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Guidelines for the required time resolution of meteorological input data for wind-driven rain calculations on buildings

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Abstract

An important question in wind-driven rain (WDR) calculations on buildings, either with semi-empirical formulae or with Computational Fluid Dynamics (CFD), concerns the required time resolution of the meteorological input data: wind speed, wind direction and horizontal rainfall intensity. Earlier work has indicated that the use of 10-minute input data can provide accurate results, while the use of arithmetically averaged hourly data can yield significant underestimations in the calculated WDR amounts. This paper builds further on this earlier work by providing a detailed investigation of the parameters that determine the required time resolution for WDR calculations on building facades: (1) the averaging technique; (2) the building geometry and the position at the building facade; and (3) the type of the rain event. It is shown that all three parameters can have a large influence on the required time resolution. Depending on these parameters, hourly or even daily wind and rain input data can provide accurate results, while in other situations they can lead to very large errors. Finally, guidelines for the required time resolution as a function of the influencing parameters are provided.

Keywords: Wind-driven rain; Driving rain; Wind flow; Building; CFD; Computational Fluid Dynamics; Sample size; Time resolution; Data averaging; Climate data

1. 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 Phillipson, 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 semi-empirical 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 (CEN 2002) is based on this method (Blocken and Carmeliet 2004). In the past years, Choi (1991, 1993, 1994a, 1994b) developed and applied a steady-state numerical simulation technique based on CFD. This technique has subsequently been adopted as the basic procedure in computational WDR studies and has been 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, 2007) and the extended simulation method was experimentally validated for low-rise and high-rise buildings (Blocken and Carmeliet 2002, 2004, 2006, Tang and Davidson 2004). The extension into the temporal domain allows this method to be applied 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

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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 "time-representative", i.e. to yield a good estimate of the corresponding WDR amount. In earlier papers (Blocken and Carmeliet 2002, 2004, 2006, Tang and Davidson 2004), time resolutions of 10 minutes and 1 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. A systematic investigation of the required time resolution has not yet been performed and there are almost no guidelines for selecting an appropriate time resolution. Investigating this issue is quite important, because the use of hourly datasets for WDR calculations is generally accepted and current practice and there is hardly any information about the related errors. For example, the existing standards for WDR calculations (BSI 1992, CEN 2002) request at best hourly averaged data. This is in contradiction with the statement by Sumner (1988) that hourly data are not appropriate where rain measurements are concerned, certainly not for the registration of short-duration showers. Also Hens (1996) states that hourly data may not be good enough for hygrothermal (heat-air-moisture; HAM) simulations where e.g. precipitation is concerned. He mentions that, given the fact that only hourly data are available for most weather stations and that the costs to obtain them are high, hourly data are often considered to be the "best" choice. But he stresses that, as a general guideline, the time-averaging period should not induce loss of important information for the case analysed. These statements and findings provide a justification for the present study.

The investigation in this paper focuses on the minimum required time resolution for accurate WDR calculations and on the errors associated with lower time resolutions. Whereas its predecessor indicated the importance of errors associated with hourly data (Blocken and Carmeliet 2007), this paper builds further on this earlier work by providing a detailed investigation of data averaging errors as a function of the four most important influencing parameters: (1) the averaging technique that was used to convert the raw measurement data to "dataset" data at a certain (lower) time resolution; (2) the averaging interval; (3) the building geometry and the position at the building facade; and (4) the type of the rain event. In addition, it provides guidelines for selecting the minimum required time resolution as a function of these influencing parameters.

In Section 2, some information about the time resolution at which wind and rain data are currently gathered and made available is provided, and the error causes associated with averaging wind and rain data are briefly discussed. The focus in this paper will be on calculations of WDR based on CFD simulations. Therefore, Section 3 briefly describes the CFD WDR model. In Section 4, the new weighted data averaging technique, which was developed in an earlier publication (Blocken and Carmeliet 2007), is briefly recalled. The insight gained by the CFD WDR model and the new weighted averaging technique provides the basis for the analysis of the influencing parameters in Section 5. In Section 6, guidelines for selecting an appropriate time resolution for WDR calculations are presented. Section 7 (discussion) and Section 8 (conclusions) conclude the paper.

2. The time resolution of meteorological data and data averaging

Meteorological measurements are conducted at a certain time resolution. Only in exceptional cases, the datasets that are made available for WDR and other calculations contain these raw data. Generally, the raw data will be converted to data at a lower time resolution (i.e. averaged over a certain averaging interval) and these averaged data are provided in the dataset. This is the current practice at most national and international meteorological networks and at many research institutes. The time resolution of datasets in general and of datasets for building physics (building science) heat-air-moisture (HAM) transfer simulations in particular is typically one hour. Currently, the use of hourly data for WDR calculations is generally accepted, although recent research has indicated that significant errors can be made, both in the WDR calculations and in the HAM simulations (Blocken et al. 2007a). The errors are caused by the loss of information by averaging the raw data. These aspects are explained in more detail below.

2.1. The time resolution of meteorological measurements

Rainfall intensity is characterised 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 often more pronounced for wind speed than for wind direction. Wind speed measurements are usually conducted at a higher resolution than the rainfall intensity (≤ 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, Fig. 1 shows a data record (rain event) of 10-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 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.

