32nd Conference on Radar Meteorology and 11th Conference on Mesoscale Processes
Albuquerque, New Mexico, American Meteorological Society

P6R.7 REVISITING "GROUND TRUTH" — ASSESSMENT OF WIND AND OUT-OF-LEVEL COLLECTOR FUNNEL EFFECTS ON RAIN GAUGE CATCH

Matthias Steiner[1*], Lisa C. Sieck[2], and Stephen J. Burges[2]

[1]Princeton University, Princeton, NJ
[2]University of Washington, Seattle, WA

1. INTRODUCTION

Gauge measurements are widely used as the true rainfall reaching the land surface for a variety of applications, ranging from the calibration of remotely sensed rainfall estimates to water budget studies. The quality of rain gauge data may be affected by mechanical or electrical failure, human or animal interference, or debris settling inside the collector funnel hindering rainwater from reaching the measuring device. Proper calibration of the gauge measuring mechanism (e.g., tipping bucket) is another important aspect for obtaining high-quality rainfall data. Less obvious sources of potential rainfall measurement errors relate to the wind effect on the rain gauge catch and whether the instrument's funnel rim (i.e., orifice) is level. These two particular effects are revisited here. It is shown that out-of-level gauges may either miss or catch too much rainwater in windy conditions, with the associated errors potentially amounting to tens of percent of the total catch.

2. BASIC CONSIDERATIONS

Without ambient wind, raindrops fall straight down from the cloud that generated them toward the land surface. Therefore, one would expect no difference in the rainfall amount recorded by similar gauges installed either above ground or placed in a pit. The effect of a horizontal wind causes raindrops to fall at an angle that is a function of the wind speed and the raindrop size. Crockford et al. (1991), for example, report rainfall angles that are as much as 60° off the vertical direction. Assuming that raindrops act as approximate tracers of the horizontal wind (e.g., Beard and Jameson 1983; Tokay and Beard 1996), the inclination α (i.e., angle off the vertical) at which raindrops fall is determined by

$$\tan\alpha = \frac{u_d}{v_d} \tag{1}$$

where u_d is the wind-induced horizontal raindrop motion and v_d the size-dependent vertical fall velocity of raindrops (e.g., Gunn and Kinzer 1949; Beard 1976; Böhm 1992; Edwards et al. 2001). This relationship is shown in Fig. 1b. The near surface wind profile typically exhibits a wind speed that increases with increasing distance above ground. The effect is that the inclination angle α of falling raindrops decreases with increasing proximity to the land surface. The inclination angle likely decreases at a smaller rate than the decrease in wind speed because the drop's inertia dampens its response to a change in wind speed. Therefore, falling raindrops (especially larger ones) may hit the land surface under some measurable angle off the vertical, even though the wind speed approaches zero at ground level.

Assuming that precipitation is uniform in space and time (i.e., no variation of the raindrop size distribution), an equal flux of rainwater will pass through two identical, horizontal, virtual measurement surfaces imagined at different altitudes above ground. This is not the case, however, if these measurement surfaces are out of level, if winds are gusty (including vertical air motions), if the rainfall is varied in space and time, and/or if the measurements interfere with the surrounding environment.

Rinehart (1983) and Hosking et al. (1985) discuss the effect of a rain gauge being out-of-level on the rainfall catch. They show that the normalized effective collection area A_e for raindrops falling at an inclination angle α (off the vertical), and a rain gauge orifice being out-of-level by a tilt angle β (off the horizontal), can be expressed as

* *Corresponding author address*: Dr. Matthias Steiner, Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey 08544; phone: 609/258-4614; email: msteiner@princeton.edu

