Dear Referees,

thank you very much for your work and the useful and valuable comments how to improve the scientific quality of our manuscript. Please find below our reply to the individual points, marked with an "AC" (author's comment).

Best regards,
Susanna Mohr on behalf of all co-authors

Response to the referee comments: Referee #1:

Separating the occurrences and measurements of different Aeolian phenomena such as synoptic cyclones, thunderstorms, tornadoes and so on is a key topic of modern wind engineering in order to perform distinct statistical analysis, to extract the main statistical parameters related to each phenomenon, and to build wind field models suitable to represent the wind loading and response of structures. Merging these separate evaluations in a unitary formulation is a further aim still in the embryonic stage.

This paper provides very interesting and new information on several aspects in the above framework, thus represents a useful and pertinent contribution to the advance of the knowledge in this field. In its whole I appreciate it and support its publication.

This paper contains a broad literature both in the fields of atmospheric sciences and wind engineering, perhaps a little biased towards the first field. Despite this I believe that some relevant contributions to this topic are not considered and some choices inherent the methods herein applied seem to be based on a limited view of some previous contributions. Under this point of view, without changing anything in the substance of this paper, I believe that a wider critical discussion on the advantages and shortcomings related to such choices may improve the quality of this paper and inspire future step forwards.

More in detail, I recommend Authors to take into account the following remarks and observations:

Section 1: At least two additional references should be considered. The first (*Gomes and Vickery,1978*) is the fundamental paper that in 1977 introduced the concept of mixed wind climate and the idea of processing separately the statistical analysis of different wind phenomena. The second (*Kasperski, 2002*) published in 2002, deals with the same topic of the present paper just with reference to Germany. A comparison with previous methods and results is recommended.

AC: We added both literatures in the introduction.

Section 2: I am quite doubtful on the decision of restricting analyses to the summer half-year. In my experience thunderstorm events are concentrated in this part of the year but are present also, in minor proportion, all over the year. Restricting analyses to a period is even more dangerous considering the aim of performing a statistical analysis of the extreme wind speed. Unavoidably this produces underestimated results. I suggest to revise this choice in next contributions.

AC: In Germany, thunderstorms do not occur very often during the winter half year and, when they occur, those events are in general embedded in frontal systems, which is not our interest in this work (avoid mixed climate). For example, Wapler (2013) showed that in Germany the number of strokes during the winter half year is one to two orders of magnitude smaller compared to the summer time. Furthermore, she identified exemplarily for a few weather stations an extremely small number of thunderstorm days during the winter half season (< 1 per month). However, in future work we will investigate the sensitivity on the results by considering the winter events more accurately.

Section 2.1: Authors base their analyses on the daily peak and subsequent mean wind speeds on 10-min and 1-h periods. They also use pressure measurements. A very similar approach is used in Uruguay and described in *Duranona (2015).* I suggest to examine this contribution.

AC: Thanks for the reference of this work. However, the author uses another definition to separate strong convective wind events from a mixed wind climate (sudden increases in wind speed, temperature drops, wind direction shifts). They did not use pressure measurements/gradients, and the overlap between the studies concerns only the results regarding the (convective) gust factors. Therefore, we added the proposed literature only in the result section.

Section 2.1: Also in the light of the occurrence of gust factors in the order of 6-10, I suggest Authors to consider the possibility that some peak values in the database may be wrong (*Cook, 2014*). The potential presence of some mistakes and the difficulty of recognizing them is a major shortcoming of this kind of analyses, where the control is very good in terms on mean values but almost impossible with reference to single peaks.

AC: Again, we explicitly checked each event with high values above 6 and could not identify any inaccuracy. For example, in those cases the mean hourly wind was < 6 m/s. Choi and Hidayat (2002) have already stated that gust factors obtained close to the storm's center may reach values between 7 and 8. Furthermore, those high values can certainly result when the duration of a gust is small or the event happens at the end of the measuring time and, thus, estimated hourly mean wind speed is almost insensitive to individual gusts..

Section 2.3: I understand that Authors have probably no other opportunity than this use of lightning data. In my experience the presence of cloud-to-cloud lightning not detected by measurements may provide some relevant drawback. I verified this by comparing similar lightning data with high-sampling velocity records.

AC: That's right and we are aware of this. But unfortunately cloud-to-cloud lightning (CC) was not recorded by BLIDS entirely due to the lower frequency range. However, several studies have shown that thunderstorms connected with only CC occur predominantly during the winter time or are in general "weaker" (cf., Rakov and Uman, 2003) and, thus, to a less degree associated with strong downdrafts or straight-line winds. We added a comment about this aspect/uncertainty in this section.

"Although three-quarters of all lightning is CC (Rakov and Uman, 2003), we assume that severe convective storms with strong downdrafts and thus strong gusts at the surface produce a sufficient number of CG flashes."

Section 2.4: The problem of the separation of different wind events is a key topic because any mistake in this stage may compromise the quality of further evaluations. I suggest Authors to dedicate a few more words to this problem for instance using a citation to *Lombardo et al. (2009)* (included in references but not cited here) and to *De Gaentano et al. (2013).*

AC: We added a comment about this problem in the section "Definition of convective gusts" considering the mentioned studies:

"The separation and classification of strong wind events into synoptically/frontal driven and convectively driven gusts is a key topic, because any inadequacies in this stage may severely affect subsequent statistics. Different approaches have been established that are either based on individual detailed inspections of the prevailing meteorological conditions (by using surface measurements, radar/satellite images,...) during the wind events or on systematic filtering using proxy data for thunderstorms such as lightning. A summary of the different methods to extract convective gusts can be found in De Gaetano et al. (2014).
We follow the approach of Choi and Hidayat (2002) and Cook et al. (2003) and considered wind gusts only in combination with a thunderstorm day."

Section 2.5: Authors speak of GEV and POT/GPD and make the choice of using POT/GPD. This is fine but again, without changing the substance of this paper, this topic is a "world" that may necessitate a some more "delicate" approach. First of all the use of POT/GPD is widely supported by some Authors but drastically opposed by others. The reference (*Harris, 2005*), for instance, is fully devoted to demonstrate that this method is wrong or at least unreliable. Our research group recently published a series of papers based on long-term Monte Carlo simulations (*Torrielli et al., 2013; 2014*) that confirms the limited reliability of the POT/GPD technique and arrives to the conclusion that the Process Analysis (*Gomez and Vickery, 1977*) (probably not easy to apply to thunderstorms) and the Penultimate distribution (*Cook and Harris, 2004; 2008*) are the best methods.

AC: We addressed this issue in the conclusion:

"Concerning extreme value statistics, the use of POT/GPD method is discussed controversially in the literature. Whereas the use is widely supported by some authors (e. g., Hosking and Wallis, 1987; Simiu and Heckert, 1996; Palutikof et al., 1999; Holmes and Moriarty, 1999; Simiu, 2007), Harris (2005) demonstrated that this method has grave defects and thus is unreliable. Therefore, over recent years new methods have been developed to overcome this problematic, which are based, for instance, on long-term Monte Carlo simulations (Torrielli et al., 2013) or the Penultimate distribution (Cook and Harris, 2004, 2008). These approaches for several cases may help to improve the statistics and to reduce underlying uncertainty."

Section 2.5: At the end of this section Authors write "that the differences between the return values estimated by both methods are considerably smaller than the uncertainties of the method itself". This is absolutely correct with reference to return periods in the order of the number of years of available data, for instance 20-50 years. Structural safety, however, needs evaluations extrapolated to return periods in the order of 500-1000 years. Here, different methods lead to divergent results (*Cook and Harris, 2004; 2008; Lagomarsino et al., 1992*).

AC: Regarding the first comment we have specified:

"…the differences between the return values as considered in this work (<100 years) estimated from both methods are considerably smaller than the uncertainties of the method itself…"

Regarding structural safety: In general, the reference velocity in national standards like DIN or EUROCODE is based on average on a return period of 50-year.

Section 3.1: Authors write: "we considered every single measurement at each station, which means that one event can be recorded on two or more stations". I think that this sentence may result misleading. Downbursts are phenomenon with a radius of a few km. It is almost impossible that the same downburst may be detected by two stations of this network. The situation is different if Authors refer to the large scale wind event that generates downbursts. This point should be clarified.

AC: We specified that:

"Note that we considered every single measurement at each station, which means that one event can be recorded on two or more stations if event is related to a meso-scale cold pool."

 Section 3.3: The last sentence deserves a citation to Authors that first expressed this concept (*Gomes and Vickery,1978*).

AC: We included the literature at this point.

Section 3.4: Line 11. The dependence of the gust factor on the averaging period is discussed also by *Solari et al. (2015).*

AC: We also referred to the literature in this paragraph.

Section 3.4: Line 20. I do not agree on the sentence according to which "turbulent factors (to replace with gust factors ?) fluctuate usually between 1.2 and 2.3". Such a large variability

necessarily depends not only on the roughness length but even more on the stability conditions. If wind is intense and of synoptic type, then atmosphere is neutrally stratified and the gust factor may vary between 1.25 and 1.75 with an average value around 1.5. In my opinion gust factors in the order of 1.75-2.3 may be ascribed to unstable conditions and intermediate events between large scale depressions and mesoscale downbursts (*De Gaetano et al., 2013*).

