Critical weather situations for renewable energies — Part A: Cyclone detection for wind power

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A B S T R A C T

A constantly increasing share of weather dependent renewable energies in Germany’s power mix poses new challenges concerning grid management and security of energy supply. An evaluation of the three year period from 2012 to 2014 reveals, that 60% of days with largest errors in the day-ahead wind power forecasts for Germany are linked to cyclones and troughs traversing the North Sea, the Baltic Sea or Germany. A cyclone detection algorithm has been developed to automatically indicate these critical weather situations. The algorithm is based on Numerical Weather Prediction model forecasts of mean sea level pressure. The cyclone detection is used to design an automated weather information tool for end-users such as Transmission System Operators (TSOs). For 2014, it identified a critical weather development in 38% of all days. The root mean square error of day-ahead wind power forecasts increased by 1% of installed capacity during these periods. A real time application of the tool is being implemented in order to support a sustainable and save integration of the increasing wind power production. It will then be provided to, and will be tested by, three German TSOs with the purpose of an operative usage to guarantee the security of supply.

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1. Introduction

The share of renewable energies in the German power mix is constantly increasing. In 2015, 35% of the country's net electricity production was provided by solar-, wind-, hydro-power and biomass, whereof the largest contribution was due to wind power with 15.1% [1]. The total installed net capacity of wind power is 43.7 GW and during favorable weather conditions it supplies more than half of the country's total energy production [2]. By nature, wind energy is strongly variable and highly weather-dependent. For an accurate detection of these strong fluctuations, transmission system operators (TSOs) need precise wind power forecasts to guarantee system stability. These, in turn, depend also on the quality of the underlying Numerical Weather Prediction (NWP) models. Weather and power forecasts are, however, afflicted with forecast errors. Certain weather situations are particularly hard to forecast and thus are challenging for TSOs.

In the mid-latitudes, day to day weather is fundamentally influenced by extra-tropical cyclones [3]. Within a cyclone, air masses circulate around a center of low air pressure and thus cyclones are also called low pressure systems or lows. On the northern hemisphere, this rotation is counter-clockwise. In the process of cyclone development, well-defined frontal systems are formed, which represent the borders between low-energy (cold) and high-energy (warm) air masses. These fronts are attached to the cyclone and especially to its movement. The presence of intense low pressure systems not only causes rather unstable, wet and windy weather conditions but also amplifies the wind power production. The associated frontal systems can cause fast changes in wind speed as well as in wind direction and may lead to critical, sharp ramps in the wind power production. Fronts with strong wind speeds in Northern Germany are even regarded as critical events concerning the net stability [4]. Large amounts of wind energy are then produced in the North of the country and need to

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be transported towards the South. Such a scenario, especially in combination with low temperatures and consequently a high energy demand, stresses the power grid and poses a challenge to the TSOs. This paper addresses day-ahead wind power forecast errors, identifies cyclones and fronts as problematic weather situations and presents an automated tool to recognize such challenging weather elements.

As low pressure systems strongly govern our weather conditions, the ability of atmospheric models to predict cyclones is intensively studied by meteorologists and climatologists. A comprehensive overview of previous extra-tropical cyclone predictability studies focusing on short to medium-range forecasts is given by Ref. [5]. Nine global ensemble prediction systems (EPS) and their ability to forecast cyclones for a 6-month period was investigated in Ref. [6]. EPS produce multiple weather forecasts, which represent a sample of possible future atmospheric states. In accordance with previous findings [7] it is shown that global deterministic models forecast the position of a cyclone with a higher accuracy than the cyclone intensity. EPS instead can add valuable information to the latter, as they show a higher skill in forecasting the strength of a cyclone. In most of the 14 reviewed global forecast systems cyclones also tend to propagate too slowly. With respect to seasonal forecasts, Ref. [8] investigated wintertime extra-tropical cyclones using the European Centre for Medium-Range Weather Forecast (ECMWF) model and concluded that higher model resolution leads to better simulation of extra-tropical cyclones. Furthermore, there is strong interest on past and future changes in cyclone intensity, frequency and changes in cyclone tracks. The latter have also a special implication on future wind resource assessments as they introduce substantial uncertainty (see Ref. [9]). Ref. [10] gives a review of mid-latitude cyclone climatologies with focus on the present climate and possible changes in the future. In Europe, special interest lies on cyclone tracks over the Mediterranean (e.g. Refs. [11,12]). Their future changes as simulated by regional climate models is addressed, e.g., in Refs. [13,14].