2.2. The time resolution of meteorological datasets

For combined wind and rain measurements, such as needed for WDR calculations, an averaging interval of 10 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 datasets are made available however is one hour or a day. These averaged hourly or daily data are usually obtained from averaging raw measurement data (e.g. 10-minute) with the arithmetic averaging technique; see Eq. (1) for the wind speed and the horizontal rainfall intensity:

$$U_j = \frac{\sum_i U_i}{n} \quad ; \quad R_{hj} = \frac{\sum_i R_{hi}}{n} \tag{1}$$

where the index j refers to the averaging interval, the index i refers to the raw data in the averaging interval and the summation extends over all data samples (n) in this interval. Note that R_{hi} refers to the "average" horizontal rainfall intensity during interval i, i.e. the horizontal rainfall amount S_{hi} for interval i divided by the duration of this interval. In the remainder of this paper, the term "averaging interval" will also be used to refer to time resolution.

2.3. 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. Three possible causes for errors due to data averaging can be identified: (1) wind-speed averaging; (2) rainfall-intensity averaging and (3) violating the co-occurrence of wind speed and rainfall intensity. The first two causes refer to the flattening of peak values, respectively of wind speed and rainfall intensity, that occur in the averaging interval. The third cause, which is the most important one, refers to the loss of information about the co-occurrence of wind and rain that is due to arithmetic data averaging. This error has been the subject of earlier investigation (Blocken and Carmeliet 2007). Such situation is illustrated in Fig. 2a and b, that represent two theoretical rain events each consisting of 6 time intervals. For each of these intervals, the (raw) wind speed and horizontal rainfall intensity values are illustrated. Arithmetically averaging these data over all 6 intervals will lead to the loss of important information about the co-occurrence wind and rain, i.e. the co-occurrence of high wind speed and high rainfall intensity values and of the co-occurrence of low wind speed and low rainfall intensity values in Fig. 2a, and vice versa for Fig. 2b. This loss of information about the co-occurrence of wind and rain can lead to large errors. 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 Fig. 2a will lead to an underestimation of the actual WDR intensity, while arithmetic averaging of the data in Fig. 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.

3. The numerical wind-driven rain model

3.1. 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 (Eq. 2):

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

where $R_{wdr}(d,t)$ and $R_h(d,t)$ are the specific WDR intensity on the building and the specific unobstructed horizontal rainfall intensity, and t is the time. $R_{wdr}(t)$ and $R_h(t)$ respectively refer to the same quantities but 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:

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

where $S_{wdr}(d,t_j)$ and $S_h(d,t_j)$ are the specific WDR amount on the building and the specific unobstructed horizontal rainfall amount during time step $[t_j, t_j+\Delta t]$ for raindrops with diameter d. $S_{wdr}(t_j)$ and $S_h(t_j)$ respectively refer to the same quantities integrated over all raindrop diameters.

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 and (6) the horizontal raindrop-size distribution. The reference wind speed U (m/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}) refers to the raindrop-size distribution as a flux through a horizontal plane.

3.2. Five-step simulation method

The numerical method for the calculation of the spatial and temporal distribution of WDR on buildings is based on the steady-state simulation procedure developed by Choi (1991, 1993, 1994a, 1994b) and on the extension of this procedure into the temporal domain by Blocken and Carmeliet (2002). The methodology consists of 5 steps:

1. The steady-state 3D 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. 2007b).
2. Raindrop trajectories are obtained by injecting raindrops of different sizes in the calculated wind-flow pattern and by solving their equations of motion. Details on this procedure can be found in Choi (1994a).
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 (Fig. 3a). To determine the WDR amount for a given rain event, the catch-ratio charts are combined with the meteorological data records of U_{10}, φ_{10} and R_h.

The last step is explained in more detail. For example, let us focus on the data record in Fig. 1. To determine the WDR amount for this rain event, this event is partitioned into a number of equidistant time steps (e.g. 10-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 (Fig. 3a). This is done by linear interpolation (Fig. 3b):

$$\eta_i = \alpha_{kl}\left(U_i - U_k\right) + \beta_{kl}\left(R_{hi} - R_{hl}\right) + \gamma_{kl} \tag{4}$$

where the coefficients 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}.

4. Arithmetic versus weighted data averaging

In Section 2.2, the arithmetic averaging technique that is traditionally used for meteorological data averaging and the related averaging errors were described. Recent research has led to a new averaging technique in which 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 (Blocken and Carmeliet 2007):

$$U_j = \frac{\sum_i U_i S_{hi}}{\sum_i S_{hi}} \quad ; \quad R_{hj} = \frac{\sum_i R_{hi} S_{hi}}{\sum_i S_{hi}} \tag{5}$$

It was proven that averaging wind and rain data with this technique, instead of Eq. (1), and using these averaged data in WDR calculations will not introduce averaging errors in 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 (e.g. surface in Fig. 3a). This linearity of η as a function of U_{10} and R_h has been the actual condition for deriving Eq. (5). 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.

5. Data averaging errors: influencing parameters and analysis

5.1. Influencing parameters

The four influencing parameters that are investigated are: (1) the averaging technique; (2) the averaging interval (time resolution); (3) the shape of the catch-ratio chart and (4) the type of the 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 10-minute measurement data into data for larger averaging intervals.

The *averaging interval* is in the range of 10 minutes to 1 day, respectively the minimum and maximum time resolution of many existing meteorological datasets.