AC: We corrected that and integrated the dependency of the gust factor values regarding atmospheric stability:

"Depending on the land use, surface roughness, or atmospheric stability, respectively, turbulent gust factors fluctuate usually between 1.2 and 2.3."

Independently of the above remarks, that I wrote in a fully constructive spirit, I confirm my appreciation towards this contribution and that I consider it appropriate for publication. I hope that Authors may consider or discuss my remarks. I suggest that this paper is accepted subject to minor revisions but I believe that a quick re-review may be useful.

Giovanni Solari Department of Civil, Chemical and Environmental Engineering Polytechnic School, University of Genoa, Italy

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Response to the referee comments: Referee #2 (Anonymous):

General comments

The manuscript "Statistical characteristics of convective wind gusts in Germany" written by Susanna Mohr et al. describes a methodology to identify and select convective wind gusts from station measurements at 110 stations within Germany. Characteristics regarding the seasonality as well as spatial variations over Germany are considered and rare convective gusts are characterised by means of extreme value statistics. Additionally, by comparing the convective gust measurements to mean winds, gust factors are quantified.

Generally, the study presents very relevant work and is an important contribution to the understanding of local small scale convective wind gusts. The manuscript is well written and the chosen methods to assess the statistical characteristics of convective gusts in general seem appropriate and well suited. However, I notice several minor flaws (which I listed below) in the methodological and statistical approach which I would recommend the authors to consider. I thus suggest the paper to be accepted after minor revisions.

Specific comments

P. 3, L. 17: Results show, that no significant differences are found in the intensity of rare convective gusts with respect to orography. Why are stations at higher ground excluded? It might be particularly worthwhile to also consider stations at higher altitudes!

AC: At higher elevated stations, the separation and classification of strong wind events into homogeneous families (convectively driven) is very difficult and we explicitly want to exclude events caused by a mixed climate (large-scale / convective conditions). We added a comment about this.

P. 4, L. 13-14: The choice of a 50-km radius does not seem to be justified by the given explanation. Since a gust front can occur several kilometers ahead of a storm center this might suggest a radius of 5, possibly 10 km.

AC: A gust front can occur several tens of kilometers ahead of a storm's center, as already shown by Klingle et al. (1987) and Pantillon et al. (2015). Note that we consider only clout-to-ground lightning. We also refer to the concept of a "trailing gust front" (typically south or southwest of the flank of a storm; see also Houze, 2014; chapter 9), where the distance between the gust and the highest lightning density is largest..

By the way, we have tested different radii and found no strong impact on the overall results. We added a comment on that in the revised version.

"The reason for the large detection radius is that gust fronts can occur several tens of kilometers ahead of a storm center with lightning activity, as already shown by Klingle et al. (1987), Houze (2014), and Pantillon et al. (2015). Note that a lower distance does not modify the overall results."

Klingle D. L.; Smith D. R. & Wolfson M. M. Gust front characteristics as detected by Doppler radar Mon. Weather Rev., 1987, 115, 905-918.

Pantillon, F.; Knippertz, P.; Marsham, J. H. & Birch, C. E. A parameterization of convective dust storms for models with mass-flux convection schemes J. Atmos. Sci., 2015, 72, 2545-2561.

Houze R. A. Cloud Dynamics (2nd Ed.) Elsevier Inc., Oxford, UK, 2014.

P. 4, L. 20 "proximity to the wind station": Pressure gradients are calculated by means of a small set of 6 climate stations. It should be explained how the pressure gradients "in proximity to the wind station" are determined and in how far it can be expected that small scale depressions can be captured (or why such small scale depressions are disregarded!).

AC: The six climate stations are more or less evenly distributed over Germany and the distance between two neighboring stations is always less than 250 km (mean 210 km). Means that the

pressure gradients between the nearest pressure station to the gust event and the others five pressure stations (cf., Section 2.1) is considered. Therefore, our filter also captures smaller-scale depressions (such as, e.g., gale Lothar in 1999, which was the most severe, but spatially most limited storm over recent decades). A comment is added in the revised version.

"In addition to wind speed, daily pressure records (KL data) were used to filter out turbulent gusts (see Sect. 2.4). For this, the pressure differences among six climate stations located over Germany were considered (Schleswig, Norderney, Hannover, Berlin-Tempelhof, Frankfurt/Main-Airport, Hof, and Augsburg). The distance between the stations is in all cases less than 250km to capture also small scale depressions."

P. 4, L. 20-22: This additional filter criterion seems a bit random/unsystematic. I suspect, that not only in April but also in autumn such weaker pressure gradients do occur. I would thus favor a more systematic treatment of seasonality. Also, this additional criterion might hinder the interpretation of spatial as well as the seasonal variance discussed later in the text.

AC: That's right, this additional criterion seems to be a bit random and cumbersome. However, we performed several comparisons using synoptic weather charts and found that an additional criterion is necessary for the month of April, where large-scale storms over the North Sea (not so common in September) may affect the gust statistics in the North German Plain (> 52°N). We specified this.

"Because storm events related to low pressure systems frequently occur in April on the north coast, we used for this month and north of 52°N (North German Plain) a filter that excludes days under the influence of weaker pressure gradients compared to the first case 5 (>2.5 Pa 1/km). This criterion was extensively tested by a comparison with synoptic weather charts."

P. 4, L 23-24: Sensitivity of what? It should be specified in which respect the sensitivity has been considered!

AC: Both the distance to a lightning recording and the thresholds of pressure gradients were identified by sensitivity and individual case studies. In doing so, we investigated the impact of varying thresholds on the sample size and the results of the statistics. We added a comment.

P. 5, L. 2: What is meant by "as the approach reproduced the sample better"?

AC: We mean "as that approach reproduced the observed gusts better". We changed the formulation.

P. 5, L 3-4: Does "uncertainties of the method itself" refer to confidence intervals on estimated return values? Should be clarified!

AC: Yes. We clarified that:

"…the method itself (here expressed by confidence bounds)…"

P. 6, L. 19-26: In Figure 1, I would propose adding confidence intervals to indicate the uncertainties in the seasonal variations. As noted above, a single event can cause the peak in beginning of April. Without a proper estimation of uncertainties (confidence intervals) I would challenge the statistical robustness of the results presented here!

AC: We included the confidence intervals in Figure 1a to show the variability. However, not in Figure 1b, since this might be confusing concerning the North/South discrepancy shown there.

P. 7, L. 7-9: Has this been tested explicitly or is this just an interpretation of the missing north-to-south gradient? Of course this could be explicitly done correlating orographic height of the station against percentile value?! This is also related to my previous comment on excluding stations at higher locations.

AC: We did not find any correlation between the percentile values and station heights. The correlation coefficient (Spearman) is in general < - 0.1. In addition, it is striking that stations above

500 m (16 station means 15%) have lower values than stations at lower elevations. We added a new Figure that shows the insensitivity of the estimated gusts on the station heights in the revised version.

P. 7, L. 27-28: Although I do not want to object to the threshold choice itself, I do want to mention that this is not how the parameter stability criterion should be interpreted! In the GPD framework, it can be inferred that if the distribution of values above a certain threshold (u_0) follows a GPD, then it follows a GPD above all thresholds higher than u_0 with a modified sigma. Shape and modified scale should thus be constant above (not near) the chosen threshold within confidence intervals! For details see Coles: An Introduction to Statistical Modeling of Extremes, 2001 p. 78/79.

AC: We modified this formulation. However, this point has already been taken into account in the investigations.

P. 8, L. 3-5: A comparison of the empirical estimates (95% percentile) and estimates from extreme value statistics might be interesting here. According to the numbers that are specified in lines 10-11 on page 7 we are then talking about a return period of about 1 year.

AC: A comparison between percentiles and RV1a shows that values with a return period of 1 year correspond to 95 % to 98 % percentiles–depending on the stations. We added a sentence.

P. 8, L. 14-15: It should be clarified how the statistical uncertainty is calculated for a region. In the caption of figure 5 it is mentioned that it corresponds to the mean of 95% confidence levels. I do not see why and how this should compare to the standard deviation for different stations (regional variability)!

AC: We modified the figure caption to clarify this:

"Mean return values of convective gusts (RV) for various return periods in four regions in Germany (gray area). Red lines indicate the standard deviation from all stations within the respective region, and black bars indicate the mean 95% confidence intervals representing *statistical uncertainties of the POT/GPD method."*

P. 10, L. 24: As mentioned in my previous comment, it should be clarified if this has been explicitly tested or weather this is simply the interpretation of Figures 2 and 4 (which do not contain an explicit information on orographic height).

AC: Yes. See comments above. Depending on RV the correlations (to station height) are between 0.2 – 0.3.

P. 10, L. 26: By definition, an event with a 20-year return period has a fixed occurrence frequency of 20 years! Please rewrite!

AC: Rewritten:

"A comparison of the 20-year return values of convective gusts with those of turbulent gusts demonstrates that the latter have higher return values."

