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On the estimation of wind comfort in a building environment by micro-scale simulation

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Abstract

A three-dimensional micro-scale model is used to study some aspects of wind comfort in a built-up area. The equations for calculating the mean wind have been extended by a Markov approach for short-term wind fluctuations. The model components have been successfully verified against wind tunnel measurements and observations of a field experiment. The simulated time series are used to estimate wind comfort measures. It turns out that the frequency of exceedance of prescribed thresholds depends strongly on the specification of the gust duration time. It was also possible to calculate the spatial distribution of a gust factor g depending on local wind characteristics. The simulated range is much broader than a value of $g = 3$–3.5 commonly used for wind comfort assessments. Again, the order of magnitude and the bandwidth of g depends strongly on the definition of a gust.

Keywords: Micro-scale simulation, wind fluctuations, wind comfort, urban environment

1 Introduction

Buildings in an urban environment change the distribution of meteorological variables like wind, temperature and radiation significantly. The magnitude of such modifications depends on the geometry and orientation of the buildings and on the interactions with surrounding buildings or other obstacles like trees. Such changes can be either favourable or unfavourable, whereby uncomfortable or even dangerous situations must be avoided as much as possible. This problem belongs to the field of human biometeorology, which addresses the interaction of humans and the urban atmospheric environment, and relevant issues in this context are wind comfort, heat stress, radiation exposure and air pollution problems (Jendritzky et al., 2012; Moonen et al., 2012).

The present paper will be confined to the aspect of local wind comfort. Detailed knowledge of airflow in a building environment is essential input information to address this problem. However, because the urban area is always embedded in a synoptic weather regime, the effects of a superimposed regional wind on local airflow must also be described.

The modifications of the airflow around an individual building are well known, including a vortex in front of the building and a large wake region behind as well as strongly increased wind speed at the corners and a broad jet with higher velocities next to the sides of the building (Martinuzzi and Tropea, 1993; Blocken and Carmeliet, 2004). In particular, areas with high wind speeds and strong turbulence are especially accountable for wind discomfort and dangerous situations. Openings in and between buildings will always cause increased discomfort and should be identified and avoided as much as possible.

Different methods are available for studying and identifying a comfortable and safe environment in the vicinity of buildings. Field experiments in a complex urban area provide important information about the real complexity of the airflow and the interactions with buildings (Fezer, 1995; Calhoun et al., 2004). However, even if performed with great care and for a representative long time, results are only a part of the whole because of limitations in the number of locations of measuring points. Nevertheless, such observations are extremely valuable and can be used to evaluate wind tunnel measurements and the results of numerical models.

The majority of studies in the past on outdoor wind at pedestrian level were performed in wind tunnels with physical models at a reduced scale (Beranek, 1984; Schatzmann and Leitl, 2011). This very powerful tool can be used to study the airflow around complex building structures provided some general similarity criteria concerning geometry, kinematics and dynamics are given. Although strict overall similarity can never be realized (Cermak, 1971), the results of wind tunnel experiments give deep insight into the complex flow structure in an urban building environment.

Numerical models, widely used in many fields of meteorology, are capable of handling the problem of human biometeorology from another perspective. For a wide spectrum of weather situations, consistent distributions of all meteorological variables, relevant for comfort aspects, can be provided (Moonen et al., 2012; Gross 2012, Janssen et al., 2013). Depending on the density of the computational grid, a large amount of information is available for the urban atmosphere in general.

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However, beside the specific advantages of a numerical model there are still some open questions concerning input parameter, parameterizations or turbulence modelling.

All the different techniques have their specific strengths and weaknesses but they can be used complementarily to each other in providing the necessary information for human comfort investigations in urban areas.

In this paper a three-dimensional micro-scale model is used to study wind comfort conditions in a built-up area. A new strategy in this field is adopted calculating short-term wind fluctuations utilizing the mean wind equations extended by a Markov approach. The verified model system has been embedded into a method for estimating wind comfort conditions in a building environment using long-term meteorological standard observations.

2 Wind comfort criteria

A moderate wind in cities is very beneficial for a healthy and comfortable urban climate. Compared to calm wind conditions, heat stress for people is minimized by an increased heat exchange between the human body and its environment, and a fresh air exchange between the polluted urban atmosphere and the clean rural surrounding significantly improves air quality.

However, stronger winds may seriously affect the living and working conditions of urban citizens. Architects, planners and municipal administrators are thus attempting to identify such windy locations and to avoid extreme wind speed. Acceptable and allowable wind speeds depend on particular pedestrian activities. In shopping streets and boulevards, where people are encouraged to linger, or in areas with street cafés and restaurants, winds should be calm to provide a reasonable and comfortable environment. People on their way to work or on urgent business errands are vulnerable to a much smaller degree and higher wind speeds are acceptable. However, it is completely unacceptable if the maximum speed exceeds values at which people begin to get blown over.

A big challenge in the past was the estimation of thresholds to separate comfortable and uncomfortable or secure and dangerous areas in a built-up environment. A traditional and very descriptive method are sand erosion experiments in wind tunnels at a reduced scale (Dezsö, 2006) to detect locations with high wind speeds. Also, the effects of wind upon people were systematically examined by full-scale experiments (Hunt et al., 1976, Jordan et al., 2008) and these results have been used to develop and to propose criteria for safety and comfort. Simulations with Computational Fluid Dynamics (CFD) are a different approach to investigating the comfort problem in a building environment. Considering all the advantages and drawbacks of CFD, this method provides additional, very valuable data to get a clearer insight into and to be able to address the problem of wind comfort in an appropriate manner (Bottema, 1993; Moonen et al., 2012; Janssen et al., 2013). In order to develop comfort criteria, the findings of wind tunnel experiments and CFD modelling must be combined with human activities and relevant biological parameters. For strolling and sitting in a street café, other standards are plausible and reasonable than for walking fast or business activities. Elderly people and children are more vulnerable to losing balance in high wind speed conditions than persons of standard weight and height.

Criteria for dangerous and uncomfortable conditions must be combined with long-term meteorological observations in order to estimate the incidence of such situations. A number of authors have followed this path and have developed wind comfort and safety criteria. Exemplarily, a limited selection of threshold ranges is presented in Table 1 while a nearly complete overview, including the comprehensive references, is given by RP (Ratcliff and Peterka,1990), BO (Bottema, 1993) or JA (Janssen et al., 2013).

