weatherqueries

by John M. Brown

Q "How much rain is lost in a standard four-inch rain gauge when the wind is a steady 20 miles per hour? ... Does drop size matter?"

Dave Nolan
Johnson City, Tennessee

A Dave, the more general question of the impact of wind on rain-gauge catch is an important one because rain gauges are used as "ground truth" for precipitation amount falling in the form of liquid, that is, rain or drizzle. So, my approach here is to take on the more general question of the impact of wind on the catch of a rain gauge, and then to address your specific question. I will also restrict my discussion to the effect of wind on the catch of rain or drizzle and not deal here with the considerable complication wind adds to the measurement of snowfall.

Rain gauges provide point measurements of rainfall, that is, measurements at a particular location. So, for establishing the precipitation climatology of particular locations (for example, average monthly and annual precipitation), data from rain gauges is critical. In day-to-day NWS operations, rain-gauge measurements are typically combined with precipitation estimates from radar and sometimes satellite. These estimates can give a useful picture of the spatial variation of precipitation, which is necessary for the prediction of runoff and streamflow. There are usually not enough rain gauges to do this, especially when the rain falls from convective clouds and there are large local variations in rainfall. Using statistical techniques that account for the error characteristics of each instrument, radar–rain-gauge comparisons of rainfall at gauge locations can be used to adjust the radar estimates of rainfall so that they are reasonably close to rain-gauge measurements at the points where the gauge measurements are made. The areal estimate of precipitation so obtained is demonstrably more accurate than either an estimate using gauges or radar alone.

It is not surprising, then, that the sources of error in precipitation measurements by rain gauges have received quite a lot of attention. Wind is certainly an important consideration, and is the most important source of error aside from instrument exposure (location of the gauge with respect to trees and other vegetation, as well as buildings and other structures, roadways, etc.). It is my intention here to restrict attention to the effect of wind on the catch of the gauge, assuming that instrument siting and installation (for example, making sure the gauge is level) are done correctly.

Figure 1 shows a four-inch rain gauge recommended for use by Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) participants. The gauge itself is made of transparent plastic and has three pieces aside from detachable mounting brackets: the outer cylinder, the funnel that fits tightly on the top of the outer cylinder and which has a beveled sharp top edge with a four-inch diameter opening, and an inner tube that fits over the bottom of the funnel inside the outer cylinder and collects the rain. The inner tube, which has an inside cross-sectional area 1/10th that of the top of the funnel, magnifies the depth of rain that falls by a factor of 10, so that one inch of rain water in the inner funnel after a rain corresponds to 0.10 inch of rain. This makes for ease of measurement. If rainfall exceeds one inch, the excess overflows the inner tube into the outer cylinder.

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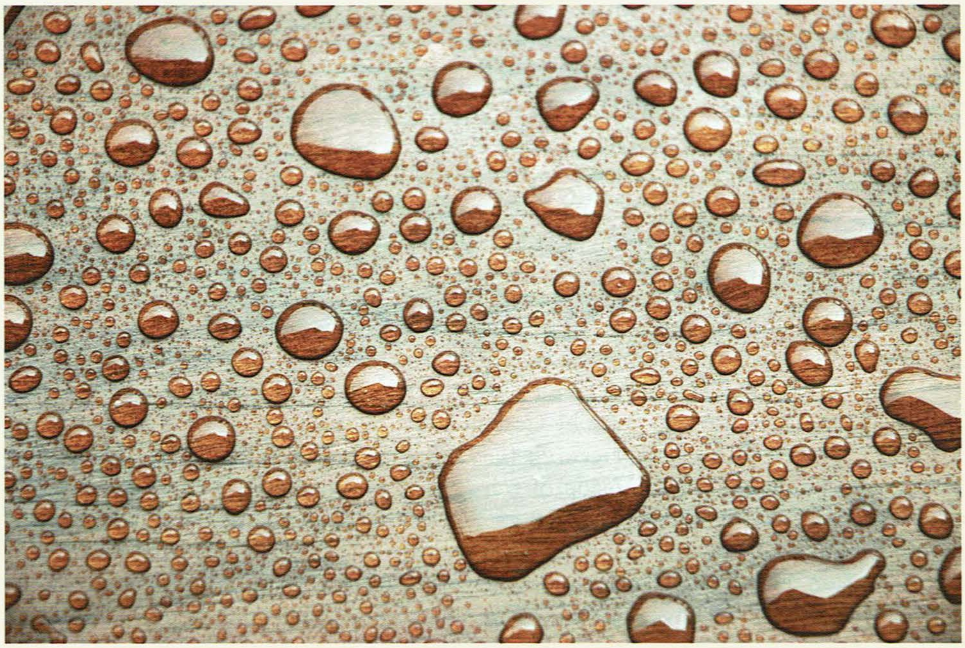
Figure 1. The type of rain gauge recommended by CoCoRaHS. The diameter of the funnel that catches the precipitation is four inches. The mounting brackets used to attach the gauge to a fixed object are on the right side of the outer cylinder.



such that the parcel accelerates toward the lower pressure and away from the higher pressure.

