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Numerical simulation studies of rain gage data correction due to wind effect

Emad Habib, Witold F. Krajewski, Vladislav Nespor, and Anton Kruger

Iowa Institute of Hydraulic Research, Civil and Environmental Engineering Department, University of Iowa, Iowa City

Abstract. Investigation of the correction of rain gage measurements due to the wind effect is described. The focus is on the effect of the temporal averaging scale on the estimation of the wind-induced error correction. Numerically derived correction formulae for a specific class of rain gage types, along with high temporal resolution measurements of rainfall and wind speed, are used to perform the study. The rainfall measurements are corrected on a variety of temporal scales ranging from 1 min to 1 month. The results showed the importance of applying the correction procedure at a short timescale, otherwise a significant overestimation of the wind-induced bias results. The wind-induced error is characterized by a nonlinear complex behavior dependent on wind speed, rainfall rate, and the microphysical rain structure quantified by a drop size distribution parameter. The estimated correction factors are found to be sensitive to the change of the drop size distribution. Finally, comparison with certain formulae reported in the literature showed a significant random scatter of the estimated correction if it is expressed only as a function of the wind speed and the drop size distribution characteristics are ignored.

1. Introduction

Despite recent advances in remote sensing of precipitation, rain gage observations remain the main basis for those operational and scientific applications and analyses that require quantification of rainfall amounts. Rain gage data are corrupted by many sources of errors both of systematic and random nature. Biased observations are of particular concern in regional and global water and energy balance studies. Unbiased rainfall measurements are also needed as major input components to surface runoff and flood-forecasting hydrological models, and for calibration and validation of the remote sensing techniques.

From the climate-monitoring point of view, the most important sources of error are the systematic components dominated by the wind effects [*Sevruk*, 1986]. The elevated gage body acts as an obstacle to the airflow that gets deviated around it and accelerated. Trajectories of rain droplets are modified and lighter particles are blown away, resulting in an undercatchment error of the gage.

Various approaches have been developed and applied to estimate the undercatchment error due to the wind. The most popular approach is to use field intercomparison data measured by gages elevated above the ground and a ground level pit gage to estimate a correction factor as a function of the wind speed and other meteorological factors. A summary of such studies and their results is given by *Sevruk* [1986] and *Sevruk and Lapin* [1993]. More recent rain gage intercomparison studies have been conducted by *Legates and DeLiberty* [1993] and *Yang et al.* [1998].

A numerically based approach is another possibility for the estimation of the wind effect on the gage catchment efficiency. Early attempts were made by *Folland* [1986] who used wind tunnel measurements of the wind flow field around the gage body combined with a simple numerical model for computing trajectories of the rain droplets. A comprehensive study was made by *Nespor and Sevruk* [1999], using the most recent computational fluid dynamics (CFD) techniques. They simulated the wind flow field around the gage body using a three-dimensional numerical model with a k-ε turbulence model [*Bradshaw*, 1978; *Wilcox*, 1994]. Information about the mean flow field and its turbulent characteristics were then used to simulate the trajectories of the rain droplets by solving the equation of motion of each individual particle. The effect of the turbulence on the dispersion of the droplets was also included. The same authors developed approximate formulae to estimate the wind-induced error as a function of gage type (body geometry), wind velocity, rainfall intensity, and a drop size distribution parameter. This methodology, compared to the field intercomparison approaches, presents a fast and robust tool to quantify the wind effect on rain gage measurements of rainfall.

Both the field intercomparison and the numerical methodologies proved that the wind-induced loss depends mainly on two variables: the wind speed and the microphysical rain structure (i.e., drop size distribution). Both are characterized by high temporal variability, while many of the field intercomparison studies and the resultant correction formulae are based on time-averaged information. *Sevruk and Hamon* [1984] showed the significance of the timescale on which the correction is made. They reported significant differences when the corrections were made on semi-daily versus monthly scale. More studies with various correction scales can be found in the works of *Sevruk* [1986] and in *Sevruk and Lapin* [1993]. Recently, *Yang et al.* [1998] performed their correction on a daily basis. Monthly data were used by *Legates and DeLiberty* [1993], who recommended to refine the correction procedure and to develop methods that can remove the gage-induced biases from daily as well as hourly data. Thus a question arises: what is the appropriate temporal scale for application of rain gage data correction schemes?

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For operational purposes it is important to understand the impact of using time-averaged variables that affect rain gage errors at scales such as day, month, and season on the estimation of the measurement corrections. Such improved understanding of the timescale effects would provide guidelines on the required resolution of the relevant variables. The main goal of this article is to investigate the effect of the temporal correction scale on the estimation of the wind-induced rainfall measurement losses. We also report on the significance and relative influence of the various involved parameters such as wind speed and rain drop size distribution.

In this study we use a numerically obtained error correction formula. We study the temporal scale effect by applying the correction procedure to time-averaged experimental data collected at very high resolution. We assume that application of the correction formulae to the very high resolution data results in negligible error of correction factor estimates. When the same formulae are applied to time-averaged data, an error results due to the nonlinear nature of the correction equation.

This paper is organized as follows: First, we present the correction formulae and discuss their assumptions. This is followed by a description of the experimental data used in the study. Next, we discuss the results of the correction procedure applied at different temporal scales along with the sensitivity analysis of the computed correction factors. We also include results of applying several correction formulae found in the literature. We close with conclusions and recommendations.

2. Methodology

2.1. Correction Formulae

As we discussed earlier, the correction formulae, based on intercomparison methods, are only valid for certain timescales. Some of them are suitable for daily or semidaily scales, while others are only applicable for longer timescales. The experimental intercomparison data limit the investigations of the effect of the temporal correction scale to the highest resolution of the collected data. For example, if only daily data are collected it is not possible to study the effect of wind and rainfall variability at the shorter scales. Also, methods based on the field intercomparison data require a long period of measurement to establish and perform the correction procedure. In contrast, a numerically derived correction procedure is a more suitable tool for scale effect investigation. It enables performing the correction procedure on a wide range of temporal scales varying from minutes to months.

