Out-of-Level Instruments: Errors in Hydrometeor Spectra and Precipitation Measurements

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ABSTRACT

Meteorological instruments which are designed to measure the size spectra of hydrometeors such as hailstones or raindrops or instruments designed to measure cumulative precipitation such as raingages can produce errors if they are not installed and maintained with their sensing surfaces level. Errors from this source have generally been assumed to be negligible or ignored completely in most studies of rainfall and hailfall apparently because levelness is often taken for granted. This paper examines the effects on spectra and integrated precipitation measurements when the wind is blowing and the measuring instrument is out of level. Examples of out-of-level instruments are given based on National Hail Research Experiment hailpad data, data from the Illinois State Water Survey raindrop camera, and government-operated and volunteer-observer raingages. Raingages, for example, that are out of level by 2° in the presence of winds of 10 m s^{-1} can produce errors on the order of 9%.

1. Introduction

The size distribution of raindrops and hailstones is of considerable interest to meteorologists. Numerous instruments exist which are used to measure their spectra as well as their cumulative masses. For rain, the most frequently used instrument is simply a raingage, of which there are many versions. Raindrop size spectra have been measured using a variety of techniques over the past 90 years, starting with that introduced by Lowe (1892). Similarly, hail size distributions have been measured using a number of different devices, ranging from the simple hailpad (Schleusener and Jennings, 1960; Decker and Calvin, 1961; Wilk, 1961) to considerably more complex instruments (Towery and Changnon, 1974).

As pointed out by Waldvogel and Schmid (1982), the two major problems with the determination of rainfall and hailfall parameters by ground-based instruments are accuracy and the representativeness of such point measurements. Representativeness and sampling errors in precipitation measurements are often a major source of error and have been studied in detail by various authors (e.g., Gertzman and Atlas, 1977; Silverman *et al.*, 1981; Waldvogel and Schmid, 1982); they will not be considered further in this study.

Studies have also been made to determine the sources of errors and accuracies achievable with precipitation-measuring instruments. Sevruk (1982) recently examined errors for raingages caused by such factors as loss due to wind deformation above the gage orifice, losses from wetting on internal walls of the collector and in the container when it is emptied, loss due to evaporation from the container, splash out and splash in, and, for snow, from blowing and drifting problems. Errors from these sources ranged from 0 to 50% for certain conditions, with most errors in the 2 to 10% range.

Hailpads have also been well studied during recent years, even arousing enough interest to warrant special discussion at a workshop on hailfall measurement (Goyer, 1978). Long *et al.* (1980) examined various sources of error for hail pads, including the pad's construction materials, calibration, and data-reduction processing.

Despite all these studies, one source of error has been largely overlooked. This is the effect resulting from installing and/or using instruments which are out of level. The existence of this source of error should be obvious to all but the most casual observer; the quantitative and qualitative effects, however, have not been fully explored, apparently because levelness is often simply taken for granted. Sevruk, for example, never even mentions out-of-levelness as a possible source of error with raingages. If raingages are maintained perfectly level, there is no problem; as will be shown later, however, this is not always the case. The purpose of this paper is to examine some of the problems which result from instruments which are out of level.

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2. Theoretical considerations

The natural precipitation of raindrops, hailstones or any other particles which exhibit a spectrum of diameters is nearly always accompanied by a horizontal wind of some speed. Further, particles are virtually always falling at very near their terminal velocity which is a function of their size, density and shape and the density of the surrounding air. Thus, when hail, for example, is falling in the presence of a crosswind, the angle of arrival of each stone at the surface is a function of both its terminal velocity and the horizontal windspeed.

Two common and useful assumptions regarding falling precipitation are used in the following study. One is to ignore the effects of updrafts and/or downdrafts near the earth's surface. The second is that the particles are moving with the horizontal wind. While changes in the horizontal and vertical components of the wind do exist, especially near the earth's surface, falling particles adjust fairly rapidly to these changes and should usually be moving quite near the horizontal wind vector and their own terminal velocity. For example, a 1-cm diameter graupel particle starting from rest can reach about 95% of its terminal velocity in a fall of less than 15 m (about 2 s). Similarly, small adjustment distances should also apply in the horizontal, and the adjustment should take place in even shorter distances for smaller particles.

