell on the square mile in the form of hail was 8.4×10^7 J. Both hailpad and hailcube data were used to delineate the pattern on Fig. 5.

Total kinetic energy, which includes the effect of wind speed, is shown in Fig. 6 for those hailcubes for which speeds are displayed in Fig. 4. The range of values is quite large, from 13.2 to 901.2 J m^{-2}. The total energy is much greater than the vertical energy. A 5:1 ratio between the total and vertical energies is not rare in this example, illustrating the importance of the wind-created portion of the energy.

b. 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 stones being windblown from the southwest. The number of stones was much higher than in the May storm, from less than 1500 to over 7000 stones m^{-2}.

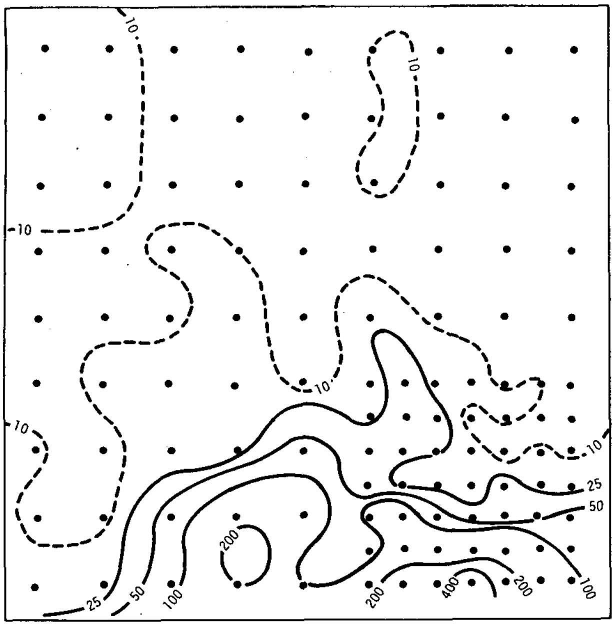

FIG. 5. Distribution of vertical kinetic energy (J m^{-2}) from storm of 21 May 1973.

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 10% of the number of either of the other two "damaged" faces. All quantities not dependent on a wind estimate, such as number of per square meter and vertical kinetic energy, were estimated from the top pads, as in conventional hailpad applications. Vertical kinetic energy (Fig. 8) extremes were 2 and 229 J m^{-2} with an average of 60.5 J m^{-2} and a total of 1.5×10^8 J over the 2.56 km^2 area.

The estimated winds and total kinetic energy are shown in Figs. 7–9. The highest speed estimate is 23.4 m s^{-1} and the lowest 10.2. The total kinetic energy ranged from a low of 11.5 J 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.

c. An additional wind factor

Since beginning work with hailcubes, we have initiated the practice of estimating the average direction of arrival from all simple hailpads as well and a rough conclusion can be drawn regarding our experience with this to date. In Illinois, there is a very strong tendency for the stones to be blown by winds which blow toward the right side of the storm, that is, the stones are

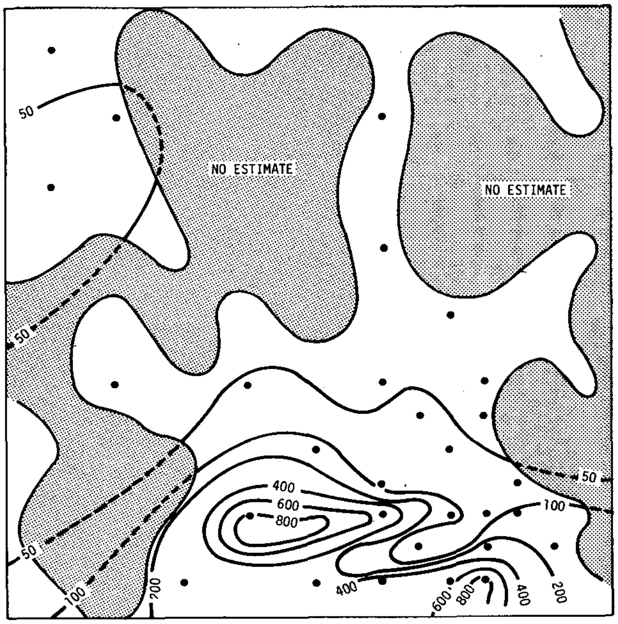

FIG. 6. Distribution of total kinetic energy (including effect of winds) (J m^{-2}) from storm of 21 May 1973.