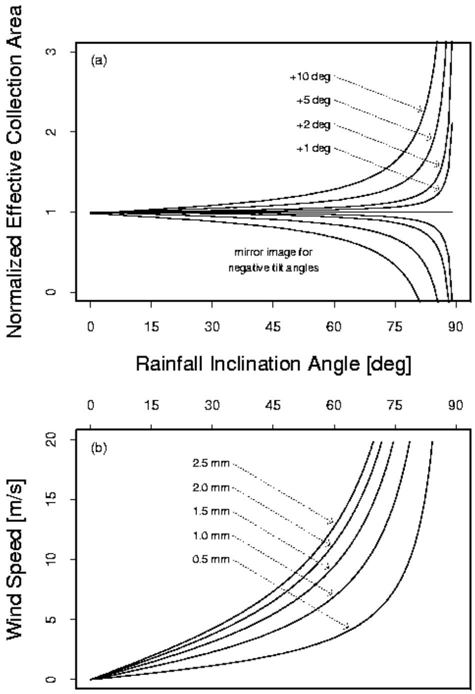

Figure 1. Normalized effective rain gauge catch area as a function of drop size, wind speed and orifice out-of-levelness. **(a)** Normalized effective rain gauge area as a function of rainfall inclination angle for various out-of-level tilts. **(b)** Rainfall inclination angle as a function of wind speed for various drop sizes. (Adapted from Sieck et al. 2005)

$$A_e = \frac{\cos(\beta - \alpha)}{\cos(\alpha)} \qquad (2)$$

Because of its dependence on α, the normalized effective area of the gauge orifice A_e is a function of both wind speed and drop size. Moreover, A_e is minimized (or maximized) when the gauge orifice is tilted away from (or into) the wind, as shown in Fig. 1a. For a given wind speed, the effect is larger for smaller raindrops and increases as a gauge becomes more out-of-level. For example, a raindrop of 2.5 mm diameter falls under an inclination angle of 34° in a horizontal wind of 5 m/s. This may result in an absolute uncertainty of approximately ±5% for the normalized effective collection area of a rain gauge that is out of level by 5°, depending on the wind direction relative to the direction of the gauge orifice tilt. However, for a smaller 0.5 mm raindrop this absolute uncertainty increases to ±20%.

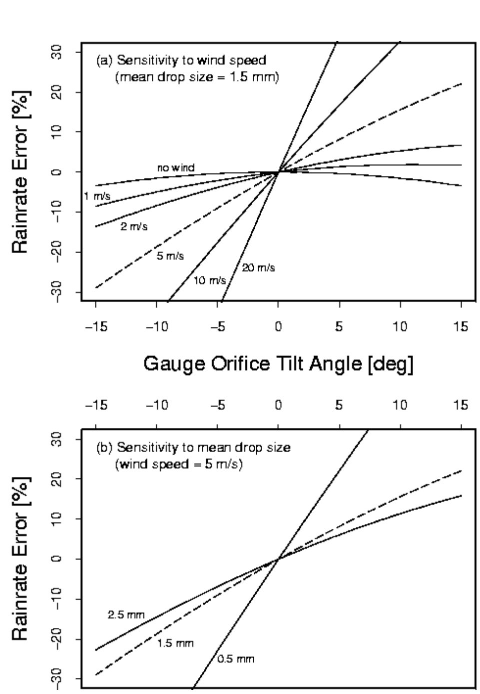

Figure 2. Rainfall rate error as a function of wind speed, mean drop size, and out-of-levelness. **(a)** Sensitivity of rainfall rate error to wind speed and gauge out-of-levelness for rainfall composed of raindrops with an exponential size distribution and mean drop size of 1.5 mm. **(b)** Sensitivity of rainfall rate error to mean drop size for a fixed wind speed of 5 m/s. (Adapted from Sieck et al. 2005)