In literature, there is a wide scattering in thresholds for wind speed and annual probability of exceedance depending on the experimental design and selection, age distribution and physical fitness of the test persons. Also for gusts, defined as wind change within a specified time interval, different approaches have been used with durations between 0.1 and 3 seconds (Jordan et al., 2008). So it is also no wonder that the estimation of the gust factor g results in very different values ranging from 1 to 7 (Isyumov and Davenport, 1975; Koss, 2006). Such a wide range is caused by the individual approaches for calculating mean wind speed, gusts and wind frequency distribution from local observations with a specific sampling time resolution of data.

3 Method and elements for wind comfort estimation

Pedestrian-level winds can be described in terms of mean velocities and gust winds. Both quantities vary within a building environment in a wide range and the approaches adopted here must be able to catch the main characteristics of the airflow at the very different scales. Thus, time series of total wind with a sufficient time resolution need to be provided in order to estimate gust winds and the annual frequency of exceeding threshold values.

A method for estimating statistical measures for wind comfort in a building environment consists of the combination of long-term meteorological observations, local wind information and the definition of comfort criteria. While comfort criteria are presented in Table 1, the procedure for calculating mean wind and wind fluctuations are given below as well as a proposal how to combine the individual elements to a consistent method.

Table 1: Selected wind comfort criteria for different activities. u_{gust} is gust wind speed, σ_u standard deviation of wind speed and g turbulence or gust factor.

	threshold	annual exceedance frequency	reference
sitting	$u = 5\,\text{m/s}$	2.5–5.0 %	JA
	$u_{\text{gust}} = u + g\sigma_u = 10\text{–}13\,\text{m/s}$	0.02 %	BO
strolling	$u = 5\,\text{m/s}$	2–10 %	JA
	$u_{\text{gust}} = u + g\sigma_u = 16\,\text{m/s}$	0.02 %	JA
walking	$u = 7.6\text{–}9.8\,\text{m/s}$	1.5–2.0 %	JA
	$u = 5\,\text{m/s}$	20 %	BO
	$u_{\text{gust}} = 13.5\,\text{m/s}$	7 %	BO
danger	$u = 15\,\text{m/s}$	0.05 %	JA
	$u_{\text{gust}} = u + g\sigma_u = 23\,\text{m/s}$	0.01 %	JA, RP

3.1 Mean wind

3.1.1 The numerical micro-scale model

For simulations of mean wind and temperature, the micro-scale model ASMUS (Ausbreitungs- und StrömungsModell für Urbane Strukturen) is used (Gross, 2012). The Navier-Stokes equations, the continuity equation and the first law of thermodynamics are used to calculate mean wind $\bar{u}_i$ and potential temperature $\bar{\theta}$. These equations are Reynolds averaged and the resulting correlations of fluctuating quantities are parameterized by flux-gradient relationships.

$$\frac{d\bar{u}_i}{dt} = -\frac{1}{\bar{\rho}}\frac{\partial p^*}{\partial x_i} + g\frac{\theta^*}{\bar{\theta}}\delta_{i3} + \frac{\partial}{\partial x_k}\left[K_m\left(\frac{\partial \bar{u}_i}{\partial x_k} + \frac{\partial \bar{u}_k}{\partial x_i}\right)\right] \tag{3.1}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{3.2}$$

$$\frac{d\bar{\theta}}{dt} = \frac{\partial}{\partial x_k}K_h\frac{\partial \bar{\theta}}{\partial x_k} \tag{3.3}$$

Beside standard notation, $\bar{\rho}$ is mean air density and p^* and θ^* are air pressure disturbance and temperature disturbance, and K_m and K_h are eddy diffusivities for momentum and heat respectively. In this study no distinction is made between K_m and K_h and eddy diffusivity is calculated by

$$K_m = 0.4\ell_g\sqrt{E} \tag{3.4}$$

with mixing length ℓ_g and turbulence kinetic energy E. While ℓ_g is related to the grid increments in the three directions $\Delta x, \Delta y, \Delta z$

$$\ell_g = \sqrt[3]{\Delta x \cdot \Delta y \cdot \Delta z} \tag{3.5}$$

turbulence kinetic energy is calculated using

$$\frac{dE}{dt} = \frac{\partial}{\partial x_k}K_m\frac{\partial E}{\partial x_k} + K_m\left(\frac{\partial \bar{u}_i}{\partial x_k} + \frac{\partial \bar{u}_k}{\partial x_i}\right)\frac{\partial \bar{u}_i}{\partial x_k} - K_h\frac{g}{\bar{\theta}}\frac{\partial \bar{\theta}}{\partial x_i}\delta_{i3} - \frac{E^{3/2}}{\ell_g} \tag{3.6}$$

Obstacles are introduced in the model by a porosity concept (Gross, 2014), where buildings are represented by impermeable grid volumes with porosity $P = 0$ and in the leafy crown of trees $P = 0.8$ is used (Gross, 2012). The set of model equations is solved on a numerical staggered grid where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls. The pressure disturbance p^* is calculated by solving a three-dimensional discrete Poisson equation directly by Gaussian elimination in the vertical and fast Fourier transforms in the horizontal directions. A grid resolution of $\Delta x = \Delta y = 1\,\text{m}$ is used in horizontal directions. In the vertical $\Delta z = 1\,\text{m}$ is adopted in the lowest 50 m of the atmosphere with an expanded grid above.

The boundary conditions for wind at the ground and at the building surfaces are zero and turbulence kinetic energy is proportional to local friction velocity squared. The friction velocity is calculated assuming a logarithmic wind profile between the surface and the closest grid value in the atmosphere with stability functions according to Dyer (1974). Temperatures at the different heights of the buildings are specified according to the thermal stability of the weather situation.

At the upper boundary at a height of 150 m an undisturbed situation is assumed with given values of wind, temperature and turbulence kinetic energy. At the lateral boundaries, no-flux conditions for all variables are used.

3.1.2 Model validation

In order to test the capability of the micro-scale model a numerical experiment was designed with a simple obstacle. The main characteristics of the airflow around a cube with uniform dimensions in all directions are well known by wind tunnel experiments and are well suited for a comparison. A grid of 300×300 (horizontal) $\times 80$ (vertical) grid points was used to study the airflow around a cube with an edge length of $h = 40\,\text{m}$. Initial profiles have been calculated for a superimposed wind of $4\,\text{ms}^{-1}$ in a neutrally stratified atmosphere.