In the present study, we use the approximate formulae for the wind-induced error developed by *Nespor and Sevruk* [1999]. *Nespor and Sevruk* [1999] used the results of the airflow simulations to compute the trajectories of the rain droplets. Then, a partial wind-induced error was computed for each individual drop size as a function of the wind speed. The partial error represents the missing amount of a hypothetical single particle size rainfall. The partial error is estimated by computing the ratio of the number of drops with wind-modified trajectories that ended up in the gage, to those which were supposed to be caught by the gage if the wind field was not deformed. *Nespor and Sevruk* [1999] investigated three different types of gages: the British Meteorological Office Mk2 gage and the Hellmann and the ASTA gages used in Switzerland. The three types have different dimensions, but all have the shape of an upright cylinder. They are geometrically similar to many other gages used in operational networks throughout the world. The estimated partial error showed a similar behavior for the three different gage types. A gamma-type function was fitted to the computed data of each gage type using a nonlinear least squares method:

$$e_p(D,u) = \beta_1(u) D^{\beta_2(u)} e^{-\beta_3(u)} \quad (1)$$

where e_p is the partial wind-induced error, D is the drop diameter, u is the wind speed, and β_1, β_2, and β_3 are gage-specific coefficients which depend solely on the wind speed and which were obtained by the nonlinear fitting of the computed data. Equation (1) is only applied for drop sizes larger than a lower limit below which the partial wind-induced error is set to unity. Drops smaller than the lower limit are all blown away from the gage orifice.

In the present study, we use the formulae developed for the Mk2 gage. This does not restrict our results to that particular gage type because our focus is on the qualitative behavior of the correction procedure as a function of the timescale. Since the formulae of the three gages, investigated by *Nespor and Sevruk* [1999], were different only in the geometry-related fitting coefficients, the choice of the gage type becomes unimportant for the purposes of this study. Our results can be extended to other gage types as long as they have a similar geometry and operational principles.

To calculate the undercatchment error, *Nespor and Sevruk* [1999] integrated the partial error evaluated by (1) over a given rainfall drop size distribution. This yields the total amount of the missing rainfall rate R^*: .

$$R^*(u,R,k) = \frac{\pi}{6} \int_0^\infty e_p(D,u) N(D,R,k) D^3 v(D) dD \quad (2)$$

where R^* is the missing rainfall, R is the true rainfall rate, N is the number of drops per unit volume and unit drop size, and v is the drop falling velocity. The drop size distribution $N(D,R,k)$ is assumed to have a gamma distribution as proposed by *Ulbrich* [1983] and can be expressed as a function of drop diameter, rainfall rate, and a rain-type parameter k. Similarly, the falling velocity v is also expressed as a gamma-type function of the drop size.

After obtaining the total missing amount of rainfall, the integral wind-induced error e_i can be expressed as the ratio between the missing rainfall rate R^* and the true rate R:

$$e_i(u,R,k) = \frac{R^*}{R} \quad (3)$$

In (2) and (3) the true rainfall rate is used as an input parameter that is not known a priori. Therefore an iterative procedure is applied where the measured rate is used as the initial guess until a convergent value is reached. The corrected rainfall rate can be estimated by adding the measured rate to the computed missing rate:

$$R_{\text{corrected}} = R_{\text{measured}} + R^* \quad (4)$$

We make a distinction between the true and the corrected rainfall only to avoid implication that the corrected rain gage observations are error free. In reality, there are several other rain gage error sources but their discussion is outside of the scope of this study. If only wind-caused error is concerned, and the random error of the correction formulae (because of assumptions used in its derivations) is ignored, the corrected rainfall is assumed equal to the true rainfall. Accordingly, the correction factor (*CF*) can be expressed as follows:

$$CF(u,R,k) = \frac{1}{1-e_i(u,R,k)} \quad (5)$$

Figure 1 shows plots for the correction factor (*CF*) computed by (5). Three examples are shown: (1) for the drop size distribution parameter *k*=-1, for orographic rain; (2) for *k*=1, for thunderstorm rain; and (3) for *k*=4, for showers [see *Ulbrich*, 1983]. The high nonlinear variation of the correction factor with the wind speed, rainfall rate, and the drop size distribution shows the complex behavior of the wind effect and its multidimensional dependence on the various wind and rainfall characteristics.

2.2. Experimental Data

The Iowa Institute of Hydraulic Research at the University of Iowa has operated a unique high-resolution surface meteorological station for more than 5 years [*Georgakakos et al.*, 1994; *Krajewski et al.*, 1998]. The station consists of several colocated instruments, namely, a tipping-bucket rain gage with a 0.01 inch resolution, optical rain gage, hygrometer, temperature sensor, wind speed and direction sensors, and barometric pressure sensor. The outputs from all these sensors are continuously sampled and archived every 2 s. However, some of the instruments have response times longer than 2 s. For example, the optical rain gage has a 10-s time constant. In this study, differences in instrument response times have been accounted for. The high-resolution data set, with the aid of the numerical correction formulae, makes it possible to perform the correction procedure on a fine temporal scale. Measurements of wind speed and rainfall rate for nine warm season months of 1996 and 1997 are used in the study. Figure 2 shows an example of rainfall and wind data for one of the storms. Within the nine months, more than 60 rain events were observed. The beginning and the end of an event are defined on the basis of an interevent duration criterion of 1 hour. Figure 3 shows a frequency distribution of the 1-min rain rates, computed from the high-resolution gage recordings, for the entire data set used in the present study. A statistical description of the measured rain events is also shown in Figure 4. The total rainfall per event ranged from a few millimeters to about 60 mm. The data also include one extreme event that lasted more than 24 hours with a total accumulation of about 250 mm. The averages of the 1-min rain rate ranged from less than 1 mm/h up to about 24 mm/h with a standard deviation in the range from 1 to 45 mm/h. The maximum recorded 1-min rain rate was about 200 mm/h with most of the events ranging from a few millimeters to about 100 mm/h. The duration and the frequency between the events