Technical corrections

P. 7, L. 7: slight variability instead of slightly variability.

AC: Corrected.

Statistical characteristics of convective wind gusts in Germany

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Abstract. Due to the small-scale and non-stationary nature of the convective wind gusts usually associated with thunderstorms, there is a considerable lack of knowledge regarding their characteristics and statistics. In an effort to remedy this situation, we investigated in this study a set of 110 climate stations of the German Weather Service between 1992 and 2014 to analyze the temporal and spatial distribution, intensity, and occurrence probability of convective gusts.

Similar to thunderstorm activity, the frequency of convective gusts decreases gradually from South to North Germany. No further spatial structures, such as a relation to orography or climate conditions, can be identified regarding their strength or likelihood. Rather, high wind speeds of above $30\,\mathrm{m\,s^{-1}}$ can be expected everywhere in Germany with almost similar occurrence probabilities. A comparison of the 20-year return values of convective gusts with those of turbulent gusts demonstrates that the latter have higher frequencies, especially in northern Germany. However, for higher return periods, this effect can be reversed at some stations.

The values of the convective gust factors are mainly in a range between 1 and 4 but can even reach values up to 10. Besides the dependency from the averaging time period of the mean wind, the values of the gust factors additionally depend on the event duration and the storm type, respectively.

Keywords: convective wind gusts, monthly distribution, spatial distribution, return periods, convective gust factor, Germany

1 Introduction

Convective wind gusts in terms of non-tornadic, straight-line winds cause significant damage to buildings and other structures in many parts of the world. Because they occur in Central Europe predominantly in the warm summer months, they may pose a significant threat to outdoor activities or open-air concerts. An example of such damage cases is the music festival *Pukkelpop* (Hasselt, Belgium) in the summer of 2011 with estimated wind speeds of between 29 and $37\,\mathrm{m\,s^{-1}}$, at which five people died and at least 140 were injured due to a stage collapse (De Meutter et al., 2015). **Another recent example is the Pentecost storm of 9 June 2014 connected with an intense bow echo in Western Europe with high wind speeds up to $40\,\mathrm{m\,s^{-1}}$ that caused six fatalities and total losses of 650 million Euros (Barthlott et al., 2017; Mathias et al., 2017).**

Various observations have shown that convectively induced storm events can reach even higher wind speeds compared to large-scale wind storms. Wind peaks of more than $50\,\mathrm{m\,s^{-1}}$ have already been recorded (Proctor, 1993; Lemon, 1998; Dotzek

et al., 2009). The highest convective gust ever observed was in 1983 during a microburst in the United States with a peak gust of $67\,\mathrm{m\,s^{-1}}$ (Fujita, 1990). Based on damage assessments, one can assume that wind speeds comparable to those of an F3 tornado are possible.

Severe convective gusts are caused either by local-scale downbursts that create strong divergent horizontal winds near the ground or by meso-scale cold pools associated with horizontal pressure gradients large enough to produce high winds speeds in the absence of strong downdrafts (Wakimoto, 2001; Markowski and Richardson, 2010). In general, the development of convective gusts is determined by diabatic processes, dynamic and thermodynamic perturbation pressures, and precipitation loading, the latter mainly as a trigger (Proctor, 1989; Wakimoto, 2001).

Due to the local-scale nature of severe convective storms, however, existing observation systems do not record convective gusts accurately, homogeneously, and uniquely. In Germany, approximately 500 climate stations currently measure wind speeds, which means that one station has to cover an area of $700\,\mathrm{km^2}$ on average, which is far from being adequate. This leads to an underestimation of local-scale events, such as microbursts that have only a small chance of being recorded, compared to larger events, such as gust fronts (Fujita, 1990; Orwig and Schroeder, 2007).

Thus, there is a considerable lack of knowledge regarding the characteristics, frequency, and climatology of convective gusts. Furthermore, their amplification by urban structures and their influence on buildings is not yet fully understood (Richter et al., 2016a, b). According to this, convective wind events are not included in the present wind load standards of buildings and structures, which so far have been based solely on the characteristics of synoptically driven wind gusts in the near-surface boundary layer (e. g., DIN EN 1991-1-4:2010-12; ASCE, 2010). However, convective and turbulent gusts differ considerably concerning vertical wind-speed profiles, the gust factor describing the turbulence (i. e., maximum to mean wind speed), or exceedance probability curves (Wood et al., 2001; Letchford et al., 2002; Holmes, 2002; Chen and Letchford, 2005).

Several studies have already shown that convective gust factors are usually larger than those of turbulent gusts (Bradbury et al., 1994; Chay et al., 2008; Holmes et al., 2008; Lombardo et al., 2014; Shu et al., 2015; Solari et al., 2015). Choi and Hidayat (2002), for example, found values between 2.2 and 6.5 for convective gusts in open terrain in Singapore. In the United States, Orwig and Schroeder (2007) calculated a factor of 1.5 triggered by a rear-flank downdraft of a supercell and a value of 3.8 during a derecho. Regarding return values, Friederichs et al. (2009) have quantified the probability of wind gusts to exceeding a certain warning level in Germany, but they did not differentiate between convective and turbulent gusts. However, as already shown by **Gomes and Vickery (1978)**, Bradbury and Deaves (1994), and Holmes (2002), both gust forms have very different exceedance probability curves **and thus have to be separated for proper extreme value analysis. The wind gust assessment of Kasperski (2002), for example, defines convective gusts when the maximum gust speed is well above the mean wind. However, the author stated that thunderstorms have almost no influence on the strong wind climate, which could be due to its insufficient definition.**

The motivation behind this study is to identify various characteristics of convective gusts by means of the statistical analysis of wind measurements in Germany, for which only limited information is available at present. A question in this context is which temporal and spatial properties convective gusts exhibit and if their distributions are similar to other severe convective events. Besides the diagnosis of maximum wind speeds, we estimated the occurrence probabilities of extreme convective gusts

for larger return periods (e. g., 50 or 100 years) and discussed those in comparison to turbulent gusts. Finally, we systematically investigated convective gust factors based on a long-term data set of more than 23 years, which has not yet been considered.

The paper is structured as follows: Section 2 gives a short overview of the data sets and statistical methods used in this study. Furthermore, it describes the filtering method for identifying convective gusts among all wind measurements. Sections 3.1 and 3.2 present the seasonal and spatial variability of past convective gusts in Germany. Section 3.3 investigates the return values of convective gusts for higher return periods and compares the results with those of turbulent gusts, while Section 3.4 discusses the results of the convective gust factor. Finally, the last Section 4 summarizes the results and gives some conclusions.

2 Data and methods

Because convective gusts associated with thunderstorms occur **predominantly** in the summer half-year in Germany (and Central Europe; Wapler, 2013; Anderson and Klugmann, 2014), our examinations were also restricted to that time period. As a result, a large fraction of turbulent gusts were already excluded in the data set.

2.1 Observation data

The study used measurements of the German Weather Service (Deutscher Wetterdienst, DWD) from two operational networks: (a) climate data of the "KL network" with hourly measurements over a period of several decades, and (b) automatic measurements with a 10-minute resolution from the "MN network". The latter started only after 1990 and has been steadily expanded over the past two decades. Whereas only between 100 and 150 stations were in operation at the end of the last 20th century, the number quadrupled up to 2014.

The climate data (KL) were considered for the 23-year period between 1992 and 2014. We used both daily maximum wind gusts (FX) and hourly mean wind speeds (FF). For both data sets, the DWD performed a basic quality control. Only stations where observations were available for the complete 23-year period with a data loss below 10 % were evaluated. Furthermore, we excluded stations located in the North Sea or Baltic Sea or above 900 m.a.s.l., where high wind gusts are strongly influenced by orographically induced flow effects **and where a separation between synoptically and convectively driven gusts is problematic (mixed wind climate).** In total, we considered the remaining 110 stations, resulting in a station density of approximately one station per 3250 km^2. Even though this density is rather low, the selected stations are almost evenly distributed across the investigation area and well represent the terrain characteristics.

In addition to wind speed, daily pressure records (KL data) were used to filter out turbulent gusts (see Sect. 2.4). For this, the **pressure** differences among six climate stations located over Germany were considered (Schleswig, Norderney, Hannover, Berlin-Tempelhof, Frankfurt/Main-Airport, Hof, and Augsburg). **In all case, the distance between two neighboring stations is less than 250 km, which ensures that also smaller-scale depressions are captured.**

For a more detailed discussion of convective gust factors, we additionally used the maximum gust and mean wind every 10 minutes (MN data). Only stations and days were considered that exist in both data sets.

2.2 Return values of turbulent gust

For the comparison of the occurrence probability between convective and turbulent gusts (Sect. 3.3), we used the return values related to winter storms from the study of Kunz et al. (2010). The return values for return periods between 1 and 100 years were calculated from KL data during the winter half-year between 1971 and 2000 using the same statistical method as applied in this study (see Sect. 2.5). In total, the data of 85 out of the 110 stations were available. For more details, the reader is referred to Kunz et al. (2010).

