
Wind-Driven Rain Assessment on Buildings Using Climatic Data Sets: What Time Resolution is Needed?

B. Blocken, PhD

J. Carmeliet, PhD

ABSTRACT

This paper provides an analysis of the required time resolution for meteorological input data (wind speed, wind direction, and horizontal rainfall intensity) to obtain accurate wind-driven rain (WDR) calculations. Earlier work has indicated that the use of ten-minute input data can provide accurate results, while the use of arithmetically averaged hourly data can give rise to significant underestimations in the calculated WDR amounts. This paper builds on this earlier work by providing an investigation of the parameters that determine the required time resolution: (1) the averaging technique, (2) the building geometry and the position at the building facade, and (3) the type of rain event. The modelling results suggest that, depending on the parameters involved, hourly and even daily wind and rain input data can provide accurate WDR calculations, while in other situations they can lead to very large errors. Finally, the importance of these parameters is evaluated by conducting WDR calculations with yearly meteorological data records for two cities in different climates.

INTRODUCTION

Wind-driven rain (WDR) is one of the most important moisture sources for building facades, and it is expected to become even more important in the future (Sanders and Philipson 2003). WDR calculations on buildings are made with either the semi-empirical WDR relationship or with numerical simulations based on computational fluid dynamics (CFD). Both methods require standard wind and rain input data for the calculations: wind speed, wind direction, and horizontal rainfall intensity. The horizontal rainfall intensity is the rainfall intensity through a horizontal plane, as measured by a traditional rain gauge with a horizontal orifice. The WDR relationship was developed by Hoppestad (1955). It is a simple analytical formula that expresses that the WDR intensity is proportional to the product of the wind-velocity component normal to the wall and the horizontal rainfall intensity. The proportionality factor in the WDR relationship is called the *WDR coefficient*. The European Standard Draft for WDR calculation is based on this method (CEN/TC89 2002). Choi (1991, 1993, 1994) developed and applied a steady-state

numerical simulation technique based on CFD. This technique has been adopted and applied by many researchers since then. It is a steady-state simulation technique allowing the determination of the spatial distribution of WDR on building facades for given (fixed) values of the wind speed, the wind direction, and the horizontal rainfall intensity. Later, Choi's simulation technique was extended into the temporal domain by Blocken and Carmeliet (2002) and the extended simulation methodology was experimentally validated (Blocken and Carmeliet 2002, 2006). The extension into the temporal domain allows the application of this method for transient rain events, i.e., with time-varying meteorological input data (fluctuating values of wind speed, wind direction, and horizontal rainfall intensity).

The extension into the temporal domain has raised an important question: "What is the required time resolution for the wind and rain input data in order to obtain accurate WDR calculation results?" The natural fluctuations in wind and rain characteristics suggest that the measurement samples of wind speed, wind direction, and horizontal rainfall intensity should be available at a sufficiently high resolution in order to be

B. Blocken is assistant professor at the Unit Building Physics and Systems, Technische Universiteit Eindhoven, The Netherlands. J. Carmeliet is full professor at the Laboratory of Building Physics, Department of Civil Engineering, Katholieke Universiteit Leuven, Belgium, and at the Unit Building Physics and Systems, Technische Universiteit Eindhoven.

“time-representative,” i.e., to yield a good estimate of the corresponding WDR amount. In earlier WDR CFD validation papers (Blocken and Carmeliet 2002, 2006; Tang and Davidson 2004), time resolutions of ten minutes and one minute have been used for WDR calculations, which yielded a good agreement with corresponding experimental WDR data. Earlier work has also shown that data at a lower time resolution (hourly) can give rise to significant errors (underestimations) in the calculated WDR amounts (Blocken and Carmeliet 2007). In these publications, however, no detailed investigation of these errors and of their influencing parameters was made.

The investigation in this paper focuses on the required time resolution for accurate WDR calculations and on the errors associated with lower time resolutions. It takes into account the fact that the magnitude of these errors does not only depend on the time resolution but also on three other parameters: (1) the averaging technique that was used to convert the raw measurement data to “data set” data at a certain (lower) time resolution, (2) the building geometry and the position at the building facade, and (3) the type of rain event. First, some information about the time resolution at which wind and rain data are currently gathered and made available is provided, and the main reason for the errors associated with averaging wind and rain data is briefly discussed. The focus in this paper is calculations of WDR based on CFD simulations. Therefore, the CFD WDR model is briefly described. Next, the new weighted data averaging technique, which was developed in an earlier publication (Blocken and Carmeliet 2007), is briefly outlined. Finally, the insight gained by the CFD WDR model and the new weighted averaging technique provides the basis for the analysis of the influencing parameters.

TIME RESOLUTION OF METEOROLOGICAL DATA AND DATA AVERAGING

Time Resolution of Meteorological Measurements

Rainfall intensity is characterized by an extreme variability in time (Sumner 1988). The shorter the measurement time interval, the more accurate the registration of the phenomena will be. However, even the most sophisticated rain gauges are incapable of measuring instantaneous rainfall (Sumner 1988). Jones and Sims (1978) correctly state that the nature of instrumentation forces a compromise whereby instantaneous precipitation is considered to be that which occurs over a duration of one minute. Sumner (1981, 1988) mentions that due to errors in timing, local turbulence, and so on, it is probably more reasonable to settle for sampling intervals of 5, 10, or 15 minutes.

Wind data (wind speed and wind direction) are also highly variable in time. This variability is generally more pronounced for wind speed than for wind direction. Wind speed measurements are usually conducted at a higher resolution than rainfall intensity measurements (≤ 1 minute or even ≤ 1 second, depending on the type of measurement equipment that is available). These “raw” measurement data are often averaged over larger time intervals (e.g., 1, 5, or 10 minutes) by the measurement equipment itself (e.g., in an ultrasonic anemometer) and/or by the datalogger (e.g., for a cup anemometer). These “pre-averaged” values will also be called “raw data” in this paper.

As an example, Figure 1 shows a data record (rain event) of ten-minute wind speed, wind direction, and horizontal rainfall intensity measurements as provided by the meteorological station at the VLIET test site of the Laboratory of Building Physics, K.U.Leuven. It clearly illustrates the temporal variability of the data, which is most pronounced for the horizontal rainfall intensity. The relative temporal variability of wind

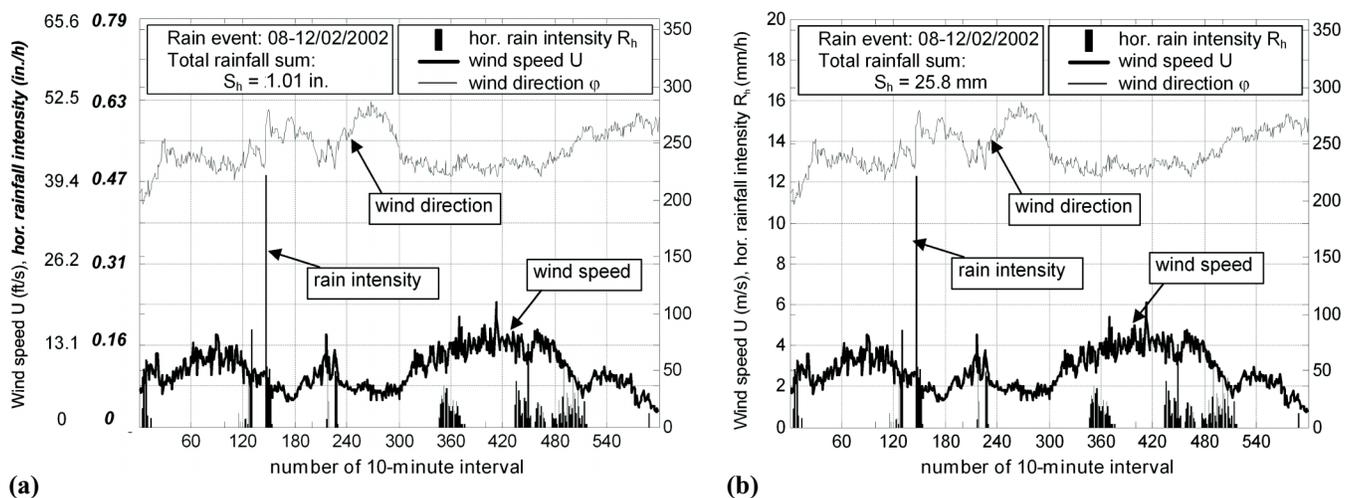


Figure 1 Meteorological data record (rain event) with ten-minute wind speed, wind direction, and horizontal rainfall intensity measurements for the period of February 8–12, 2002, in (a) I-P units and (b) SI units.