Consider now the three cases illustrated in Fig. 1. If a hailpad (or any other surface area) is perfectly level, then a unit area of space approaching the surface at angle ϕ will reach the surface with the same area (Fig. 1a). When the sensing surface is out of level by angle θ and aimed away from the wind, the effective cross-sectional area detected by the sensor is reduced; in the extreme case where $\phi = 90° + \theta$ (and θ is negative), the effective area reaches zero (Fig. 1b). On the other hand, if the sensor is aimed into the wind (positive θ) the effective area increases (Fig. 1c). If the actual area is A and the effective area onto which A is projected is A', the ratio of these is defined to be the normalized effective collection area A_e and is given by

$$A_e \equiv \frac{A}{A'} = \frac{\cos(\theta - \phi)}{\cos\phi}. \qquad (1)$$

Fig. 2 shows the normalized effective collection area as functions of the angle of incidence of a particle and the tilt angle of the instrument.

The angle of incidence ϕ is a function of the terminal velocity V_t of the particle and the horizontal windspeed W and is given by

$$\phi = \tan^{-1}\left(\frac{W}{V_t}\right). \qquad (2)$$

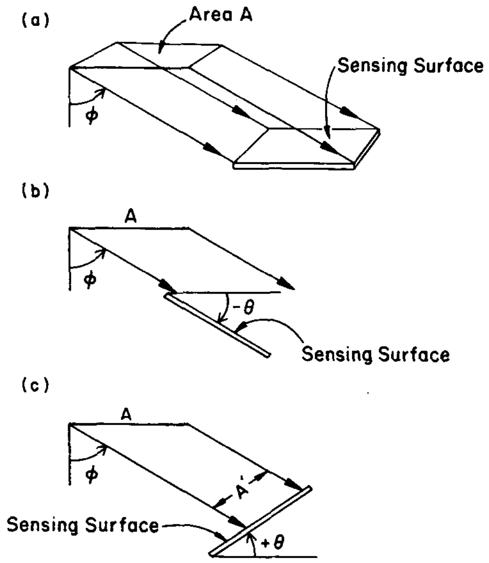

FIG. 1. Fall of a unit area of sample space onto an instrument which is (a) perfectly level (perspective view), (b) tilted away from the wind (side view), or (c) tilted into the wind (side view). The angle of incidence ϕ is measured from a vertical reference line and the tilt angle θ is measured from a horizontal reference.

Terminal velocities for raindrops have been measured experimentally by Laws (1941) and by Gunn and Kinzer (1949). Foote and duToit (1969) have fit the terminal velocities of Gunn and Kinzer with third, fifth and ninth degree polynomials, each of which gives progressively better fits to the original experimental results. For hailstones, the terminal velocity is usually approximated by an equation of the following form:

$$V_t = kD^{1/2}, \qquad (3)$$

where D is the hailstone diameter (cm) and k is an empirical constant. For northeast Colorado, $k = 11.45$ m s^{-1} cm$^{-1/2}$ (Matson and Huggins, 1980).

Raindrop and hailstone size spectra are often expressed in exponential form because of the ease with which these may be manipulated analytically and because these spectra are often approximately exponentially distributed. These spectra take the form

$$N(D) = N_0e^{-\lambda D}, \qquad (4)$$

where λ and N_0 are empirical constants and $N(D)$ is the number of particles of diameter D in a specified size interval. For hail the interval is typically 1 to 10 mm while for rain it may be 0.1 mm.