2.3 Lightning data

Data from the lightning information service "BLitz InformationDienst Siemens" (BLIDS), which is part of the EUropean Cooperation for LIghtning Detection network (EUCLID; Schulz et al., 2016; Drüe et al., 2007), were used to ensure that wind measurements were related to thunderstorm events. We considered only the time and location of the lightning, whereas polarity and power information was neglected. Because cloud-to-cloud (CC) lightning was not recorded entirely due to the lower frequency range (Drüe et al., 2007), only cloud-to-ground (CG) lightning was taken into account for identifying thunderstorm days. **Although three-quarters of all lightning is CC (Rakov and Uman, 2003), we assume that severe convective storms with strong downdrafts and thus strong gusts at the surface produce a sufficient number of CG flashes.** Lightning detection has been available since 1992 in Germany, whereby the replacement of the lightning sensors in 2000 did not affect our filter approach.

2.4 Definition of convective gusts

The separation and classification of strong wind events into synoptically/frontal driven and convectively driven gusts is a key topic, because any inadequacies in this stage may severely affect subsequent statistics. Different approaches have been established that are either based on individual detailed inspections of the prevailing meteorological conditions (by using surface measurements, radar/satellite images,...) during the wind events or on systematic filtering using proxy data for thunderstorms such as lightning. A summary of the different methods to extract convective gusts can be found in De Gaetano et al. (2014).

We follow the approach of Choi and Hidayat (2002) and Cook et al. (2003) and considered wind gusts only in combination with a thunderstorm day. In this process, a thunderstorm day is classified when at least five lightning flashes occur in a box of $10 \times 10 \, \text{km}^2$ (Piper and Kunz, 2017). Such a thunderstorm day has to be within a 50-km radius around the wind record. The reason for the large detection radius is that gust fronts can occur several **tens of** kilometers ahead of a storm center with lightning activity**, as already shown by Klingle et al. (1987), Houze (2014), and Pantillon et al. (2015). Note that a lower distance does not modify the overall results.**

However, the occurrence of lightning (or thunder) does not necessarily mean that a severe wind gust was generated by a thunderstorm cloud. In fact, low pressure systems and related cold fronts, especially during the summer, may also produce severe gusts. Because the driver is a mixture of convectively driven processes and pressure gradient in those cases, we wanted

to exclude such events from the sample. Therefore, our filtering additionally eliminates events that are related to large pressure gradients. In a first step, we excluded high-wind events on days with strong pressure gradients of $4\,\mathrm{Pa\,km^{-1}}$ or more in proximity to the wind station. **Means that pressure gradients between the nearest (to the gust event) pressure station and the others five pressure stations (cf., Section 2.1) are considered.** Because storm events related to low pressure systems frequently occur in April on the north coast, we used for this month and north of $52°N$ **(North German Plain)** a filter that excludes days under the influence of weaker pressure gradients compared to the first case $(> 2.5\,\mathrm{Pa\,km^{-1}})$. **This criterion was extensively tested by a comparison with s synoptic weather charts.**

Both the distance to a lightning recording and the thresholds of pressure gradients were identified by sensitivity and individual case studies **by investigating the impact of varying thresholds on the sample size and the following results**. In the case of considering only events greater than or equal to $18\,\mathrm{m\,s^{-1}}$, the two filters together lead to a reduction in data of 63 %, whereas the pressure filter constitutes only a small fraction (1 %). This procedure reduces the sampling, but the resulting event set is still a representative basis for our assessment.

2.5 Extreme value statistics

Basically, two different methods exist for describing extreme events, i.e., for assessing the tail behavior of the distribution of interest. One is the classical generalized extreme value (GEV) distribution, which comprises three different distributions considering only annual maxima (Fisher and Tippett, 1928; Jenkinson, 1955). The other approach is the peaks-over-threshold (POT) method, at which all events above a chosen threshold ζ are selected for calculating the upper tail of a sample with the generalized Pareto distribution (GPD; Palutikof et al., 1999; Coles et al., 2001). This method increases the number of considered events and thus reduces statistical uncertainty (Brabson and Palutikof, 2000). After testing both methods, we chose the POT/GPD method to relate wind speeds and probability, as **that approach reproduced the observed gusts better**. Note, however, that the differences between the return values **as considered in this work $(< 100$ years)** estimated from both methods are considerably smaller than the uncertainties of the method itself **(here expressed by confidence bounds)**.

The cumulative distribution function (CDF) of the GPD is

$$F(x) = 1 - [1 + \frac{k}{\sigma}(x - \zeta)]^{-1/k} \qquad \text{if } k \neq 0 \tag{1}$$

$$F(x) = 1 - \exp\left[-\frac{(x - \zeta)}{\sigma}\right] \qquad \text{if } k = 0 \quad, \tag{2}$$

where x is the random variable (cf., Coles et al., 2001). The shape parameter k indicates the width, and the scale parameter σ indicates the slope of the CDF. Both parameters were estimated using the maximum likelihood method as a reliable and robust estimator (Hosking and Wallis, 1987; Kunz et al., 2010). The parameter k is typically valid within the range of $-0.5 < k < +0.5$ (Abild et al., 1992).

With the crossing rate λ as the expected number of peaks above ζ, wind speed is a function of the return period T

$$X_T = \zeta + \frac{\sigma}{k}[(\lambda T)^k - 1] \qquad \text{if } k \neq 0 \tag{3}$$

$$X_T = \zeta + \sigma \ln(\lambda T) \qquad \text{if } k = 0 \quad. \tag{4}$$

5

For $k < 0$, the function converges asymptotically toward an upper bound. However, it is infinity if $k \geq 0$, implying an unbounded increase in wind speed for increasing return periods, which is physically unrealistic (Holmes and Moriarty, 1999).

The application of the POT/GPD requires that the event set be independent and identically distributed. Therefore, we used the daily wind maximum assuming that two events at midnight do not occur. This is in agreement with Lombardo et al. (2009), who found a negligible dependence on whether the minimum time distance between successive convective gust peaks was between 6 or 12 h.

To consider statistical uncertainty, the 95 % confidence bounds are calculated by bootstrapping. This method is based on a number n of samples—here $n = 1000$ times—obtained by random resampling with the replacing of the original data set (Efron and Tibshirani, 1993).

Because $F(x)$, k, and σ are strongly controlled by the choice of ζ, this quantity must be adapted to the climatology of the respective data set (here, for each station). We applied two different techniques for the threshold selection **(Coles et al., 2001)**: First, we plotted the mean residual life graph, also known as conditional mean exceedance, which shows the mean excess over a threshold $E(x - \zeta \,|\, x > \zeta)$. The idea is to find the lowest threshold, at which the graph is nearly linear (constant slope)—taking into account the 95 % confidence bounds. Second, by using the parameter stability plots (k or σ against varying ζ), a threshold can be identified, where both parameters **above** are almost constant. Note, however, that despite the thorough determination of ζ, the results still depend (slightly) on that parameter, whereby the differences are small and within the confidence bounds.

3 Statistical characteristics of convective gusts

Focusing on severe wind events, we considered in the following particularly gusts greater than or equal to $18 \, \mathrm{m \, s^{-1}}$, which corresponds to the warning criterion level 2 of DWD (warning of significant weather). In Section 3.1, a second threshold of $25 \, \mathrm{m \, s^{-1}}$ was used, defining severe wind gusts in the United States according to the National Oceanic and Atmospheric Administration (NOAA).

3.1 Seasonal variability

Similar to other convective-related phenomena in Germany, such as lightning, hail, or tornadoes (Wapler, 2013; Piper and Kunz, 2017; Puskeiler et al., 2016; Groenemeijer and Kühne, 2014), convective gusts occur predominantly in the warm summer months between May and August, when atmospheric conditions favor the formation of deep moist convection. Most events of the sample exceeding a threshold of $18 \, \mathrm{m \, s^{-1}}$ (in total 5274 events; KL data) are observed in June and July (53 %) with the absolute maximum in the second half of June and July (11-day running mean in Fig. 1a). Occurrence probability is similar in May and August (17/18 %), while it is in the order of 6 % in April and September. Note that we considered every single measurement at each station, which means that one event can be recorded on two or more stations **if the event is related to a meso-scale cold pool**.

The monthly distributions considering higher thresholds are very similar (Fig. 1a). Severe events ($\geq 25 \, \mathrm{m \, s^{-1}}$) are slightly more frequent in July, wherever the differences in June are negligible. **However, due to the limited sample size typically**

connected with extremes, we observed a very high day-to-day variability (95 % confidence intervals; dashed lines in Fig. 1a). Furthermore, severe gusts occur very rarely in April or September, when prevailing atmospheric conditions do not usually favor severe thunderstorms. Note that the peak at the beginning of April for both thresholds is caused by one single event (4 April 2001). On that day, a cold front with a large number of embedded thunderstorms moved over Germany and
5 produced several convective gusts with velocities up to $32\,\mathrm{m\,s^{-1}}$.