speed, and especially of wind direction, is significantly less. Due to the limited temporal variability of the wind direction, we will specifically focus on the time resolution of wind speed and horizontal rainfall intensity in the remainder of this paper.

Time Resolution of Meteorological Data Sets

For combined wind and rain measurements, such as are needed for WDR calculations, an averaging interval of ten minutes seems to be a reasonable choice (based on the guidelines by Sumner [1981, 1988] and on the existence of the spectral gap in the wind-speed power spectrum [Van der Hoven 1957]). The common averaging interval at which data in meteorological data sets are made available, however, is one hour or a day. These averaged hourly or daily data are usually obtained from the raw measurement data (e.g., ten-minute averaged data) by using the arithmetic averaging technique; see Equation 1 for the wind speed and the horizontal rainfall intensity.

$$U_j = \frac{\sum U_i}{n} ; R_{hj} = \frac{\sum R_{hi}}{n} \quad (1)$$

where

j = the averaging interval

i = the raw data in the averaging interval

n = the total number of data samples in this interval

In the remainder of this paper, the term “averaging interval” will be used to refer to time resolution.

Arithmetic Data Averaging and Related Errors

Averaging data will inevitably lead to a loss of information, which, in turn, can cause errors in the calculated WDR amounts. The most important error is due to the loss of information about the co-occurrence of wind and rain. This error has been the subject of earlier investigation (Blocken and Carmeliet 2007). As an example, let us focus on the (a) and (b) examples in Figures 2A and 2B, which represent two theoretical rain events, each consisting of six time intervals. For each of these intervals, the (raw) wind speed and horizontal rainfall intensity values are illustrated. Arithmetically averaging these data over all six intervals will lead to the loss of important information about the co-occurrence of wind and rain, i.e., the co-occurrence of high wind speed and the high rainfall intensity values and of the co-occurrence of low wind speed and low rainfall intensity values in the (a) examples of Figures 2A and 2B and vice versa for the (b) examples in Figures 2A and 2B. This loss of information about the co-occurrence of wind and rain can lead to large errors, as was shown by Blocken and Carmeliet (2007). It is important to note that the errors can be overestimations as well as underestimations. Since the WDR intensity is approximately proportional to the product of wind speed and horizontal rainfall intensity, arithmetic averaging of the data in example (a) of Figures 2A and 2B will lead to an underestimation of the actual WDR intensity, while arithmetic

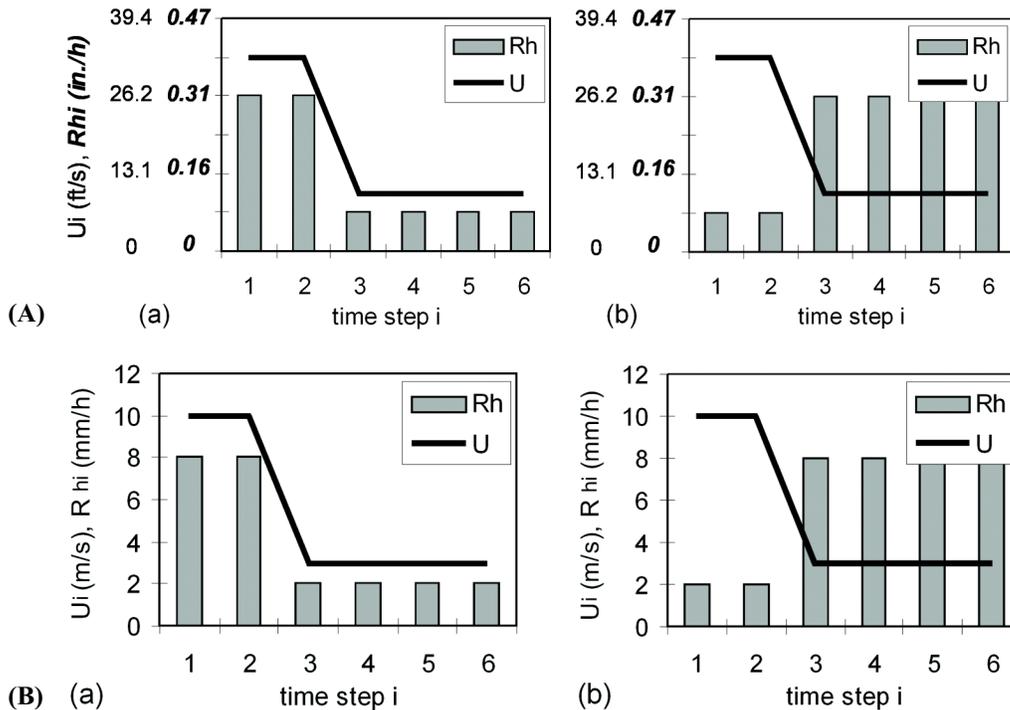


Figure 2 Two theoretical meteorological data records (rain events) with “raw” measurement data of wind speed U and horizontal rainfall intensity R_h in (A) I-P units and (B) SI units.

averaging of the data in example (b) of Figures 2A and 2B will yield an overestimation. In the remainder of this paper, the focus is on WDR calculations that are based on CFD simulation results. Therefore, the CFD WDR model—and especially its extension into the time domain—are briefly explained in the next section.

THE NUMERICAL WIND-DRIVEN RAIN MODEL

Definitions and Parameters

The quantities that are used to describe the WDR intensity are the specific catch ratio $\eta_d(d)$, related to the raindrop diameter d , and the catch ratio η , related to the entire spectrum of raindrop diameters (Equation 2):

$$\eta_d(d, t) = \frac{R_{wdr}(d, t)}{R_h(d, t)} \quad ; \quad \eta(t) = \frac{R_{wdr}(t)}{R_h(t)} \quad (2)$$

where

- $R_{wdr}(d, t)$ = the specific WDR intensity on the building
- $R_h(d, t)$ = the specific unobstructed horizontal rainfall intensity
- t = the time
- $R_{wdr}(t)$ = the WDR intensity on the building, integrated over all raindrop diameters
- $R_h(t)$ = the unobstructed horizontal rainfall intensity, integrated over all raindrop diameters