Because natural rainfall is composed of drops of varied sizes, the uncertainty of the gauge catch has to be determined from an evaluation of the entire drop spectrum. The associated rainfall rate (mm/h) is defined as

$$\tilde{R} = \frac{6\pi}{10^4} \int_{D_{\min}}^{D_{\max}} A_e N(D) D^3 v_d \, dD \qquad (3)$$

where the integration is carried out over the full drop size distribution $N(D)$ — i.e., from the smallest ($D_{\min}$) to the largest raindrop size ($D_{\max}$). The uncertainty of the rainfall catch by an out-of-level gauge under windy conditions is demonstrated by Fig. 2. There is essentially little uncertainty in the rain gauge catch for calm conditions, even if the gauge is somewhat out-of-level (Fig. 2a). However, a relatively small tilt of the gauge orifice may yield a noticeable uncertainty in rain gauge catch even for weak winds. This uncertainty increases significantly for strong winds. For example, a typical wind speed of 5 m/s may produce a catch uncertainty of ±10% for rainfall collected by a gauge that is 5° out-of-level. This uncertainty is smaller for showers (mean raindrop size $D_m = 2.5$ mm) but significantly larger for drizzle rain ($D_m = 0.5$ mm), as highlighted by Fig. 2b.

In windy conditions, a standing gauge disturbs the approaching airflow. The effect of the flow deflection and its associated eddies and turbulence patterns about the gauge and within the funnel causes some of the raindrops (especially smaller ones) to be ejected from the funnel region (Nešpor and Sevruk 1999). The particular flow pattern and the resulting systematic undercatch of rainwater depend on the gauge design.

3. ASSESSMENT OF WIND EFFECT

In its simplest form, an assessment of the wind effect on rain gauge catch involves the comparison of rainfall accumulations recorded by a wind-exposed aboveground gauge to a collocated gauge buried in a pit with orifice rim level with the ground surface. Such comparisons have been facilitated by extensive data collected from March 2001 to April 2003 in the center of the Goodwin Creek research watershed in northern Mississippi (Steiner et al. 1999; Alonso and Bingner 2000; Sieck et al. 2005). In particular, we are comparing rainfall recorded by a weighing Belfort (BEL) gauge with orifice 1.25 m above ground to rainfall amounts of a nearby simple collector (50SW) installed in a drained pit.