As a result of the gauge obstructing the flow, there is higher pressure on the upwind side of the gauge than away from the gauge or on its downwind side. It turns out that the magnitude of this pressure perturbation is roughly proportional to the square of the wind speed, so that a 20-mph wind will be associated with a pressure perturbation by the gauge four times larger than that with a 10-mph wind. Because this pressure perturbation is not confined to the immediate proximity of the gauge, but extends some distance from it, the flow is affected by the gauge at some distance around and above it, and it is this disturbance in the flow that is of central importance to our question.

So how does wind affect the "catch" of rain by a rain gauge? Air in motion has momentum. This means it will move in a straight line unless there are forces acting upon it to slow it down, speed it up, or change its direction of movement. It is often convenient to argue from the perspective of small portions of air (sometimes referred to as "air parcels"). Air, being a gas, is composed of molecules that are in a constant state of agitation and are colliding with one another. However, there are so many of them so close together under conditions that exist through much of the atmosphere that their individual random motions average out and the air can be considered a continuous fluid. An air parcel can be thought of as being big enough (but still smaller than a small insect) that the air molecules within it stay within it and the parcel can then be treated dynamically as a "thing" (like an air bubble) moving at a certain speed in a certain direction. The "wind," then, can be thought of as a bunch of air parcels moving in a certain direction (the direction toward which the wind is blowing).

Consider what happens when the wind is blowing, and there is a rain gauge, as in Figure 1. The air parcels approaching the gauge on the upwind side can't go through the gauge. (If they are going fast enough, they could conceivably knock it over, but we will assume that the rain gauge mount is sufficiently sturdy that this possibility can be ignored.) The air parcels can't go through it, but they can go over it, they can go under it (depending on how it is mounted), they can go around it. But, in order for this to happen, they must experience a change in their direction and speed of motion, and this requires a force to act upon them. We call this force a pressure-gradient force because the force results from the air pressure on one side of the parcel being different from that on the other side,

Regardless of how raindrops form (a complex subject beyond the scope of this discussion), what we really want to know is how much water actually reaches the ground. As drops of rain or drizzle fall to earth, they can be assumed to fall at their terminal speed, that is, the speed at which the downward acceleration due to gravity is balanced by the upward acceleration induced by the aerodynamic drag of the air on the drop. Since this aerodynamic drag is roughly proportional to the surface area of the drop, and the gravitational acceleration of the drop is proportional to its mass (or, equivalently, its volume, since its density is constant, being that of water), larger raindrops fall faster than small ones. Cloud (or fog) drops, typically of size about 0.01 or 0.02 millimeters in diameter, hardly fall at all, but travel with the air in which they are embedded. This is why we observe fog swirling around obstacles and otherwise revealing turbulent motions of the air. Drizzle drops, of size 0.1 to 0.5 millimeter, do fall, but at speeds that may be difficult to detect without careful observation, especially if it is windy. Your umbrella has some utility in drizzle if the wind is light, but even a light breeze can on occasion take drizzle drops and carry them under your umbrella. Rain drops on the other hand can fall at speeds up to eight or nine meters per second, which is faster than most humans can run and fast enough that it is very obvious that they are falling, and an umbrella offers protection unless the wind is strong.

Small drops are most affected by the flow of air around the rain gauge, causing some (or even all) to miss the funnel completely. The presence of wind itself does not change the amount of rain that reaches the ground, but it can affect the amount that we think falls on the ground, based on a rain-gauge measurement. So, yes, as Dave suggests, drop size does matter.

How has the impact of wind on the catch been investigated? The standard for rain gauges is known as a "pit gauge." As the name implies, building a pit gauge involves digging a shallow pit in the ground and collecting the rain in a container that fits into this pit. The pit must be located on a level piece of ground with short ground cover and well away from buildings, trees, bushes, and the like. The gauge is thus submerged, presenting no barrier to perturb the airflow. (There still should be some means of minimizing splash into the gauge from raindrops falling nearby but not into the gauge.) Comparisons can then be made between the catch of the pit gauge and a conventional rain gauge. To obtain a useful data sample, this needs to be done for a large variety of conditions in order to quantify the impact of wind on the catch of the conventional gauge. To obtain statistically reliable results requires many rain events. Investigators in rainy England collected data for five years in order to obtain a large enough number of independent measurements for reliable statistics covering several types of weather situations.