The effect of a tilted instrument is to modify the size spectra sampled in a way which changes the effective sampling area. Thus, we can combine Eqs. (1), (2) and (4) along with the expression for terminal velocity appropriate to the hydrometeor particle type to give the modified spectra resulting from using an instrument which is out of level, *viz*

$$N'(D) = N_0e^{\lambda D}\frac{\cos[\theta - \tan^{-1}(W/V_t)]}{\cos[\tan^{-1}(W/V_t)]}. \qquad (5)$$

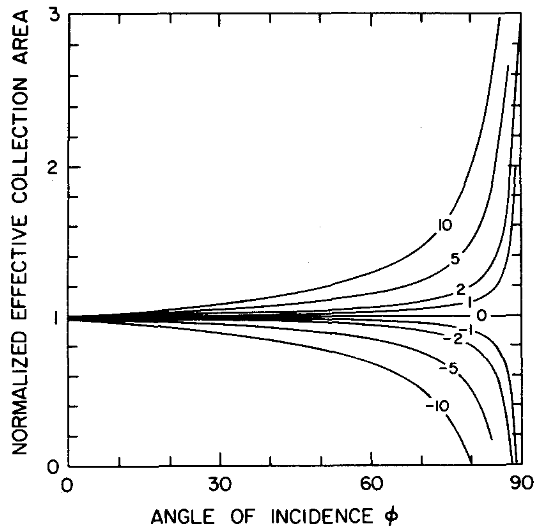

FIG. 2. The effects of instrument tilt angle and angle of incidence of precipitation on the effective collection area of an instrument. The angle of incidence depends upon the windspeed and terminal velocity of the particle. The individual lines are marked with the tilt (degrees) of the instrument and follow the sign convention introduced in Fig. 1.

As an example of the effects of wind and hailpad out-of-levelness on a hail spectrum which is initially exponential, consider Fig. 3. It shows the effects of a 20 m s^{-1} crosswind and various hailpad tilts for an exponential distribution having $\lambda = 4.56$ cm^{-1} and $N_0 = 18.5$ m^{-3} cm^{-1} where these values are averages from 24 hail spectra measured by Federer and Waldvogel (1975).

Given that we know the size spectrum of rain or hail, there are other properties about the event which may be of interest. For rain we are often interested in the rainrate and the total accumulation. For hail our interest extends to knowledge of the momentum and kinetic energy of the hailfall. Each of these is calculable from basic physics and the size spectrum. As an example, let us consider rainrate. It is simply the integrated mass of rain hitting a unit area in a unit of time but expressed in terms of depth, i.e., mm h^{-1}. In equation form it is

$$R = \int_0^{D_{\max}} \frac{\pi}{6} N(D) D^3 V_t dD, \tag{6}$$

where $D_{\max}$ is the largest diameter raindrop in the sample (and all other terms are as previously defined).

The effects of out-of-level instruments is of most importance for size spectra measurements. The magnitude of the bias, as already shown, depends upon both the windspeed and the tilt of the instrument. Under calm conditions or with the wind blowing perpendicular to the axis of maximum tilt, no error would occur. The effects are somewhat less important (but still not negligible) for parameters which depend upon higher powers of diameter than does the number distribution. This is because the values of such higher-power parameters are dominated by the contributions of the larger particles whose concentrations are affected by out-of-levelness comparatively little. Fig. 4 shows the cumulative fraction of various parameters as a function of the hailstone diameter for an exponential spectrum. The parameters are (with the power of diameter upon which each depends indicated in parentheses after each parameter): The number N of stones per unit volume (1); the rate R at which stones of a given size and smaller hit the surface per unit time (3.5); the hail content W of a unit volume of space, e.g., g m^{-3} (4); the hailfall rate, H e.g., mm h^{-1} (4.5); the kinetic energy KE (5.5); and the radar reflectivity Z (7). Those parameters which depend upon higher powers of diameter should be affected the least by an instrument being out of level. However, in all cases there would be some effect.