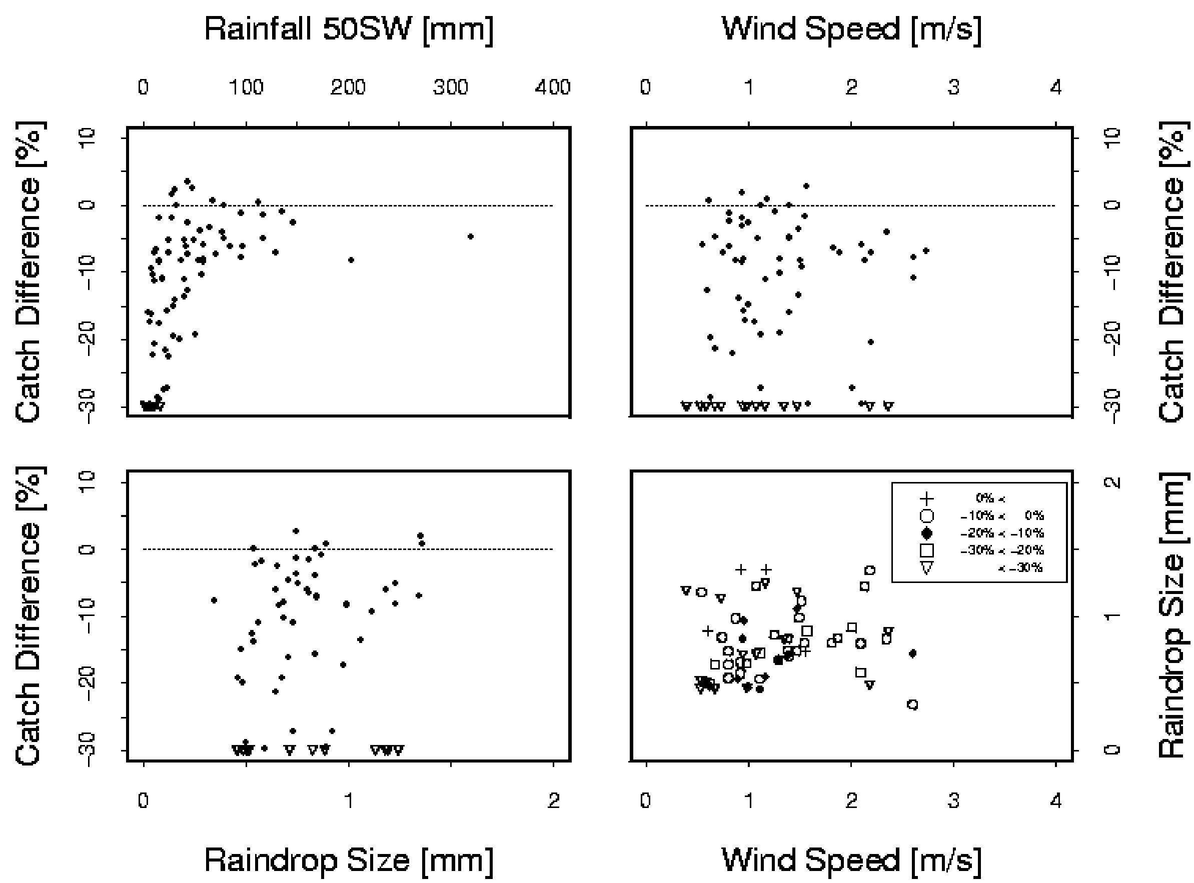

Figure 3. Difference between aboveground (BEL) and buried rainfall amounts (50SW) as a function of **(a)** storm total rainfall, **(b)** median wind speed during storm, and **(c)** median raindrop size. Panel **(d)** shows the catch difference as a function of both median wind speed and raindrop size. The top-standing triangles along the bottom of panels (a)-(c) indicate data falling outside the plotting area (i.e., larger undercatch). (Adapted from Sieck et al. 2005)

The two years worth of careful data collected at station 50 (centered on the Goodwin Creek catchment) by the pit collector (50SW) and the nearby aboveground BEL gauges were explored to evaluate a potential dependence of the recorded rainfall amount differences to overall rainfall, raindrop size, and/or wind speed (Fig. 3). The contemporaneous and collocated raindrop size distributions were recorded by a Joss-Waldvogel (1967) disdrometer. Boundary layer wind profile information was obtained from observations made at 0.5, 2.0, 3.7, and 10 m above ground level (see Sieck et al. 2005 for details).

The collector 50SW generally had a larger rainfall catch than the BEL, as expected, due to the effects of wind exposure on the aboveground gauge (Fig. 3a). The undercatch seems not to depend on the storm total rainfall amount. Moreover, the rainfall catch difference between the buried and aboveground gauges does not display relationships with wind speed (Fig. 3b), drop size (Fig. 3c), or a combination thereof (Fig. 3d). Based on the discussion in section 2, one would have anticipated some tendency towards larger catch differences with smaller drop sizes and higher wind speeds. The lack thereof may be a consequence of the manifold and significant uncertainties associated with experimental observations that might mask any such trends beyond recognition.

Rainfall differences for all gauges across the Goodwin Creek watershed with a companion buried collection device are presented in Fig. 4. This figure shows boxplots (with minimum, lower quartile, median, upper quartile, and maximum) of the ratio of aboveground to buried rain gauge storm totals (based on tips or collected volumes), for data available from March 2001 through April 2003 (see Sieck et al. 2005 for details). There is significant spread in the data for all gauges, although somewhat less so for the Texas Electronics Inc. (TXI) and Australian Hydrological Services Pty. Ltd. (TB3) tipping-bucket gauges than the weighing BEL and tipping-bucket USDA Agricultural Research Services (ARS) gauges. The ratios indicate both rainfall undercatch as well as overcatch of the wind-exposed aboveground gauge, yet the median of the aboveground-to-buried ratio is less than 100% for all gauges except the calibrated TXI at station 41. Since the uncalibrated aboveground-to-buried ratio for that gauge falls well below 100%, there may be a problem with the calibration curve for that particular gauge.