By splitting the observations into a north and south region comprising 55 stations for each sample ($\sim 51.4°$N), it is found that the maxima are shifted about 15 days against each other with the earlier occurrence in the north (Fig. 1b). However, this difference is observed only when individual events were considered. For the number of convective wind gust days, this shift vanishes (not shown). Furthermore, it is striking that the differences between the north and south are pronounced in May, July,
10 and August but not in June. Unfortunately, underlying causes have not yet been identified.

Interesting is the drop in the number of convective gusts around 15 June for both thresholds and in the two regions. One explanation for this drop could be the cold spell, which is frequently observed in the middle of June in Central Europe (in German: "Schafskälte"), and which may reduce thunderstorm activity.

Our results are roughly consistent with previous studies considering convective gusts in Germany: in particular, the growth
15 after April due to increasing temperature and decreasing stability, the highest activity in the two months of June and July, and the subsequent decrease at the end of the summer. However, Tous and Romero (2006), Dotzek and Friedrich (2009), and Gatzen (2013) observed significantly higher gust activity in August than in May. Furthermore, all three studies disagreed about whether June or July exhibits the highest number of convective gusts. Differences in our study are the data basis (European Severe Weather Database, ESWD; Tous and Romero, 2006; Dotzek and Friedrich, 2009), the determination of the data basis
20 (Gatzen, 2013), and the investigated time period.

3.2 Spatial distribution

In accordance with the thunderstorm activity (Piper and Kunz, 2017), convective gusts exceeding a lower threshold of $18\,\mathrm{m\,s^{-1}}$ occur more frequently in the southern half of Germany compared to the north (Fig. 2a). Whereas the overall number of those events at the northern stations is 40 ± 17 on average ($\pm$ standard deviation) during the 23-year period, the number is 56 ± 22
25 in the southern part.

This north-to-south gradient, however, cannot be observed in the analysis of high percentile values. The 95 % percentile values (Fig. 2b) are on average $18.9 \pm 1.3\,\mathrm{m\,s^{-1}}$ but show only **slight** variability over Germany. Furthermore, a relation between percentile values and orography, as is the case for turbulent gusts (Hofherr and Kunz, 2010; Kunz et al., 2010), cannot be established **(Fig. 3)**. Moreover, local minima or maxima seem to be the result of the stochastic nature of convection. Note that
30 the 95 % percentile represents approximately between 10 and 30 gusts per station in 23 years in North Germany and between 35 and 50 in South Germany.

Almost the same applies to the distribution of the peak values per station (Fig. 2c). Again, distinct spatial differences of maximum convective gust speeds or relationships to orography are not found. Figure 2c rather suggests that peak values exceeding $30\,\mathrm{m\,s^{-1}}$ can be expected everywhere in Germany (on average: $30.2 \pm 4.4\,\mathrm{m\,s^{-1}}$). The strongest convective gust in the past

two to three decades was $52.6 \, \text{m s}^{-1}$ (Fig. 2c blue dot) and was recorded on 29 July 2005 in Zinnwald-Georgenfeld (Saxon Switzerland-East Ore Mountains).

3.3   Return values and periods

Estimating with the POT/GPD method the occurrence probability of extreme wind gusts for return periods larger than the
5   investigation period, the choice of the threshold ζ must be performed carefully. Because each station has its own climatological background and underlying distribution function, the shape and scale parameters, k and σ, can show clear differences among all locations. Because the sample sizes of the stations are different, the use of percentile values appears to be more reasonable than implementing a fixed number of the strongest events.

Based on the mean residual life graph and parameter stability plots (both for k and σ) for each station, we identified the
10   80 % percentile as an appropriate threshold ζ, resulting in values between 12.5 and $17.0 \, \text{m s}^{-1}$ for the majority of stations (Fig. 4d). Only two stations exhibit thresholds below this range. As presented in Figures 4a–c, this range fulfills the criteria of both techniques—conditional mean exceedance and parameter stability plots—very well (see Sect. 2.5). For example, for the station of Munich-City (blue dot in Fig. 4b and c), the k and σ stability plots show almost constant behavior for slightly varying threshold values **above** the resulting value of $\zeta = 14.6 \, \text{m s}^{-1}$ (red lines in Fig. 4b and c).

15   Based on all selected 110 stations in Germany, the return values of convective gusts for return periods of 20 years (RV_{20a}) and 50 years (RV_{50a}) are on average $27.8 \pm 2.5 \, \text{m s}^{-1}$ and $30.2 \pm 3.1 \, \text{m s}^{-1}$, respectively (Fig. 5). In addition, isolated high values are estimated between 32 and $36 \, \text{m s}^{-1}$ for RV_{20a} and between 36 and $40 \, \text{m s}^{-1}$ for RV_{50a}. High return values of up to $50 \, \text{m s}^{-1}$ for RV_{50a} as estimated by Lombardo (2012) for the West Texas region (United States) cannot be estimated for Germany. Note, however, that a value above $50 \, \text{m s}^{-1}$ has already been observed (cf. Fig. 2c, **Zinnwald-Georgenfeld), but with**
20   **an extremely high estimated return period of approximately 1,000 years (see also Seregina et al., 2014, supplemental material Table 1)**. Depending on the respective probability density function (or the parameters k and σ; see Fig. 4e and f), the increase between both return values substantially differs among the stations. Although the differences between RV_{20a} and RV_{50a} are on average $2.3 \pm 0.9 \, \text{m s}^{-1}$, there are individual stations with differences between 4 and $6 \, \text{m s}^{-1}$ (e.g., Lahr; blue dot in the southwest corner of Fig. 5b). Furthermore, a comparison with Figure 2b shows that stations with similar 95 % percentile
25   values do not have to show similar return values influenced by the underlying probability density function as well. **For example, convective gusts with a one year return period (RV_{1a}) correspond—depending on the station—to its 95 % to 98 % percentiles (correlation of 0.97).**

Depending on the station and thus on the individual shape parameter k, the uncertainty due to the application of an extreme value statistic is in a range between 3 and $16 \, \text{m s}^{-1}$ with a median of $6.5 \, \text{m s}^{-1}$ for RV_{20a} and between 4 and $25 \, \text{m s}^{-1}$ with
30   a median of $9.5 \, \text{m s}^{-1}$ for RV_{50a} (not shown). Higher values of confidence bounds are primarily caused by positive k values (semi-logarithmic connection, see Eq. 4), leading to an unbounded behavior of the upper distribution function. This is due to the fact that k depends on the range of the data sample considered for the GPD calculation. Especially single maxima or individual outliers result in positive k values (not shown). As shown in Figure 4e, the maximum likelihood method estimates for 32 % of all stations positive k values.

Figure 6 summarizes the results for five return periods $(1, 10, 20, 50,$ and 100 years) in four regions of Germany. As expected, statistical uncertainty (black bars) increases with return periods, mainly caused by stations with positive k values. Furthermore, the confidence bounds are in most cases—except for one year events—higher than the regional variability (red lines). Due to the limited data availability of 23 years, the results for the 100-year events exhibit high uncertainties (on average $\sim 14\,\mathrm{m\,s^{-1}}$) and

5 should be handled with care. In summary, convective gusts above 20 $(25)\,\mathrm{m\,s^{-1}}$ are on average observed throughout Germany each (10) year(s). This result is similar to a study of Holmes (2002), who showed that the occurrence rate of downbursts exceeding $21\,\mathrm{m\,s^{-1}}$ is around one event per year at stations in the Melbourne area in Australia.

Both Figures 5 and 6 show a tendency of slightly higher mean return values for southern stations compared to those in the north. For example, RV_{20a} is on average $27.0 \pm 2.0\,\mathrm{m\,s^{-1}}$ in the north and $28.7 \pm 2.6\,\mathrm{m\,s^{-1}}$ in the south (Fig. 5a). However, the

10 differences are smaller than the variability of the stations in the respective areas or statistical uncertainty due to the application of the statistical method, respectively. In agreement with the **percentile values** or the maxima (Fig. 2 **and Fig. 3**), no specific pattern related to the terrain or climate conditions can be identified. The convective gust intensity depends primarily on characteristics detached from the surface, as the intensification forces are particularly the mid-tropospheric flow, vertical temperature gradient, cloud water content, droplet size, and rain fall velocity (Proctor, 1989; Wakimoto, 2001). Surface roughness, which

15 is essential for turbulent gusts, seems to be less important for convective gusts (Solari et al., 2015).

Comparing our results with return values for turbulent gusts as estimated by Kunz et al. (2010) and Hofherr and Kunz (2010) for winter storms in Germany, it is found that the RV_{20a} of the turbulent gusts are significantly larger (average: $7.3 \pm 3.9\,\mathrm{m\,s^{-1}}$; Fig. 7). The difference in the north (9.0 ± 3.2) is more pronounced than that in the south (5.6 ± 3.8). This difference is mainly due to the fact that the return values of turbulent gusts show a distinct north-to-south gradient over Germany caused by the

20 higher frequency of low pressure systems coming from the Atlantic Ocean in the north (Ulbrich et al., 2009; Feser et al., 2015). Thunderstorm activity in that area, on the other hand, is substantially reduced (Piper and Kunz, 2017) due to the higher stability near the North Sea and Baltic Sea (Mohr and Kunz, 2013).