3. Results

a. *Example of a problem for hail spectra from hailpad data*

While the results of Eq. (5) and Fig. 3 suggest that out-of-level instruments might be a problem, are hailpads or other instruments actually enough out of level during real situations to cause a problem? To answer this question, let us first examine some hailpad data collected during the 1975 field season of the National Hail Research Experiment (NHRE) conducted in northeast Colorado. During this year NHRE had 25 pairs of hailpads set up along a single line with pairs being spaced at about 3 m intervals and the individual

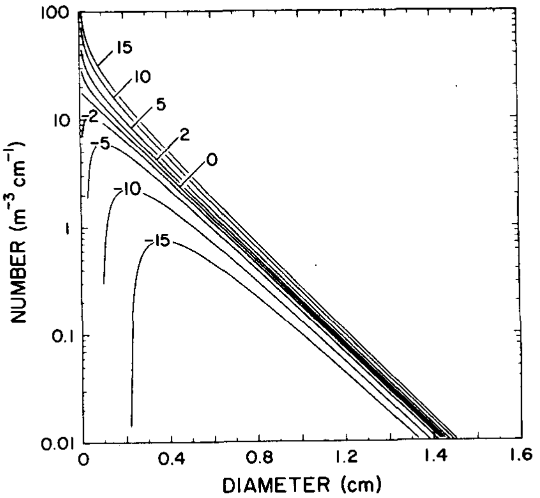

FIG. 3. The effects of various hailpad tilts on a hailstone size spectrum which is initially exponential (the central straight line). Tilt angles (degrees) are marked on each curve.

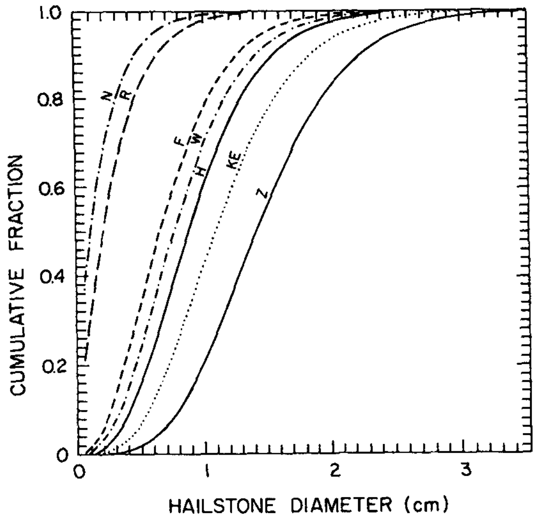

FIG. 4. Cumulative distribution of various hail spectra properties as a function of hailstone diameter for the same spectrum as used in Fig. 3. The individual curves represent the number distribution *N*, the rate *R* at which stones are hitting the surface, the fraction *F* of all area being hit which is hit by stones of a given size or smaller, the hail water content *W*, the hail rate *H*, the kinetic energy *KE*, and the reflectivity *Z*. The diameter for each parameter at 0.5 cumulative fraction is the "median-parameter diameter."

pads in one pair being about 1 m apart. On two occasions the tilt and orientation of each of these pads was measured with the aid of a level laid across the pads in east–west and again in north–south directions.

Fig. 5 shows the computed tilt angles for 14 and 17 July 1975. The average scatter along the least-squares best-fit line is about 0.3°. This may be an indication of the accuracy obtainable in the measurements or it may be caused by real day-to-day variations in the actual tilt. In either case, this 0.3° variation is not excessive. What is disturbing is that the average out-of-levelness is as large as it is (about 1.8° and 2.1°, respectively, on the two days) and that the extreme value is over 7°. This is especially disturbing since these pads were located at the main field site of NHRE where they would presumably be under close scrutiny; elsewhere the problem could be much worse.

One other observation that can be made from Fig. 5 is that the trend appears to be that the pads are getting more out of level at a rate of about 0.03° per day. The means of the samples are statistically significantly different at the 2% significance level. This suggests that these pads should have been checked and/or releveled approximately monthly to prevent them from becoming more than a degree out of level, assuming that they were perfectly installed. Similar rechecking would also be advisable for other instruments.

