Behavior of Dust Devils

Ronald L. Ives
Department of Geography, Indiana University, Bloomington, Ind.

Abstract

Behavior of dust devils in several parts of North America is outlined; field data are presented; and the geneal behavior of dust devils in these areas found to be in substantial accord with physical theories presented by Humphreys.

Dust devils, also known as *sand devils*, *dust whirls* and *diablos*,[1] have been described by many explorers and geographers, but have received little attention from meteorologists, possibly because these wind features are most frequent where human activities and occupation are least.

Data here presented are based on visual observation of several thousand dust devils in arid regions between Guaymas, Sonora, and Medicine Hat, Alberta; and on numerous instrumental observations in the Utah Desert area. Findings during this study are in substantial accord with previous ones as reviewed by Humphreys (1940).

General Description

A typical dust devil is a small whirlwind, shaped roughly like a cone, with the apex near or at the ground surface, and the base some distance above ground level. Dust, which makes this transitory wind feature visible, is of local origin, and apparently is an incidental component, having little influence on the mechanics of the atmospheric vortex. A typical dust devil is shown in Figure 1. Although nearly all dust devils resemble an inverted cone, extreme variations in height, and in the height-basal diameter ratio, are encountered in the field.

Trajectories

Study of the trajectories of dust devils discloses that they have many forms of motion, ranging from substantially zero through "pure random" to several systematic forms. Complicated "mixed cases" are frequently encountered, as are non-random motions, which cannot be accounted for with any confidence by application of known principles.

Stationary Dust Devils.—Occasionally a dust devil will migrate to, or originate over, a small topographic "high," and there "camp" for an extended period; usually removing all loose dust and other light debris from the immediate vicinity. This commonly occurs, in flat desert areas, over large anthills. An extreme case was observed some years ago, during the construction of a large railroad embankment near Altar, Sonora. In midmorning, a large dust devil suddenly appeared at the end of the embankment, and removed therefrom approximately one cubic yard of sand per

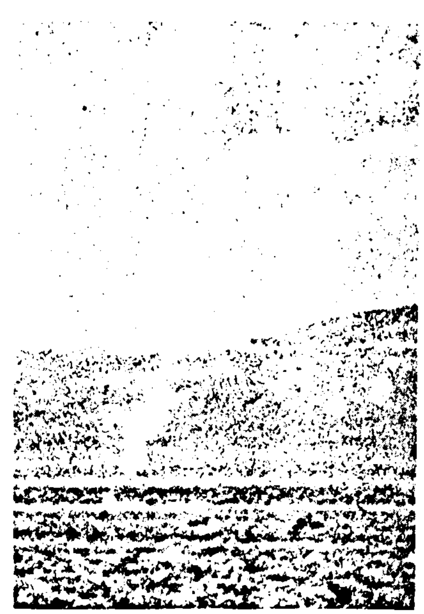

Fig. 1. A typical dust devil, approximately 2,000 feet high, in the Dugway Valley, Utah. The base is just above the Stansbury shoreline. Motion of the dust devil is from left to right in this view.

[1] The term *diablo* is current among Spanish-speaking people. A few Indians along the shore of the Gulf of California call these same whirlwinds *molinas de arena* (sand-mills), a term possibly learned from Spanish Jesuits in the late 1600s, who taught an abridged form of Spanish in the area.

hour for four hours. Erosion was halted, and the dust devil broken up, by parking a bulldozer at the end of the fill. A similar case, reported by Picete from the vicinity of Cairo, Egypt, is cited by Humphreys (1940, p. 153).

Migratory Dust Devils.—Commonly, dust devils are not stationary, but move slowly and erratically in a fairly definite direction. In some instances, this direction is determined by a small topographic ridge, such as a railroad embankment, road fill, or ancient bar. More often, the net travel of a migratory dust devil is about the same as that of the local wind, although the total travel of the base of the dust devil, apparently due to pure random wanderings of the axis, is usually considerably greater, as is indicated in FIGURE 2.