The unobstructed horizontal rainfall intensity is the intensity of rainfall through a horizontal plane that is situated outside the wind-flow pattern that is disturbed by the building (i.e., the rainfall that would be measured by a rain gauge with a horizontal orifice at ground level, placed in an open field). In practical applications the (specific) catch ratio will be measured and calculated for discrete time steps ($t_j, t_j + \Delta t$). The (specific) catch ratio for a discrete time step is redefined as

$$\eta_d(d, t_j) = \frac{\int_{t_j}^{t_j + \Delta t} R_{wdr}(d, t) dt}{\int_{t_j}^{t_j + \Delta t} R_h(d, t) dt} = \frac{S_{wdr}(d, t_j)}{S_h(d, t_j)} \quad (3)$$

$$\eta(t_j) = \frac{\int_{t_j}^{t_j + \Delta t} R_{wdr}(t) dt}{\int_{t_j}^{t_j + \Delta t} R_h(t) dt} = \frac{S_{wdr}(t_j)}{S_h(t_j)} \quad (4)$$

where

- $S_{wdr}(d, t_j)$ = the specific WDR sum on the building during time step ($t_j, t_j + \Delta t$)
- $S_h(d, t_j)$ = the specific unobstructed horizontal rainfall sum during time step ($t_j, t_j + \Delta t$)
- $S_{wdr}(t_j)$ = the WDR sum, integrated over all raindrop diameters, during time step ($t_j, t_j + \Delta t$)
- $S_h(t_j)$ = the unobstructed horizontal rainfall sum, integrated over all raindrop diameters, during time step ($t_j, t_j + \Delta t$)

The catch ratio η is a complicated function of space and time. The six basic influencing parameters for η are:

1. the building geometry (including environment topology)
2. the position on the building facade
3. the reference wind speed
4. the reference wind direction
5. the horizontal rainfall intensity
6. the raindrop-size distribution

The reference wind speed U (m/s [ft/s]) is usually taken as the horizontal component of the wind-velocity vector at 10 m height in the upstream undisturbed flow (U_{10}). The reference wind direction ϕ_{10} (degrees from north) refers to the direction of the reference wind speed. The horizontal raindrop-size distribution $f_h(d)$ (m^{-1} [ft^{-1}]) refers to the raindrop-size distribution as a flux through a horizontal plane (Blocken and Carmeliet 2004).

Five-Step Simulation Methodology

The numerical methodology for the calculation of the spatial and temporal distribution of WDR on buildings consists of five steps:

1. The steady-state three-dimensional wind-flow pattern around the building is calculated using a CFD code. The Reynolds-Averaged Navier-Stokes equations are solved and closure is usually obtained by employing a k- ϵ turbulence model. Unintended streamwise gradients in the approach flow should be investigated and limited to ensure the accuracy of the simulation (Blocken et al. 2007).
2. Raindrop trajectories are obtained by injecting raindrops of different sizes into the calculated wind-flow pattern and by solving their equations of motion.
3. The specific catch ratio η_d is determined based on the configuration of the calculated raindrop trajectories that were injected in the wind-flow field and that ended on the building facade.
4. The catch ratio η is calculated from the specific catch ratio and from the raindrop-size distribution. This can be performed for different positions at the building facade and for different values of the reference wind speed U_{10} , the wind direction ϕ_{10} , and the horizontal rainfall intensity R_h .
5. The information obtained in the previous steps is used to construct catch-ratio charts. These charts provide η as a function of the reference wind speed U_{10} and the horizontal rainfall intensity R_h for a given position on the building facade and for a given wind direction (e.g., see Figure 3a). Note that these charts were constructed based on a set of CFD simulations for discrete couples of wind speed and rainfall intensity (U_k, R_{hl}) that yielded values for the corresponding catch ratio η_{kl} . These points (U_k, R_{hl}, η_{kl}) are indicated in Figure 3a. To determine the WDR amount for a given rain event, the catch-ratio charts are combined with the meteorological data records of the

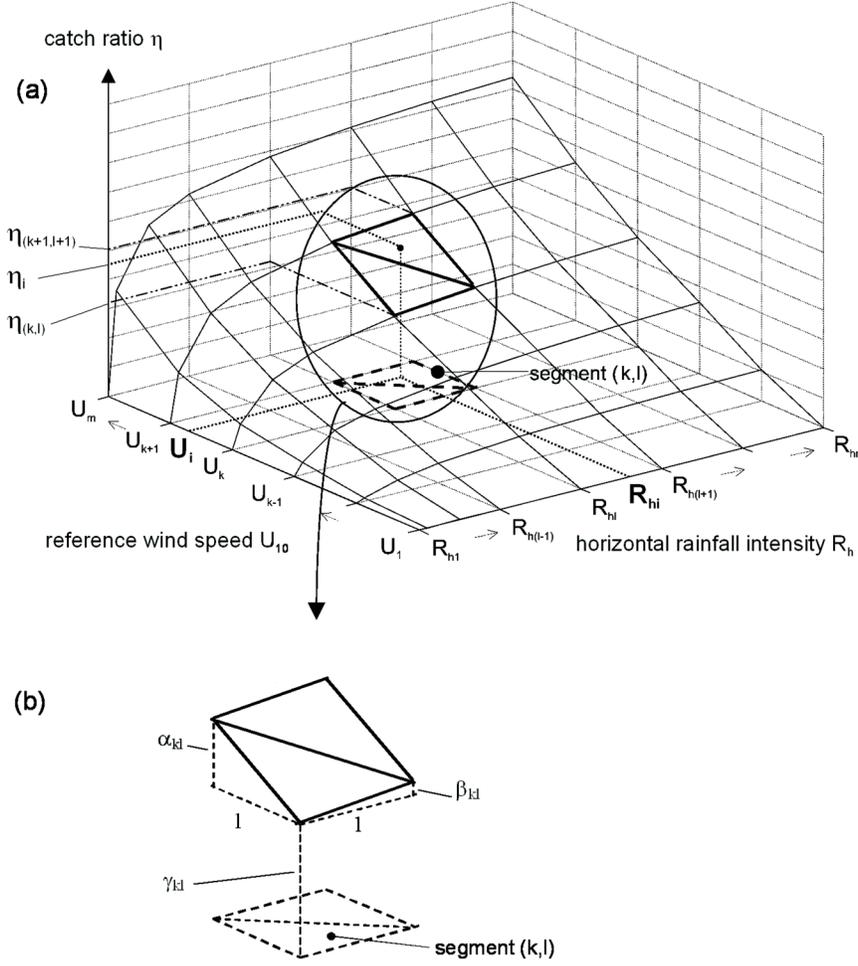


Figure 3 (a) Example of a catch-ratio chart as generated by CFD simulations. The chart provides the catch ratio as a discrete function of the reference wind speed U_{10} and the horizontal rainfall intensity R_h for a certain fixed position at the building facade and for a given wind direction. (b) Intermediate values are obtained by linear interpolation from the calculated (U_{10}, R_h, η) points.

reference wind speed, the wind direction, and the horizontal rainfall intensity.

The last step is explained in more detail. For example, let us focus on the data record in Figure 1 and on the catch-ratio chart in Figure 3a. To determine the WDR amount for this rain event, the event is partitioned into a number of equidistant time steps (e.g., ten-minute intervals). The meteorological data for a certain time step i are the reference wind speed U_i , the wind direction ϕ_i , and the horizontal rainfall intensity R_{hi} . Each time step is considered steady-state, and the meteorological data for each time step are used to extract the corresponding catch ratio from the catch-ratio chart. This is done by linear interpolation between the discrete points (U_k, R_{hl}, η) that resulted from the CFD simulations. For example, when U_i is situated between U_k and U_{k+1} and R_{hi} between R_{hl} and $R_{h(i+1)}$, the catch ratio is obtained as follows (see Figure 3b):

$$\eta_i = \alpha_{kl}(U_i - U_k) + \beta_{kl}(R_{hi} - R_{hl}) + \gamma_{kl} \quad (5)$$

where α_{kl} and β_{kl} are the slopes of the segment surface $\eta(U_{10}, R_h)$ in point $\eta(U_k, R_{hl})$ in the direction of the U_{10} and R_h -axis, respectively, and γ_{kl} is equal to $\eta(U_k, R_{hl})$.

