Analysis of one- and two-dimensional mean gust shapes using a large-eddy simulation model

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ABSTRACT

In this paper we present mean gust shapes representing strong discrete gusts of the atmospheric boundary layer. High resolution large-eddy simulations were carried out to simulate the turbulent flow during an idealized strong-wind event. Both one- and two-dimensional gusts were analyzed. One-dimensional results show significant differences compared to the classical one-minus-cosine law used in wind turbine and aircraft design processes. In contrast, they agree well with gust shapes from previous studies obtained from mast measurements. Two-dimensional mean gust shapes show an elliptical form with different aspect rations for different gust diameters.

1 INTRODUCTION

During the design processes of wind turbines and aircraft it is of utmost importance to consider the influence of the atmospheric turbulence on the material. Fatigue loads as well as extreme loads are a result of the interaction of the atmosphere with the structures. Extreme loads are caused by strong isolated wind pulses, which are also known as (wind) gusts. Existing one-dimensional analytical models describing discrete gust events are based on rather simple approximations such as a cosine gust (Burton et al., 2011). The time-dependent gust velocity can be written as

$$\mathrm{u(t)} = \left(\frac{\mathrm{A}}{2}\right)\left(1 - \cos\left(\frac{2\pi \mathrm{t}}{\mathrm{T}}\right)\right) \qquad (1)$$

where *A* is the amplitude and *T* the duration period of the gust. This gust shape approximation describes the shape of an idealized discrete gust and has been used for many decades in the different application fields mentioned above. Although results obtained from mast measurements of Camp (1968) and Verheiji et. al (1992) indicate more complex gust shapes, they have not been considered in the regulations for structure design processes e.g. of the IEC (International Electrotechnical Commission) or the FAR (Federal Aviation Regulations). The limited database and consequently the limited knowledge of gust shapes can be explained by the high complexity of the atmospheric turbulence and the rather simple measurement methods used in the studies mentioned above. Modern research methods like large-eddy simulations (LES) enable turbulence resolving simulations of the atmospheric flow and hence detailed investigations of turbulence structures respectively gusts. Furthermore, the LES provides three-dimensional data of the turbulent atmosphere, which offers the opportunity to analyze multi-dimensional flow structures.

The aim of the present study was to characterize atmospheric gusts by shape, amplitude and length. High resolution large-eddy simulations were carried out to simulate the turbulent flow of the atmospheric boundary layer. Mean gust shapes were calculated representing gusts of certain length classes. Beside one-dimensional gusts, two-dimensional gusts were analyzed at different heights. The latter cannot be examined by mast measurements and thus provide new information of gusts such as the lateral shape.

2 METHODS

The LES model PALM (revision 1048) used for the investigations has been developed at the Institut für Meteorologie und Klimatologie at the Leibniz Universität Hannover (Raasch and Schröter, 2001). In the present study, PALM was used to simulate the dry atmosphere, where it solves the filtered non-hydrostatic, incompressible Boussinesq equations, the first law of the thermodynamics and the equation for turbulent kinetic energy (TKE). It scales very well on parallel computers and hence it can be used for high resolution simulations of the atmospheric boundary layer. In order to resolve gusts affecting structures like aircraft wings or wind turbine blades, the grid resolution was chosen with one order of magnitude lower than these structures. With a minimum wing or rotor span of some decameters, and a certain level of insurance, a model resolution of 2 m was chosen for this study.

One relevant meteorological scenario causing intensive turbulence and gusts is a low-pressure system (or extratropical cyclone) that occur in the middle latitudes of the earth. In Europe, they often occur in winter and are associated with stormy weather conditions. During such a strong-wind event, turbulence in the lowest part of the atmosphere is generated by the wind shear which is a result of the strong prevailing wind and the surface friction. Due to intense turbulent mixing, the boundary layer is typically neutrally stratified. Since the focus of this study lies on the boundary layer turbulence and its gusts on the one hand and limited computational resources prevent an LES of a complete low-pressure area on the other hand, only a small part of such a weather system was simulated. The model domain was chosen to be large enough to contain the largest scales of the boundary layer turbulence which are of the same size as the boundary layer height z_i. In the simulations, z_i was fixed at about 700 m by a temperature inversion of 2 K/100 m in the initial temperature profile. The boundary layer below was neutrally stratified. The total model domain size is 2000 m in both horizontal directions and 1800 m in the vertical direction. The vertical grid is stretched above a height of 800 m.