Systematic Dust Devil Motion.—In a few dish-shaped playas, dust devils follow a regular spiral course, on windless days. This behavior has been observed in the Ajo Valley (centered about Lat. 32°25′ N; Long. 112°48′W), Arizona, and Saline Valley (centered about Lat. 36°40′N; Long. 117°35′ W), California, by the writer, and has been reported to him as occurring in several circular playas in central Nevada. This motion is diagrammed in FIGURE 3. Rotation of the path of the dust devils, in both areas observed, was always counterclockwise, although the vortices rotated either way, and in some instances (apparently) reversed direction after passing over small obstacles. In the Ajo Valley,

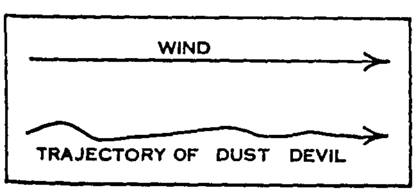

FIG. 2. Trajectory of dust devil when migrating under influence of wind.

several dust devils, in the same track, but several circuits apart, may be present simultaneously. This was not seen in Saline Valley.

Trajectory Controls.—Field observations indicate that the trajectory of a dust devil is largely controlled by local topography where there is little or no regional wind; but that, when regional wind reaches a definite speed, approximating three miles per

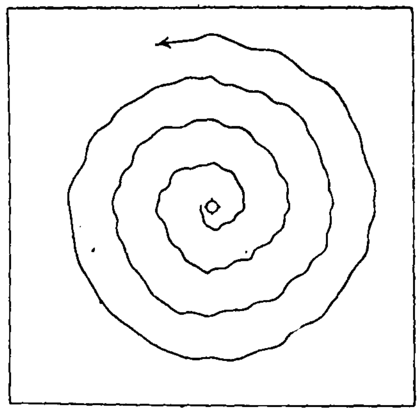

FIG. 3. Trajectory of dust devils in windless weather in a circular playa.

hour in many areas, the wind, and not the local topography, becomes the main controlling factor.

At the peripheries of some desert basins, such as the Pahranagat and Snake Valleys, in southeastern Nevada, and Darwin Wash, California, local canyon winds, of convectional origin, modify dust devil trajectories markedly.

FAVORABLE GEOGRAPHIC CONDITIONS

Dust devils are most frequently seen in broad arid basins, where there is little surface vegetation, and much loose *surface* dust. This dust layer need not be thick, there being enough dust on many supposedly bare rock surfaces, such as the Snake River lava plain (southern Idaho), or the Pinacate lava field (northwestern Sonora), to make dust devils clearly visible.

Dust devils are rarely seen in areas of deciduous forest, well watered grasslands, salt marshes, or over lakes. Where local relief is considerable, as in badlands, dissected plateaus, or mountains, they are seldom reported.

FAVORABLE ATMOSPHERIC CONDITIONS

In geographically favorable areas, dust devils occur most frequently in clear weather, METRIC

m	C	ΔT(c)
0	71.1	32.0
0.3	61.1	22.1
1.5	46.7	7.7
152	37.8	3.9
610	33.3	

when the surface has been heated for some hours, and when there is little surface wind. Under these conditions, the surface air is very hot with respect to that a few hundred feet aloft, and the lapse rate, near the ground, is decidedly superadiabatic. Typical favorable conditions, measured during a "Great-Basin-High" regime, are: surface temperature, 160°F; one foot above surface, 142°F; five feet above surface, 116°F; 500 feet above surface, 100°F; 2,000 feet above surface, 92°F; "rough air" at 2,500 feet.[3]

These atmospheric conditions, both in theory and in the field, are the same as those favoring development of inferior, or "water" mirages (see Humphreys 1940, p. 151).

Field Observations

Although dust devils occur in many parts of the world, in a variety of environments, their behavior, wherever noted, is about the same, as are the dimensions, and other factors involved. A large part of the observational data here presented, and all of the instrumental data, was obtained in the Salt Lake Desert, Utah. So far as can be determined from numerous observations elsewhere, all dust devils are dynamically similar.