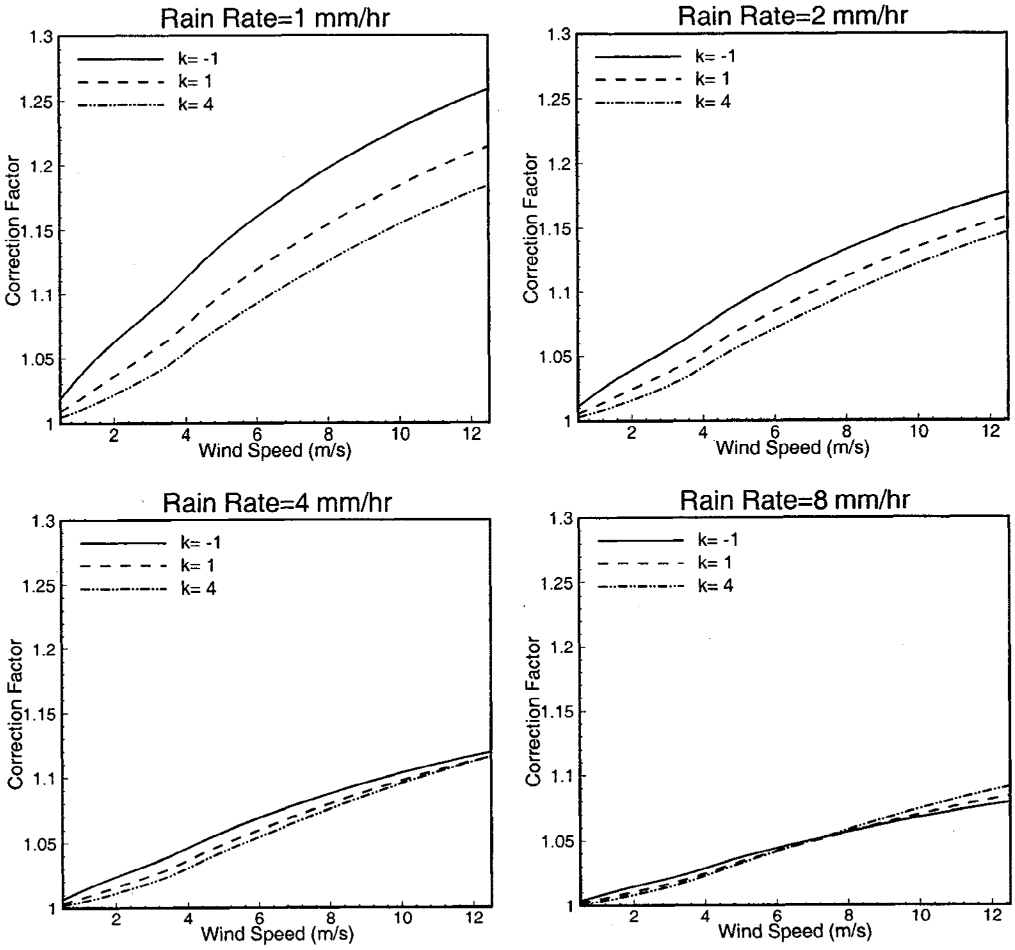

Figure 1. Plots of the correction factor defined by equations (3) and (5) as a function of wind speed, rainfall rate, and a drop size distribution parameter k.

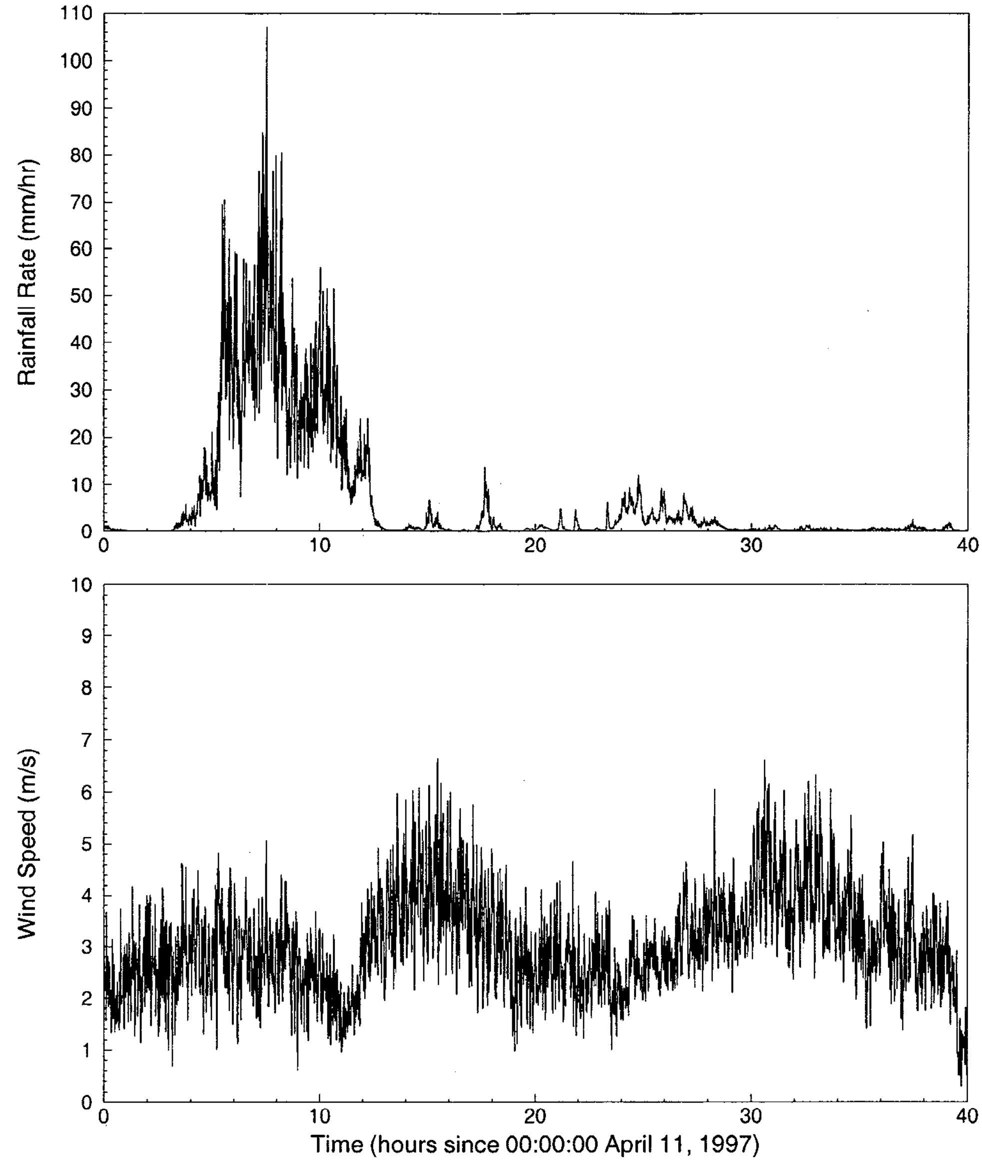

Figure 2. An example of the experimental data used in the present study. The measurements are every 2 s.