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 Fig. 4a-c. 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. Fig. 4d provides an indication of the positions on building facades where each type is applicable. The three charts themselves were obtained from CFD simulations for the south-west facade of the VLIET test building of the Laboratory of Building Physics (Blocken and Carmeliet 2006): (Fig. 5: position 3, position 20 and position 4), because this building exhibits the typical features for all three types. Note however that the characteristic shape of these charts has been confirmed by CFD simulations of WDR on a variety of different building configurations (Blocken and Carmeliet 2006). The charts of type 1 are characterised 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). This chart type is representative for most part of all building facades, except for the roof edge and for 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 edge 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. For example for the VLIET building (Fig. 5) – which is an exceptional case because it is a (very) low-rise building with large roof overhang lengths especially for the sloped-roof module – chart type 1 is present at positions 3, 6, 9, 10-18. Charts of type 2 are present at positions 19 and 20 (top edge, no roof overhang present) and charts of type 3 at positions 1, 2, 4, 5, 7, 8 (roof overhang). 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 the study: a cumuliform and a stratiform rain event. The terminology "cumuliform-stratiform" stems from the type of clouds generating the rain. *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). The temporal variability of stratiform rain events is less pronounced than that of cumuliform rain events. The two typical rain events that will be used in this study are illustrated in Fig. 6.

5.2. Analysis of data averaging errors

WDR calculations have been made for various combinations of the influencing parameters. Fig. 7 illustrates the errors that are introduced by using input data of averaging intervals that are larger than 10 minutes in combination with the different averaging techniques, different rain events and different chart types. The errors are calculated as follows:

$$e = 100 \cdot \frac{S_{wdr\_AVG} - S_{wdr\_REF}}{S_{wdr\_REF}} \quad (\%) \tag{6}$$

where S_{wdr_AVG} is the WDR amount calculated with the averaged data and S_{wdr_REF} is the WDR amount calculated with the 10-minute data (reference solution). The following observations are made:

(1) For the cumuliform rain event:
   - (a) Fig. 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% (underestimation of WDR amount). On the other hand, the weighted averaging technique shows a very good performance for all averaging intervals, even up to 1 day, which is quite remarkable.
   - (b) Fig. 7b: For chart type 2, the errors introduced by the arithmetic averaging technique are less pronounced, but always larger than the errors by the weighted averaging technique.
   - (c) Fig. 7c: For chart type 3, the effect of the roof overhang causes both averaging techniques to yield large errors.

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

To explain the observations in Fig. 7, we focus on Fig. 8. It 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. 10-minute values within an hour). In Section 4, the linearity condition was introduced as the necessary and sufficient condition for the weighted averaging technique to be exact. Whether this 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.

(1) *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 Fig. 8a-c), 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 cumuliform rain events, the fluctuations of wind speed and horizontal rainfall intensity are more pronounced than in stratiform rain events (see Fig. 6).

(2) *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 of the chart and increases the possibility that this part will show non-linearity.

(3) *The shape of the catch-ratio chart*: (see Fig. 8)
  (a) 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.
  (b) 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.
  (c) 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 Fig. 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. Note however that linearity is a necessary, but not a sufficient condition for the arithmetic averaging technique to be exact.

6. Guidelines

From existing information (Van der Hoven 1957, Jones and Sims 1978, Sumner 1981, 1988) and from the present study of the errors associated with different time resolutions, different averaging techniques, different catch-ratio charts and different rain events, the following guidelines for the required time resolution of meteorological data for WDR calculations can be distilled.

1. A good choice for the time resolution of wind and rain measurements is 10 minutes. This choice is based on the spectral gap in the wind-speed power spectrum, the high temporal variability of rainfall and the limitations in time resolution of rain gauges and rain measurements (Van der Hoven 1957, Jones and Sims 1978, Sumner 1981, 1988).
2. Generally, hourly or daily data can be used instead but only if they have been obtained from averaging 10-minute measurement data with the weighted averaging technique.
3. Special attention is required when using arithmetically averaged data, even when they are available on an hourly basis. Very large errors in the calculated WDR amounts can be introduced (e.g. up to -25 % and -50% in the cases studied here). Therefore, in general, the use of such data should be avoided. There are only a few exceptions, in which the use of arithmetically averaged hourly data can provide good results:
   (a) When calculations are only made for the top edge of building facades without roof overhang and without other details or rooftop structures near this edge.
   (b) When calculations are made for stratiform rain events that show a clear and pronounced stationary character.

   Note however that also in these cases the weighted averaging technique will generally provide better results.
4. Accurately taking into account the effect of important horizontal projections such as roof overhangs appears to be very difficult. The large errors at lower time resolutions suggest that significant errors probably also occur when using 10 minute data in this situation.
5. When WDR calculations are performed for long periods of time (e.g. one month or one year), the data records will often comprise both cumuliform and stratiform rain events. In that case the strictest guidelines given above should be followed. Only for climates in which stratiform rain events are clearly dominant and

in which cumuliform rain events are scarce, arithmetically averaged hourly data may be allowed. In all other cases, hourly or daily data are only allowed if obtained by weighted averaging.

7. Discussion

The study in this paper has focused on a minimum averaging interval of 10 minutes for the meteorological input data, which is considered to be a good choice. One might consider using 1-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). (2) When using very small time steps, the numerical WDR model that has been used looses 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 has been 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 1 to 10 minutes, depending on the injection height in the model and the raindrop size. Because in reality, 10-minute data wind-speed data are quite stationary as well (Van der Hoven 1957), it makes most sense to perform the calculations with 10-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.