Relation to Mirages.—Identity of conditions favoring occurrence of dust devils and of inferior mirages has been mentioned previously. When a dust devil occurs in a mirage area, the reflective surface is disrupted near the base of the vortex (which is approximately the apex of the inverted cone), and the dust devil apparently "eats a hole" in the mirage. This is shown schematically in Figure 4, the actual boundaries as seen being somewhat indefinite. Length of the "window" along the trajectory of the dust devil is commonly from 200 to 1,000 feet; width is commonly 100 to 500 feet.

A dust devil can sometimes be started by creating a minor disturbance in a mirage, as by firing a mortar shell into the "lake," or by driving a jeep through it. In some instances, the path of a medium-sized animal, such as a jackrabbit or a coyote, across the desert, is marked by a succession of small dust devils. It is quite possible, although not conclusively shown by field observations, that most dust devils are "started" by small animals.

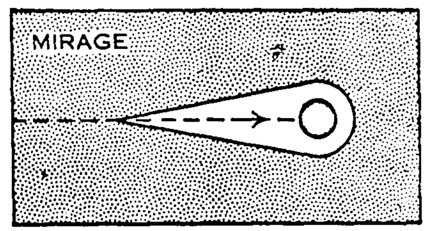

Fig. 4. "Hole" or "window" in mirage produced by dust devil.

Usual Dimensions.—Heights of dust devils range from a few feet to a few thousand feet, values exceeding 2,500 feet being uncommon. Major diameters ("top") are almost invariably less than half the height; and are usually less than one-third of that dimension.

In semiarid areas, or localized dry areas in humid regions (such as plowed fields or new fills), dust devils rarely exceed 100 feet in height.

In many areas of true desert, heights average about 600 feet. This limit is reached in many parts of the "Dust Bowl," in the Red Desert of Wyoming, and in the Pecos Valley of Texas.

Where aridity is extreme, and vegetation nearly or entirely lacking, as in parts of the Salt Lake Desert, Death Valley, the deserts bordering on the Gulf of California, and parts only of the Atacama Desert, visible heights of from 2,000 to 2,500 feet are commonly attained.

Several dust-laden wind vortices, towering more than 5,000 feet above ground, have been seen by the writer in Baja California. These, which swept out over the Gulf and raised waterspouts, may represent a maximum development of dust devil action; or may have been tornados. As these disturb-

[3] The first three temperatures were measured with a fine-wire thermocouple, polished to minimize the effect of incident radiation. The two upper-air temperatures were measured with a slip-stream thermometer. Both thermometers were checked by comparison with a standard Weather Bureau station thermometer. A "boundary layer" condition is suspected at the surface.

creating a minor disturbance in a mirage, as by firing a mortar shell into the "lake," or by driving a jeep through it. In some instances, the path of a medium-sized animal, such as a jackrabbit or a coyote, across the desert, is marked by a succession of small dust devils. It is quite possible, although not conclusively shown by field observations, that most dust devils are "started" by small animals.

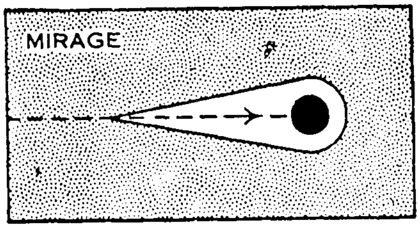

FIG. 4. "Hole" or "window" in mirage produced by dust devil.

Usual Dimensions.—Heights of dust devils range from a few feet to a few thousand feet, values exceeding 2,500 feet being uncommon. Major diameters ("top") are almost invariably less than half the height; and are usually less than one-third of that dimension.

In semiarid areas, or localized dry areas in humid regions (such as plowed fields or new fills), dust devils rarely exceed 100 feet in height.

In many areas of true desert, heights average about 600 feet. This limit is reached in many parts of the "Dust Bowl," in the Red Desert of Wyoming, and in the Pecos Valley of Texas.