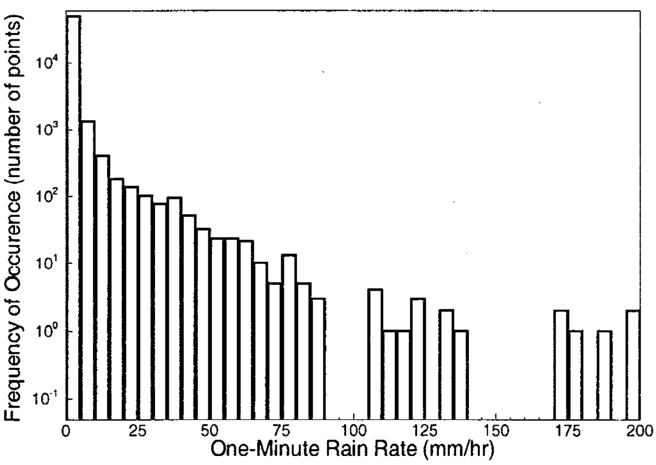

Figure 3. Frequency distribution of the 1-min rain rates computed from the high-resolution recordings of the experimental data used in the present study. A bin size of 5 mm/h is used.

cover a wide range of timescales. The duration of most of the storms was of the order of few hours with a frequency of occurrence of a few days to a few weeks. The recorded wind speed averaged over 1 min was as high as 15 m/s. Figure 5 shows a scatterplot of the rainfall and the wind recordings. The 1-min rain rate was plotted with fewer data points and in a logarithmic scale for better clarity. Figure 5 also shows the distribution of the recorded wind speed conditioned on the 1-min rain rate. The conditional distribution has a stable median with respect to the rain rates. It also shows a relatively low scatter with significant extreme values. According to our experimental data, the wind distribution shows similar characteristics for the no-rain situation compared to the rainy conditions.

3. Results and Discussions

3.1. Effect of Correction Temporal Scale

To investigate the effect of the temporal averaging scale on the estimation of the wind-induced error, a wide range of scales

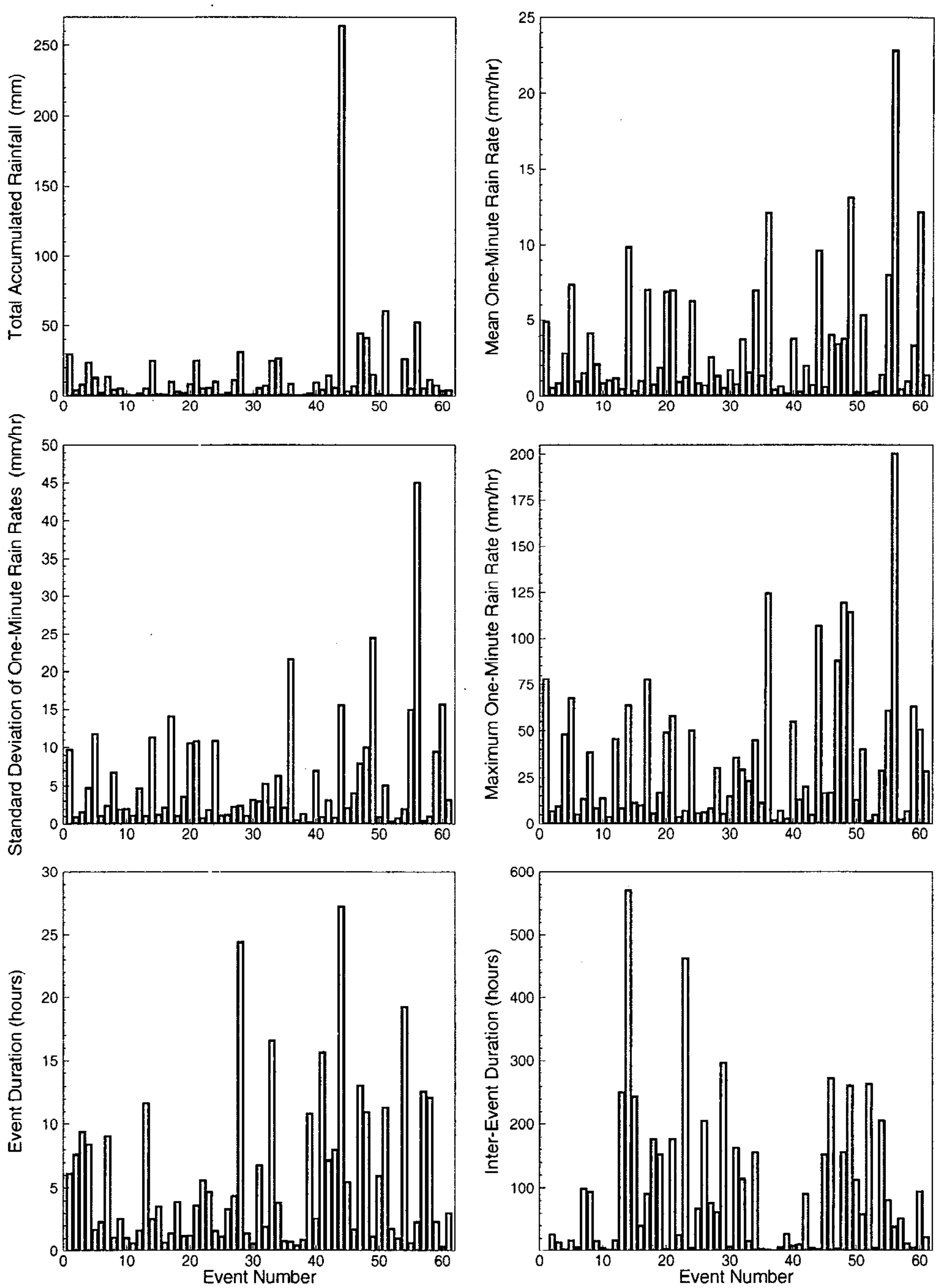

Figure 4. Statistical characteristics of the measured rain events used in the present study.

has to be considered. In this study, we performed the corrections with the timescale ranging from 1 min up to 1 month. For each timescale the error was estimated by applying (2) and (3). The investigation was performed by using the optical gage data and treating them as if they were collected by the Mk2 gage. In this respect, we do not attempt to correct actual errors, but we simply use our high-resolution data to illustrate the averaging scale effect on the correction error.