On average, the aboveground gauges exhibited smaller storm total rainfall accumulations than the corresponding buried gauges due to the

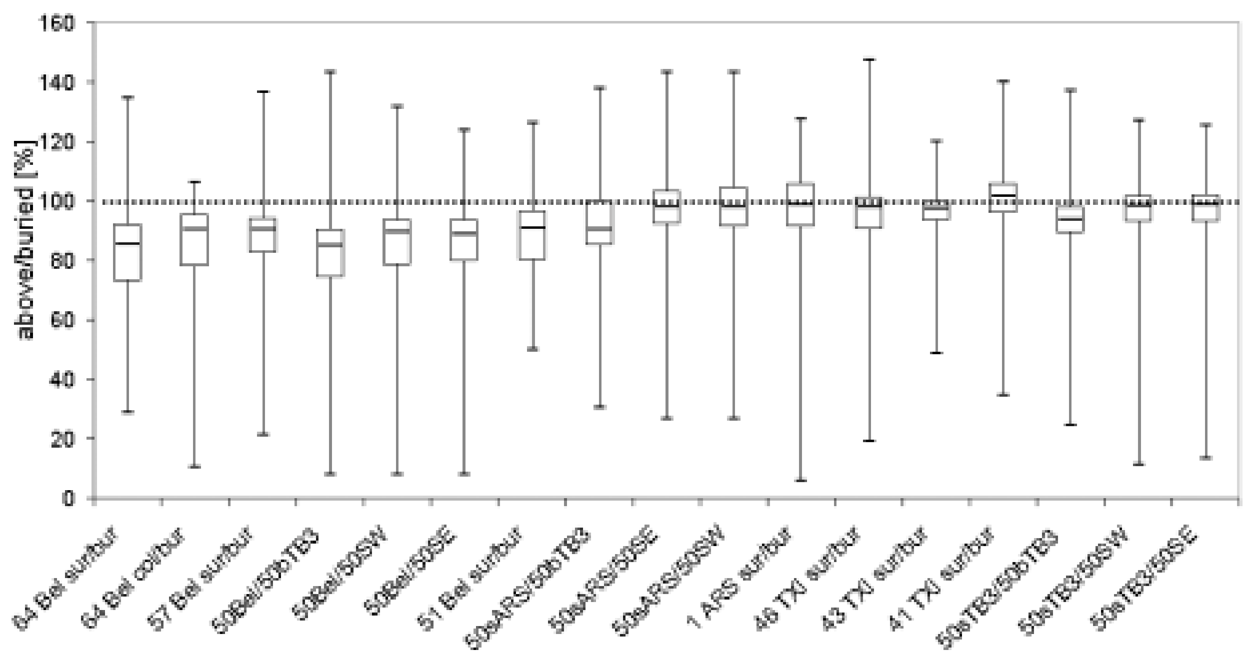

Figure 4. Boxplots of the ratio of calibrated aboveground to buried storm rainfall totals for the period from March 2001 to April 2003 for all gauges with buried collectors or rain gauges nearby, arranged by gauge type. (Adapted from Sieck et al. 2005)

effect of wind exposure. The BEL rain gauges (Stations 50, 51, 57, and 64) experienced an average undercatch of approximately 15%, while the TXI (Stations 41, 43, and 46) and the two ARS (Stations 1 and 50) gauges with buried gauges near them had average undercatches of about 8% and 5%, respectively. Our results are comparable to the findings of Duchon and Essenberg (2001).

4. SUMMARY AND CONCLUSIONS

Rain gauges mounted above ground are exposed to the ambient wind, which may yield an underestimate of the true rainfall reaching the land surface. Underestimation may be on the order of 5%-10%, or larger, depending on the gauge type and the wind exposure above ground.