Where aridity is extreme, and vegetation nearly or entirely lacking, as in parts of the Salt Lake Desert, Death Valley, the deserts bordering on the Gulf of California, and parts only of the Atacama Desert, visible heights of from 2,000 to 2,500 feet are commonly attained.

Several dust-laden wind vortices, towering more than 5,000 feet above ground, have been seen by the writer in Baja California. These, which swept out over the Gulf and raised waterspouts, may represent a maximum development of dust devil action; or may have been tornados. As these disturb-

ances occurred in early morning, immediately following a desiccating fallwind, and preceding a small hurricane, their classification is somewhat doubtful.[3]

Numerous observations, in areas of adequate dust supply, show that the visible top of a dust devil coincides quite closely with the level at which a large smoke column "mushrooms" after initial stabilization (FIG. 5). This elevation is also that of the base of a zone of extreme atmospheric turbulence, or "bumpiness," as determined by flying through it in a light plane. Lapse rate changes from distinctly superadiabatic below this turbulent zone to slightly subadiabatic (as shown by radiosonde observations) above it. In a few instances only, a weak inferior mirage was noted at this level.

Behavior with respect to Obstacles.—Dust devil trajectories are modified or interrupted by a number of obstacles, many of them topographically minor. Although each area has its own local peculiarities, the following generalities seem justified.

When a dust devil encounters a topographic high, it tends to climb to the summit, and then to "camp" there. The dust devil will not usually descend a slope, even if aided by a wind. It will, however, move

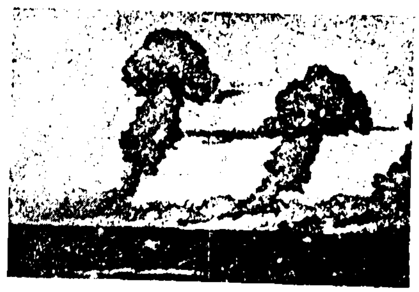

FIG. 5. "Mushrooming" of smoke columns. In many instances, the base of the "mushroom" coincides with the maximum level reached by dust devils.

across a slope with little deviation, unless influenced by a local wind.

When a dust devil encounters a topographic low of small dimensions, such as a ditch or small wash, it usually "jumps" the low, as in FIGURE 6. Some local modification of the trajectory may occur if the

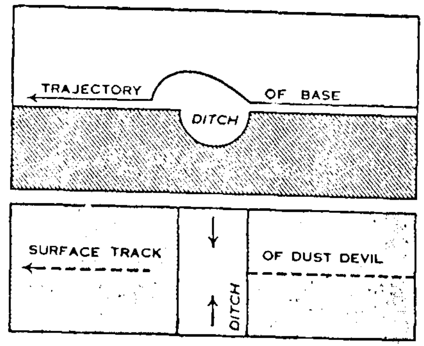

FIG. 6. Behavior of a dust devil when crossing a minor topographic low. Upper figure shows trajectory of visible base; lower figure shows surface track of dust devil. Arrows in ditch show direction of motion of debris (tumbleweeds) during passage.

angle between dust devil trajectory and ditch course is acute.

When a dust devil travels from a land area to a water surface, it becomes invisible, but the vortex does not necessarily dissipate immediately, and it may raise whitecaps or salt whirls for a short distance. Attempts to follow those vortices over water, by use of viewing devices, such as polarizing screens, were not entirely successful, but indicated atmospheric turbulence for some time after disappearance of normally-visible evidence of air motion. With one possible exception, previously cited, dust devils do not produce waterspouts when they travel out over water surfaces.

Duration and Length of Track.—Theoretically, a dust devil can continue to exist, if stationary, until it exhausts the available supply of heated air; and, if in motion, until it travels out of a favorable environment.