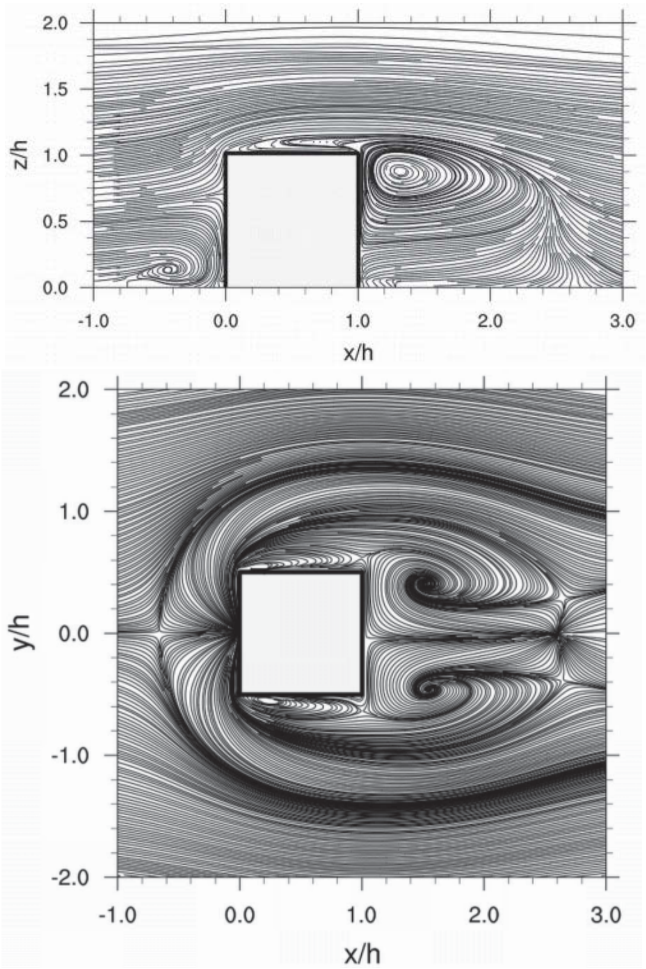

Figure 1: Simulated streamlines for the airflow around a cube. Above: vertical cross section along the centre line at $y/h = 0$; below: horizontal cross section at $z/h = 0.05$.

In Fig. 1, simulated airflow is presented in a vertical cross section along the centre line and in a horizontal plane at $z/h = 0.05$. The main characteristics of the flow modifications, like the long recirculation downstream of the cube, the upstream flow vortex, a recirculation region on top of the building and flow separation with recirculation at the sharp side edges, are well pronounced. The simulated dimensions of these vortices compare very reasonably to wind tunnel (WT) observations (Martinuzzi and Tropea, 1993; Bottema, 1993) and LES simulations (Fuhrmann, 2013).

The length of the upstream vortex is calculated with a value of about $z/h = 0.85$ (WT: 0.8–1.0; LES: 0.9–1.0) and the downstream recirculation zone with a horizontal extension of $z/h = 1.6$ (WT: 1.6; LES: 1.6–1.8). As in the LES simulation, the recirculation on top of the obstacle extends nearly over the entire width of the cube.

In addition to the comparison shown here, the model has been verified against a wide variety of wind tunnel measurements according to VDI 3783 (Gross, 2011). One main finding of this verification, which is important for the applicability of the method presented later, is the independency of the results from the wind speed of the superimposed flow.

3.2 Wind fluctuations

The mechanical effect of wind on human bodies is determined by the mean wind but also by the short-term gustiness. It is often convenient to consider a 1–3-second gust wind since this is the scale in which a person can respond to the unbalancing effects of wind force (Penwarden, 1973; Hunt et al., 1976). However, Jordan et al. (2008) reported a much shorter time in the order of 0.3–0.4 s where people must adjust to the acceleration and change of wind. The spread of the relevant gust duration times found in experiments is caused by different experimental designs, different wind averaging times and the individual response of people to wind.

Against this background it is necessary to make available wind time series by a numerical model including not only the mean wind but also the gusts. This task is comparable to the estimation of the dispersion of air pollutants in a turbulent atmosphere where similar wind information is necessary. For air pollution problems, atmospheric turbulence is derived, e.g., from a Markov process of an autocorrelated time series of wind fluctuation u'_n around the mean at different times n ($u'_n = u'(n\Delta t)$) in time increments Δt (VDI 3945, Janicke, 2000). The same approach is adopted here to estimate the short-term wind fluctuation by

$$u'_{n+1} = u'_n R_L + \varepsilon. \tag{3.7}$$

In the equation above, R_L is the Lagrangian correlation coefficient and ε a random number from a Gaussian distribution with zero mean and unit variance. A time series expansion for R_L results in an exponential function

$$R_L = \exp\left(-\frac{\Delta t}{T_L}\right) \tag{3.8}$$

with integral time scale T_L calculated by

$$T_L = \frac{K_m}{\sigma_u^2} = \frac{K_m}{2E}. \tag{3.9}$$

Examples of simulated time series for a typical daytime situation with stronger mean wind and larger turbulence and for a night-time hour with reduced wind and weak turbulence obtained with the approach described above are given in Fig. 2. It is obvious that organized wind variations with larger time scales (e.g. 10 s and more) are superimposed by short-time turbulent gusts. The fluctuations with high frequencies are less pronounced during stable night-time conditions.

A very similar procedure as presented above was used by Graf et al. (2013) for calculating the wind-generated surface waves for an Alpine lake using COSMO-2 winds and synthetic gusts.

An other approach for estimating the gust wind speed u_{gust} by a mean value (e.g. one-hour mean $\bar{u}$) which is commonly used is practice is

$$u_{\text{gust}} = \bar{u} + g\sigma_u. \tag{3.10}$$

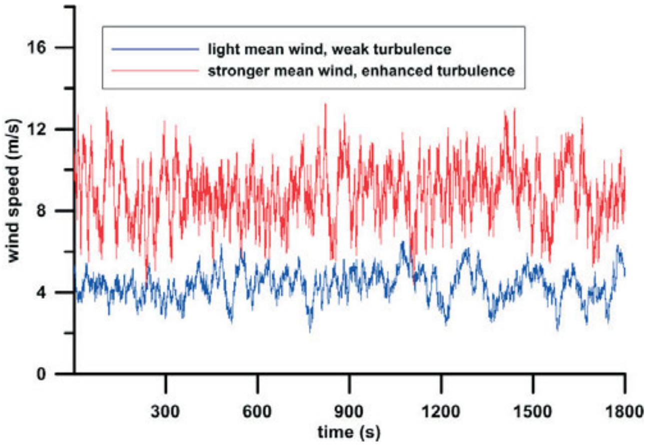

Figure 2: Simulated autocorrelated half-hour time series for two different meteorological conditions.