If the pads are out of level in random amounts and along random directions and if the amount by which pads are out of level is not too large, the cumulative effects of this source of error should tend to cancel out. Unfortunately, if the direction in which pads tilt is itself a function of windspeed and direction, pads might lean in some nonrandom direction. Figure 6 shows that the distribution of direction of the axis of maximum tilt for the 50 NHRE pads was not at all random. Apparently something such as an earlier windstorm had acted to give a rather biased distribution of tilt directions. It is also possible that, because of the sloping ground where the pads were installed, they may have been visually "leveled" with regard to the nearby terrain and not to a truly horizontal reference; this could also give a nonrandom distribution of tilt orientations. The use of a level instrument for installing and servicing hailpads and raingages would avoid this potential problem.

There should probably be little effect from this source of error on the results of hail suppression experiments unless the experimental evaluations depend heavily upon the numbers of small stones. Experiments evaluated on the basis of kinetic energy or other more global parameters should not be biased

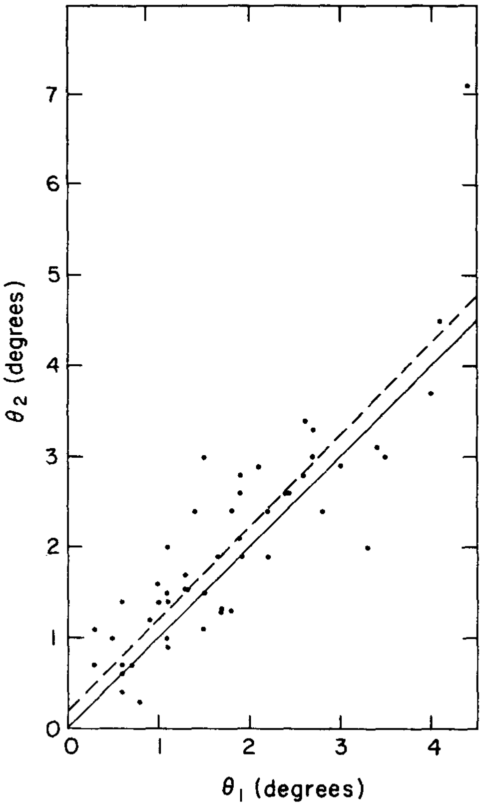

FIG. 5. Measured tilt angles for 50 hailpads on 14 July 1974 (abscissa) and again on 17 July 1975 (ordinate). The one-to-one line (solid) is shown along with the least-squares best-fit line (dashed) $\theta_1 = 0.17° + 1.02\theta_2$.

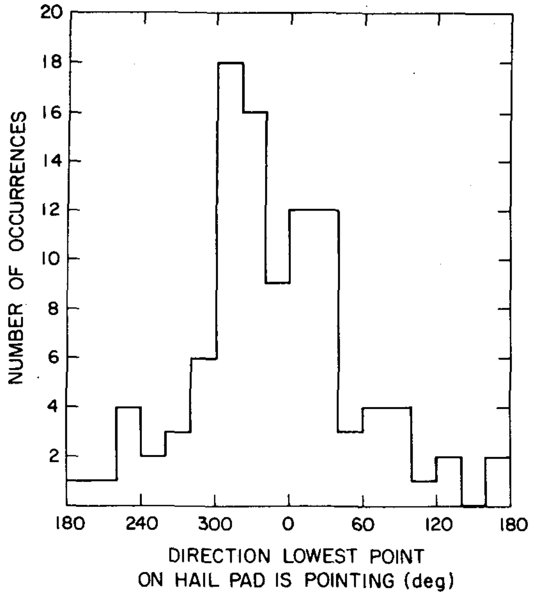

FIG. 6. Distribution of the direction of tilt for the 50 pads used in Fig. 5.

significantly from this effect. This is especially true if the same hailpads or instruments are used for both seed and no-seed data. The use of hail spectra from target/control type experiments, however, might have slight effects resulting from different tilts and/or winds in each of the two areas.