Favorable meteorological conditions, in high-latitude deserts, exist from about two hours after sunrise until a short time after sunset, or somewhat more than fourteen hours during the summer season. Consequently, the theoretical limit of the duration of a stationary dust devil in such an environment is slightly less than the length of

[3] Local Indian fisherman (mostly Yaquis) state that these disturbances precede and warn of hurricanes, and appear every fall except during the *año seco*. Although weather lore in this area is a weird mixture of keen observation, several Indian theologies, and much misunderstood science, forecasts by these Indian fishermen run about 70 percent accurate for minor features, and 90 percent for hurricanes.

the legal day. No dust devil seen by the writer, or reported to him, has even closely approached this limit; few have lasted for even half of this theoretical maximum.

A rough relation has been noted between the size of a dust devil and the time which it lasts. An average figure, based on observations in the Salt Lake Desert, is one hour of duration for each thousand feet of height, provided the dust devil, during this time, does not travel out of the favorable geographical environment, or into a cloud shadow.

Net length of trajectory of a dust devil migrating under the influence of wind can be determined by simple and obvious computations, but gross length, or total travel, is somewhat more difficult to compute. One carefully conducted set of measurements indicated the gross travel of a migrating dust devil was about 2½ times the net travel; while another series showed that the gross travel equalled the local wind speed plus 4½ mph. As the wind speed in the area where the tests were conducted was close to 3 miles per hour when dust devils were most numerous, it cannot be stated with any confidence whether gross dust devil travel is better expressed by CS or $S + K$, where S = wind speed, C and K are constants.

Dust devils with a height of about 2,500 feet (triangulated), a life of seven hours, and a net travel of forty miles have been seen by the writer in a few instances on the Bonneville Salt Flats in western Utah (see USC and GS *Salt Lake City* Sectional Aeronautical Map). Such development is exceptional even for this area, which is topographically and meteorologically extremely favorable to dust devil development. Net course and rate of travel in these instances was about the same as the local wind, and extinction of the dust devils was due to "running out of environment."

Vortex Conditions.—Attempts to measure the horizontal and vertical wind components in dust devils, by chasing them in a jeep, and inserting a portable airmeter into the vortex, disclosed that both the horizontal and vertical components exceeded 20 miles per hour, the limit of dependable indication of the airmeter.

Temperature measurements, made by inserting a thermocouple into the vortex, indicate that internal temperature is lower than that of external air by several degrees. This value may be as great as six degrees (F), although, because of the effect of vehicle vibration on the bridge galvanometer, and possible errors in placement of the thermocouple, considerable error is possible. In one instance where a dust devil passed over a fixed recorder, air temperature rose 2F° above its previous average value, then fell 5F° below it, and returned to the original value, all in one minute. Because of recorder damping, these values are not maxima. Initial temperature rise is tentatively attributed to friction of heated sand on the thermocouple.

A piece of metal inserted into a dust devil a few feet above the ground becomes strongly charged with respect to ground, the amount of charge and its polarity being apparently a function of the nature of the dust particles.

When an aneroid barometer was inserted into a dust devil, the indicated pressure rose slightly as the outer, dust-laden zone was penetrated, then fell markedly near the center, which is largely free of dust. Internal pressures from ½ to 2½ inches of mercury below those outside were indicated by this procedure.

Because dust devils carry various objects aloft, such as mice and tumbleweeds, another determination of the vertical wind component can be made on the assumption that the wind speed necessary to carry an object upward is not less than the maximum speed of free fall of that same object ("terminal velocity"). The largest object seen to fall from a dust devil being a kangaroo rat (*Dipydomys* sp.), the terminal velocity of this animal was measured by dropping several of them from the top of the control tower and timing the last 20 feet of fall. This was found to vary from 25 to 30 mph, the animal being apparently unhurt after landing, although usually very angry. This would indicate that the maximum upward component in a dust devil per hour, the limit of dependable indication of the airmeter.