σ_u is the standard deviation of wind and g a factor with a typical order of magnitude of three (Koss, 2006). However, the definition of a gust wind speed by a turbulent factor g, constant in space and time, does not consider the strong variability of the local velocity fluctuations. As demonstrated by Isyumov and Davenport (1975), g depends on the local mean value and average peak value of the wind and may reach much higher values than $g = 3$. For windier locations, the authors determine g from the observed frequency distribution for wind with values around and less than 4, while in calmer regions g rises up to more than 7.

3.3 Wind comfort estimation

Wind comfort measures can be estimated by combining the simulated wind distributions for individual weather situations with synoptic data, characterizing the regional climatological wind regime. For such long-term observations, the data of a nearby weather station of the national meteorological agency can be used. In general, these data are one-hour mean values and, as for air pollution studies, the wind statistics should be representative of the climatological mean of the region. In this study, wind speed and wind direction at 10 m height at the airport for the year 2001 are used as a typical wind year for the Hannover area. In order to make these data available as wind forcing of the micro-scale model, the 10 m observations are extrapolated logarithmically to a height of 150 m, the upper boundary of the model. For roughness length a value of $z_o = 0.03\,m$ is adopted and thermal stability is roughly characterized by stability classes determined from routinely observed weather elements. Wind direction is kept constant in the whole layer. As a result, wind forcing for every hour of one representative year is available.

The distribution in space of mean wind in a building environment is calculated by the micro-scale model for 36 wind directions with an interval of 10 ° and for an undisturbed wind speed at 10 m of 3.8 ms^{-1}, which is the climatological mean. Assuming the validity of similarity, local time series can be determined by a combination of the micro-scale model results and the observations for a representative year. For all 8760 hours, the results of the specific numerical experiment for the observed wind direction are chosen and wind speed is adapted to the superimposed value using similarity assumptions.

The local time series of fluctuating velocity u' for the time in between the hour is calculated by Eq. (3.7) using simulated turbulence kinetic energy and eddy diffusivity. Time series of total wind $\bar{u}+u'$ are then used to calculate statistical measures and exceedances of threshold values that are suitable for a comparison with the comfort criteria used.

4 Results

The method for calculating mean and fluctuating velocity introduced above is applied for the inner centre of Hannover, a typical mid-size German city. The opera building, embedded in a spacious shopping zone, dominates the cityscape in this area (Fig. 3). Five- to seven-storey buildings are typically in the centre with a maximum building height in the area of interest of more than 40 m. Deep street canyons alternate with broad boulevards, a spacious central plaza is contrasted by narrow courtyards. The complex situation is completed by different 14 m high trees on the open space to the south of the opera and along the street to the east.

4.1 Mean wind and turbulence

The areal distribution of mean wind and turbulence quantities has been calculated in steps of 10 ° for the superimposed wind direction. Depending on the local interactions between superimposed wind and the multitude of obstacles, the airflow is affected in many ways: channelling, deflection, calm zones and windy areas. An analysis of the wind flow patterns indicates the large sensitivity of pedestrian-level wind depending on small variations of the direction of the superimposed flow (Fig. 4). There are different zones with high wind speeds, especially around the opera building but also in areas where the bordering buildings give rise to strong channelling effects. Wind speed below the trees is reduced; however, an airflow between the floor and the lower part of the crown is still obvious. This flow reduction by trees is well pronounced for all wind directions parallel to the alley south of the opera, while for a perpendicular direction of the oncoming wind (270 °) the barrier is narrow and airflow is not influenced significantly.

A 10-day period out of the complete simulated time series of one year, derived by a combination of observations of a rural weather station and the results of the micro-scale model, is given in Fig. 5. The observations (DWD) show a strong diurnal variation with high surface wind speeds during the daytime hours and a strong

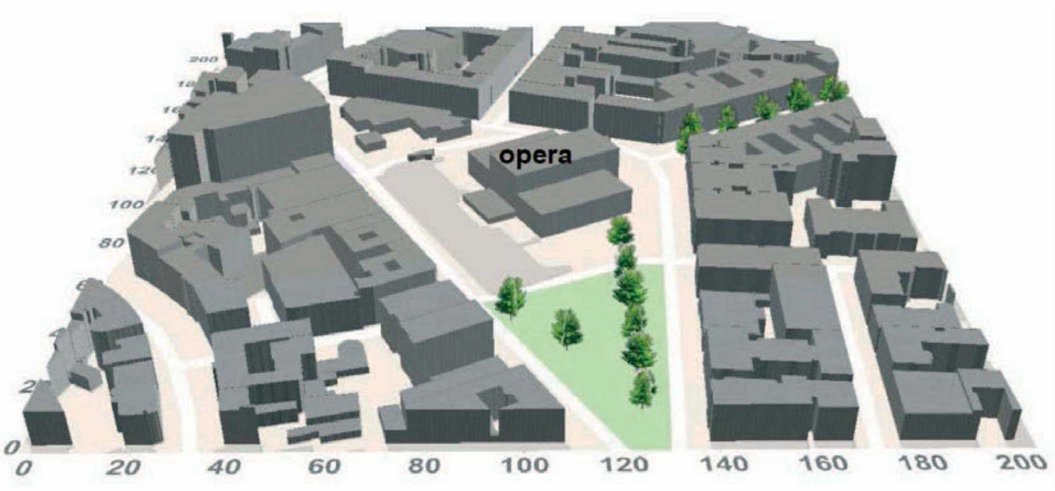

Figure 3: Three-dimensional perspective view of the urban building environment.