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

The parameter “type of rain event” as investigated in this paper can to some extent be a reflection of the type of the climate. The number of stratiform and cumuliform rain events in a year can to a large extent be dictated by the climate. For example, data analysis by Choi (2001) has shown that Singapore (climate type “Af”, moist tropical climate) has more than 200 cumuliform thunderstorms a year, while data analysis by the authors has shown that Flanders and the Netherlands (climate type “Cf”, humid middle latitude climate) have a majority of stratiform rain events. Generally however, all climates contain a mixture of both and the strictest time resolution guidelines should be followed. Some information on the importance of climate for hourly data averaging errors is given in (Blocken and Carmeliet 2007).

In this paper, only errors caused by averaging of the meteorological variables wind speed and horizontal rainfall intensity have been investigated. While relatively speaking, the fluctuations of wind speed and rainfall intensity are often more pronounced than those of wind direction, additional errors will be introduced by wind direction averaging. Future research should focus on this potentially important additional source of error.

As mentioned before, most existing meteorological datasets for building applications contain at best hourly data. The use of such data for e.g. HAM simulations is current practice. For example, the leading commercial and non-commercial advanced HAM codes WUFI (WUFI ORNL/IBP) (Künzel 1994, Künzel et al. 2004), CHAMPS-BES (formerly called DELPHIN) (Grunewald 1997, Grunewald and Nicolai 2006), HYGirc (Cornick et al. 2003, Maref et al. 2004, NRC 2007) and HAMFEM (Janssen 2002, Janssen et al. 2007) that are used worldwide for hygrothermal building envelope analysis, contain and employ meteorological datasets for a large number of cities all over the world. Unfortunately, almost all of these datasets consist of arithmetically averaged hourly data, due to the lack of data at shorter time intervals. Efforts should be made to persuade national and international meteorological organisations and research institutes to provide either higher resolution (10 minute) meteorological datasets or weighted averaged datasets to the community.

8. Conclusions

- The required time resolution of wind and rain input data for wind-driven rain (WDR) calculations and the errors involved are mainly 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).
- Each of the four parameters can have a large influence on the required time resolution. Depending on these parameters, the minimum required time resolution may vary from 10 minutes to 1 day.

- Guidelines for the required time resolution have been presented. They indicate that generally, hourly and daily data are not appropriate for WDR studies when they have been obtained by the traditional approach of arithmetic averaging of the raw 10-minute measurement data.
- Hourly and daily data can be appropriate for WDR studies when they have been obtained by application of the new weighted averaging technique for averaging the 10-minute data. Weighted averaged data can provide very good results in most situations, up to averaging intervals of one day, which is quite remarkable.
- Future datasets of wind and rain data should either comprise 10-minute data or hourly or daily data that have been obtained using the weighted averaging technique. It would be very valuable if national and international meteorological organisations and research institutes would supplement their existing historical hourly or daily data records with the weighted averaged wind and rain data, calculated based on the corresponding 10-minute data. These 10-minute data have often been measured but not made available.

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FIGURE CAPTIONS

Figure 1. Meteorological data record (rain event) with 10-minute wind speed, wind direction and horizontal rainfall intensity measurements for the period 08-12/02/2002.

Figure 2. Two theoretical meteorological data records (rain events) with "raw" measurement data of wind speed U and horizontal rainfall intensity R_h.

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.

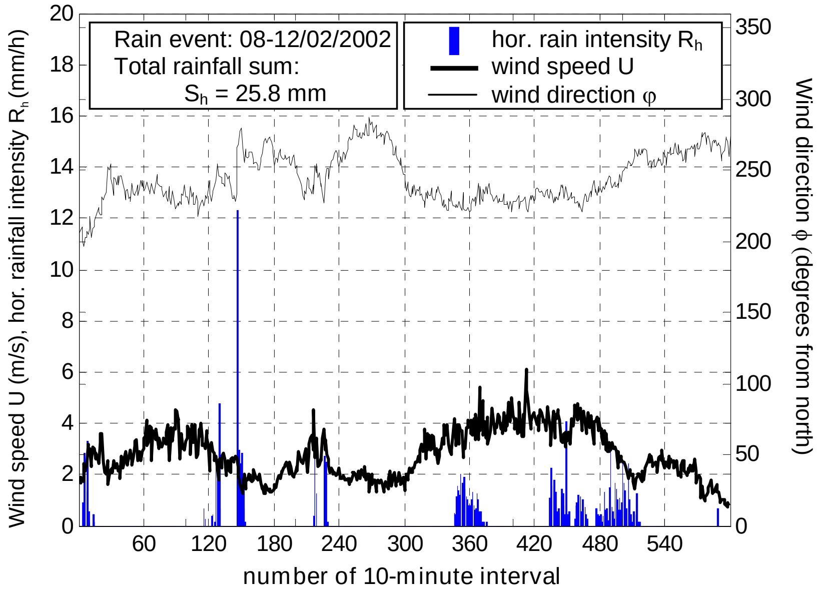
Figure 4. Classification of catch-ratio charts into three characteristic types. (a-c) Chart type 1, 2 and 3. The position number that is indicated refers to the position on the VLIET test building in Fig. 5. (d) Indication of the positions on building facades where a certain type of catch-ratio chart will be present.