Temperature measurements, made by inserting a thermocouple into the vortex, indicate that internal temperature is lower than that of external air by several degrees. This value may be as great as six degrees (F), although, because of the effect of vehicle vibration on the bridge galvanometer, and possible errors in placement of the thermocouple, considerable error is possible. In one instance where a dust devil passed over a fixed recorder, air temperature rose 2F° above its previous average value, then fell 5F° below it, and returned to the original value, all in one minute. Because of recorder damping, these values are not maxima. Initial temperature rise is tentatively attributed to friction of heated sand on the thermocouple.

A piece of metal inserted into a dust devil a few feet above the ground becomes strongly charged with respect to ground, the amount of charge and its polarity being apparently a function of the nature of the dust particles.

When an aneroid barometer was inserted into a dust devil, the indicated pressure rose slightly as the outer, dust-laden zone was penetrated, then fell markedly near the center, which is largely free of dust. Internal pressures from ½ to 2½ inches of mercury below those outside were indicated by this procedure.

Because dust devils carry various objects aloft, such as mice and tumbleweeds, another determination of the vertical wind component can be made on the assumption that the wind speed necessary to carry an object upward is not less than the maximum speed of free fall of that same object ("terminal velocity"). The largest object seen to fall from a dust devil being a kangaroo rat (*Dipydomys* sp.), the terminal velocity of this animal was measured by dropping several of them from the top of the control tower and timing the last 20 feet of fall. This was found to vary from 25 to 30 mph, the animal being apparently unhurt after landing, although usually very angry. This would indicate that the maximum upward component in a dust devil

exceeds 25 miles per hour. If, as has been reported by some desert residents, but not seen by the writer, cottontails and jackrabbits are carried aloft by dust devils, the upward component may exceed 35 miles per hour, the terminal velocity of a jackrabbit (which is stunned and internally injured on landing).

Occasional passage of dust devils over fixed wind recording stations gave indications of horizontal winds that accelerated from near zero (0–3 mph) to speeds of from 50 to more than 90 mph, and then returned to approximately their previous low value, all within 30–100 seconds. During this same interval, the wind vane made several complete revolutions. Speed traces overlapped when wind speeds exceeded about 90 mph, and the direction recorder did not respond to vane rotations at a rate exceedinig 10 rpm. In several instances, recorders were found with all bearings burned out, and all cavities packed with sand, due apparently to a dust devil "camping" at the instrument station.

Application of standard engineering computations to damage caused when large dust devils passed through an outdoor storage yard indicated that the maximum overturning force (the square root of the sum of the squares of the horizontal and vertical forces) in no instance equalled that produced by a wind of 150 mph; that the horizontal component exceeded the vertical; that the maximum force was concentrated in a path less than ten feet wide; and that wind speed 25 feet on each side of the central track in no observed instance exceeded 20 mph. The above computations were corrected for the altitude (4,300′ msl), but not for possible "rocking" or resonance effects.

Meteorological Significance

Both theory and field observations indicate that dust devils are normal phenomena in flat areas when wind speed is low and the lapse rate is steep. In most general terms, the frequency of occurrence of dust devils is a direct, but not simple, function of the magnitude of local thermal instability, not otherwise relieved. Vertical dimensions of dust devils are limited, at least in part, by the vertical extent of this instability.

In most desert areas, and some others, the net incident radiation is of such magnitude that air temperatures, if the surface air were confined, would exceed those actually recorded by many degrees. Disposition of this "entropic excess" is usually attributed to convective motions of the lower atmosphere. That these motions take place, and that their magnitude is sometimes very great, is amply shown by air currents in the immediate vicinity of cumuli. In most desert, and some other, areas, however, the magnitude of such convections is entirely inadequate to account for all thermal relief.

Where terrain is favorable, thermal relief is attained by lateral migration of heated air to cooler areas. The peripheral anabatic winds of some desert basins are an extreme development of this effect. With one or two doubtful exceptions in the Death Valley area, these also are of insufficient magnitude to bring about the known reduction of air temperature. They may, however, in some instances, cause as much as half of it.

If all thermal relief not otherwise accounted for is attributed to dust devils (or similar vortices, not necessarily visible), then they may be credited with a maximum relief of one-third of the total.