In the performed numerical simulation, the purely dynamical driven meteorological conditions as described above were reached by a strong geostrophic wind u_g of 30 m/s and surface friction (z_0 = 0.5 m). Data were analyzed after a transient phase of one hour. To obtain information about discrete gusts from the time depending three-dimensional data output of the simulation, instantaneous horizontal cross-sections at different heights were extracted between one and three hours simulation time. Instead of time dependent velocity information, like obtained from mast measurements, space dependent wind speed information are provided from these instantaneous wind velocity fields. Assuming that the frozen turbulence hypothesis is applicable (because of the high magnitude of the mean wind speed), the time can be transferred to the stream-wise component in space. It means that in the equation for the time dependent gust velocity (eq. 1) t can be replaced by x. All gust shapes presented below follow this assumption and are thus dependent on space.

Exemplarily, Fig. 1 shows instantaneous cross-sections of the two horizontal wind components u and v and the vertical wind component w. Since the geostrophic wind vector points into the direction of the u-component, the maximum values in Fig. 1a reach about 22 m/s at this altitude (z = 50 m). The horizontal mean wind speed of u is 13.5 m/s. The wind velocities of the v-component reach values up to 12 m/s (Fig. 1b). The mean wind speed of v is 3.8 m/s which is a results of the rotated wind vector in the boundary layer due to the coriolis force. The corresponding values of w (Fig. 1c) are 6 m/s as maximum value and 0 m/s as mean wind speed. In all flow fields of Fig. 1, large flow structures up to several hundred meters in diameter as well as small structures of a few decameters are visible. The smallest resolved eddies, which have a size of about 10 m, are not visible in Fig. 1 since the illustrated area is relatively large. The focus of the present studies lies on the smaller turbulent structures with diameters between 10 m and 150 m, which might affect buildings or structures like wind turbines or aircraft significantly.