An alternative in this day of high-performance computing is to actually compute the airflow perturbation by a rain gauge of specified size, and use this airflow to compute the trajectories of drops of a certain diameter falling in the vicinity of the gauge. This can be compared with the trajectories of the drops if the virtual rain gauge was not there. The fraction of drops that miss the rain gauge because of its perturbation of the airflow can then be computed. This was done some years ago by investigators in Switzerland, and the results were published in the *Journal of Atmospheric and Oceanic Technology*. As a check on the validity of their calculations, they put a rain gauge with the size and shape of the one used in their numerical simulation into a wind tunnel and made airflow measurements near the funnel. The computer-modeled and -measured airflow perturbations were judged to be close enough to justify using results from the computer calculations as a tool to examine the effect of wind on the rainfall catch. An example of their findings is reproduced in Figure 2 for a gauge (Mk2 gauge, used in the United Kingdom) similar in design to that in Figure 1, but having a five-inch diameter funnel instead of four. It should be noted that these calculations assume the wind is steady, that is, effects of the gustiness of the wind are ignored.

In Figure 2, there are four curves showing the fraction of drops missing the rain gauge (y-axis, labeled "partial wind-induced error e_p" plotted against drop diameter in millimeters, x-axis) corresponding to different wind speeds in meters per second (m/s; one m/s equals approximately 2.24 mph, so 20 mph = just under 9 m/s, very close to the 8 m/s curve with the solid black triangles in Figure 2). Assuming that the five-inch-diameter funnel gauge error characteristics are very similar to the CoCoRaHS four-inch gauge, then Figure 2 indicates that for a 20-mph wind, no drops of diameter 0.35 millimeter (drizzle size) will be collected, but for drops of one millimeter, about 93% will be collected, and for 1.5-millimeter drops, over 95% will be collected. Given that in a typical light rain, half the rainfall will come in the form of drops of one millimeter diameter or larger, the undercatch in a 20-mph wind is likely to be only between 10% and 15 %, depending on the distribution of drop size in the rain. For heavier rains, the undercatch due to wind is likely to be considerably less, since drop sizes in heavier rains tend to be larger. Based on the results in this study, for a typical heavy rain of 0.5 inches per hour, the catch, even for a 35-mph wind, will still be about 95% of what it would be with no wind.

In summary, the effect of wind on decreasing the catch of a rain gauge is larger for stronger wind, and is larger for small raindrops, and especially drizzle drops, for a given wind speed. Even so, the four-inch gauge recommended for CoCoRHS appears to suffer little loss of catch, even for strong wind, in heavy rain situations, assuming it is sited and mounted properly. W

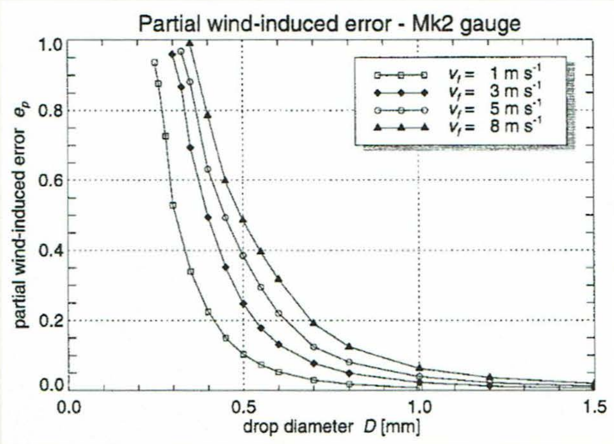


Figure 2. Fraction of drops missing the rain gauge as result of the wind perturbation produced by the gauge for wind speeds of 1, 3, 5, and 8 m/s, corresponding to approximately 2, 7, 11, and 18 mph, respectively, plotted as a function of drop diameter. The four different wind speeds used are shown in the inset, upper right corner. Stronger winds cause a greater proportion of drops to miss the gauge, for a given drop size. Larger drop sizes have a greater chance of ending up being collected.

JOHN M. BROWN was born and raised in San Diego, California, where he became fascinated by clouds, wind, and rain from his earliest years. Since completing his education at UCLA and MIT, he has worked as a meteorologist in various capacities. He is currently a research meteorologist at NOAA's Earth System Research Lab in Boulder, Colorado.