Gauges that are out-of-level may contribute substantial additional uncertainty (either under- or overcatch). The effect of out-of-levelness may be of similar or greater magnitude than the wind-induced drop size effects on the rain gauge catch.

Quantification of the wind effects on the rain gauge catch is nontrivial, as our experience with the Goodwin Creek data reveals. Further careful experimental and numerical research is needed to achieve a better quantitative understanding of the wind effect on the rain gauge catch.

Acknowledgments. This research was supported by the National Science Foundation (NSF) under Grants EAR-9909696 and EAR-0409501 to Princeton University and EAR-9909579 to the University of Washington. In part this study was also supported by NSF Grant ATM-0223798 and the National Aeronautics and Space Administration (NASA) through Grant NAG5-13624 both to Princeton University. This work could not have been done without the extraordinary assistance provided by Dr. Carlos Alonso, Danny Brewer, Bob Darden, and Jerry Tuttle of the ARS National Sedimentation Laboratory in Oxford, Mississippi. Their combined effort in maintaining the rain gauge network and collection of special data for us at the Goodwin Creek watershed is greatly valued.

REFERENCES

Alonso, C. V., and R. L. Bingner, 2000. Goodwin Creek Experimental Watershed: A unique field laboratory. *ASCE Journal of Hydraulic Engineering*, **126**, 174-177.

Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft. *Journal of the Atmospheric Sciences*, **33**, 851-864.

Beard, K. V., and A. R. Jameson, 1983: Raindrop canting. *Journal of the Atmospheric Sciences*, **40**, 448-454.

Böhm, J. P., 1992: A general hydrodynamic theory for mixed-phase microphysics. Part I: Drag and fall speed of hydrometeors. *Atmospheric Research*, **27**, 253-274.

Crockford, R. H., D. P. Richardson, P. M. Fleming, and J. D. Kalma, 1991: A comparison of methods for measuring the angle and direction of rainfall. *Agricultural and Forest Meteorology*, **55**, 213-231.

Duchon, C. E., and G. R. Essenberg, 2001: Comparative rainfall observations from pit and aboveground rain gauges with and without wind shields. *Water Resources Research*, **37**, 3253-3263.

Edwards, B. F., J. W. Wilder, and E. E. Scime, 2001: Dynamics of falling raindrops. *European Journal of Physics*, **22**, 113-118.

Gunn, R., and G. D. Kinzer, 1949: The terminal velocity of fall for water drops in stagnant air. *Journal of Meteorology*, **6**, 243-248.

Hosking, J. G., C. D. Stow, and S. G. Bradley, 1985: Corrections for horizontal winds and wind shear in raindrop size spectrometers. *Journal of Atmospheric and Oceanic Technology*, **2**, 181-189.

Joss, J., and A. Waldvogel, 1967: Ein Spektrograph für Niederschlagstropfen mit automatischer Auswertung. *Pure and Applied Geophysics*, **68**, 240-246.

Nešpor, V., and B. Sevruk, 1999: Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation. *Journal of Atmospheric and Oceanic Technology*, **16**, 450-464.

Rinehart, R. E., 1983: Out-of-level instruments: Errors in hydrometeor spectra and precipitation measurements. *Journal of Climate and Applied Meteorology*, **22**, 1404-1410.

Sieck, C., S. J. Burges, and M. Steiner, 2005: Challenges in obtaining reliable measurements of point rainfall. *Water Resources Research*, (submitted).

Steiner, M., J. A. Smith, S. J. Burges, C. V. Alonso, and R. W. Darden, 1999: Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation. *Water Resources Research*, **35**, 2487-2503.

Tokay, A., and K. V. Beard, 1996: A field study of raindrop oscillations. Part I: Observation of size spectra and evaluation of oscillation causes. *Journal of Applied Meteorology*, **35**, 1671-1687.