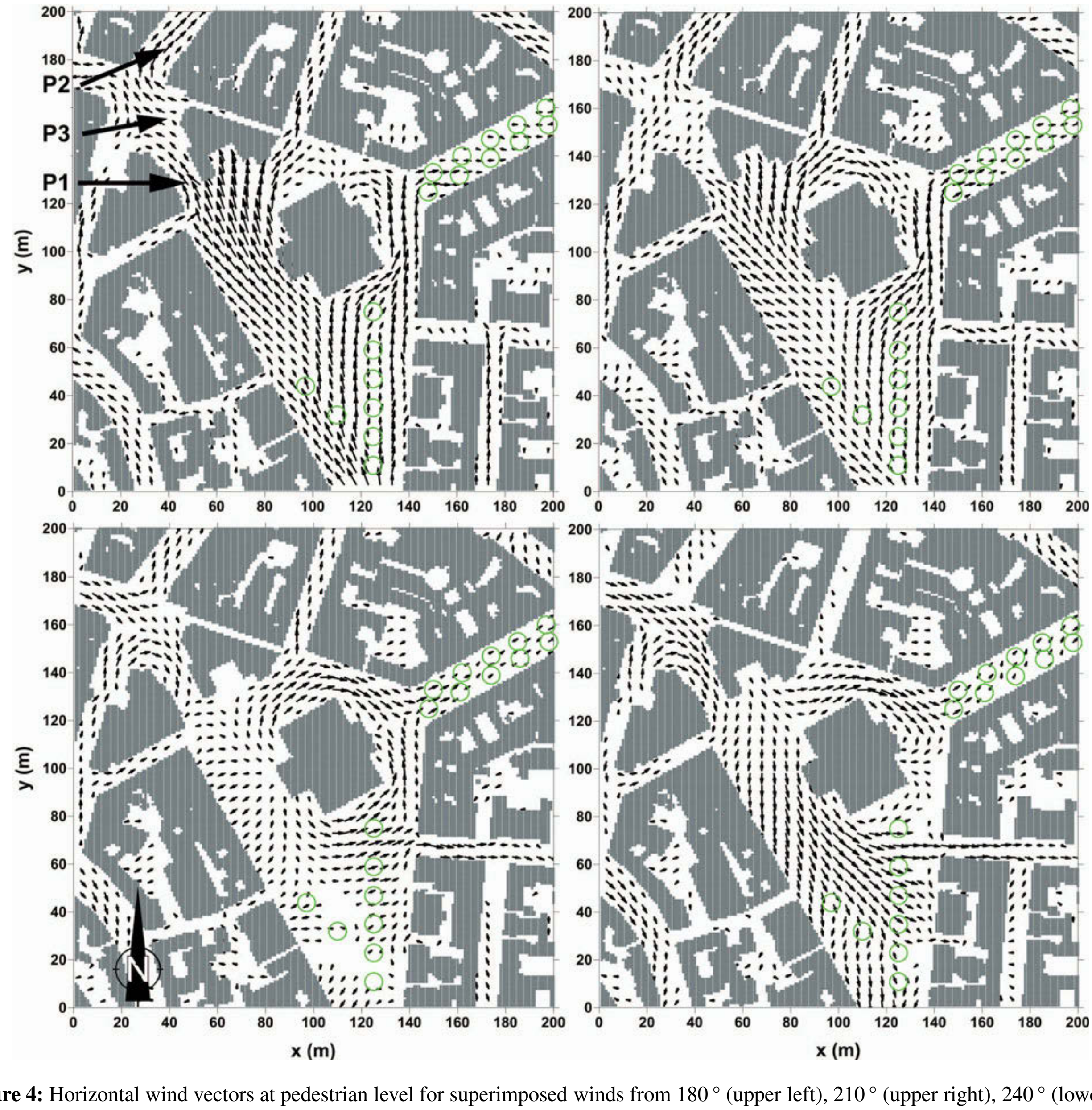

Figure 4: Horizontal wind vectors at pedestrian level for superimposed winds from 180 ° (upper left), 210 ° (upper right), 240 ° (lower left) and 270 ° (lower right). The locations of the trees are indicated by green circles. P1–P3 are reference sites mentioned in the text.

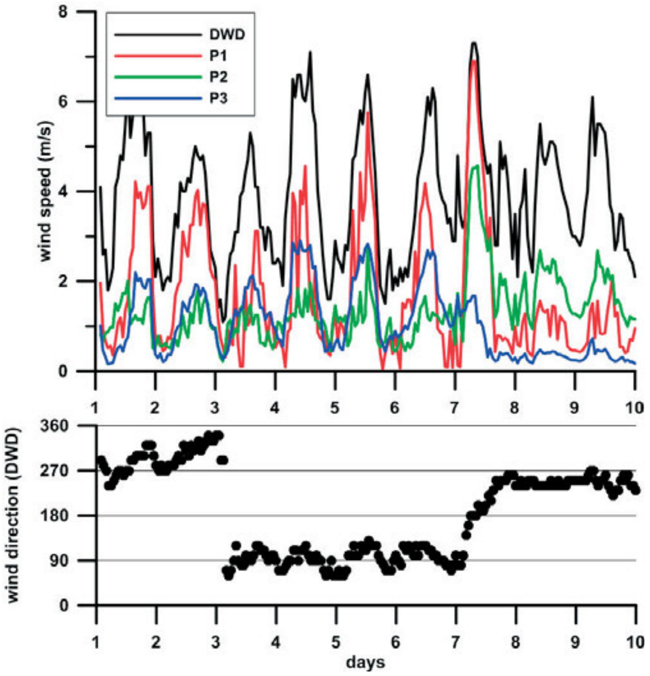

Figure 5: Simulated time series of wind speed at pedestrian level at different locations for prescribed superimposed rural wind (DWD). Observed and adopted rural wind direction is given in the lower panel.

decrease at night. Wind direction in this period is around west for the first two and the last three days, while easterly winds are dominant in between. At three selected sites P1-P3 in the urban area (see Fig. 4), wind speed in general is reduced due to the large number of obstacles. Site P1, located between two narrow buildings, is especially exposed for wind directions around east and around west to north. Caused by channelling effects wind speed at this site at pedestrian level is in the order of magnitude of the rural value at 10 m above ground. For south-westerly flows, as occurred on days 7 to 10, P1 is in the wake of a very high building resulting in a significant reduction of near surface mean wind speed.