The input to the correction formulae is the wind speed and the measured rate of rainfall averaged over a certain period of time which corresponds to the correction scale. The averaging process is simply a linear function:

$$\overline{X}[T] = \frac{1}{n\Delta t}\sum_{i}^{n} X_i \qquad (6)$$

where X is the variable to averaged, T is the averaging period, and Δt is the resolution of the recorded signal. Since the experimental measurements do not provide information on the rain type and its drop size distribution and since the focus is on the effect of the temporal correction scale, the drop size distribution parameter was kept constant during the entire correction procedure and also from 1 month to the other. However, the sensitivity of the wind-induced error to the change of the rainfall structure, represented by the drop size distribution parameter, will

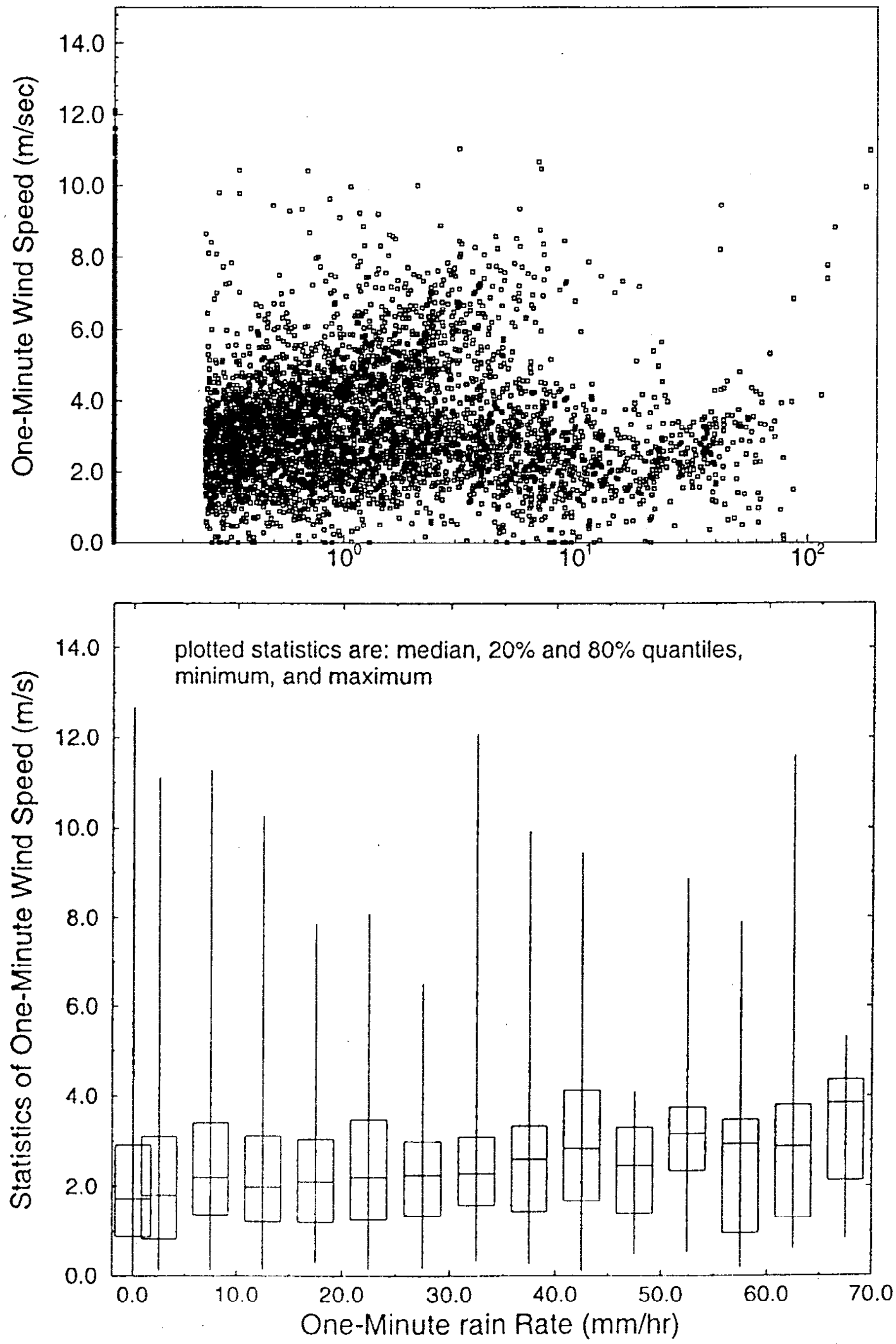

Figure 5. Distribution of 1-min wind speed and rain rate data. The top figure shows a scatterplot. The bottom figure shows the conditional distribution of the wind speed observations.

be considered in section 3.2. Having estimated the error associated with a certain correction scale, the missing rainfall could be computed and accumulated for the entire month to yield an estimate for the wind-induced error. This procedure was repeated for each temporal correction scale and for the available nine months of measurements. The results are summarized in Figure 6. In this figure, each curve represents a certain month. In the plot the error values obtained at the smallest scale are assumed to be the "correct" correction. This is a reasonable assumption since the nonsteady motion effects of the drops along their trajectories seem negligible due to small inertia involved. The drops adjust their trajectories to wind gusts quickly, and therefore following the temporal variability of the wind seems the most crucial aspect of a successful application of the correction procedure.

The plotted results show a common trend of the behavior of the computed error with the variation of the correction scale. Generally, the wind-induced error increases nonlinearly with the correction timescale. The rate of increase is higher at small timescales of a few hours and up to 1 or 2 days, where it becomes smaller at larger timescales. The wind-induced error continues to increase at a lower rate for scales up to 2 weeks and then reaches an asymptotic/equilibrium state where no significant changes are noticed. However, some data showed a local reduction of the computed error with the increase of the timescale. Most likely,