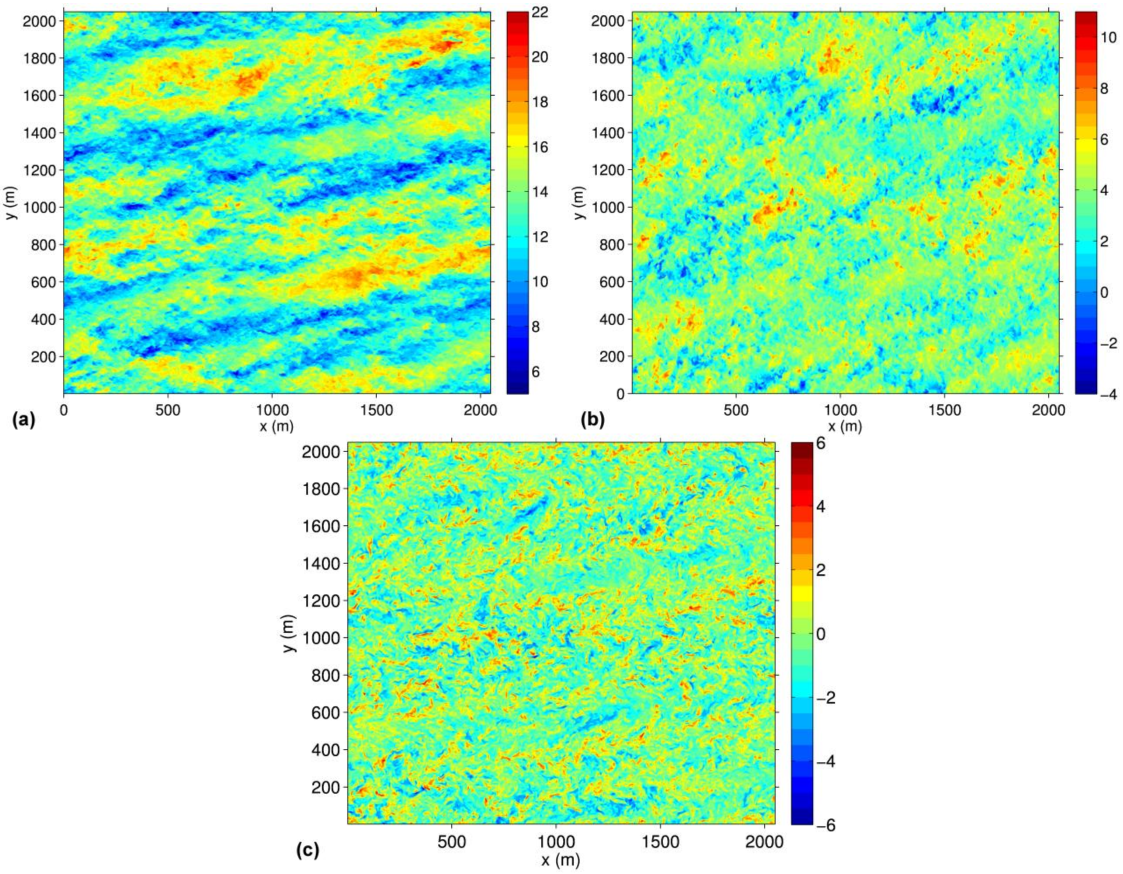

Figure 1: Cross-sections of the instantaneous wind fields of the u- (a), v- (b) and w-component (c) at an altitude of 50 m after two hours simulation time. Wind speeds in m/s are colored.

In case of the one-dimensional analysis, one-dimensional virtual wind measurements of all wind components were made. Several measuring paths parallel to the *x*-axis at regular intervals of 100 m at 24 points in time ensure a large data base and hence a sufficient statistics of the calculated mean gust shapes. All three wind components were analyzed separately to determine the influence of the mean wind flow on the different wind components. The starting point of a gust is defined as the local minimum in the wind speed signal which is followed by an increase of at least 3 m/s and a decrease to the starting point value. Only positive gusts were considered.

In case of the two-dimensional gust analysis, two-dimensional structures were extracted from the same horizontal cross-sections as in the one-dimensional gust analysis. The complete wind velocity fields of all wind components at each point in time were analyzed. Instead of the local minima around a peak value (one-dimensional analysis), a constant value defines the lateral gust edges. This threshold value was calculated for each velocity component and height and lies slightly above the horizontal mean wind speed of the corresponding wind field. All wind speed values below this threshold were cut off from the data field. An object detection algorithm based on the Matlab image processing toolbox function *bwlabel* was applied to detect the two-dimensional gusts.

The gust criteria for both one- and two- dimensional gust analysis can be summarized as follows:

- The minimum amplitude is 3 m/s.
- The minimum gust length or diameter is 25 m (1D) and 10 m (2D).
- The maximum gust length or diameter is 150 m.

3 RESULTS

To investigate mean gust shapes, different gust classes corresponding to different gusts lengths were defined. This classification is based on the results of Camp (1968) and Verheij (1992), who present in their studies a dependence of the gust shape from the gust length respectively duration. In the one-dimensional analyzes, five classes between 25 m and 150 m at intervals of 25 m were defined. For each gust class, one mean gust shape was calculated. Before averaging the gusts, they were normalized both in their velocity and length. Normalized variables are marked with an asterisk. The results show that the one-dimensional mean gusts shapes are more complex than the simple cosine-approximation suggests (see Fig. 2). The main difference is the rather constant middle part, which becomes longer with larger gust lengths. This result agrees well with mast measurements of Camp (1968). Differences between the three wind components illustrated in Fig. 2 can be seen in the slope of the middle part. In the *u*-component (Fig. 2a), it is slightly increasing (especially in the larger gusts) and leads to an asymmetrical gust shape. In contrast, the shapes of the *v*- and *w*-components gusts are nearly symmetrical. Furthermore, they have a larger spatial extend in the upper part than the corresponding gusts of the u-component (compare the width of the curves at a normalized velocity of e.g. 0.9 in Fig. 2). More than 60% of the largest mean gust of the *v*-component and more than 80% of the *w*-component consists of the constant middle part (solid black lines in Fig. 2b and c). A further result of the analysis of one-dimensional gust shapes is their dependence on height above ground. In comparison with the gust shapes presented in Fig. 2 (at 50 m height), gust shape curves become wider at lower altitudes and narrower at higher altitudes (not illustrated here). This is visible in all wind components and classes.