b. Example of a problem for raindrop spectra from raindrop camera data

Size sorting of particles because of winds may also be a significant source of error in the raindrop spectra data collected with the raindrop camera operated during the 1950's and 1960's by the Illinois State Water Survey (Jones, 1959; Mueller, 1966). In this camera (see Fig. 7) the raindrops fell through a separation between two sections of the camera body. When the wind blew directly through this opening, no problem existed. When the wind blew normal to this opening, a size sorting of the drops likely occurred such that the smaller particles were reduced in number relative to the larger particles. Raindrop size spectra from this camera were log-normally distributed most of the time (Mueller, 1966); this is exactly the direction that this size-discrimination effect would act.

Fig. 8 shows the useful collection volume as functions of raindrop diameter and windspeed calculated for this camera's 14 inch by 30 inch aperture (assumed to be rectangular in shape rather than cylindrical for this analysis). It assumed that the winds were approaching along the camera body normal to the aperture, i.e., the worst case situation, and that the wind was unmodified by the presence of the camera itself. In reality, the camera probably produced a "wind shadow" such that small drops could fall farther through the sensing volume than the calculations allow. Fig. 9 shows the resultant modification to an exponential size spectra for the same conditions. It clearly

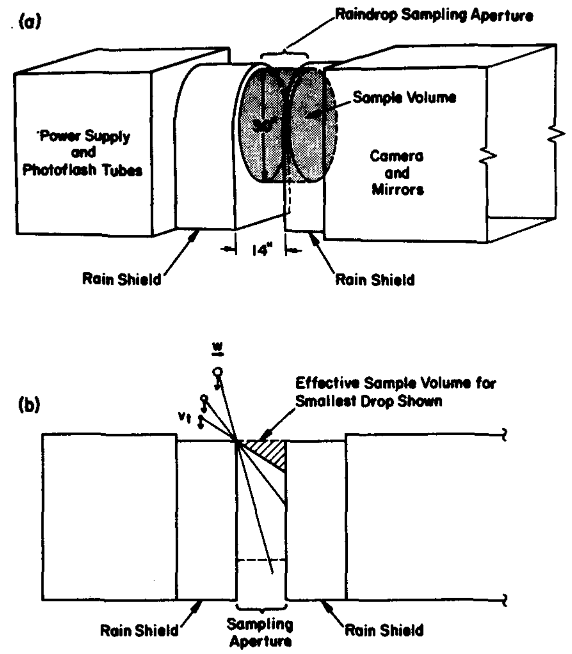

FIG. 7. Schematic drawing of the raindrop camera showing (a) a perspective view of the sampling volume and its relationship to the major camera components and housings and (b) a side view of the sample volume indicating how the effective sample volume changes with drop terminal velocity for a given windspeed.

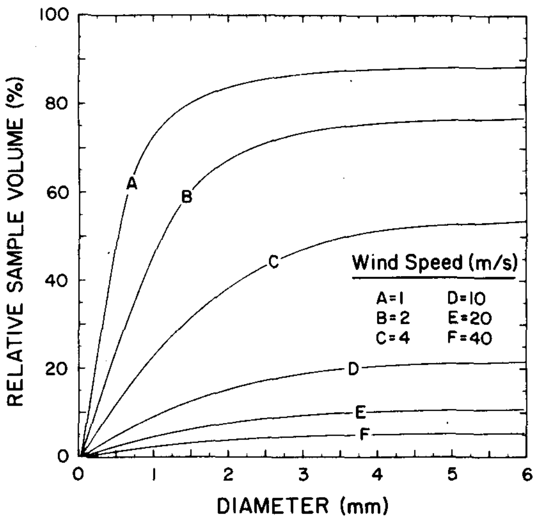

FIG. 8. The effect of windspeed and raindrop diameter on the useful sample volume of the raindrop camera, assuming that the wind is blowing along the length of the camera, i.e., the worst-case situation.