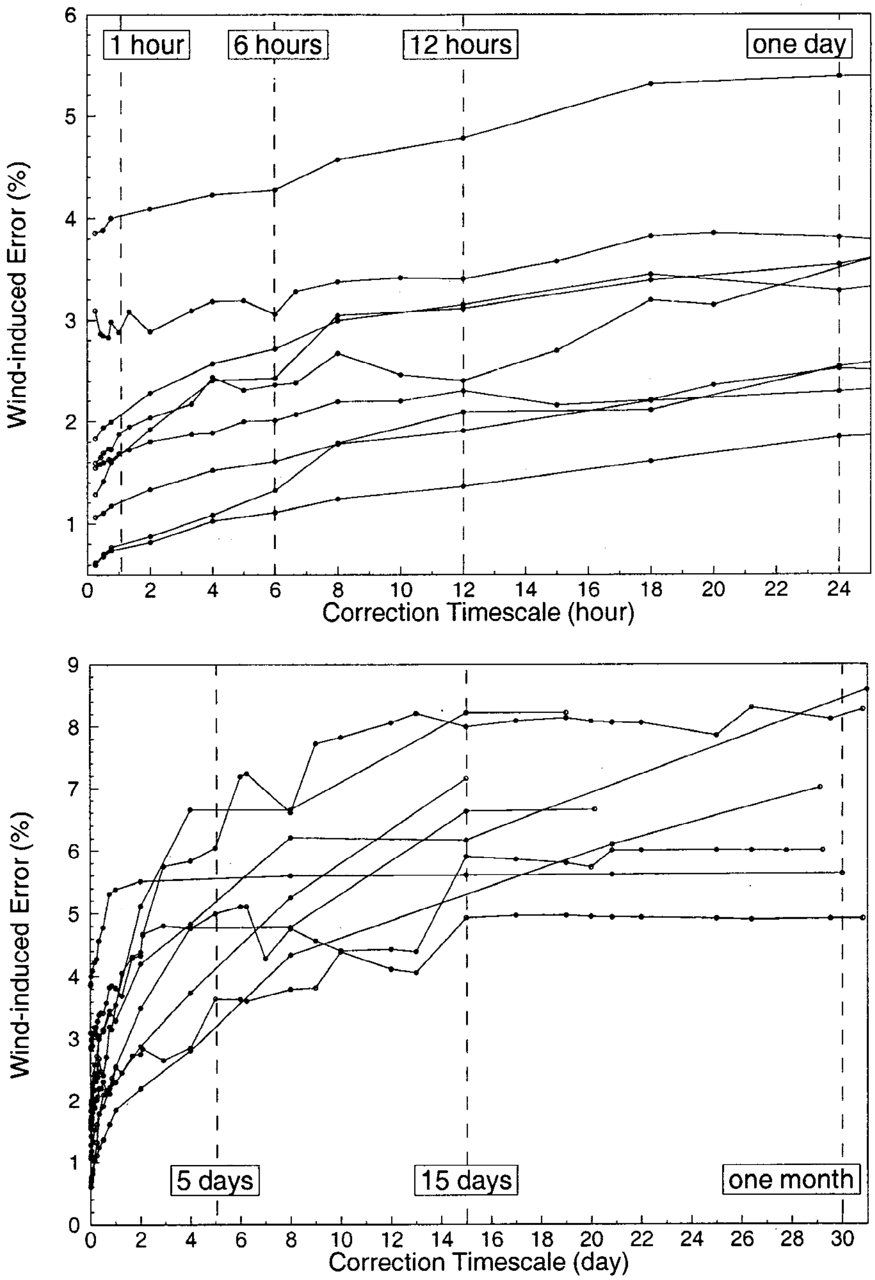

Figure 6. Variation of the wind-induced error with the increase of the correction temporal scale. Each line represents 1 month of the corrected data. The figure on the bottom shows the computed error for the entire range of the correction scale. The top figure is the same but with zooming on the scale up to 1 day. A constant value of k=1 was assumed.

these represent artifacts of sampling variability. Some data did not show a significant change in the computed error with the change of the timescale and some oscillations were obtained at small correction scales. The overall behavior of the wind-induced error and its significant variation with the temporal correction scale is due to the highly nonlinearity nature of the process of the wind effect on the rainfall measurements. This emphasizes the nonlinear dependence of the wind effect on the wind speed, the rainfall intensity, and the drop size distribution. Such dependence can be clearly seen in the structure of the correction formulae and their plots, as was shown in Figure 1.

The general behavior of the computed wind-induced error indicates the importance of the timescale on which the correction is made. The increase of the correction timescale would lead to a significant overestimation of the wind-induced error. If the measurements are corrected on a daily scale instead of a few minutes or hourly scale, the wind-induced error could be overestimated by a factor of about 2-3 times. The error overestimation gets as high as 5 times if the corrections were performed on a half monthly or monthly scale. This shows a vital need for the refinement of the correction procedure in order to obtain reliable and unbiased rainfall estimates.

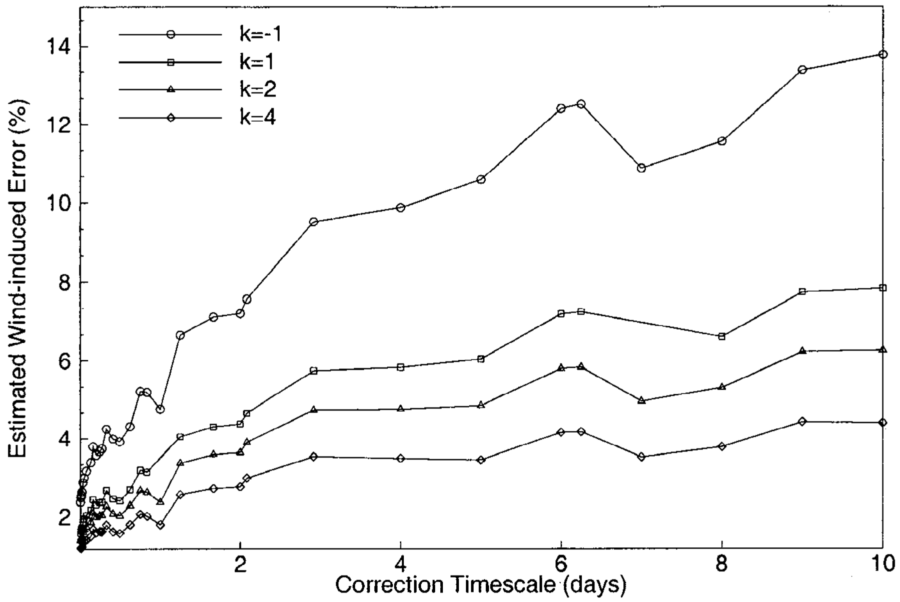

Figure 7. Sensitivity of the computed wind-induced error to the drop size distribution characterized by the parameter k as a function of the correction scale.