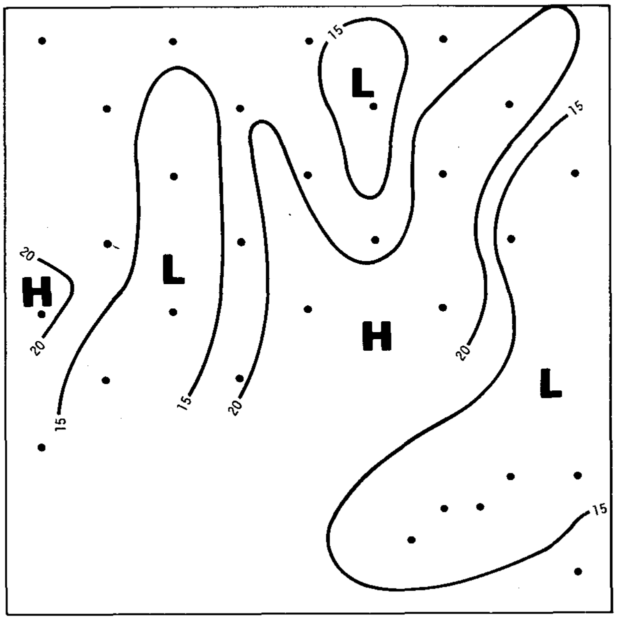

FIG. 7. Distribution of wind speeds accompanying hail (m s^{-1}) from storm of 22 July 1973.

usually moving to the right of the hailstreak motion as indicated by the orientation of the long axis of the hailstreak. The resultant picture is one of a moving source region aloft releasing hailstones into winds (downdraft) blowing across its direction of motion.

6. Summary and comments

Wind can be shown to enhance the damaging potential of hail by many times its potential in the absence of wind. This can be understood through a very simplified analysis such as has been presented and from the examples of real hailstorms which have been shown.

An instrument, the "hailcube," has been developed which seems capable of estimating the effects of wind accompanying hail. It is simple in principle, inexpensive to build, and analysis and interpretation of the data are easy and straightforward. Results from field measurements with the instrument seem quite reasonable.

The success achieved to date in relating simple hailpad measurements of energy to real damage to crops is undoubtedly due to the fact that in cases of crop damage, there is almost always a wind effect present. If most of the time the wind is not extreme (neither calm nor too severe) there should be an average loose correlation between the various energy fluxes described above. Taking account of the wind-induced fluxes can be expected to markedly reduce the scatter in the energy-damage regressions.

The powerful role of wind in hail damage to crops is not without interest in hail prevention research. It is not difficult, for example, to envision the result of seeding a hailstorm to be a reduction in the number of large stones, an increase in the number of small stones, and a concomitant increase in the total melting and evaporation taking place. The cooling due to the latent heat could exert a strengthening effect on the downdraft with a resultant increase in the winds. The net effect on crop damage would then be uncertain. The only modification presently predicted by the hypotheses under test is a reduction of $(KE_v)_v$, the vertical flux of the vertical kinetic energy.

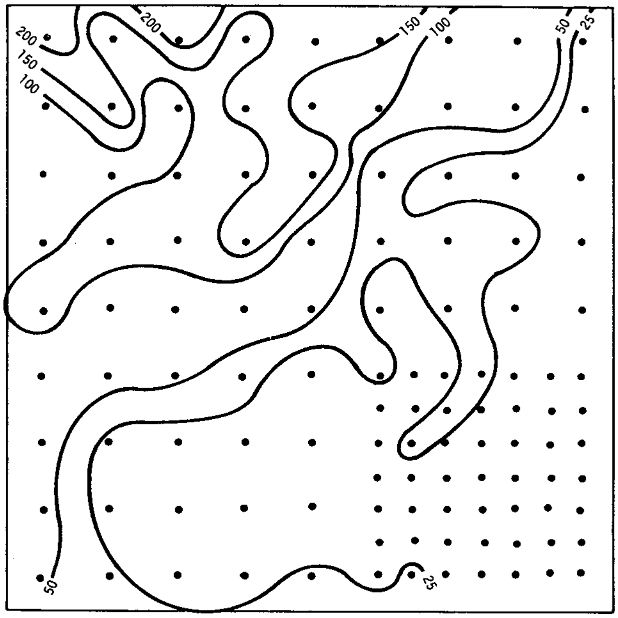

FIG. 8. Distribution of vertical kinetic energy ($J\ m^{-2}$) from storm of 22 July 1973.

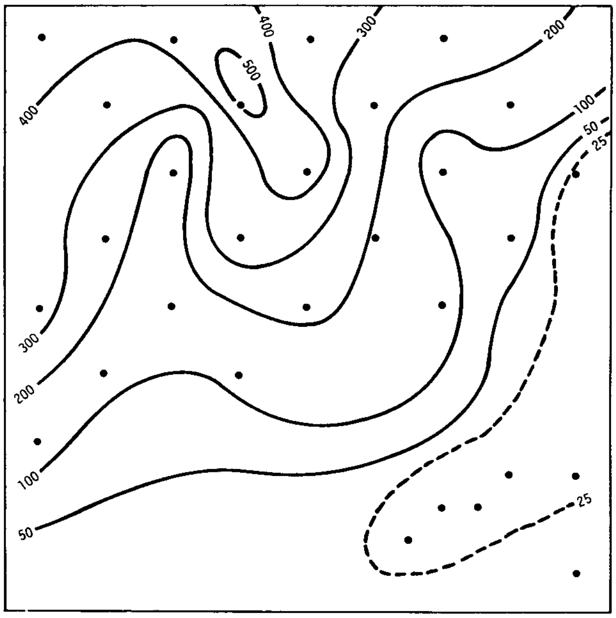

FIG. 9. Distribution of total kinetic energy ($J\ m^{-2}$) from storm of 22 July 1973.

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