Finally, in some cases, the return values of convective gusts may become larger than those of turbulent gusts for higher return periods. This effect strongly depends on the underlying distribution function (not shown). For example, for RV_{100a}, this

25 applies for 13 out of the 85 stations ($15\,\%$) considered for this comparison, which all (except one) are situated south of $52°\mathrm{N}$. These findings point out the need to distinguish between the two types of gusts for their statistics **as already mentioned by Gomes and Vickery (1978)**.

3.4 Thunderstorm or convective gust factor

Especially in the field of wind engineering for calculating structural design or wind loadings (Davenport, 1967), gust factors

30 are commonly used to estimate the relation between gusts and mean wind. This relation for turbulent gusts depends on various effects, such as the surface roughness of the surroundings, thermal stability, or wind shear, mainly affecting the turbulence characteristics of flows. In the case of convective gusts, however, gust factors, which will be estimated in the following based on the comprehensive available data set of the 110 stations in Germany, are severely affected by the averaging period of the mean wind (Lombardo et al., 2014).

The gust factor GF_t considered here represents the ratio of the maximum wind speed v_{max} to the mean wind speed $\overline{v_t}$ over an averaging time period t (Holmes, 2015; Solari et al., 2015). Usually, v_{max} is averaged over 3 s in accordance with the World Meteorological Organization (WMO, 2010):

$$\mathrm{GF}_t = \frac{v_{max}}{\overline{v_t}} \quad , \tag{5}$$

5 with time periods $t = 10$-min or 1-hr to calculate $\overline{v_t}$ and GF_t. Here, we used for $\overline{v_t}$ both MN (10-min) and KL data (1-hr). To enable a direct comparison of GF for the two averaging periods, we considered only events for which both data (MN and KL) are available. In total, 4,658 convective gusts with $\geq 18 \, \mathrm{m \, s^{-1}}$ were selected, corresponding to 88 % of cases in the KL data.

The convective gust factors, GF_{10min} and GF_{1hr}, are substantially larger than typical values of the (turbulent) gust factors (Fig. 8). Depending on the land use, surface roughness, **or atmospheric stability**, respectively, turbulent gust factors fluctuate

10 usually between 1.2 and 2.3 (Wieringa, 1986; Brasseur, 2001; Hofherr and Kunz, 2010). In particular, GF_{1hr} with an average of 2.9 ± 1.0 is well above that range (Fig. 8a blue). For GF_{1hr}, single values between 6 and 10 are even computed (1 %). In contrast, GF_{10min} shows lower values with an average of 2.1 ± 0.8 (Fig. 8a pink). A simple fit (non-parametric) demonstrates that the spread of GF_{1hr} is nearly twice that of GF_{10min}. The reason for the considerable differences between the turbulent and convective gust factors is that the latter strongly depends on the event duration or on the storm type substantially affecting

15 the mean wind.

Comparable results and values have already been observed in other studies, which, however, were not based on such a large sample as that considered in this work (e. g. Orwig and Schroeder, 2007; Holmes et al., 2008; Shu et al., 2015; Solari et al., 2015). Choi and Hidayat (2002), for example, found GF_{1hr} values between 2.2 and 6.5 for convective winds in open terrain in Singapore. They also stated that gust factors obtained close to the storm center may reach values between 7 and 8. Lombardo

20 et al. (2014) estimated with an empiric function values between 1.5 and 3 for an average period of 10-min and between 3 and 6 for hourly data. **Based on a sample of approximately 550 events, Durañona (2015) calculated GF_{10min} values between 1.2 and 4.1.**

Comparing GF_{10min} and GF_{1hr} for all single events shows significant differences between both (Fig. 8b). In 90 % of all cases, GF_{1hr} is greater than GF_{10min} (on average 1.0 ± 0.8). It is interesting to note that GF_{10min} values in 10 % of the cases

25 are larger than GF_{1hr} values. The reasons for this counterintuitive behavior are the fixed defined measurement intervals and the event duration. If a gust occurs at the end of a 10-min interval, lower wind measurement at the beginning can lead to lower 10-min mean wind speeds compared to a 1-hr mean. A calculation by a running-average method prevents this effect (Chay et al., 2008; Solari et al., 2015; Mohr et al., in prep.). This is, however, only possible when high resolved measurements are operationally archived, which is currently not the case.

30 ## 4 Discussion and conclusions

This study has examined the statistical characteristics of convective gusts in terms of non-tornadic, straight-line winds in Germany with a focus on their temporal and spatial distribution, including their intensities and occurrence probabilities. The

data basis was the wind measurements of 110 climate stations of the German Weather Service (DWD) between 1992 and 2014 in the summer half-year. First, we generated a convective gust event set by filtering all wind measurements with lightning and daily pressure gradient data to ensure the conjunction with downbursts, gust fronts, or cold pools of thunderstorm events and to exclude a connection to low pressure systems and related cold fronts. Afterward, we investigated monthly and spatial distributions of past events exceeding a lower threshold of $18\,\mathrm{m\,s^{-1}}$, which corresponds approximately to the $95\,\%$ percentile of the filtered wind data set. By applying peaks over threshold (POT) in conjunction with the generalized Pareto distribution (GPD), we estimated the probabilities of extreme events for different return periods and compared the results with those for turbulent gusts. Finally, convective gust factors (based on both 10-min and hourly mean wind speeds) were calculated based on a long-term event set.

The following major points and conclusions can be inferred from the results obtained:

1. Most of the convective wind gusts occurred during the warmest months June and July in accordance with other phenomena associated with thunderstorms. However, the monthly distributions of northern and southern stations show some discrepancies, such as the occurrence of maxima.

2. The frequency of convective gusts is higher in South Germany compared to the north. However, the intensity or probability distribution in terms of percentiles, maximum values, or return values show neither a large-scale gradient related to the climate conditions nor local-scale variability related to orography. Quite the reverse: High wind speeds above $30\,\mathrm{m\,s^{-1}}$ can be expected everywhere in Germany with a similar occurrence probability.

3. A comparison of the 20-year return values of convective gusts with those of turbulent gusts demonstrates that the latter have higher **return values**. This might be explained by the fact that more stations are affected during winter storms compared to thunderstorm events, resulting in an increased representativity. For higher return periods, this effect, however, can be reversed at some stations. Furthermore, the difference between both gust types is more pronounced in the north, where deep depressions coming from the Atlantic play a more major role than thunderstorm activity does.

4. Quantified from the comprehensive convective gust event set, the convective gust factors (GF) show on average values of 2.1 ± 0.8 (10-min mean wind) or 2.9 ± 1.0 (hourly mean wind), which are well above the range of turbulent gust factors. Furthermore, single values between 6 and 10 were even observed. The broad range demonstrates the large temporal variability of convective storms. Besides the dependency of the mean wind by the averaging time period, the values strongly depend on the event duration or storm type. **As already noted by Durañona (2015), the convective gust factor may be a good additional indicator to separate strong wind gust caused by severe thunderstorms from a mixed wind climate.**

A potential weakness of our paper is the representation of the comparatively low number of stations. This weakness cannot, however, be overcome, but growth would continue in the future, when the ongoing reduction of observation stations is maintained.

Important to keep in mind is the fact that, due to thunderstorms characteristics, current monitoring systems tend to underestimate the intensity (and also the likelihood) of convective events (see also Trapp et al., 2006). This leads to an underestimation of the hazard and damage potential of those events, which may have important consequences for the wind load standards of buildings and structures. These have to be be revised accordingly by considering the characteristics of convective gusts.

5   **Concerning extreme value statistics, the use of POT/GPD method is discussed controversially in the literature. Whereas the use is widely supported by some authors (e. g., Hosking and Wallis, 1987; Simiu and Heckert, 1996; Palutikof et al., 1999; Holmes and Moriarty, 1999; Simiu, 2007), Harris (2005) demonstrated that this method has grave defects and thus is unreliable. Therefore, over recent years new methods have been developed to overcome this problematic, which are based, for instance, on long-term Monte Carlo simulations (Torrielli et al., 2013) or on the Penultimate**

10   **distribution (Cook and Harris, 2004, 2008). These approaches for several cases may help to improve the statistics and to reduce underlying uncertainty.**

5   Data availability

The hourly climate data (KL network) are freely available from the Climate Data Center (CDC) of the German Weather Service (DWD) via ftp (ftp://ftp-cdc.dwd.de/pub/CDC). The 10-minute data (MN network) are not freely available, but can be

15   requested from the DWD. The lightning data can be requested from the lightning information service BLitz InformationDienst Siemens (BLIDS; http://blids.de).