Figure 5. VLIET test building (north-west and south-west facade) with sloped-roof module (roof overhang length 0.44 – 0.41 m), terrace module (no overhang) and flat-roof module (overhang length 0.32-0.30 m) and with indication of positions and numbers.

Figure 6. (a) Example cumuliform and (b) example stratiform rain event with 10-minute values of the wind speed, wind direction and horizontal rainfall intensity.

Figure 7. The relative errors (%) that are introduced in the calculated wind-driven rain amount by using averaged data instead of the raw 10-minute data, for different averaging intervals, different averaging techniques, different chart types and different rain events (ar.avg = arithmetic averaging; w.avg = weighted averaging).

Figure 8. Illustration of the location of two sets of six datapoints (U_i, R_i, η_i) on the three types of catch-ratio charts, for highly fluctuating versus weakly fluctuating wind speed and rainfall intensity.



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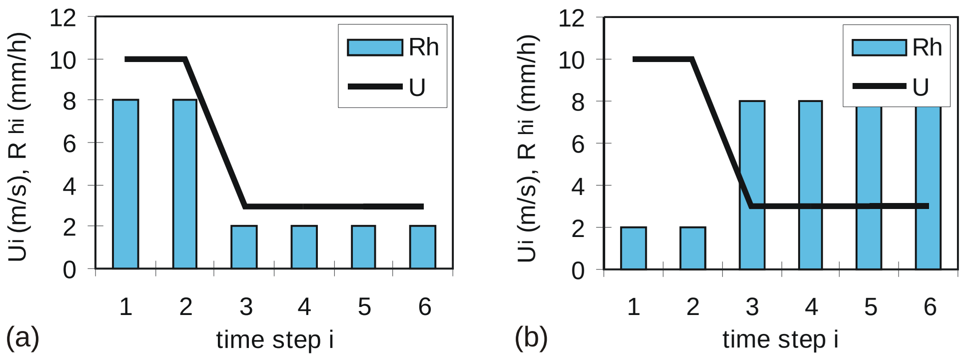

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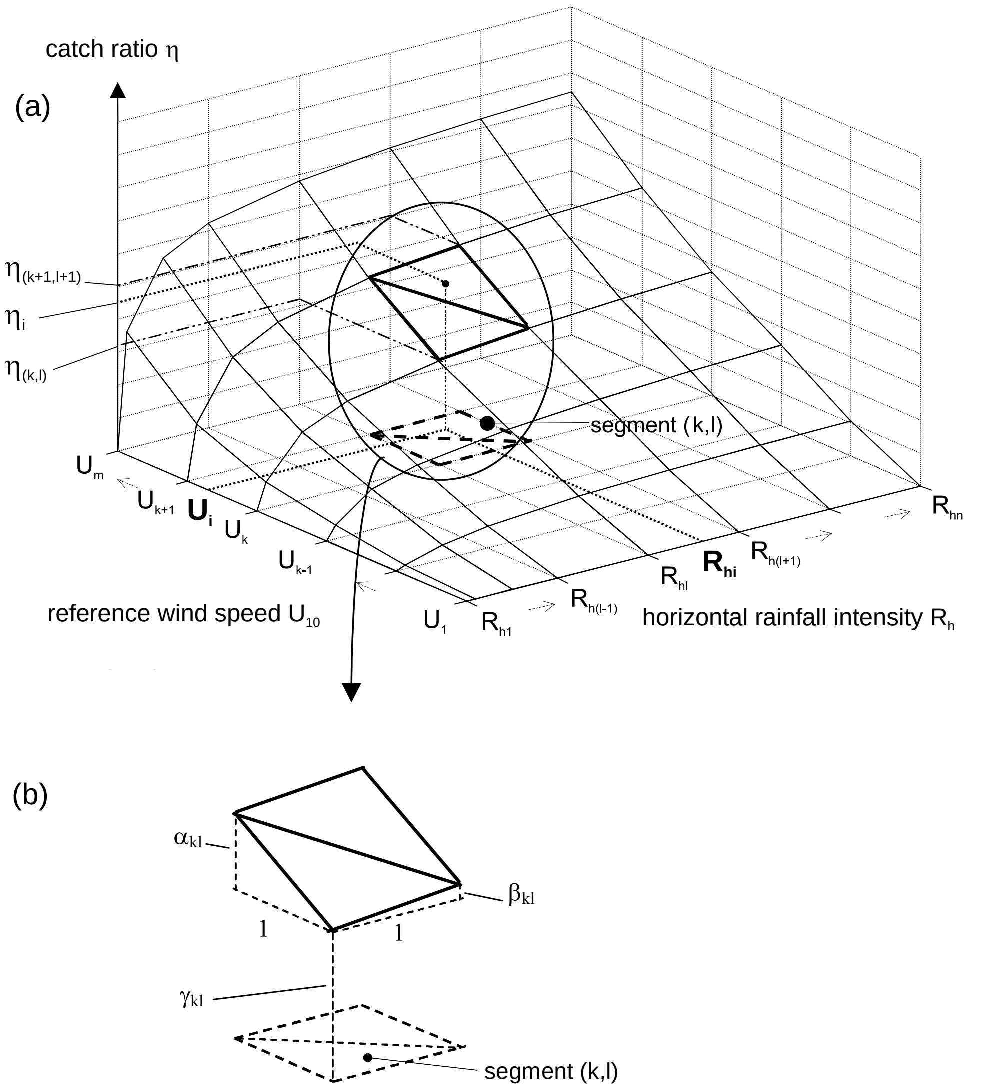