This way, the catch ratio η_i for each time step i can be obtained. The corresponding WDR amount S_{wdri} is obtained by multiplying η_i with the horizontal rainfall amount S_{hi} .

ARITHMETIC VERSUS WEIGHTED DATA AVERAGING

Earlier research has led to a new averaging technique that was obtained from a mathematical derivation based on the typical shape of the catch-ratio charts (Blocken and Carmeliet 2007). In this technique, averaged values of wind speed U_j and horizontal rainfall intensity R_{hj} are obtained by averaging the “raw” high-resolution data U_i and R_{hi} with the horizontal rainfall amounts S_{hi} as weighting factors:

$$U_j = \frac{\sum_i U_i S_{hi}}{\sum_i S_{hi}} ; R_{hj} = \frac{\sum_i R_{hi} S_{hi}}{\sum_i S_{hi}} \quad (6)$$

It was proven that averaging wind and rain data with this technique, instead of by using Equation 1, and using these averaged data in WDR calculations does not introduce errors into the calculated WDR amounts when the catch ratio η is a linear function of U_{10} and R_h for the averaging interval considered. In other words, no averaging errors are introduced when all points (U_i, R_{hi}, η_i) in the averaging interval are situated on the same linear catch-ratio surface. This linearity of η as a function of U_{10} and R_h has been the actual condition for deriving Equation 6. It will be referred to as the *linearity condition* in the remainder of this paper. In the next section, it will be shown that the errors caused by data averaging are indeed to a large extent determined by the actual shape (linearity) of the catch-ratio chart.

Note that the weighted averaging technique takes into account the co-occurrence of wind and rain by applying the appropriate weights to those values of wind speed and rainfall intensity that are most important for the total WDR amount. Indeed, the wind-speed values during heavy rain showers are to be given a larger weight than wind-speed values during a light-intensity spell as the contribution of the former wind-speed values to the total WDR amount is larger. The justification for weighting the rainfall intensity with the rainfall amounts also results from the mathematical derivation in Blocken and Carmeliet (2007) but is more difficult to interpret physically than for the wind speed.

DATA AVERAGING ERRORS: INFLUENCING PARAMETERS AND ANALYSIS

Influencing Parameters

The four influencing parameters that are investigated in this section are (1) the averaging technique, (2) the averaging interval (time resolution), (3) the shape of the catch-ratio chart, and (4) the type of rain event.

The *averaging technique* will be either the commonly used arithmetic averaging technique or the new weighted averaging technique. They are used to convert the ten-minute measurement data into data for larger averaging intervals.

The *averaging interval* is in the range of ten minutes to one day, respectively the minimum and maximum time resolution of most existing meteorological data sets.

The *shape of the catch-ratio chart* depends on a number of parameters, the most important of which are the building geometry and the position on the building facade. Based on a large number of catch-ratio charts obtained by WDR simulations for different buildings and for different positions on the building facades (Blocken and Carmeliet 2002, 2006), three categories or types of catch-ratio charts could be discerned. A typical chart of each type is given in Figures 4a–4c. Note that

this classification is made based on the shape of the catch-ratio surface in the charts and not on the values in these charts. The charts of type 1 are characterized by a linear dependence of the catch ratio on the wind speed and by a pronounced curvature of the η - R_h curves at light to moderate rainfall intensities ($R_h < 7.6$ mm/h [0.30 in./h]). This chart type is representative for most parts of all building facades, except for the roof edge and the regions below horizontal projections such as roof overhangs (where shelter from rain is provided). The charts of type 2 are approximately linear surfaces, with a low dependence of η as a function of R_h , also for the lower rainfall intensities. They are representative only for the top edges of building facades. Note that they are not representative for the vertical edges, where type 1 occurs. The charts of type 3 are similar to those of type 1, except for the cut-off of the catch ratio for a certain range of wind-speed values. This is due to the shelter provided by horizontal projections. They are representative for a certain part of the facade that is situated below these projections. The data averaging errors associated with these three types of catch-ratio charts will be studied.

Two types of real rain events are considered in this study: a cumuliform and a stratiform rain event. The terminology “cumuliform-stratiform” stems from the type of clouds generating the rain (see Figure 5). *Cumuliform clouds* or heap clouds develop in an unstable atmosphere as a result of fast and local rising air currents. The type of rainfall from these clouds is referred to as *showers*. Showers usually start and stop suddenly and are generally of short duration. *Stratiform clouds* or layer clouds develop in a stable atmosphere as a result of widespread cooling and by condensation processes that are slow but persistent. The precipitation from these clouds starts and stops slowly, is quite steady (although it can exhibit breaks), often lasts for many hours, and is generally of light to moderate intensity ($R_h < 7.6$ mm/h [0.30 in./h]). The temporal variability of stratiform rain events is less pronounced than that of cumuliform rain events. The typical cumuliform and stratiform rain events that will be used in this study are illustrated in Figure 6.

Analysis of Data-Averaging Errors

WDR calculations have been made for various combinations of the influencing parameters. Figure 7 illustrates the errors that are introduced by using input data of averaging intervals that are larger than ten minutes in combination with the different rain events, the different chart types, and the two different averaging techniques. The errors are calculated as follows:

$$e = 100 \cdot \frac{S_{wdr_AVG} - S_{wdr_REF}}{S_{wdr_REF}} \quad (\%) \quad (7)$$

where

S_{wdr_AVG} = the WDR amount calculated with the averaged data
 S_{wdr_REF} = the WDR amount calculated with the ten-minute data (reference solution)

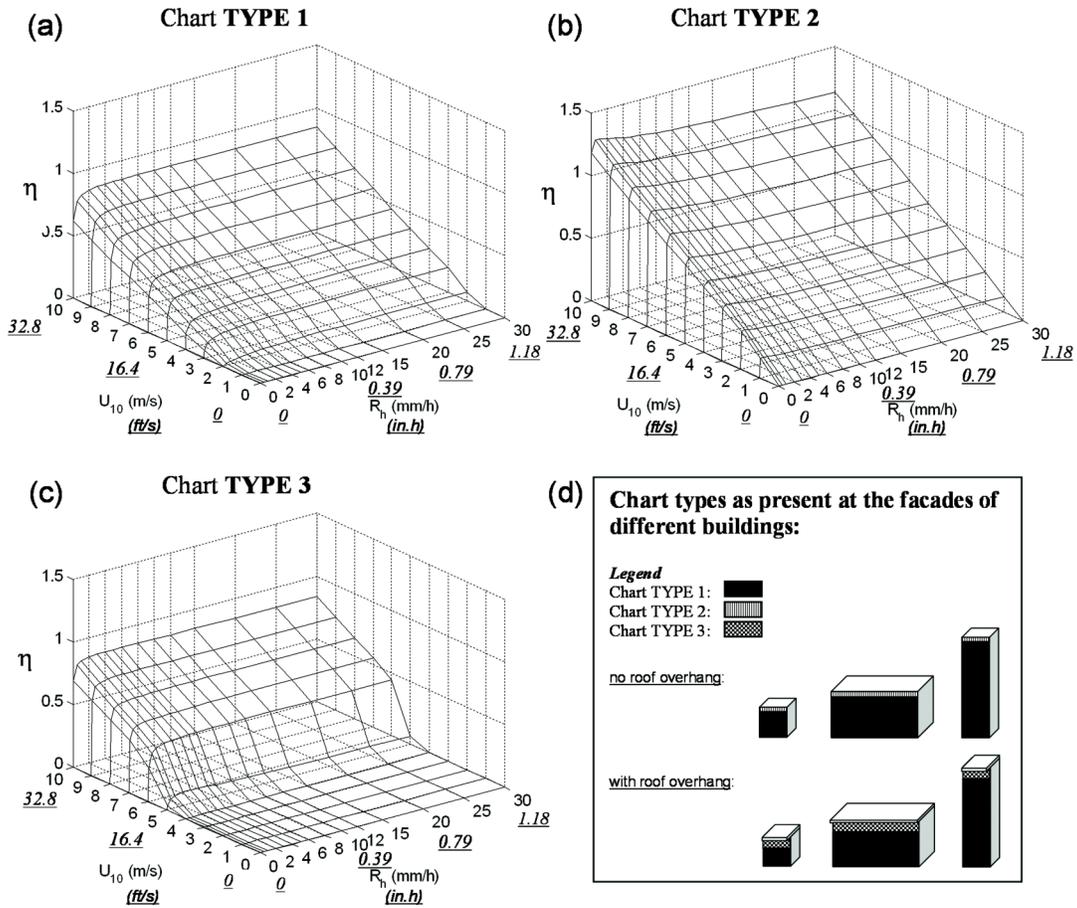


Figure 4 Classification of catch-ratio charts into three characteristic types.