3.2. Sensitivity of Wind-Induced Error to Drop Size Distribution

In the previous section, the drop size distribution was considered invariant throughout the correction procedure. In reality, the drop size distribution changes from a storm to storm and during the same storm. Also, the experimental measurements used in this study showed a high temporal variability of the rainfall rate and the wind speed during the rain event. However, the measurements do not provide any information about the drop size distribution and its temporal variability. Therefore a sensitivity analysis is performed to investigate the dependence of the wind effect on the drop size distribution. One month of data was considered assuming various values of the drop size distribution parameter k. Low values of k ($-2<k<2$) characterize orographic and thunderstorm rains, while higher values (up to 5) are associated with stratiform rain and showers. Figure 7 shows the values of the wind-induced error computed for four different values of k. For the same wind speed and rainfall rate measurements, the computed error, with a k value of -1, is about 3 times more than it is with a k value of 4. This shows that the error is highly sensitive to the rain drop size distribution quantified by the parameter k. One can also notice that the difference in the wind-induced error computed for various values of k gets higher with the increase of the correction timescale. To investigate the effect of the variability of k within storms and from storm to storm, we modeled it as a purely random variable. Holding k as a constant and treating it as a random variable represents two extreme cases, where the real unknown k lies somewhere in between. Modeling k as a random variable was suggested by *Chandrasekar and Bringi* [1987] and also used by *Krajewski et al.* [1993]. In the present study, we consider a 1 month of the experimental data to perform the correction with random k at various scales. During the time period that corresponds to the correction scale, k is randomly sampled at each time the wind-induced error is computed using the error formulae (2) and (3). A uniform distribution with an assumed interval was used to sample k:

$$k = U\{k_{\min}, k_{\max}\} \quad (7)$$

The results are shown in Figure 8. The solid lines correspond to various realizations obtained with k sampled by the uniform distribution (7), and the dotted line corresponds to the results obtained with holding k as a constant equivalent to the average value of the same uniform distribution.

Despite the oscillation of the computed error obtained with k as a random variable, the general behavior is similar to the one obtained with constant k. This indicates that even when k is not kept constant, the wind-induced error would be overestimated for longer integration timescales as was concluded before. Again, this emphasizes the nonlinear dependence of the wind effect on the drop size distribution. Information about the rainfall type, structure, and its drop size distribution is essential to obtain a reliable quantification of the wind effect.

3.3. Comparison With Previous Formulae

As was shown earlier, various correction formulae and models have previously been developed on the basis of field intercomparison data. In the following, we compare the correction formulae used in the present study with some of the previous ones using the same set of the 9-month data. *Legates and DeLiberty* [1993] investigated the precipitation measurement biases in the United States where they used the following formula to compute the correction factor of monthly rainfall measurements:

$$CF = \frac{100}{100 - 2.12u} \quad (8)$$

In (8), u is the wind speed in meters per second obtained from mean monthly data. Recently, *Yang et al.* [1998] studied the accuracy of NWS 8" standard gage where daily measurements were corrected using the following formula:

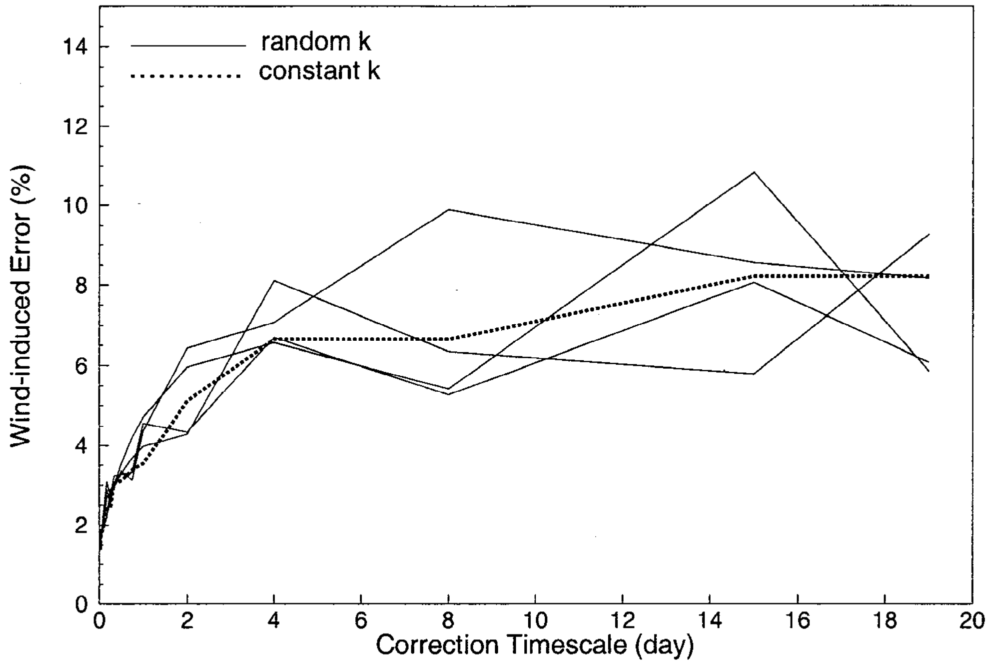

Figure 8. Variation of the wind-induced error with the increase of the correction temporal scale. The solid lines are various realizations obtained with k sampled by the uniform distribution (7). The dotted line represents the results obtained with holding k as a constant equivalent to the average value of the same uniform distribution.

$$CF = 100exp(-4.606 + 0.041u^{0.69}) \quad (9)$$

In (9) u is the average daily wind speed in meters per second. Both (8) and (9) use the wind speed as the only input parameter, and they showed a significant scatter as reported in the literature. For example, (9) was fitted using field intercomparison data with a determination coefficient R^2 less than 0.3. Although these two formulae were developed for different gages and sites and under different meteorological conditions, it is still reasonable to use them for comparative purposes since the comparison is not used for validation or calibration purposes. Instead, we use it to illustrate the significance of including the rain rate and the drop size distribution in the correction procedure. Figure 9 shows the values of the correction factor computed by the formulae used in the present study plotted as a function of the wind speed only, compared to the two formulae (8) and (9). We apply the correction at two timescales: 1 min that corresponds to the timescale of the formulae used in the present study and a daily scale that corresponds to (9). No comparison was made on a monthly scale due to the limited data set (9 months only). Figure 9 shows only a portion of the data points for better clarity. While (8) and (9) use the wind speed as the only input parameter, the formulae of the present study use the wind speed, the rainfall rate, and the drop size distribution parameter. The latter was assumed to be constant (k=1) throughout the rain events. Although the two formulae of *Legates and DeLiberty* [1993] and *Yang et al.* [1998] pass through the values obtained in the present study, a significant random scatter can be clearly noticed. This scatter indicates that the wind effect on the rainfall measurements cannot be described as a function of the wind speed only. It emphasizes the importance of including the rainfall intensity and the drop size distribution as input parameters into the correction procedure. A similar conclusion was made by *Sevruk and Hamon* [1984] who reported that a relationship between the correction factor and the wind speed only showed a large scatter and was not able to describe the performance of the gages. They introduced an additional input parameter that is related to the rainfall structure and can be computed on the basis of the proportions of the small rainfall intensity. However, a nonnegligible scatter could still be seen in the fitted formulae of *Sevruk et al.* [1984]. Again, this emphasizes the results of the present study, which indicated that the wind-induced error of the rainfall measurements is characterized by a nonlinear complex performance. Such performance may be fully described only if information about the wind speed, rainfall rates, and the drop size distribution during the precipitation event were available at a relatively small temporal scale.