All the above mentioned studies rely on automated cyclone identification and tracking algorithms in order to be able to produce statistics over many cyclone cases. Depending on the intended application, many different cyclone detection and tracking methods have been developed. Most of them follow a Lagrangian point of view, which means that they identify a cyclone as a cyclonic (counter-clockwise) atmospheric circulation around a low pressure center and follow the cyclone as it moves through space and time. Commonly used for the identification of cyclones is the mean sea level pressure (MSLP) field, which represents the atmospheric pressure at sea level. In meteorology, it is also conventional to analyze the (geopotential) height of different vertical levels with constant air pressure. Within both representations of the atmospheric state, cyclones can be identified as local minima, as implemented e.g. in Ref. [15] for the MSLP field or in Ref. [16] or [17] for the 1000 hPa or 700 hPa field, respectively. Instead of looking for local minima, some cyclone detection algorithms compute the Laplacian of the MSLP field. Therein, cyclones coincide with local maxima, as used, e.g., in Refs. [18,19]. Low pressure systems are also marked by high values of relative vorticity, which is a measure for the rotation in a fluid. The 850 hPa relative vorticity field is used e.g. in Ref. [20] to identify cyclones. Other concepts include the analysis of wind fields (e.g. Refs. [21,22]). Ref. [23] even use a variety of meteorological fields at multiple levels as input for the cyclone detection and tracking algorithm from Ref. [24] and combine the information to investigate northern hemisphere winter storm tracks. Ref. [25] also use a hybrid of local minima in the 1000 hPa field and maxima in the vorticity field. Furthermore, their objective identification method comprises the complete life-cycle of cyclonic features, including fronts. An extensive overview of the many different cyclone detection algorithms is given, for example, in Refs. [26,10] or [27]. The latter publication summarizes results of the project Intercomparison of Mid Latitude Storm Diagnostics (IMLAST). Therein, 15 detection and tracking algorithms for extratropical cyclones have been applied to the same reanalysis data-set and their results are compared in order to assess the method related uncertainty. The cyclone detection algorithms greatly differ in the way they preprocess data. Depending on the resolution of the input fields, an interpolation or a smoothing and up-scaling step may be applied. Furthermore, various threshold settings may be chosen appropriately. Amongst others, Ref. [27] point out, that even though all approaches share a common physical understanding of cyclones, they differ greatly in its implementation and thus all have their individual strengths and weaknesses. Depending on the intended application, a cyclone detection or tracking algorithm has to be chosen and tuned carefully.

In the following, an automated tool is presented that gives an a priori-indication of weather situations which are shown to be critical for German TSOs. Therefore, a cyclone detection algorithm is developed on the basis of the valuable experiences and results of all the aforesaid studies. The developed algorithm is based on day-ahead forecasts of the NWP-model COSMO-EU [28] from the German Weather Service (DWD) and it is optimized and carefully tuned for the needs of German TSOs. Thus, the focus of the cyclone detection lies on Northern Europe and concentrates on scales which influence the Germany-wide wind energy production and prediction. By evaluating the location and movement of identified cyclones and troughs, critical weather situations are identified and an automated warning is produced. Until now, no such product is available to the German TSOs.

In section 2, the paper gives an overview of the wind power capacity in Germany and the German TSOs. Also introduced is the used wind power forecast and production data. In section 3, day ahead wind power forecast errors for 2012–2014 are evaluated in more detail and their connection to the underlying weather situation is investigated. The method of the developed cyclone detection algorithm is explained in section 4. The results are summarized in section 5, in which also the performance of a derived, automated weather information tool is presented. The conclusions of the paper can be found in section 6.