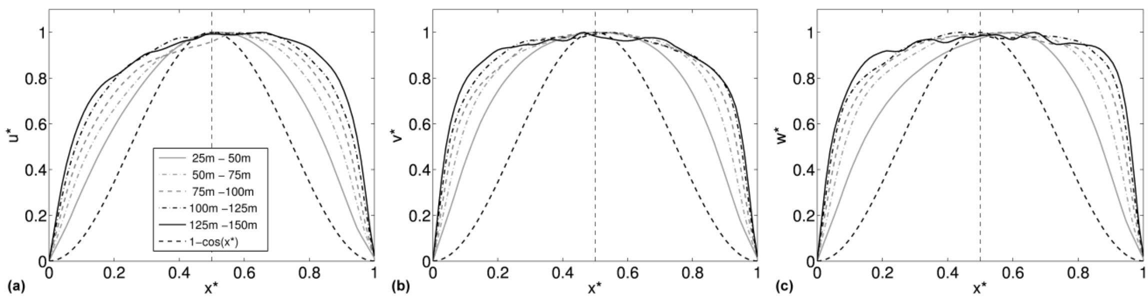

Figure 2: One-dimensional mean gust shapes of all five gust classes of the u- (a), v- (b) and w-component (c) at an altitude of 50 m.

Fig. 3 shows the mean gust shapes of two-dimensional gusts at an altitude of 50 m. Due to the little differences between the gust classes, only three gust classes (instead of fife in the one-dimensional case) were defined. The smallest and largest gust classes of the three wind components at an altitude of 50 m are shown in Fig. 3. The main characteristic, which is visible in all Figures, is the elliptical shape. In the mean gust shapes, this characteristic is only visible because each discrete gust was rotated in such a way that the main axis lied parallel to the *x*-axis before averaging them. Without the rotation, the mean gust shapes would be nearly circular. This would not reflect the rather elongated form of the single gusts.

In all wind velocity components illustrated in Fig. 3, aspect ratios become larger for the larger gust classes. The smallest aspect ratio is visible for the smallest gust class 1 of the vertical velocity component (Fig. 3c, left). As in the one-dimensional mean gust shapes, the maximum of the larger two-dimensional mean gust shape of the *u*-component (Fig. 3a, right) is shifted to the right. In contrast, the maximum of the larger vertical mean gust lies on the left side of the ellipse (Fig. 3c, right). Furthermore, a local minimum in the center of this gust can be seen in the velocity contours.