4. Future Work

The experimental data of the present study did not provide full information about the drop size distribution where the parameter k had to be assumed. Recently, a two-dimensional (2-D) video distrometer has been deployed at the same experimental site of IIHR which makes it possible, for future investigations, to incorporate the measured drop size distribution and its temporal variation into the proposed numerical simulation procedure. This would shed more light on the significance of the microphysical rainfall structure effect and may resolve some aspects of the complex performance of the wind effect on the rain gage measurements.

5. Conclusions

The wind effect on the rain gage measurements was investigated. A numerically based correction procedure developed for a

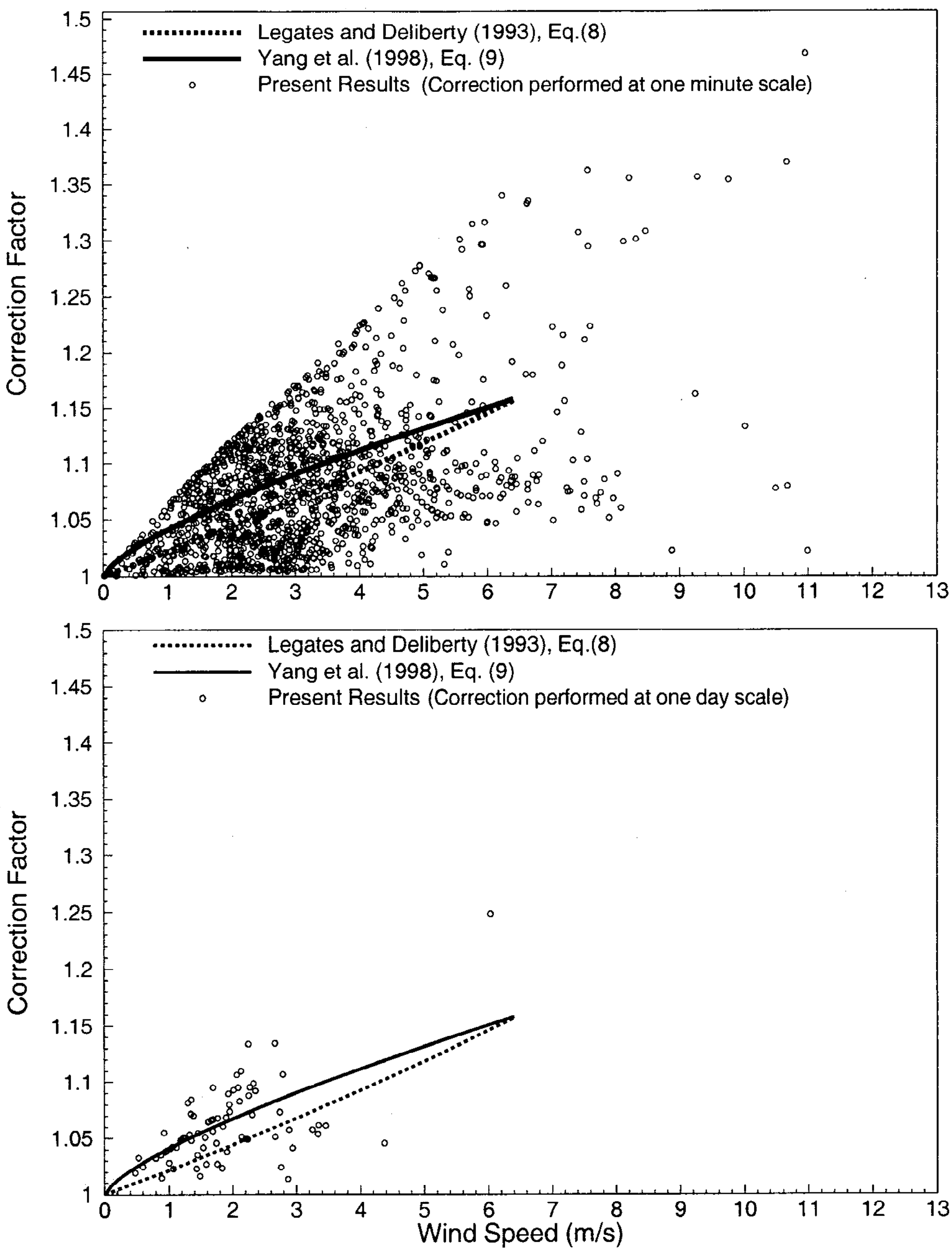

Figure 9. Comparison of the current correction formulae, equations (2), (3), and (5), with previous formulae of *Legates and DeLiberty* [1993], equation (8), and *Yang et al.* [1998], equation (9). The corrections are made with 1-min scale (top figure) and daily scale (bottom figure). A constant value of k=1 was used.

specific class of gage types was used to evaluate the effect of the temporal correction scale on the quantification of the wind-induced error. The estimated wind-induced error was found to be nonlinearly dependent on the temporal correction scale. Performing the correction on relatively large timescales would lead to an overestimation of the wind-induced error by a factor of as high as 5 times more than if the correction was made on a smaller timescale. On the basis of the results of the computed corrections, an hourly scale or less is recommended for both collection and correction of the rainfall measurements. The wind-induced error was found to be characterized by a complex nonlinear performance which can be understood only by considering information about meteorological variables that affect the rain gage, i.e., the wind speed, rainfall intensity, and drop size distribution. The latter parameter has a significant effect on the estimation of the wind error, which was found to be sensitive to different values of the drop size distribution parameter. This was emphasized when comparison with previous formulae showed significant scatter if the correction factor was expressed as a function of the wind speed only.

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E. Habib, W.F. Krajewski, V. Nespor, and A. Kruger, Iowa Institute of Hydraulic Research, Civil and Environmental Engineering Department, University of Iowa, Iowa City, Iowa 52242. (ehabib@iihr.uiowa.edu; witold-krajewski@uiowa.edu; kruger@iihr.uiowa.edu)

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