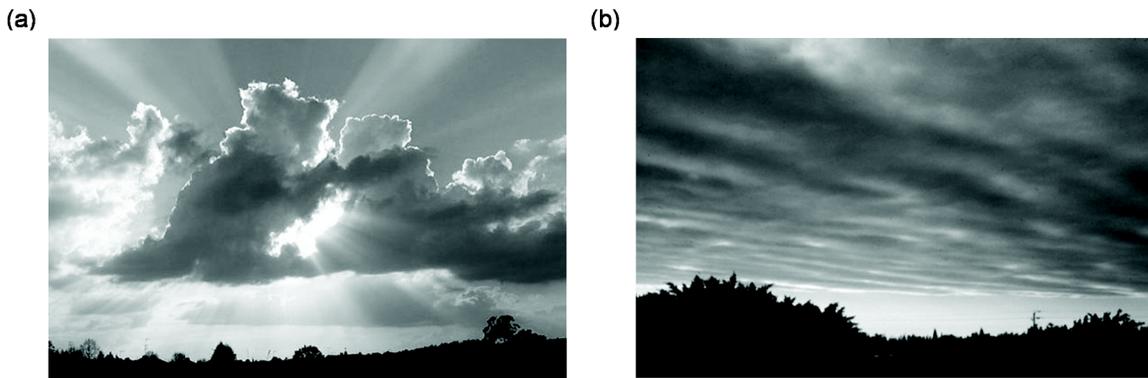


Figure 5 (a) Cumuliform and (b) stratiform clouds.

The following observations are made:

For the cumuliform rain event:

1. Figure 7a: For the most common chart type (type 1), the errors introduced by using the arithmetic averaging technique are very large. Even on an hourly basis, the error goes up to -25% (an underestimation of the WDR amount). On the other hand, the weighted averaging technique shows a

very good performance for all averaging intervals, even up to one day, which is quite remarkable.

2. Figure 7b: For chart type 2, the errors introduced by the arithmetic averaging technique are less pronounced but are always larger than the errors by the weighted averaging technique.
3. Figure 7c: For chart type 3, the effect of the roof overhang causes both averaging techniques to yield large errors.

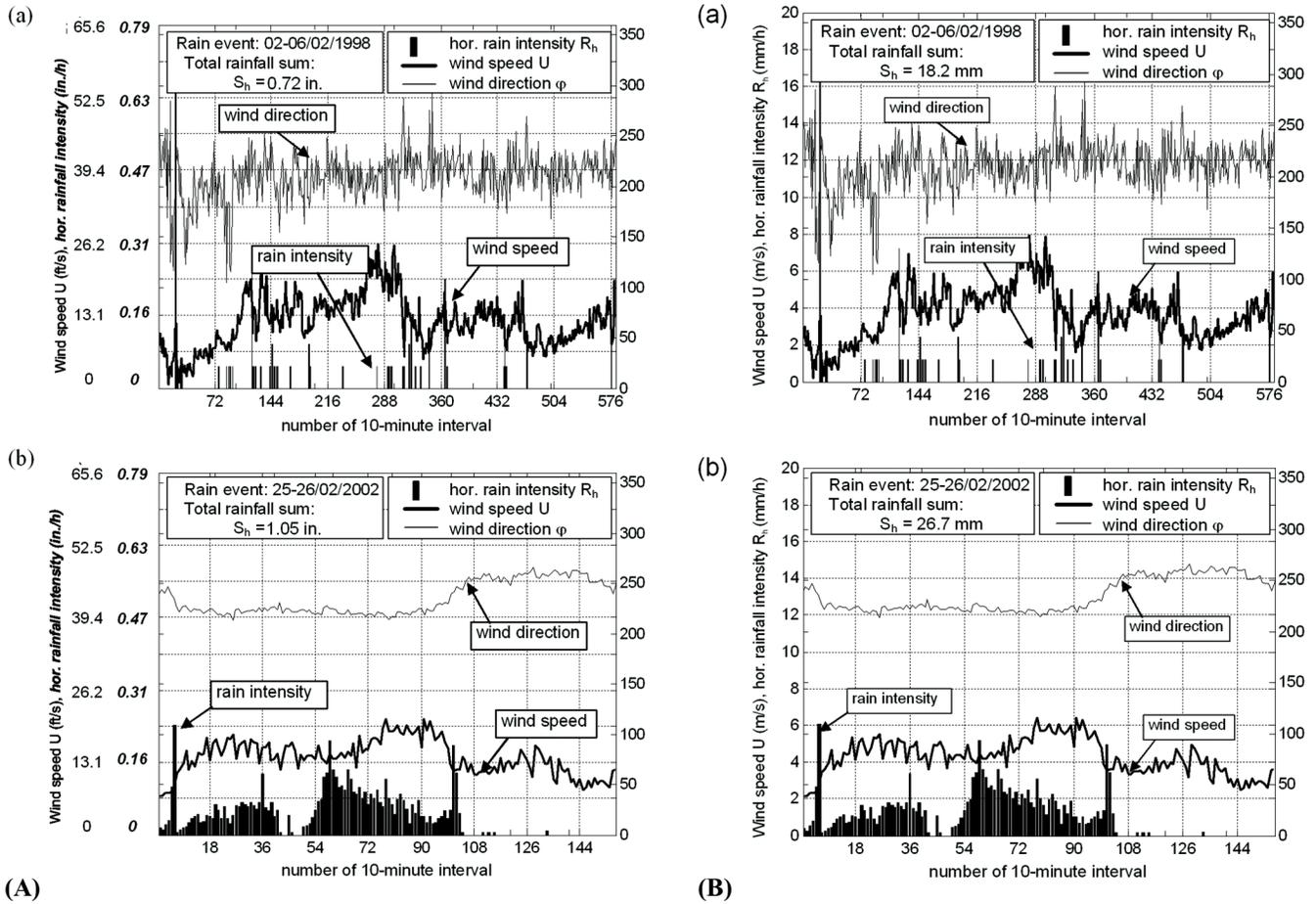


Figure 6 (A) I-P units and (B) SI units for (a) example cumuliiform and (b) example stratiform rain event. The data record of each rain event comprises ten-minute values of the wind speed, wind direction, and horizontal rainfall intensity. The cumuliiform rain event is characterized by a higher temporal variability of especially the horizontal rainfall intensity.

For the stratiform rain event:

1. Figure 7d: The performance of the arithmetic averaging technique is significantly better for the stratiform rain event than for the cumuliiform rain event (Figure 7a). The weighted averaging technique again shows a good performance for all averaging intervals up to at least one day.
2. Figure 7e: Both the arithmetic and the weighted averaging technique provide good results.
3. Figure 7f: The effect of the roof overhang causes both averaging techniques to yield large errors.