Beside the mean wind, gusts are very relevant for estimating uncomfortable or even dangerous conditions at pedestrian level. Short-term fluctuations can be calculated from Markov time series within every hour. u' is determined with a time step of $\Delta t = 0.1$ s and the resulting time serie is used to estimate the sensitivity of different sampling intervals on gusts. There is a relatively wide spread of values in the literature from 0.2 s to 3 s for defining a gust as the most intense wind fluctuation within a selected time increment.

The calculated time series can be used to evaluate the effects of different durations on gust wind speed. The length of the time increments was chosen as 0.4 s, 1 s, 4 s and 10 s, which covers approximately the spectrum of the values in literature (Hunt et al., 1976; Jordan et al., 2008). For a sunny summer day, frequency distributions of gusts have been calculated for turbulent daytime hours (08–18 hours) as well as for night-time conditions (22–04 hours). The results are presented in Fig. 6 and show on a logarithmic scale a reversed U-shaped distribution for all selected duration times. The longer the time scale, the greater the probability of stronger gusts is. This simulated behaviour is comprehensible by analysing the time series shown in Fig. 2. For short time intervals, only small changes in wind speed, calculated from the beginning to the end of the increment, can be captured, while for longer time intervals the probability of larger differences in wind speed in the auto correlated time series increases. The distribution for night-time hours is very similar except for the overall tendency for smaller gust values for all duration times.

A comparison with observations, including for a sunny summer day in an urban environment, shows very similar results for the frequency distributions. The data were sampled with an ultrasonic anemometer with a sampling rate of 10 Hz (Goldbach and Kuttler, 2013). Like the simulation results, the observations show distinctly different distributions during day and night. For longer time periods the distribution widens and gust speeds up to 5 ms^{-1} occur during daytime.

The results of the simulations presented here can also be used to estimate the gust factor according to Eq. (3.10). For each hour of the year u_{gust}, $\bar{u}$ and σ_u are calculated, where u_{gust} is the maximum wind speed within this hour. The resulting local frequency distributions for the turbulence factor are used to determine a "climatological" g as the median of the distribution. Depending on local wind and turbulence, highly variable through the year and day, the climatological g varies within a certain range of $g = 3.2$–3.6 in the windier places and even larger values $g > 4$ in the calmer regions, especially near buildings or around trees (Fig. 7). The results presented in this Fig. are estimated for a 3-second interval for gust calculation. However, the magnitude of the gust factor depends on the time increment for which mean wind, gust speed and standard deviation σ_u are defined. In order to estimate a characteristic "climatological" g, an areal mean at pedestrian level has been calculated. This evaluation for different time increments demonstrates the strong dependency of the prescribed timescale for which the relevant parameters are representative (Fig. 8). For longer evaluation times, g tends toward smaller values that correspond with gusts occurring more frequently and of longer duration (Bottema, 1993). For a gust evaluation time interval of 3 s, the gust factor is in the order of $g = 3.5$, which is a very common value found in literature (Melbourne, 1978). For very short characteristic times below one second, g increases to values above 4 but gradually decreases as the time interval increases. These findings suggest that the gust factor approach for estimating peak gusts by using local mean wind and standard deviation can be used if an appropriate value for g is used. This might be the reason for the wide range of values of the gust factor cited in literature, since in some experimental work, carried out e.g. by Hunt et al. (1976) or Jackson (1978), gust duration and gust dimensions are of-

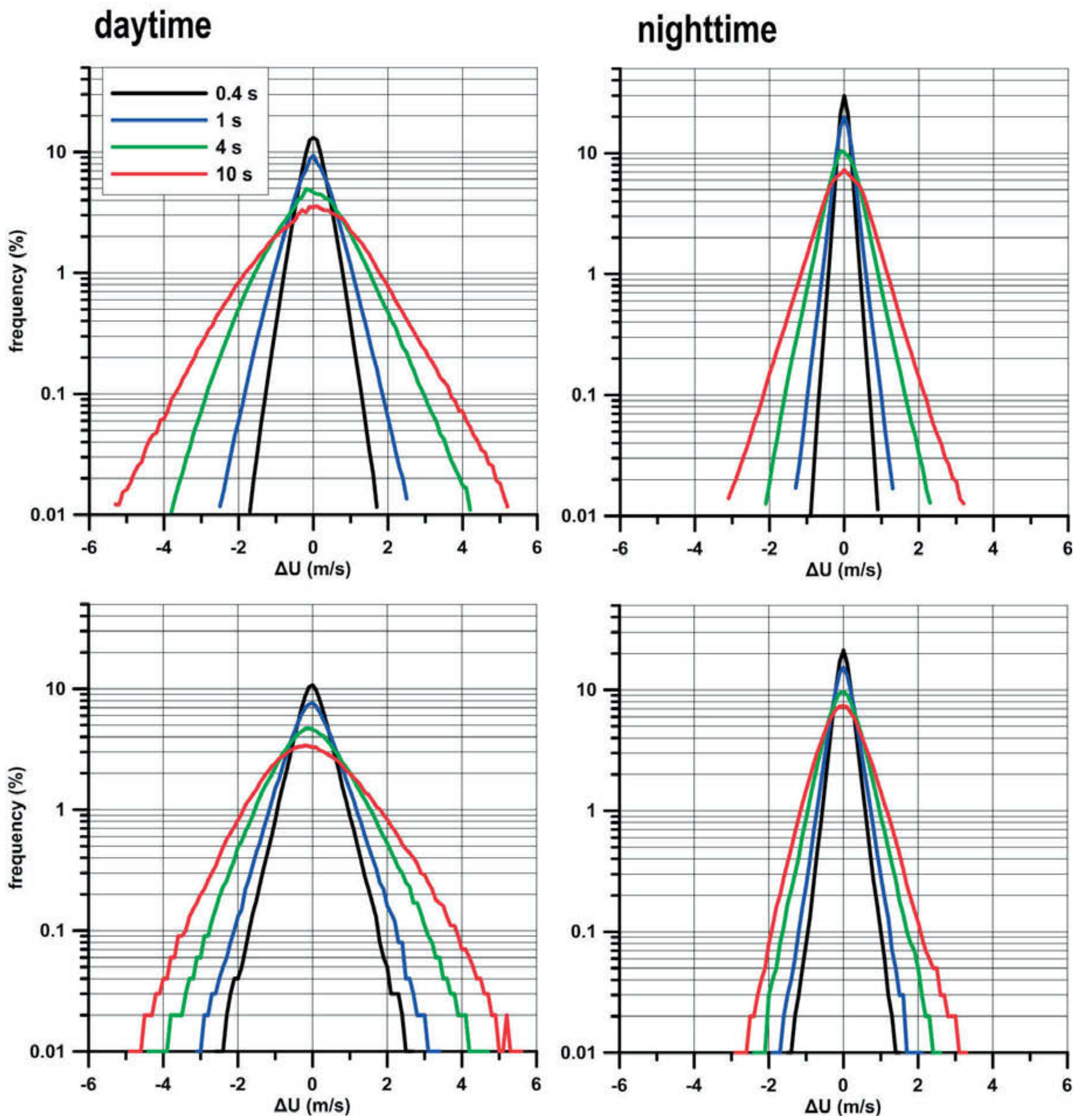

Figure 6: Simulated (above) and observed (below) frequency distribution of gusts during day and night for different gust time increments.