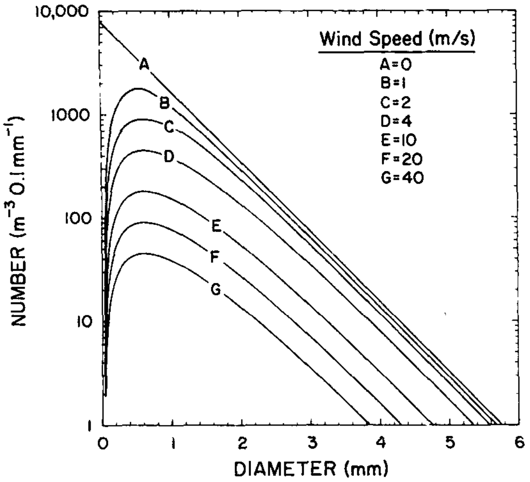

FIG. 9. The effects of windspeed on an initial exponential raindrop distribution sampled by the raindrop camera. The exponential distribution is a Marshall-Palmer distribution for a rainrate of 100 mm h^{-1}.

shows that an exponential distribution can be converted to a log normal-like distribution. The peak of the modified distribution shown, however, is below the typically observed peak at similar rain rates.

An even more disturbing feature of Figs. 8 and 9, however, is the rather severe reduction in the numbers of even large drops under fairly light winds. Winds of 5 to 10 m s^{-1} are not at all uncommon when it is raining. If the median volume diameter is, say, 2 mm and the wind normal to the camera's aperture is 10 m s^{-1}, the drop camera would sample only 15% as many raindrops as existed in the true distribution. On a logarithmic scale this would be an 8 dB decrease. This effect could obviously have serious implications on any comparisons between drop camera data and radar data.

This wind-sorting effect should be related to the sine of the wind direction relative to the camera's aperture. For the number of drops sampled to be reduced to no more than ½ their initial value requires that the wind direction be within about ±25° either side of the camera. If wind directions are random, this would occur about 28% of the time. Thus, the effects shown in Figs. 8 and 9 are probably about ¼ greater than those that might have existed for average wind directions.

c. *Example of a problem for rainfall from raingage data*

If we compare the results of calculating the rainrate from Eq. (6) with the results of using a size spectra modified by Eq. (5) under various conditions of tilt and wind, we can determine the error a raingage might experience for these conditions. Figure 10 shows the results of such an analysis for a Marshall and Palmer (1948) drop-size distribution for a rain rate of 100 mm h^{-1} under various gage tilts and with winds up to 40 m s^{-1} blowing directly along the axis of maximum tilt, with the gage either tilted into or away from the wind. It used the third degree polynomial from Foote and duToit (1969) fit to the measurements of Gunn and Kinzer (1949) to calculate the terminal velocities. A careful examination of the zero velocity line shows that there is an increasing error with increasing tilt in the complete absence of wind. This is simply due to the fact that the collection cross-sectional area for raingages decreases with the cosine of the tilt of the gage.

The results shown in Fig. 10 indicate that relatively small tilts and relatively light winds can produce significant errors. For example, a gage which is out of level by 2° with wind of 10 m s^{-1} (blowing along the direction of maximum tilt) can produce errors on the order of 9%. Under conditions of stronger winds, the errors can become very large, especially if the gage is out of level by more than a couple of degrees.

To determine the possible extent of this source of error on real rainfall data, a number of raingages were examined for levelness. Of the 19 gages examined, 7 were run by various government agencies while the remaining 12 are part of an informal network of volunteer observers in the Boulder, Colorado, area. All of the volunteers could be classified as professional (or very interested amateur) meteorologists.