The observations depicted in Figure 7 can be explained by focusing on Figure 8, which shows the three types of catch-ratio charts with each chart containing two sets of six data points (U_i, R_{hi}, η_i) on the η -surface. Each set constitutes the raw data within a certain averaging interval (e.g., ten-minute values within an hour). Whether the linearity condition is satisfied or not depends on (1) the temporal variability of the wind and rain data, which is related to the type of the rain

event, (2) the size of the averaging interval, and (3) the shape of the catch-ratio chart.

The temporal variability of the wind and rain data: The higher the temporal variability, the larger the spreading of the data points across the catch-ratio chart and the larger the part of this chart where the linearity condition must be satisfied. When the six data points of one set are clustered closely together, i.e., for weakly fluctuating wind and rain values (see Figures 8a–8c), the linearity condition is likely to be satisfied. On the other hand, when the six data points are spread across the catch-ratio chart, i.e., for highly fluctuating wind or rain values, this condition is less likely to be satisfied. Therefore, the errors will depend on the type of the rain event. In cumuliiform rain events, the fluctuations of wind speed and horizontal rainfall intensity are more pronounced than in stratiform rain events (see Figure 6).

The size of the averaging interval: The larger the size of the averaging interval, the larger the amount of data to be averaged and the likelier higher fluctuations within this interval will be. This will cause the data samples to cover a larger part

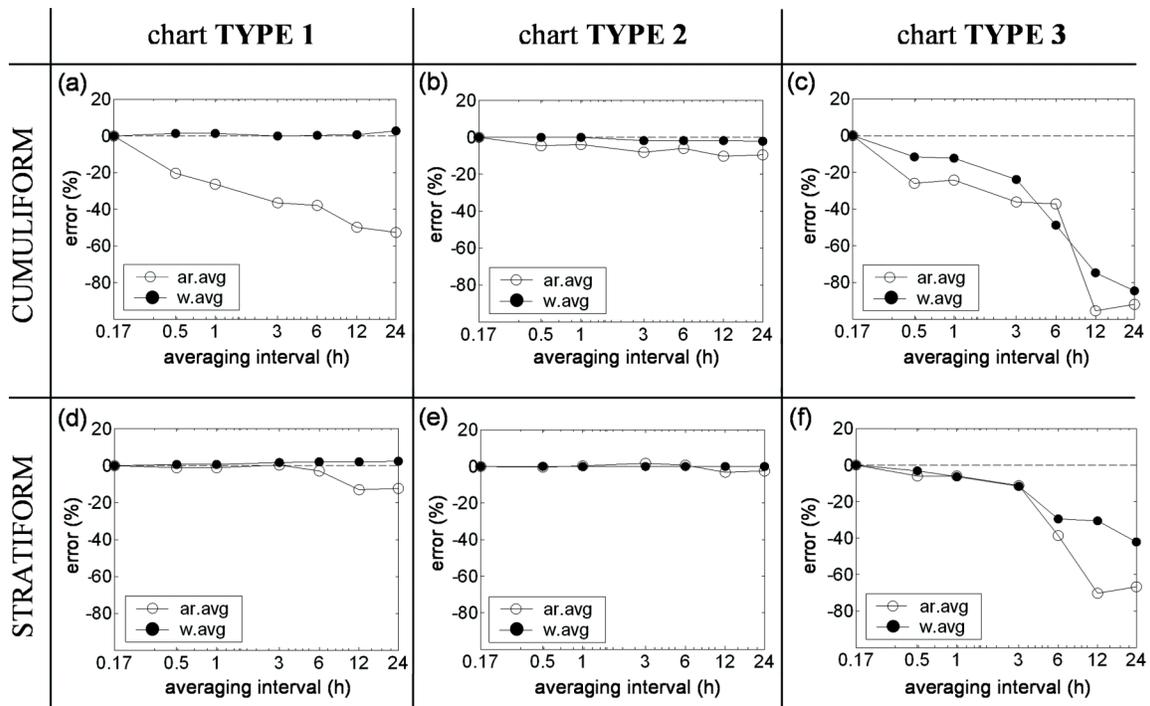


Figure 7 The errors (%) that are introduced in the calculated wind-driven rain amount by using averaged data instead of the raw ten-minute data. The averaging intervals are: 0.5 hour, 1 hour, 3 hours, 6 hours, 12 hours, and 1 day. The errors are displayed for the arithmetic (ar.avg) and the weighted (w.avg) averaging technique, for the three chart types, and for the cumuliform and the stratiform rain events.

of the chart and increases the possibility that this part will show nonlinearity.

The shape of the catch-ratio chart: (see Figure 8):

- Charts of type 1: for light to moderate horizontal rainfall intensities, the catch-ratio chart shows a significant curvature. As a result, the linearity condition can be violated.
- Charts of type 2: the catch-ratio chart is almost completely linear and the linearity condition will be satisfied for almost all sets of data, no matter how large the data fluctuations are.
- Charts of type 3: the chart shows a cut-off of the catch ratio below a certain threshold wind speed. When all data samples in the averaging interval are situated below or above this threshold, the situation is identical to that of chart type 1. If the data samples in the averaging interval are situated below as well as above the threshold, the linearity condition is severely violated, which can give rise to large errors, as shown in Figures 7c and 7f.

In general, the weighted averaging technique shows a very good performance for both rain events, for all averaging intervals (up to at least 1 day), and for the catch-ratio charts of type 1 and type 2. The arithmetic averaging technique is clearly inferior. It shows a poor performance for the cumuliform rain event and for catch-ratio chart type 1. On the other

hand, it provides a fair to good performance for both rain events for chart type 2, due to the linearity of the catch-ratio chart.

APPLICATION FOR YEARLY DATA SETS

This section demonstrates the importance of the above-mentioned parameters and of the errors associated with an inadequate choice of time resolution by WDR calculations with real, yearly wind and rain data records for two cities with different climates: Eindhoven, The Netherlands, and Bloomington, Indiana, USA. The data of each city are available at ten-minute intervals. The climate types are Cfb and Dfa, according to the Köppen Climate Classification System (Strahler and Strahler 1984). The letters in the classification refer to the main climate type and the two subtypes: “C” refers to a “Humid Middle Latitude Climate,” while “D” indicates a “Continental Climate”; the second letter, “f,” refers to a climate that is “moist with adequate precipitation in all months and no dry season”; and the third letter, which is of less importance for this study, indicates the type of summer (hot = “a” or warm = “b”).

The WDR calculations are conducted with an example η -chart of type 1 in Figure 4. Note that η -charts are generally independent of climate; they mainly depend on the building geometry (including environment topography), on the position