Field observations suggest, but computations do not conclusively demonstrate, that there is an upper limit to the amount of thermal relief which can be brought about by ordinary (or classical) convection, and a lower limit (perhaps 10F° lapse from surface to 100 feet above it) below which dust devils are negligible factors in thermal relief.

Conclusion

By application of physical theory to the sketchy data then available, Humphreys (1940, pp. 151–155), prior to 1928, outlined a theory of dust devil behavior which is supported by observations here described. Extension of this theory, to cover air motion within the vortex, should be practicable within the near future.

Field data here presented are regarded as a second approximation, probable error being between 10 and 20%. Further observations, to a higher degree of accuracy, should be made as soon as instrument developments make them possible.

Field instruments now (1946) available which are sufficiently portable for use in areas where dust devils are plentiful are, in general, too slow in their responses, and too subject to dust damage, to permit greater data refinements.

Relief of "entropic excesses" by dust devils in desert areas certainly occurs, but its relative magnitude, under a variety of conditions, needs more accurate determination; as does the magnitude of similar thermal adjustments, in nondesert areas, by whirlwinds similar to dust devils, but invisible because of lack of dust.

ACKNOWLEDGMENTS

The writer is indebted to Sr. Alberto Celaya, of Sonoyta, Sonora, R. M., for helpful environmental data; to Sr. José Juan, of Quitovaquita, Arizona, for informative descriptions of Indian forecasting methods; to Col. John R. Burns, CWS, for assistance with investigations in the Salt Lake Desert; and to Dr. S. W. Grinnell, of Stanford University, for helpful discussions of instrumentation and field problems.

REFERENCE

Humphreys, W. J. 1940. *Physics of the Air*, 3rd ed., New York, 1940, pp. 151–155.

Meteorology Articles for High-School Students

The March 3–7 issue of *Current Science and Aviation*, which goes to high-school students throughout the country, is devoted almost exclusively to meteorology. There are articles on "Radar and Weather", "Weather, Climate and Business", in which the American Meteorological Society's interest in industrial meteorology is quoted, "West Coast Weather Hop", "—Or Southeast Hurricane 'Op' ", "Arcata: Landing Aids Experiment Station", "Weather to Order". All articles are illustrated. In the section on "Science Activities" are presented 13 questions of fact, 10 questions for thought, 5 things to do, and references to 8 recent articles about weather. Also in "Sky Quiz" are 5 multiple choice questions, for example, "Atomic bombs may some day be used to control the weather, to make rain, or to smash hurricanes. True or false?" This is a question to which the meteorologists still do not know the answer. The illustrations include a rawin station, an automobile squashed by an uprooted tree, hurricane damage, maps of weather spots of the world and of the United States, showing the locations of the hottest, coldest, wettest, driest, snowiest, sunniest, cloudiest, windiest, and stormiest weather, a radiosonde balloon, a propeller type of air mixer for orchards to prevent frost, a wind vane-anemometer assembly, weather plane, radar landing apparatus, and the North American Aviation 75-ton steel "proving room".—*C. F. B.*

Weather Catastrophes

In the 10 years 1937–1946, there were 96 weather catastrophes in the United States causing 3,137 deaths, or 10.5 and 24.2% of the respective totals of all catastrophes in this period, according to a compilation of the Metropolitan Life Insurance Company, published in their *Statistical Bulletin*, Mar., 1947, pp. 1–4. By "catastrophe" is meant an accident or condition killing 5 or more people. There were 14 occasions when the loss of life was 100 or more, of which 6 were weather, ranking 1st (1938 hurricane, 682 lives), 3rd (1937 Ohio-Mississippi valley floods, claiming 360), 7th (Feb.–Mar. 1938, southern California floods, 181), 9th (1944, June 23 tornadoes in Pa., W. Va., and Md., 159), 11th (1945, Apr. 12, tornadoes in Okla., Mo., and Ark., 119), and 13th (1942, Mar. 17, tornadoes in southern and midwestern states, 111).—*C. F. B.*