Fig. 11 shows the distribution of the number of gages as a function of out-of-levelness. The average tilt of all government gages was 1.6° while that for the volunteers was 2.7°, giving an overall average of 2.3°. Because of the relatively small sample size used, this average may not represent the true average of all gages particularly well. It also likely underestimates the ex-

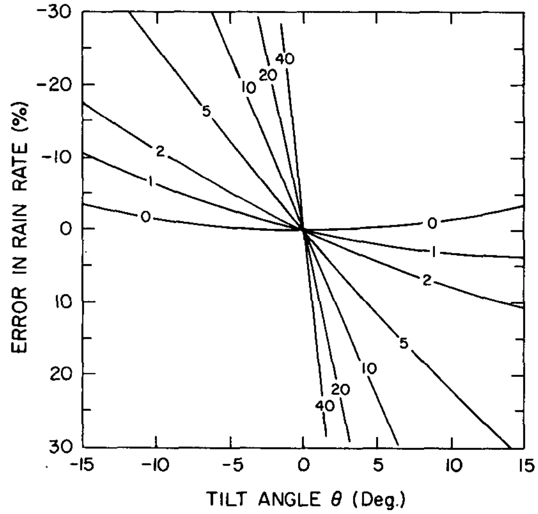

FIG. 10. The effects of windspeed and raingage out-of-levelness on the percentage errors produced. These results assume a Marshall-Palmer size distribution for a rainrate of 100 mm h^{-1} and used the third-degree fit from Foote and duToit to the Gunn and Kinzer terminal velocity measurements. Wind speeds (m s^{-1}) are marked on each line.

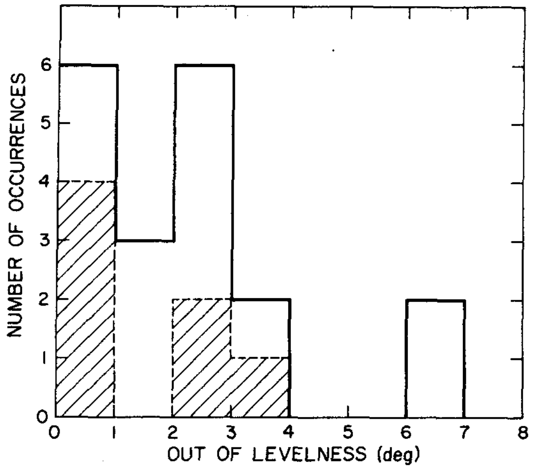

FIG. 11. Distribution of the number of gages found to be out of level by the amounts along the abscissa. Government-operated gages are marked with cross hatching while those from the volunteer network are plain.

treme tilts which probably exist at some gages. Nevertheless, it does suggest that many gages are not quite level and that some are so far out of level as to produce sizeable errors for some rain and wind conditions.

4. Conclusions

Instruments which are out of level can distort the size spectra sampled. The magnitude of this distortion depends upon the relative magnitudes of the terminal velocity of the individual particles, the windspeed, the angle between the wind and the direction of the axis of maximum tilt of the instrument, and the tilt of the instrument. Small particles in moderate to strong wind situations will be the most affected.

Measurements of actual hailpad levelness suggests that even closely supervised installations can suffer from poor pad installation and/or maintenance. Temporal changes likely degrade these orientations even farther. Further, the pads can, as was found in the 1975 NHRE data, have definite nonrandom orientations. This could introduce a bias into some calculations made from such data.

Wind sorting of raindrops photographed by the Illinois State Water Survey raindrop camera may have significantly reduced the numbers of all size raindrops whenever the wind did not blow directly through the camera's aperture. Again, this would be most important for the smallest sizes.

Raingages which are out of level by as little as 1° or 2° can produce errors of a few percent under moderate to strong wind situations. Errors from this source may be as large or larger than those from other sources considered in earlier studies. A sampling of both government-operated raingages and some unofficial gages of professional meteorologists found an average out-of-levelness on the order of 2.3°, with extreme tilts up to 6.7°.

It is important that raingages, hailpads and other instruments designed to measure the spectra and cumulative amounts of rain and hail be carefully leveled. While slight misalignments produce negligible errors, larger degrees of out of levelness can be significant. Since this source of error should be under the control of a well-managed data collection program, efforts to eliminate out-of-levelness as a problem would be worthwhile.

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