2. Wind power data

The presented work focuses on wind energy production in Germany and the corresponding day-ahead forecast errors. The installed wind energy in Germany is unequally distributed, with most wind power installed in the northern lowlands. Fig. 1(a) shows the spatial distribution of installed onshore wind energy in 2014 (from Ref. [29], therein Figure 12) and in Fig. 1(b) the control areas of the four German TSOs: Amprion, TransnetBW, TenneT and 50 Hertz are depicted. In the area of TransnetBW, the least amount of wind energy production capacity is installed. The TSO’s focus lies on balancing demand and supply as accurately as possible. All arising discrepancies need to be compensated. In order to compute day-ahead wind power forecast errors, the so-called Meta-forecasts (best possible forecast of the four German TSOs) are used. These forecasts provide the basis for the day-ahead processes (system operation and marketing) and are published on the TSO’s web pages ([30–33]) together with an estimation of the actual power production. The power forecast and production values have a temporal resolution of 15 min and are the basis for all further investigations. The time period between 2012 and 2014 is considered.
3. Evaluation of large wind power forecast errors

Within the project cooperation EWeLiNE (http://www.projekt-eweline.de/en/index.html), the TSOs Amprion, TenneT and 50 Hertz are reporting large, crucial day-ahead power forecast errors to the German Weather Service, where an evaluation of the underlying weather situation is made. One of these reports concerned the 09-08-2014 which is presented in some detail. It is followed by the extraction and the analysis of the 100 days with the largest wind power forecast errors in 2012–2014 and an evaluation of the underlying weather situations.

3.1. Case study for the 09-08-2014

Due to the severity of the forecast error, this case is presented in further detail. The relationship between NWP forecasts and the resulting power forecast error for Germany is demonstrated. The case was also chosen, because during this day, a low pressure system was located in the North Sea. As will be shown in section 3.3, these situations are frequently connected with large wind power forecast errors. Thus, it will be used as reference case for explaining the cyclone detection algorithm (section 4) and its automated application (section 5.3).

In Fig. 2(a) the day-ahead wind power forecast errors for Germany on the 09-08-2014 are shown and in Fig. 2(b) the errors are divided into the four control areas of the German TSOs. The largest day-ahead forecast errors can be found within the control areas of 50 Hertz and TenneT. In the region of TransnetBW, the smallest absolute errors are observed, as only little wind energy production capacity is installed within this area (cf. Fig. 1(a)). The peak of errors reaches 7802 MW at 12:30 CET, on the daily average the wind energy production was underestimated by 3191 MW. For the whole day, the accumulated absolute forecast error yields 331 GW, which is 35% of the total production on that day. The increase of forecast error, its maximum around noon and the decrease in the afternoon is connected to the approach, the deepening and the departure of a cyclone in the North Sea.

The weather situation over West and Central Europe is dominated by an upper air trough with its low pressure center in the South of Iceland. A short-wave trough aloft is steered around the central low and reaches Germany in the morning. A corresponding secondary surface low moves from the English Channel towards the North of the North Sea. During the day, it deepens rapidly and reaches a pressure minima of 985 hPa in the afternoon. A frontal system is embedded in a surface trough, which extends from the center of the secondary cyclone in the North Sea over Denmark to North-Eastern Germany. The location of such fronts is depending on the shape and location of the associated low pressure system. Errors in its forecast can lead not only to amplitude but also to phase errors in wind power forecasts. Generally, mesoscale phenomena such as secondary cyclones and fronts are intrinsically less predictable by NWP models [35].

As an example for an NWP forecast of the weather situation during the case study, the analysis and the +36 h forecast of the mean sea level pressure field from the weather prediction model COSMO-EU are visualized in Fig. 3(a) and (b), respectively. Forecast errors in comparison to the analysis are marked by red and blue shading. Both target 12.00 UTC on 09-08-2014. The local area model COSMO-EU slightly underestimates the strength of the low pressure system in comparison to the COSMO-EU analysis by 2.7 hPa. More severe is the influence of the differing location and shape of the surface low in the NWP forecast. As a consequence, the pressure gradient and the corresponding wind speeds over Northern Germany are forecasted too low by the COSMO-EU model. Furthermore, the associated trough and the frontal system propagate too slowly in the model.