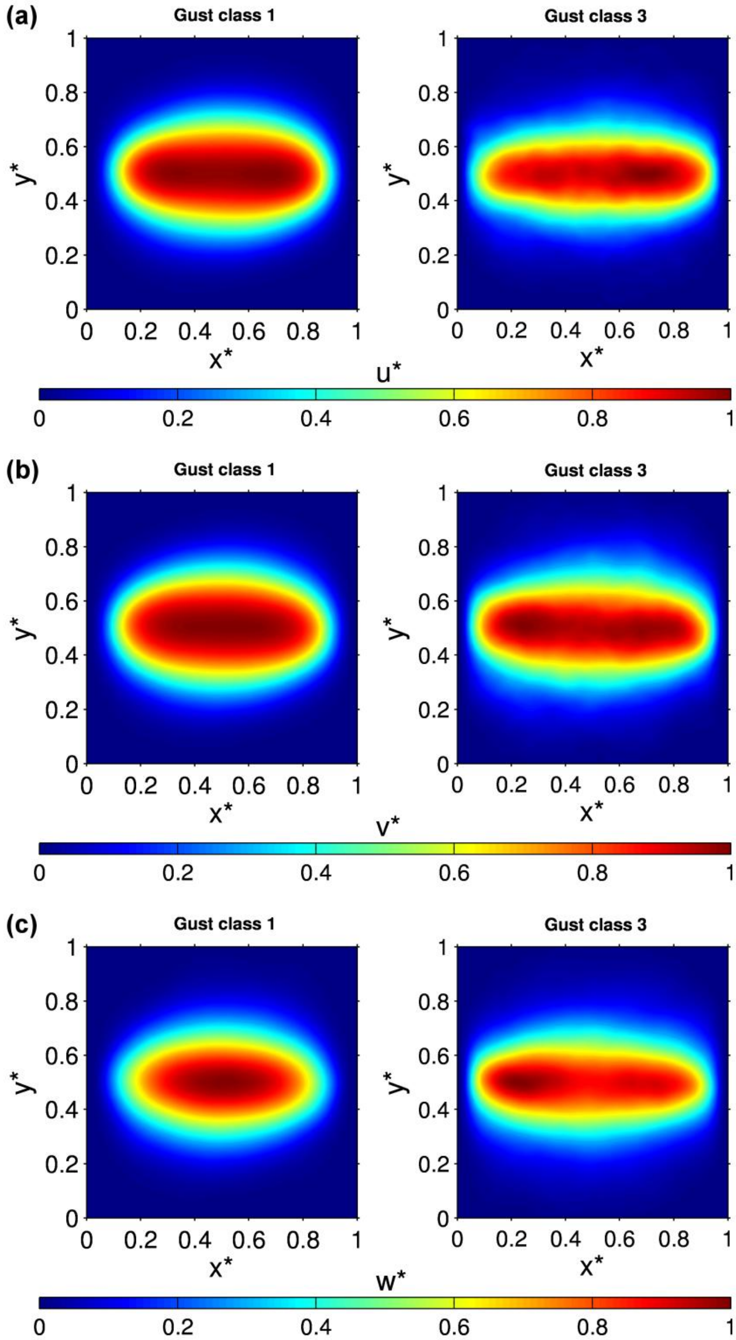

Figure 3: Mean two-dimensional gust shapes of the u- (a), v- (b) and w-component (c) at an altitude of 50 m.

4 CONCLUSIONS

High resolution LES enable detailed analysis of turbulent structures in the atmospheric boundary layer. Both one- and two-dimensional gusts show different mean gust shapes depending on the velocity component, gust length and altitude. In comparison with the one-minus-cosine gust, the one-dimensional mean gust shapes are more complex and show partly distinct differences (especially the larger gusts). In contrast, mean gust shapes presented in this study reflect the main characteristics of the mean gust shapes obtained from different mast measurements (Camp, 1968; Verheij et. al, 1992) very well.

Two-dimensional gust shape analysis provide more information about the lateral velocity gradients of the mean gusts. All gust shapes show an elliptical shape. A validation of these results based on field measurements is not possible yet, because of the lack of multidimensional high resolution measuring data containing turbulence information of the atmosphere. However, due to the agreement of the one-dimensional mean gust shapes presented here with results from mast measurements on the one hand and the consistent method (same database, same gust extraction method as far as possible) used for one- and two-dimensional gusts analysis, it seem to be reasonable to assume that the two-dimensional results are meaningful and represent typical gusts in the atmospheric boundary layer.

For the practical application of the presented results in design processes of structures, it is of particular interest if the shown gust shapes lead to different results in load calculations than the existing gust models like the one-minus-cosine law. The main differences of the one-dimensional gust shapes in comparison to the one-minus-cosine gust shape are the steep increase and decrease. This leads to stronger velocity gradients and may possibly cause stronger loads on the structures. To estimate the influence of two-dimensional gusts on structures in previous studies, two rather simple methods based on the one-dimensional gust shapes are known to the authors: It can be assumed that the two-dimensional gust shape consists of the one-dimensional gust shape (e.g one-minus-cosine) which is either uniform over the whole width of the structure or is cut off at a certain point of the domain. It is obvious, that both methods do not agree with the two-dimensional gust shapes presented in this study and hence do not represent realistic gusts.

An analytical approximation of the mean gust shapes presented in this study can help to derive new or improve existing gust models which are used during the design processes of wind turbines, aircraft or other structures. This work will be presented in a more comprehensive article.

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