ten not described explicitly (Bottema, 1993). However, adopting a constant gust factor within a complex building environment may result in significant overestimation or underprediction of the local wind comfort situation.

4.2 Wind comfort

The local times series of mean wind and gusts can be used to estimate the wind comfort situation in the complex built-up area considered here. From the many options for comfort criteria the $5\,ms^{-1}$ threshold is selected to assess the effects on typical pedestrian activities like sitting, strolling or walking and the $15\,ms^{-1}$ threshold to identify locations with an unacceptable wind climate or even danger. In Fig. 9, the frequency of exceeding the critical value of $5\,ms^{-1}$ for different definitions of gusts is presented. While the distribution in general is very similar for all time increments adopted here to define a gust, ranging from 0.4 s to 10 s, the probability of uncomfortable situations increases significantly for longer gust times. In the light of the observations presented in Fig. 6, this finding is comprehensive, since for longer gust duration times much larger velocity fluctuations may occur. The large open space around the exposed opera building and narrow streets with an unfavourable orientation concerning the wind direction of the superimposed wind can be identified as vulnerable areas. The shelter effect of trees is particularly well illustrated by a local reduction of uncomfortable situations over the year. Although turbulence is increased around the vegetation, the reduction of mean wind speed is the predominant factor that determines the magnitude of the gust wind speed.

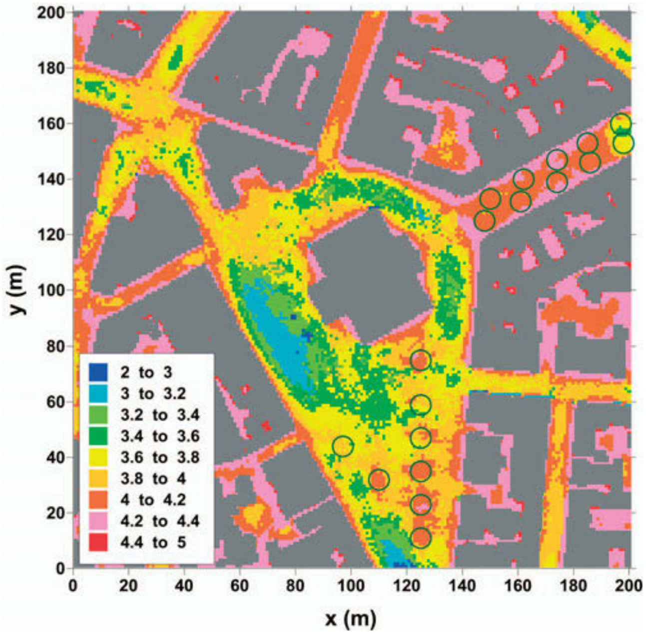

Figure 7: Horizontal distribution of gust factor g at pedestrian level for a time increment of 3 s for gust definition. Locations of trees are indicated by green circles.

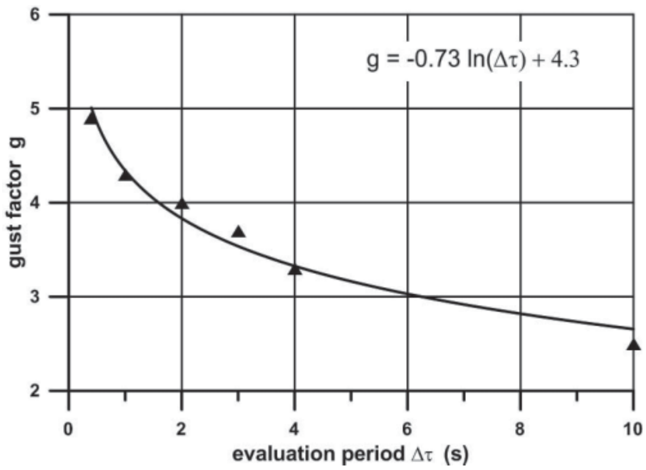

Figure 8: Climatological mean gust factor g as a function of gust time increment. Triangles: simulation result; solid line: fit.

Situations with wind speeds above $15\,\mathrm{ms}^{-1}$, which are by some definitions dangerous, are much less frequent than uncomfortable conditions. Such areas are restricted to large open spaces while shopping boulevards and open-air dining spaces are not affected (Fig. 10). Depending on gust definition, almost no location fulfils the criterion for danger for a 0.4 s gust, while e.g. a 4 s gust above $15\,\mathrm{ms}^{-1}$ occurs for one to five hours per year in limited areas.

However, both examples demonstrate clearly that the time increment for defining a gust is a very essential parameter to assess wind comfort and wind danger. While Janssen et al. (2013) have demonstrated the significant dependency on assessment results by using different comfort criteria, another important aspect that should be taken into consideration is the definition of a gust. Depending on the gust time increment used and the choice of the various comfort criteria, wind at pedestrian level may be far above or even far below a defined threshold.

5 Conclusions

In this paper a three-dimensional micro-scale model was used to study the airflow in a complex building environment. While mean wind is determined by solving the Navier-Stokes equation, wind fluctuations are derived from a Markov process of an autocorrelated time series. Both components have been combined to a simulated wind registration including short-term gustiness. With such information it is possible to study and to assess the wind situation in a built-up area with respect to the comfort of and danger for pedestrians.