Note, that for computing wind power forecasts, as displayed in Fig. 2, the results of different NWP models are combined with different power prediction models and different post-processing methods. The assumption is made, that most of the underlying NWP models had problems to forecast the low pressure system in the North Sea in this case study and that this problem transferred into the power forecasts. The evaluation of different case studies reported by the TSOs revealed that serious wind power forecast errors may be linked to specific weather situations, that are hard to forecast by the NWP models. Thus, in the following, the connection between large day-ahead wind power forecast errors and distinct weather situations is evaluated.
3.2. 100 days with the largest errors

The 100 days with the largest day-ahead wind power forecast errors are extracted from 2012 until 2014. To ensure temporal comparability, the power forecasts and production values are normalized by the installed capacity for all further evaluations. From 2012 to 2014, the installed wind power capacity increased from 28336 MW to 35876 MW. The temporal evolution of the monthly mean absolute day-ahead wind power forecast error (MAE) for Germany is shown in Fig. 4. A seasonal dependency with larger or more frequent power forecast errors in colder months can be observed. To extract days with large errors, the summed, absolute errors from 28336 MW to 35876 MW. The temporal evolution of the

3.3. Underlying weather situations

In order to confirm and specify the assumption, that large power forecast errors are connected with certain weather situations, the days with largest errors are analyzed from a meteorological point of view. Therefore, a subjective, meteorological inspection for the independent 88 dates with the large wind power forecast errors is conducted. The focus lies on the synoptic scale, which includes high and low pressure systems and their associated frontal zones [36]. These atmospheric systems are of interest, as they significantly govern the weather situations in Central Europe [37]. The relative location of lows with respect to Germany turned out to be of importance. The subjective evaluation yields seven categories, which are visualized in Fig. 5. The dark blue and green category summarize cases, where a larger scale cyclone with pressure center in the vicinity of Iceland, over Scandinavia or Great Britain could be identified. In 22.7% of days with large errors (light blue), Northern Germany was influenced by a trough, which often coincided with a front. If 37.5% of all cases, a low pressure system in the North Sea, the Baltic Sea, or over Germany was identified (red, orange, yellow, respectively). The category Others comprises, for example, days with large convective activity or cases, where higher upper-air wind speeds were mixed downwards and the NWP models did not predict the strong mixing. Note, that for the

![Fig. 3. Analysis and forecast of mean sea level pressure field (MSLP) of the NWP model COSMO-EU for the 09-08-2014, 12:00 UTC. The white contour line indicates the 1010 hPa line. In a), the analysis for the target time is visualized and b) shows the -36 h forecast as well as the differences of both in color shading.](image_url)

![Fig. 4. Wind power forecast error for the years 2012–2014. Temporal evolution of the monthly mean absolute day-ahead wind power forecast error (MAE) for Germany in percent of installed capacity (% of inst. cap.).](image_url)

![Table 1](image_url)
4. Methodology of the automated cyclone detection

An automated algorithm is designed to detect the discussed critical weather elements (low pressure systems and associated troughs) from NWP-model forecasts, which are available even days in advance. To explain the cyclone detection algorithm, the case-study for the 09-08-2014 large wind day-ahead forecast error will be used, which was previously presented in section 3.1.

Forecasts from the European local area NWP model COSMO-EU from DWD are used for the development of the cyclone detection algorithm. These forecasts and analyses cover the Eastern Atlantic and Europe (see e.g. Fig. 3). The cyclone recognition is solely based on the mean sea level pressure field. The different subtasks to identify a cyclone are iteratively explained in the following.