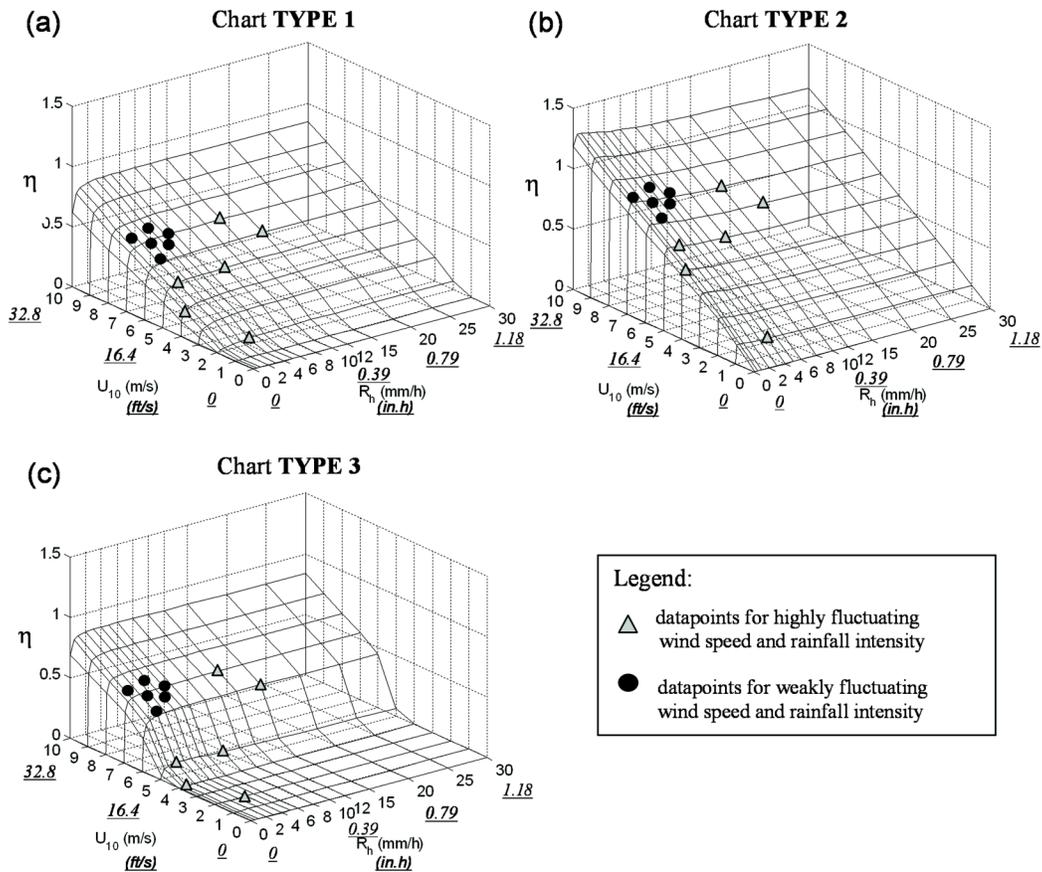


Figure 8 Illustration of the location of two sets of six data points (U_i , R_i , η_i) on the three types of catch-ratio charts. One set (triangles) represents the case of highly fluctuating wind speed and rainfall intensity. The other set (circles) represents weakly fluctuating wind speed and rainfall intensity. The higher the fluctuations in these variables, the larger their spreading across the catch-ratio chart and the likelier the violation of the linearity condition.

on the building facade, and only to a lesser extent on the rain-drop size-distribution (Blocken and Carmeliet 2002; Tang and Davidson 2004). In this study, the size distribution by Best (1950) was adopted to construct the η -charts. This size distribution is based on a large number of measurements in different countries with different climates, and its use in CFD calculations has been validated on several occasions (Blocken and Carmeliet 2002, 2006; Tang and Davidson 2004). The WDR calculations are performed with the ten-minute data and with hourly data obtained by either arithmetic averaging (arith. avg) or weighted averaging (weight. avg) of the ten-minute data. To evaluate the averaging techniques for the full set of data, this exercise assumes that the wind direction is perpendicular to the facade at all times. Figure 9 displays the results in terms of the cumulative WDR amount. It clearly shows that the common way of calculating WDR, i.e., using arithmetically averaged hourly data, leads to large underestimation errors (errors at the end of the year: Eindhoven = 11%, Bloomington = 45%). On the other hand, the use of hourly data obtained with the

proposed weighted averaging technique provides very accurate results (errors: 0% and 4%, respectively).

The main reason for the different errors for each city is the different wind and rain climatology, i.e., the different variability and the corresponding different co-occurrence of the variables wind speed and horizontal rainfall intensity. The type of rainfall is especially important. Previously, two main types were distinguished: cumuliiform and stratiform rains. The temporal variability of stratiform rain events is less pronounced than that of cumuliiform rain events. As a result, cumuliiform rain events show larger changes in the co-occurrence of wind and rain, and errors due to data averaging will be more pronounced. An analysis of the meteorological data indicated that rainfall in Eindhoven is dominated by stratiform rains. This is also indicated in Figure 9a by the gradual increase of the cumulative curves in time, which means that most rainfall series are spread over several hours, which is typical for stratiform rain events. Rainfall in Bloomington, on the other hand, is dominated by cumuliiform rains. This is indi-

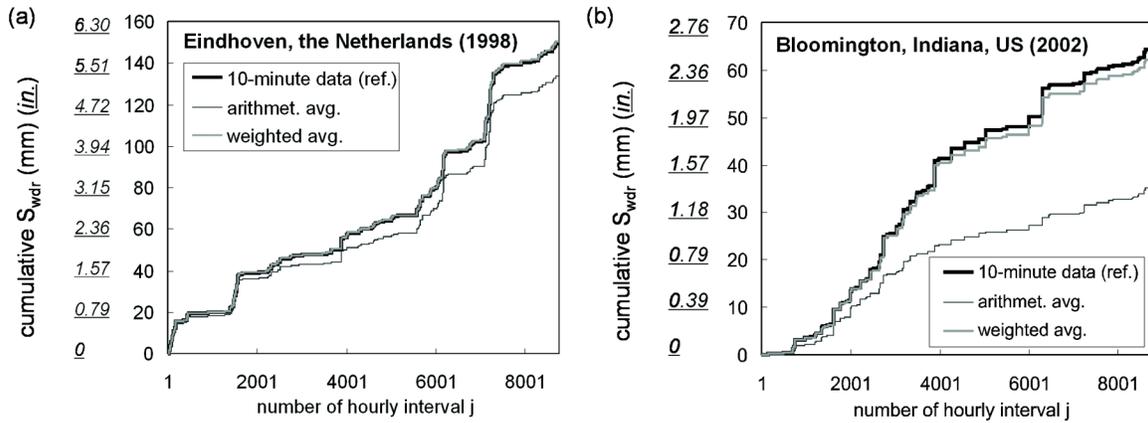


Figure 9 Comparison of cumulative hourly wind-driven rain results obtained with ten-minute data (reference solution) and with arithmetically averaged and weighted averaged hourly data for (a) Eindhoven, The Netherlands (1998), and (b) Bloomington, Indiana, USA (2002).

cated in Figure 9b by the steep increases of the cumulative WDR amount at discrete moments in time, indicating that most rain events only last for one hour at most, which is typical for cumuliform rain events.

DISCUSSION

The study discussed in this paper focused on a minimum averaging interval of ten minutes for the meteorological input data, which is considered to be a good choice. One might consider using one-minute data as well. However, using such data, and especially data at even lower time steps, is considered less appropriate. Two reasons for this are (1) as mentioned before, one minute is considered to be the minimum sample size of rain measurements and, due to errors in timing, local turbulence, and so on, larger intervals are recommended (Jones and Sims 1978; Sumner 1981, 1988) and (2) when using very small time steps, the numerical WDR model that has been used loses touch with reality. This is due to the difference in dealing with the temporal domain between the WDR model and reality. The catch-ratio charts in the WDR model are constructed based on a series of steady-state simulations (fixed wind speed, wind direction, and rainfall intensity). Each raindrop trajectory is calculated based on a steady-state (stationary) wind field, hence, with a stationary wind field acting on the raindrop in the period between its injection in the computational domain and its impact on the building facade. The duration of this period in reality ranges from one to ten minutes, depending on the injection height in the model and the raindrop size. Because in reality ten-minute data wind-speed data are quite stationary as well (Van der Hoven 1957), it makes most sense to perform the calculations with ten-minute wind-speed values. This will provide the best matching (stationarity) between the WDR model and reality.