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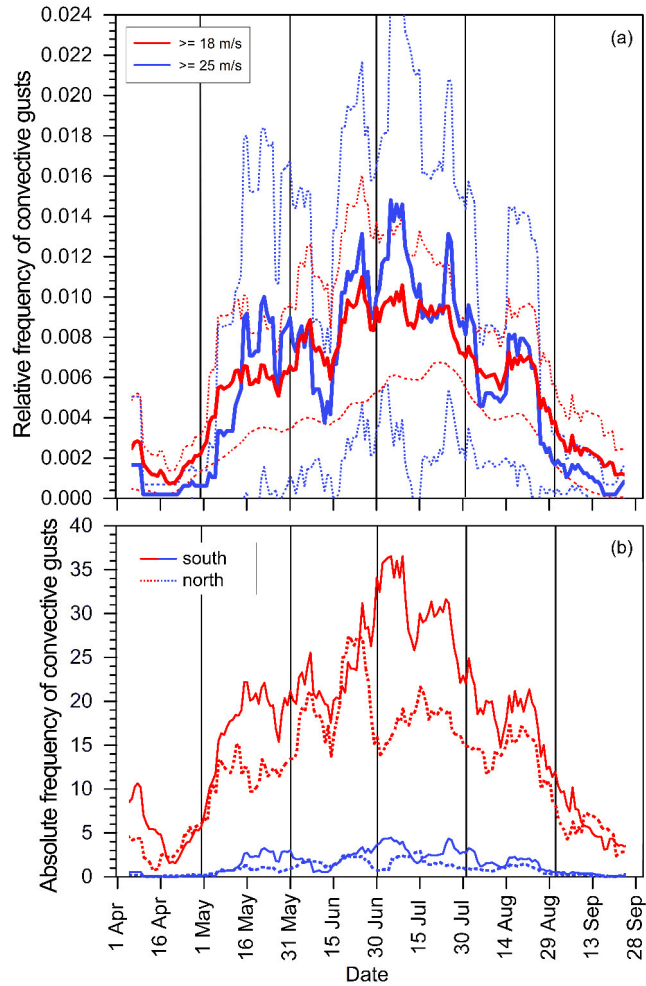
Figure 1. Mean seasonal distribution (running 11-day) of (a) relative **(incl. 95 % confidence intervals; dashed)** and (b) absolute frequency of convective gusts exceeding a threshold of $18\,\mathrm{m\,s^{-1}}$ (red) and $25\,\mathrm{m\,s^{-1}}$ (blue) considering (a) all stations in Germany, (b) stations north (dashed) and south (solid) of $51°\mathrm{N}$ (1992 – 2014).

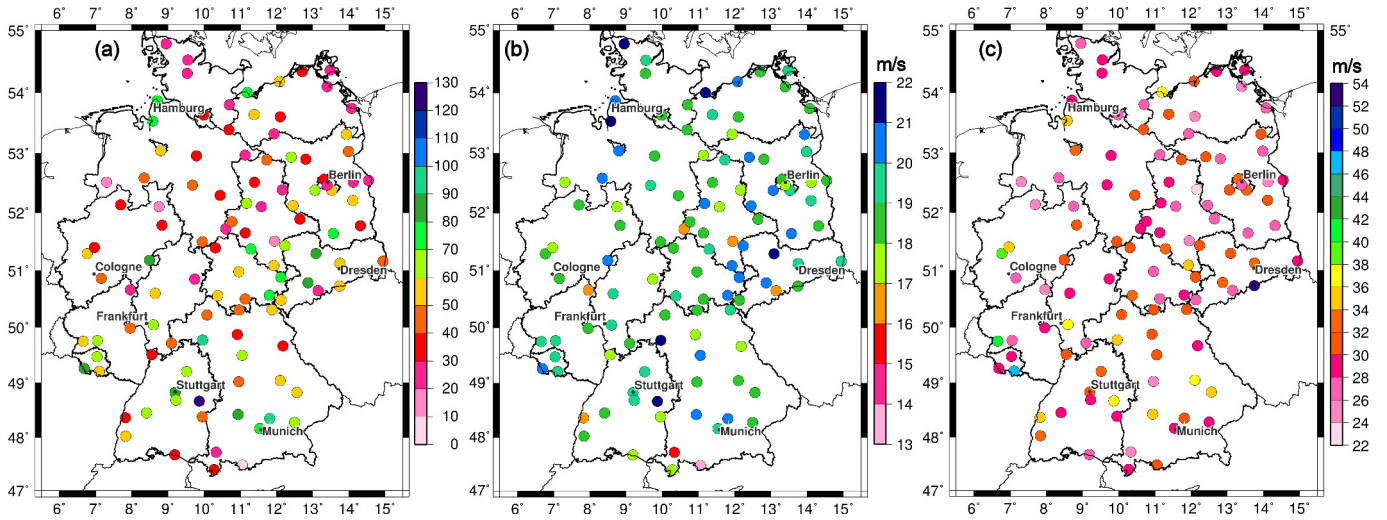**Figure 2.** Spatial distribution of (a) the number of convective gusts exceeding a threshold of $18\,\mathrm{m\,s^{-1}}$, (b) the 95 % percentile of the convective gust sample, and (c) the maximum convective gust (1992 – 2014).
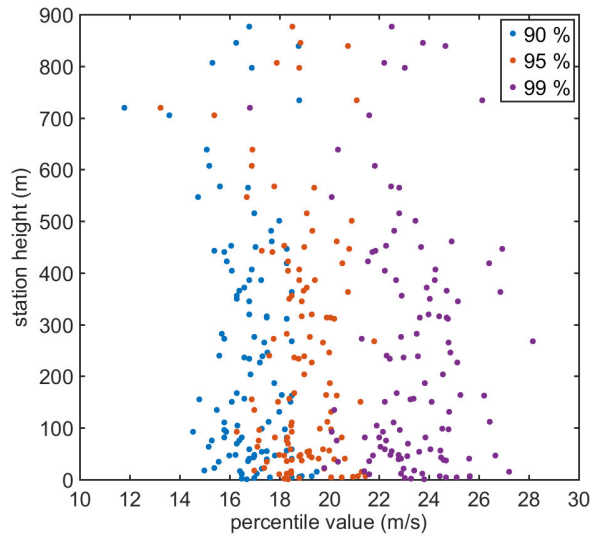
Figure 3. Scatterplot between different percentile values (90 % in blue, 95 % in red, 99 % in purple) of the convective gust sample and the respective station height.
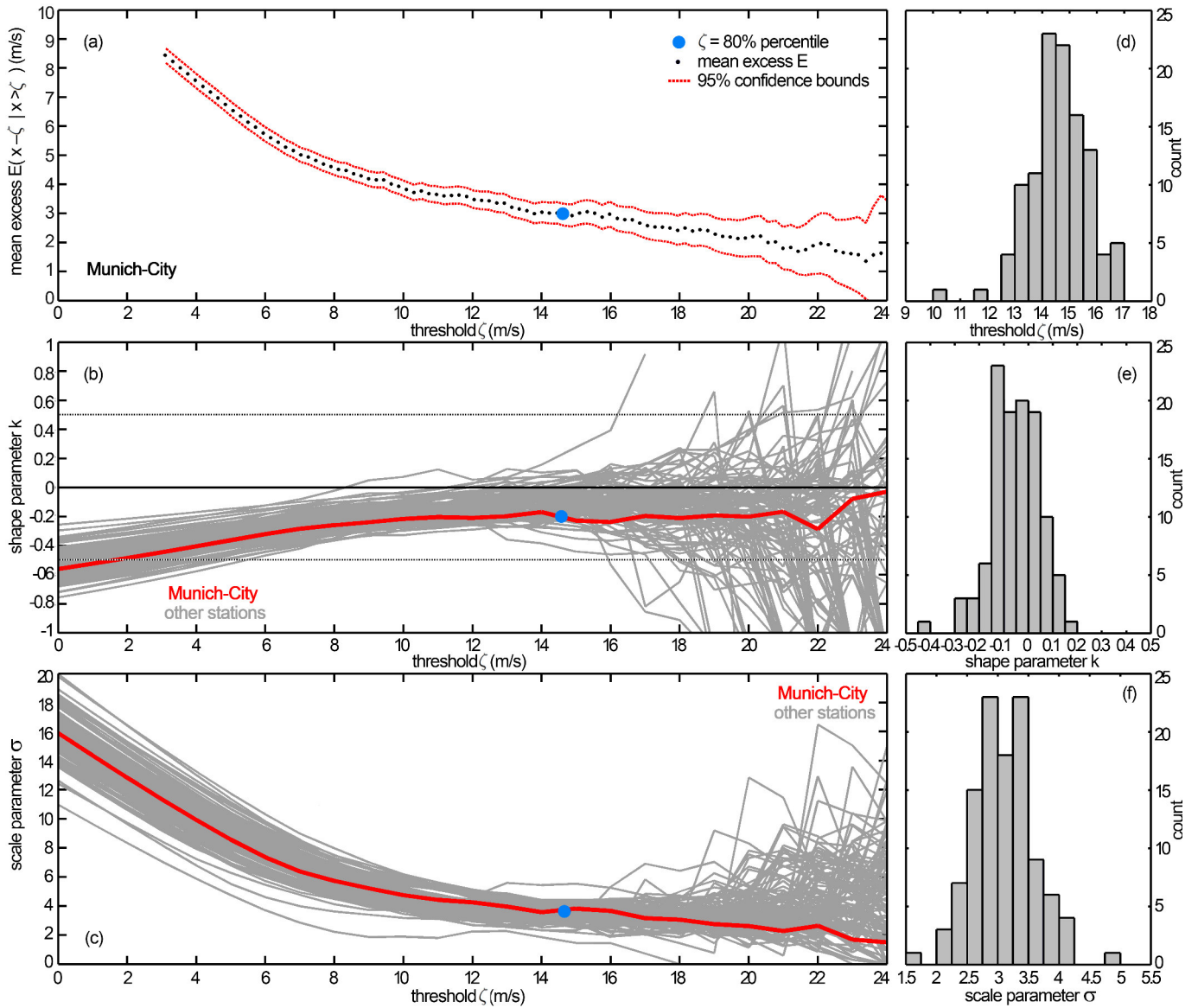
Figure 4. (a) Mean residual life plot exemplary for the station Munich-City with the 80 % percentile threshold (blue dot). (b) Stability plot of the shape parameter k for all 110 stations (gray) and exemplary for Munich-City (red), and (c) as (b) for the scale parameter σ. Depending on the 80 % percentile of all 110 stations, the resulting histogram of (d) threshold ζ, (e) shape parameter k, and (f) scale parameter σ for the GPD.
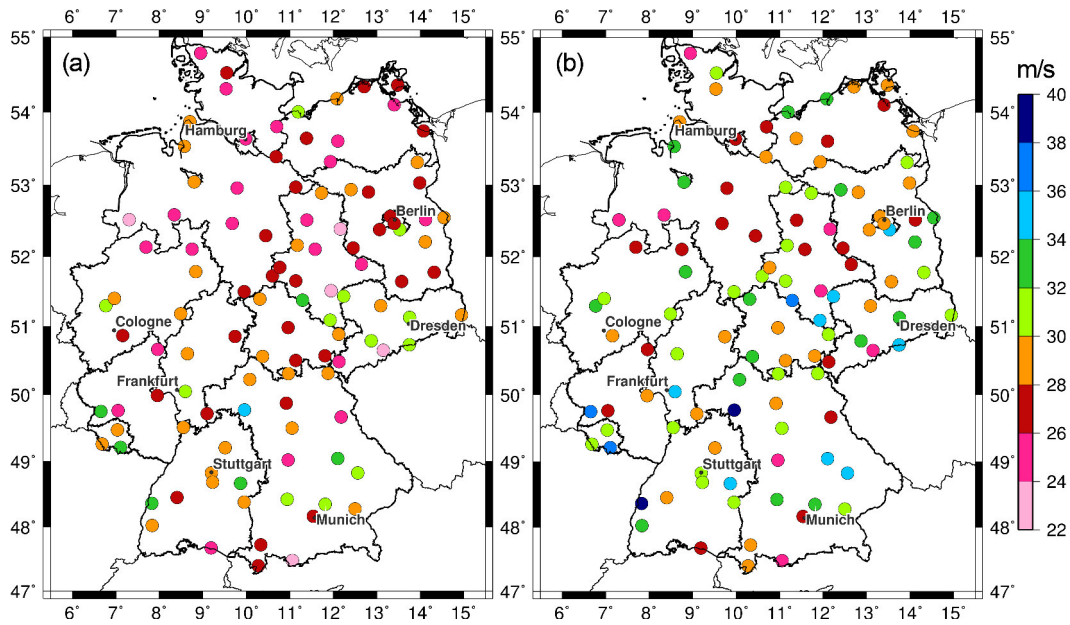
Figure 5. Spatial distribution of a convective gust for a return period of (a) 20 years (RV_{20a}) and 50 year (RV_{50a}).
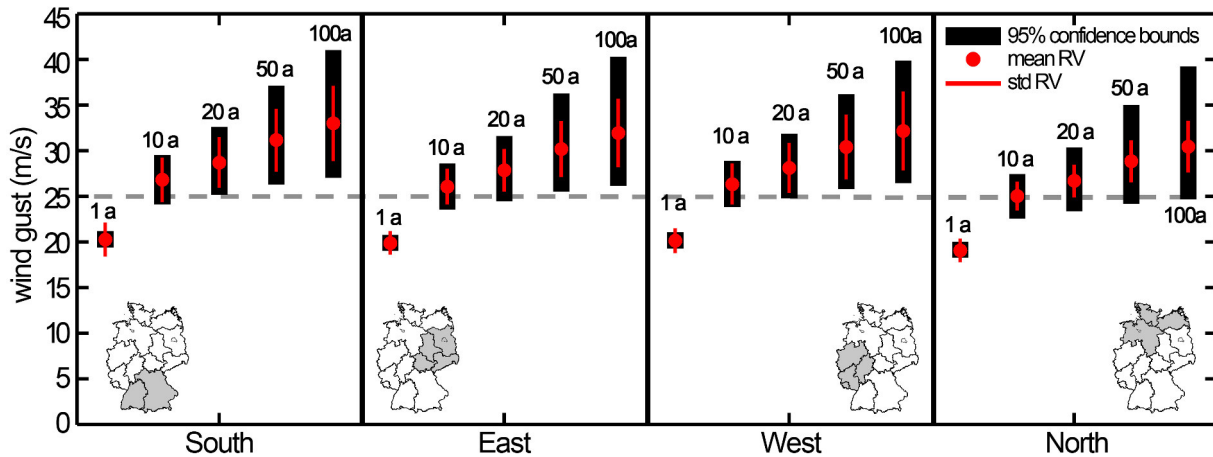