4.1. Smoothing

The non-hydrostatic NWP model COSMO-EU has a horizontal resolution of approximately 7 km. Thus, many small scale signals are present in the MSLP field (see Fig. 6(a)). In a first step, these small scale signals are smoothed. For each grid-point \( p_{i,j} \) with \( i \) and \( j \) denoting the latitude and longitude direction, the nine point local smoothing algorithm

\[
p_{i,j} = p_{i,j} + \left( \frac{q_1}{4} \right) \left[ p_{i-1,j+1} + p_{i-1,j} + p_{i,j+1} + p_{i+1,j} - 4p_{i,j} \right] + \left( \frac{q_2}{4} \right) \left[ p_{i-1,j-1} + p_{i-1,j} + p_{i+1,j+1} + p_{i+1,j} - 4p_{i,j} \right]
\]

is used. Herein, the parameters \( q_1 \) and \( q_2 \) control the degree of smoothing and are set to \( q_1 = 0.5 \) and \( q_2 = 0.25 \). The algorithm is applied several times to the MSLP field till a desired degree of smoothing is reached (see Fig. 6(b)). In comparison to Gaussian smoothing similar results are obtained. However, the local method showed the advantage that troughs with a smaller horizontal extend were better retained and is the method of choice hereafter.

4.2. Upscaling

Extra-tropical cyclones span horizontal scales from several hundreds to a few thousand kilometers. This study aims to identify lows in the upper meso-\( \alpha \) and the lower macro-\( \beta \) scale as classified by Ref. [38] (meso-\( \alpha \): ca. 200–2,000 km, macro-\( \beta \): ca. 2,000–10,000 km). Thus, the horizontal resolution of the MSLP field is upsampled to a grid spacing of approximately 140 km, which means that only every 20th grid point is considered. This reduces computation time and serves as a filter concerning the scales in question. The resulting grid is illustrated in Fig. 6(c).

4.3. Computation of vorticity

Instead of searching the MSLP field for local minima, cyclones are identified according to their vorticity, which is a measure for the rotation in a fluid. This has the advantage, that not only closed depressions are recognized but also open lows or intensive troughs can be detected, which often coincide with strong cold fronts. The quasi-geostrophic model (see e.g. Ref. [39]) is a simplified but representative description of larger, synoptic-scale motions. Following this model, the geostrophic relative vorticity \( \zeta_g \) can be expressed in \( z \)-coordinates as follows

\[
\zeta_g = \frac{1}{f} \mathbf{\nabla}^2 p.
\]

Therein, \( f \) is the Coriolis parameter, \( \rho \) is the air density and \( p \) is the pressure at a constant height-level. Thus, the Laplacian of the MSLP field is computed to serve as a proxy for the geostrophic relative vorticity [18]. Variations in air density and the Coriolis parameter are neglected as the focus is not on absolute values but on exceeding a subjective threshold (see following paragraph). The resulting field of \( \mathbf{\nabla}^2 p \) values, which can also be interpreted as the curvature of the MSLP field, is depicted in Fig. 6(d). By convention, positive vorticity values mark counter-clockwise (cyclonic) rotation. The two cyclone centers in the North Sea and South of Iceland are thus marked by large positive \( \mathbf{\nabla}^2 p \) values.

4.4. Object recognition

Grid points exceeding the subjectively chosen curvature threshold of \( \mathbf{\nabla}^2 p = 9 \text{ hPa m}^{-2} \) are assigned to be part of a low pressure system. All neighboring grid points exceeding this threshold are combined to one object. This allows for the recognition of separate cyclones or multiple cyclone centers. Within every object, the location of the pressure minimum in the original fine scale grid is defined to be the cyclone center. Fig. 6(e) visualizes the two separate cyclonic objects which had been recognized in the case study.

4.5. Spatiotemporal cyclone movement

Herein, a detected cyclone is constrained to last for at least 3 h. Within that time span, a cyclone is allowed to move across a maximal distance (here: one upsampled grid point, yielding in a radius of approximately 140 km).