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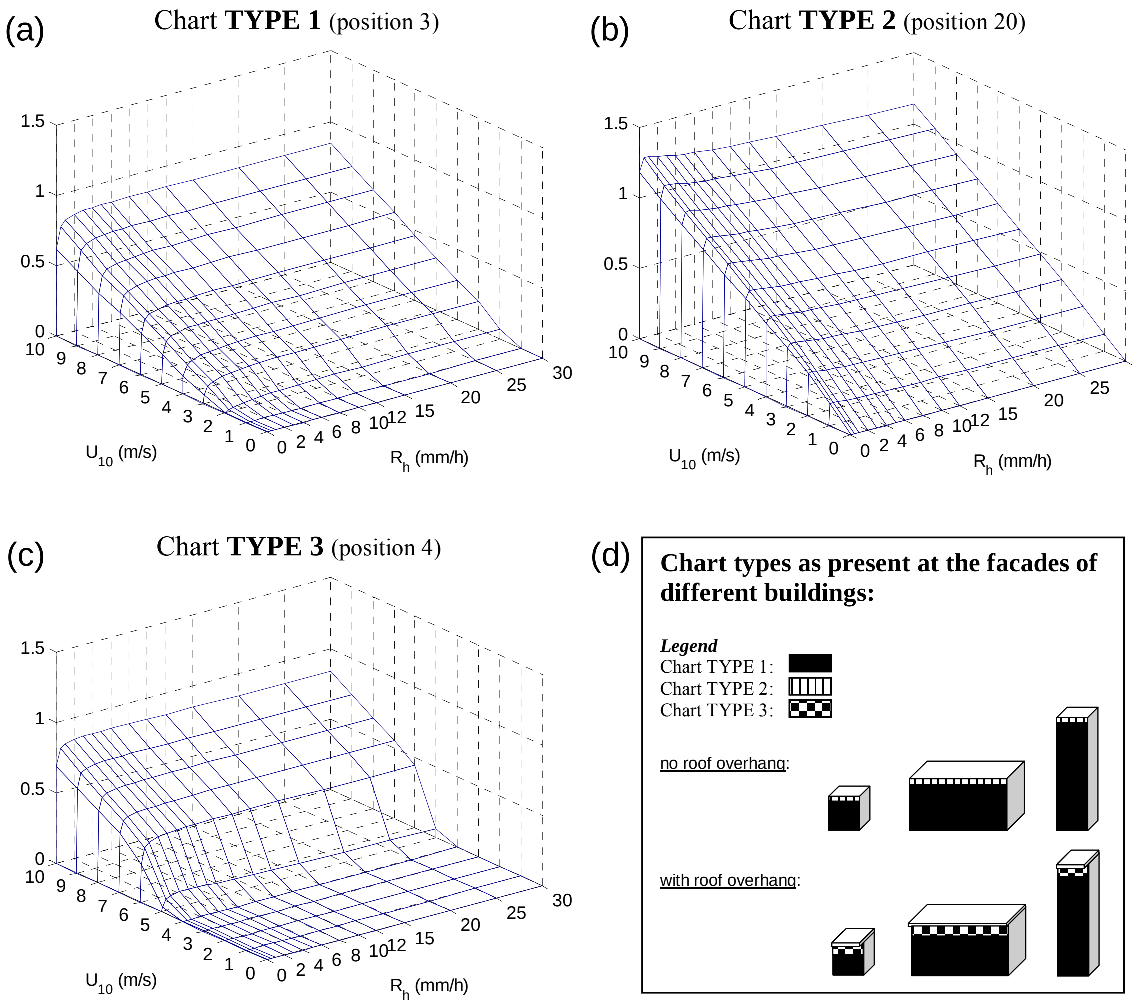

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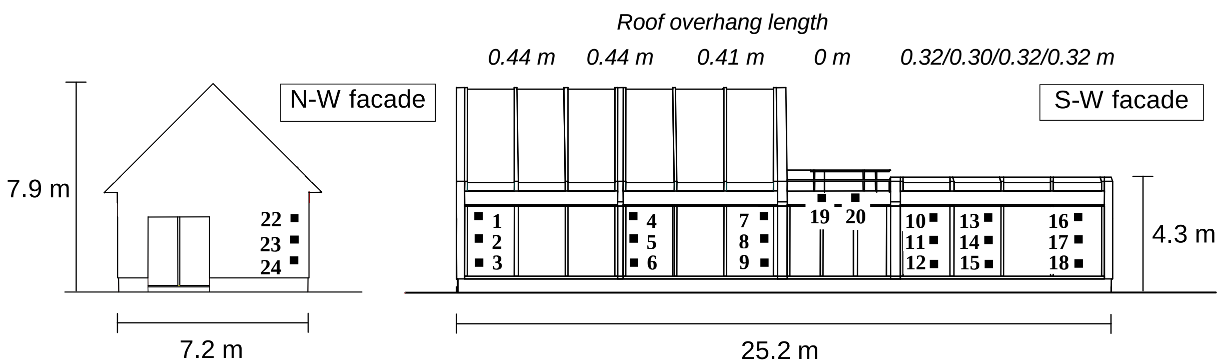