The model has been successfully verified against wind tunnel experiments, and simulated mean airflow around a cubic obstacle displays all characteristic wind modifications with recirculation, vortex formation and flow separation near edges. The results of the wind fluctuation approach have been compared to wind registrations near buildings with a height sampling rate. The observed frequency distribution for gusts can be reproduced by the model with high accuracy. In particular, the significant differences between day and night have been captured by the model very reasonably. Encouraged by these results, the model system was applied for wind comfort studies in a complex building environment.

Such an estimation consists of a combination of the regional climatological wind regime, local wind distribution and comfort criteria with thresholds and acceptable exceedance frequencies. Comfort criteria and thresholds are usually determined by wind tunnel experiments with special emphasis on gusts. However, definitions of gusts are not uniform and results are therefore limited to the specific conditions adopted for the individual experiment. The simulated 10 Hz wind time series for one year is used to estimate the effects of different gust definitions. Depending on the gust time increment used, significant differences for the exceedance of thresholds have been calculated. The results concisely confirm the great importance of a clear definition of gusts in order to assign the experimental findings and the resulting conclusions in a consistent manner.

The gust wind speed is usually estimated from the mean wind by an empirical gust factor g with a typical order of magnitude of $g = 3$–3.5. However, a constant gust factor does not consider the complexity of local velocity fluctuations in a building environment. The numerical results have been used to calculate local gust factors that show a large spatial variation as well as a much broader spectrum of values. A "climatological" mean value at pedestrian level of $g = 3$–3.5 corresponds to a characteristic gust time of around 3 s, a value that is often quoted as a useful reference duration. Longer gust duration is associated with smaller values of g while for shorter times a significant increase of g is simulated.

Figure 9: Horizontal distribution of exceedance probability for hours with wind speeds greater than $5\,\mathrm{m\,s^{-1}}$ for different gust definition times of 0.4 s, 1 s, 4 s and 10 s.

The main findings of this paper emphasize the necessity for standardization and the use of consistent parameters like threshold wind speeds, gust duration and annual exceeding probabilities in order to achieve an objective assessment of wind comfort in cities.

It should be mentioned here, that the numerical model provides detailed and valuable insight on wind comfort in a complex environment. However, shortcomings of this method caused by model characteristics like grid resolution or parameterizations or effects not included (e.g. driving cars) define the limits of application. To guarantee realistic results, numerical modelling should always be accompanied by field measurements.

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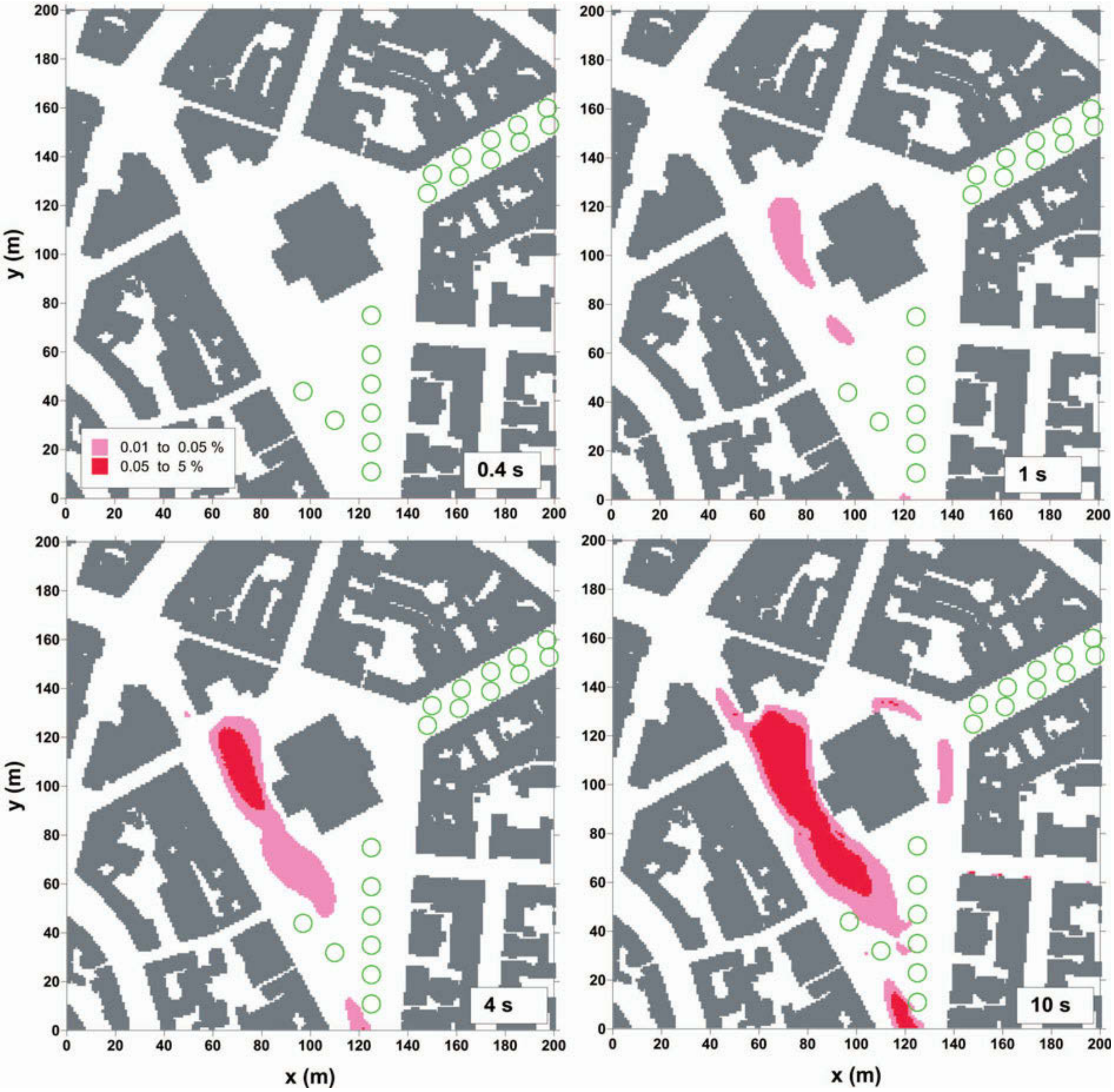

Figure 10: Horizontal distribution of exceedance probability for hours with wind speeds greater than $15\,\mathrm{ms}^{-1}$ for different gust definition times of 0.4 s, 1 s, 4 s and 10 s.

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