Both arithmetically averaged and weighted averaged hourly, daily, etc., data fail to accurately predict WDR at facade positions that are partly sheltered from WDR. However, these

positions are of lesser importance, as one is generally interested in the WDR intensities at more exposed positions.

For the cases studied in this paper, the use of arithmetically averaged hourly or daily data instead of ten-minute data has been shown to consistently yield underestimations of the calculated WDR amounts. Previously it was mentioned that the situation in the (a) examples in Figures 2A and 2B leads to underestimations while the situation in the (b) examples in Figures 2A and 2B leads to overestimations. This indicates that the majority of errors in the calculations in this paper has originated from violating the co-occurrence of high wind speed with high rainfall intensity values and of low wind speed with low rainfall intensity values (example (a) of Figures 2A and 2B) rather than from violating the co-occurrence of high wind speed with low rainfall intensity and vice versa (example (b) of Figures 2A and 2B). This indirectly provides information on the physical co-occurrence of wind and rain in the rain events and climates investigated.

This paper has focused on CFD simulations of WDR. As discussed previously, the other calculation method (the semi-empirical WDR relationship) can in fact be regarded as a simplified version of the CFD-based method (Blocken and Carmeliet 2004). Therefore, this method is subjected to similar conclusions.

For practical purposes, it will be useful to be able to assess whether the rain events in a certain city are more of the stratiform or of the cumuliform type. Two methods are suggested here that could help in such assessment, assuming that only hourly data are available. The first method is a test that consists of calculating the yearly WDR exposure with an example catch-ratio chart (e.g., the chart in Figure 4) by (1) using hourly data and (2) using daily data that have been obtained by arithmetic averaging of the hourly data. A significant difference between the resulting calculated WDR amounts indicates that the yearly rain history contains a significant amount of cumuliform rain events (see, for example, the differences

between using hourly and daily data in Figure 7). This method is based on the fact that differences between the use of hourly versus daily data suggest that there will also be differences between the use of ten-minute versus hourly data. The second method consists of plotting the yearly cumulative WDR amount calculated based on hourly data (see Figure 9). As mentioned in the previous section, a gradual increase of the cumulative curves in time means that most rainfall series are spread over several hours, which is typical for stratiform rain events (Figure 9a). On the other hand, steep increases of the cumulative WDR amount at discrete moments in time indicate that most rain events only last for one hour at most, which is typical for cumuliform rain events (Figure 9b).

It is important to note that the study in this paper is based on numerical modelling of WDR with CFD and that this numerical approach is supported by earlier validation studies (Blocken and Carmeliet 2002, 2006; Tang and Davidson 2004). These validation efforts, however, were limited to isolated low-rise and high-rise buildings in only two different climates. WDR is influenced by a large variety of parameters and has long been recognized as being very complex. Therefore, many more validation studies for other building configurations in other climates and in urban environments are needed to provide more confidence in the numerical modelling of WDR with CFD and to be able to investigate the validity of the conclusions of the present study in these situations.

CONCLUSIONS

The parameters determining the required time resolution of wind and rain input data for WDR calculations were investigated, and the magnitude of the errors that can be introduced by the choice of an inadequate time resolution has been illustrated. The results of this study suggest the following conclusions.

The magnitude of the errors associated with the use of a certain time resolution is determined by four parameters: (1) the averaging technique used to convert the raw data to data at a certain (lower) time resolution, (2) the averaging interval (time resolution) itself, (3) the building geometry and the position at the building facade for which the calculations are made, and (4) the type of the rain event (cumuliform versus stratiform). Depending on the four parameters listed above, the minimum required time resolution may vary from ten minutes to one day.

Generally, hourly and daily data are not appropriate for WDR studies when they have been obtained by arithmetic averaging of the raw ten-minute measurement data. However, the use of such data is common practice in WDR studies and because of that significant errors can be made.

Hourly and daily data can be appropriate for WDR studies when they have been obtained by weighted averaging of the ten-minute data. The weighted averaging technique was derived in an earlier publication to prevent or at least limit the loss of information due to data averaging. Weighted averaged data provides very good results, except for facade positions below horizontal projections, for which both averaging tech-

niques fail. For all other facades and facade positions, the technique is very accurate. This is true for all averaging intervals up to at least one day, which is quite remarkable.

Unfortunately, ten-minute data sets are not available for the vast majority of the world's weather stations. Therefore, it is suggested that future measurements are made at ten-minute intervals and that the resulting data sets of wind and rain data should either contain these ten-minute data or should contain hourly or daily data that have been obtained from ten-minute data using the weighted averaging technique.

ACKNOWLEDGMENTS

This research was conducted while the first author was a postdoctoral fellow of the FWO-Flanders (Research Fund-Flanders) that supports and stimulates fundamental research in Flanders (Belgium), whose financial contribution is gratefully acknowledged.

REFERENCES

- Best, A.C. 1950. The size distribution of raindrops. *Quarterly Journal of the Royal Meteorological Society* 76:16–36.
- Blocken, B., and J. Carmeliet. 2002. Spatial and temporal distribution of driving rain on a low-rise building. *Wind and Structures* 5(5):441–62.
- Blocken, B., and J. Carmeliet. 2004. A review of wind-driven rain research in building science. *Journal of Wind Engineering and Industrial Aerodynamics* 92(13):1079–1130.
- Blocken, B., and J. Carmeliet. 2006. The influence of the wind-blocking effect by a building on its wind-driven rain exposure. *Journal of Wind Engineering and Industrial Aerodynamics* 94(2):101–27.
- Blocken, B., and J. Carmeliet. 2007. On the errors associated with the use of hourly data in wind-driven rain calculations on building facades. *Atmospheric Environment*. In press.
- Blocken, B., T. Stathopoulos, and J. Carmeliet. 2007. CFD simulation of the atmospheric boundary layer: Wall function problems. *Atmospheric Environment* 41(2):238–52.
- CEN/TC89. 2002. *Hygrothermal performance of buildings—Climatic data—Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data*. prEN ISO 15927-3, Standard under approval. European Committee for Standardization, Brussels, Belgium.
- Choi, E.C.C. 1991. Numerical simulation of wind-driven rain falling onto a 2-D building. *Proceedings of the Asia Pacific Conference on Computational Mechanics, Hong Kong*, pp. 1721–28.
- Choi, E.C.C. 1993. Simulation of wind-driven rain around a building. *Journal of Wind Engineering and Industrial Aerodynamics* 46&47:721–29.

- Choi, E.C.C. 1994. Determination of wind-driven rain intensity on building faces. *Journal of Wind Engineering and Industrial Aerodynamics* 51:55–69.
- Hoppestad, S. 1955. *Slagregn i Norge* (in Norwegian). Rapport Nr. 13, Norwegian Building Research Institute, Oslo.
- Jones, D.M.A., and A.L. Sims. 1978. Climatology of instantaneous rainfall rates. *Journal of Applied Meteorology* 17:1135–50.
- Sanders, C.H., and M.C. Phillipson. 2003. UK adaptation strategy and technical measures: The impacts of climate change on buildings. *Building Research and Information* 31(3–4):210–21.
- Strahler, A.N., and A.H. Strahler. 1984. *Elements of Physical Geography*. New York: John Wiley & Sons.
- Sumner, G.N. 1981. The nature and development of rainstorms in coastal East Africa. *Journal of Climate* 1(2):131–52.
- Sumner, G. 1988. *Precipitation: Process and Analysis*. New York: John Wiley & Sons.
- Tang, W., and C.I. Davidson. 2004. Erosion of limestone building surfaces caused by wind-driven rain. 2. Numerical modelling. *Atmospheric Environment* 38(33):5601–09.
- Van der Hoven, I. 1957. Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. *Journal of Meteorology* 14:160–64.