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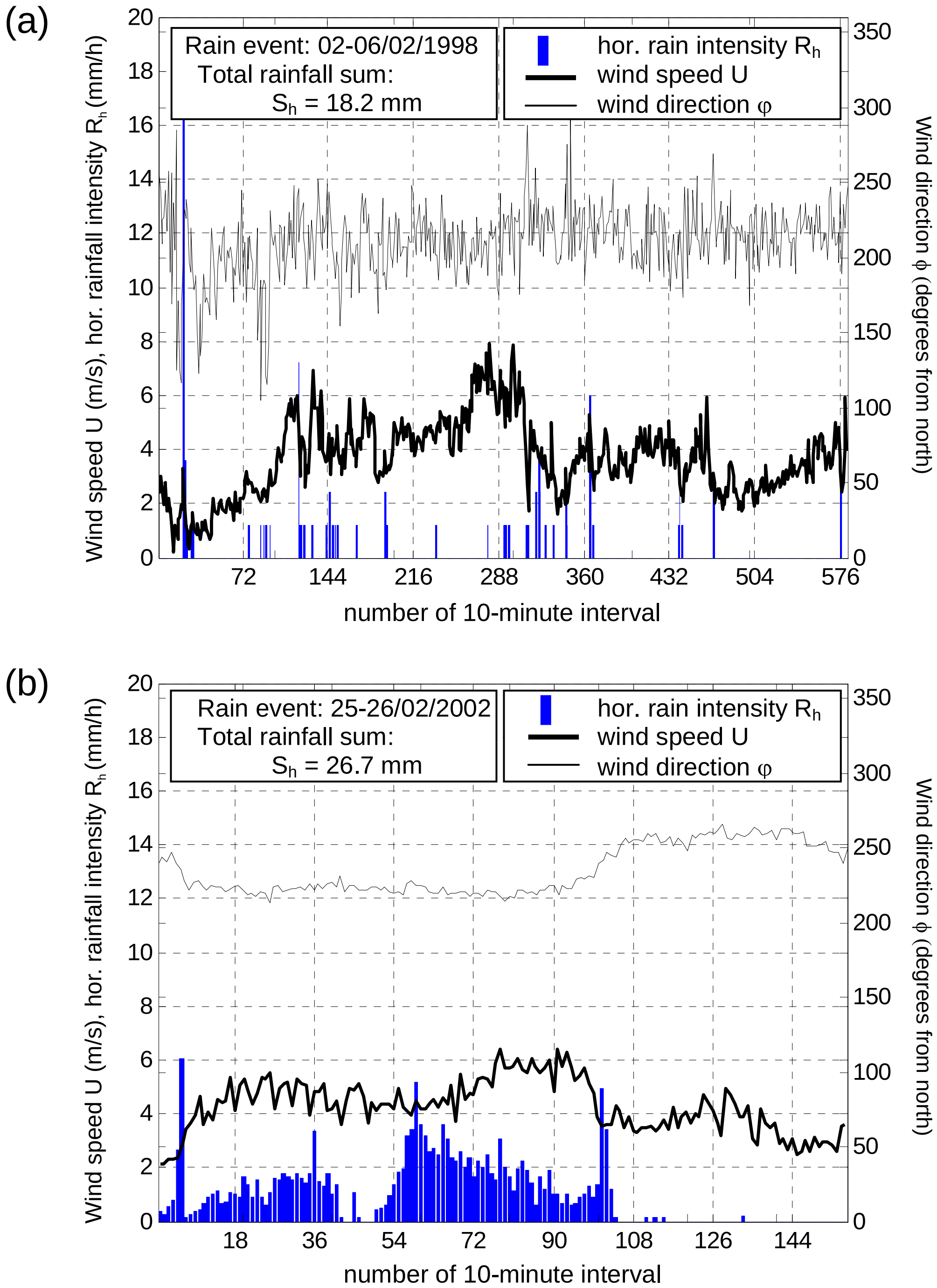