Figure 6. Mean return values of convective gusts (RV) for various return periods in four regions in Germany (gray area). Red lines indicate the standard deviation from all stations within **the respective region**, and black bars indicate the mean 95 % confidence intervals **representing statistical uncertainties of the POT/GPD method**.
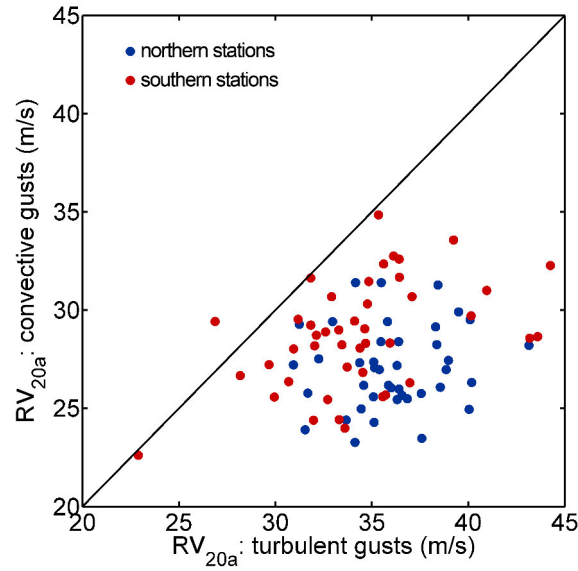
Figure 7. Scatterplot between the return value of a convective and turbulent gust for a return period of 20 years split into northern (blue) and southern stations (red).
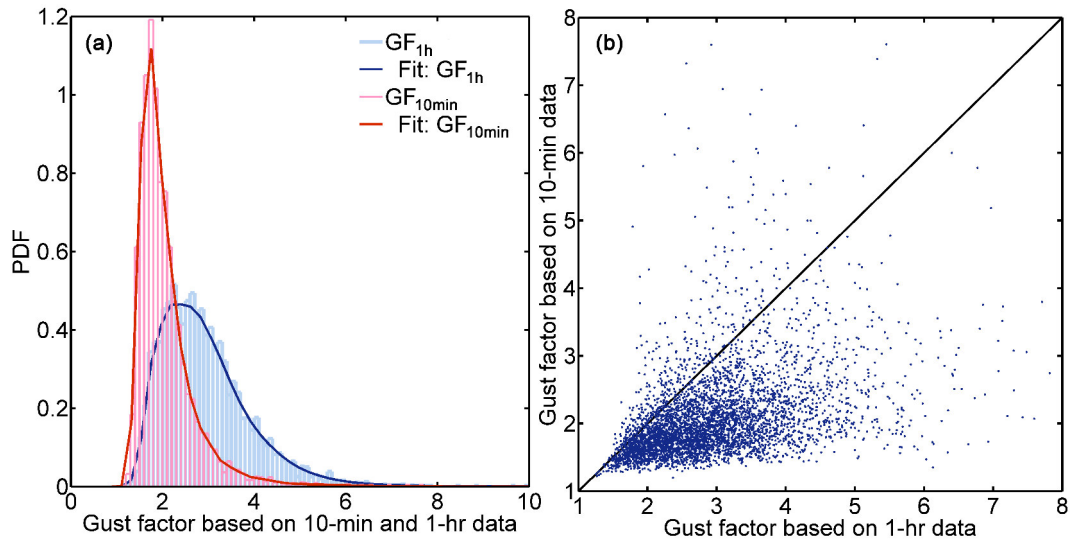

Figure 8. (a) Probability density function of convective gust factors based on both 1-hr measurements (GF_{1hr}; KL data) and on 10-min measurements (GF_{10min}; MN data), including a non-parametric fit. (b) Scatterplot between GF based on both MN and KL data.