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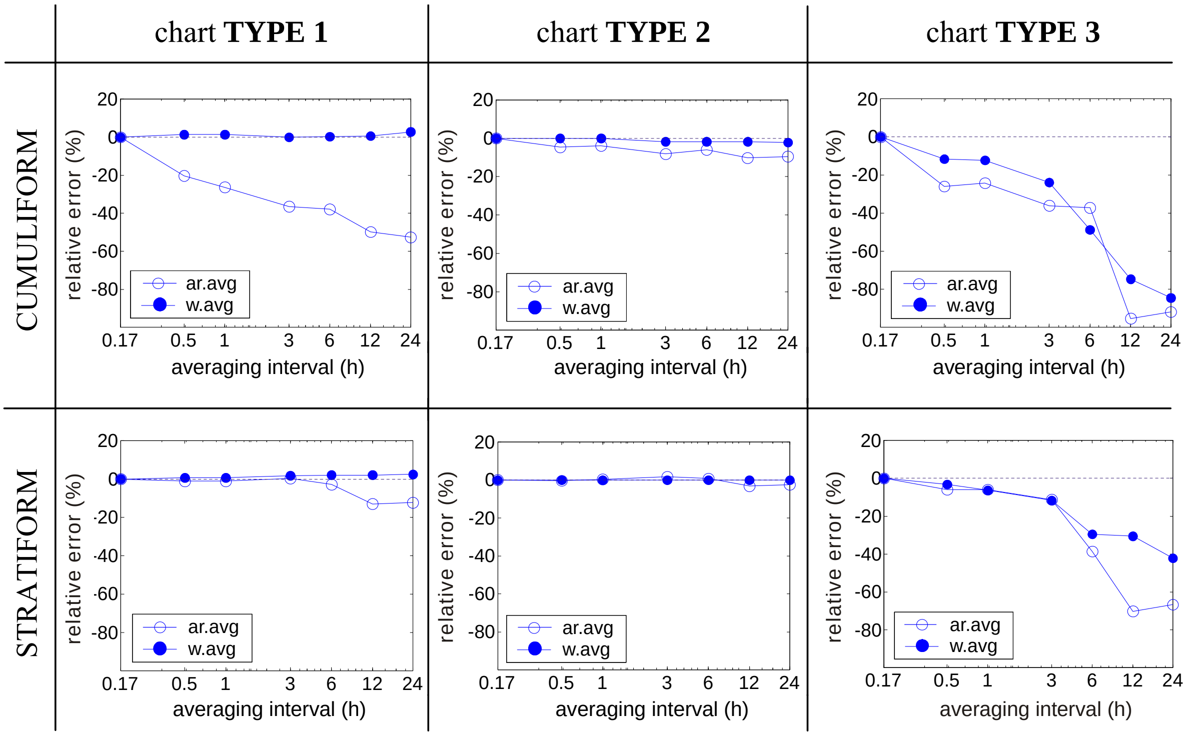

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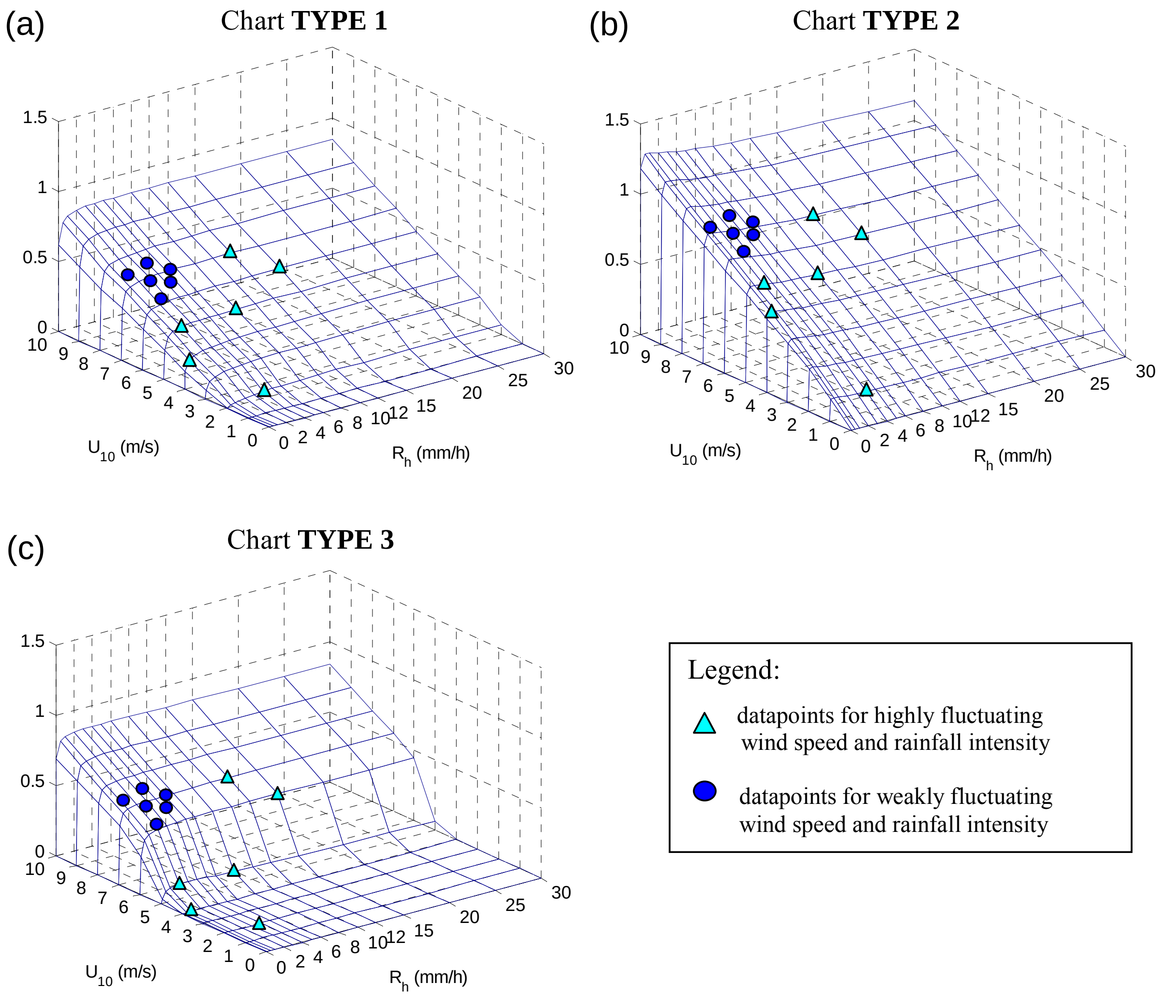

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