The successive application of the described steps constitutes the cyclone detection algorithm. Fig. 6(f) summarizes the result of this process. It shows the slightly smoothed, forecasted MSLP field (isolines) for 09-08-2014 12:00 UTC, where the white line marks the 1010 hPa line. Additionally, areas of high positive relative vorticity are indicated by yellow to red shading. The cyclone detection algorithm identified the two cyclones in the Northwest and determined their centers which are marked by black dots. The Scandinavian Mountains are approached by a southerly flow, which in turn is modified by the mountain range. A positive pressure disturbance is formed upstream of the mountains and in the lee
An area of lower air pressure establishes. This so-called lee effect ([40,41]) is visible in the MSLP field by means of a stationary lee trough [36]. The cyclone detection algorithm highlights this trough in the Northwest of the Scandinavian Mountains as well. Note, that the cyclone north of the Black Sea at the eastward boundary of the domain was not identified. The effective area for cyclone recognition (c.f. Fig. 6(d)) is a little bit smaller than the presented COSMO-EU domain due to the numerical discretization of the Laplace-operator.

Overall, the cyclone detection algorithm is able to identify the centers of synoptic scale low pressure systems and furthermore, can highlight areas of high cyclonic vorticity.

5. Results and discussion

In the following, the performance of the cyclone detection algorithm is evaluated to confirm its applicability. Thereafter, the algorithm is used to objectively analyze the weather situations during the extracted 100 days with large wind power forecast errors. Finally, by use of the cyclone detection algorithm, an automated tool for end-users is developed, which can issue warnings if a critical weather situation is recognized. The tool is applied for 2014 and the day-ahead wind power forecast errors during the issued weather warnings are evaluated.

5.1. Performance of the cyclone detection algorithm

In order to investigate the performance of the cyclone detection algorithm, it is applied to a dataset comprising 5 years of COSMO-EU analyses (2010–2014). Within this period, the detection algorithm is applied to the 00 and 12 UTC analyses. Note, that the above mentioned spatiotemporal constraints concerning the cyclone movement are not applied due to the coarse temporal resolution of the available data. The COSMO-EU analyses have a horizontal resolution of approximately 7 km. Following the approach as in Ref. [15], a cyclone frequency is computed. Therefore, the number of occurrences is counted when the curvature of a grid point on the coarse grid exceeds the set threshold of 6 hPa m$^{-2}$. The resulting field is subsequently averaged over the considered time period and referred to as cyclone frequency $f_c$. The results are depicted in Fig. 7, where intra-annual variations are presented in some detail. The following observations concerning $f_c$ are made:

- The general cyclone frequency is higher in the colder months October to March. In this period, the mean $f_c$ averaged over the whole analysis area is 1.84 times higher than for the warmer months.
- Two distinct areas with high cyclonic activity can be identified. These are the Northwest of the considered domain (South of Iceland and the Norwegian Sea) and the Mediterranean region.
- The observed intra-annual variability in the Northwest of the domain is coherent with the seasonal evolution of the Atlantic storm tracks. In winter, they range from the North American East Coast to the Barents Sea, in summer they are generally weaker [15].

![Fig. 6. The cyclone detection process is explained with the help of a case study. All sub-figures are based on the +36 h COSMO-EU forecast of mean sea level pressure (MSLP), for 09-08-2014, 12:00 UTC. The white contour line in the MSLP fields indicates the 1010 hPa line. a) Original MSLP forecast, b) smoothed MSLP field, c) upscaled grid, d) Laplacian of upscaled MSLP, e) recognized objects, f) location of cyclone centers and areas with increased positive vorticity as final result.](image-url)
As the algorithm not only identifies closed lows but also open depressions and troughs in the MSLP field, lee effects induced by the Scandinavian Mountains stand out.

The cyclone frequency in the Mediterranean Basin is higher in the colder months, as most of the cyclones affecting this region originate from the Atlantic storm tracks (as summarized in Ref. [42]). Furthermore, the positive difference in sea and land temperatures enhances cyclone formation and intensification.

Typical cyclogenic areas in the Mediterranean can also be distinguished in Fig. 7. The most prominent is located in the area of the Gulf of Genoa. Lee effects in the South of the Alps as well as high baroclinity due to the inflow of cold air from the North stimulate the genesis or intensification of cyclones. Also the Adriatic Sea shows a pronounced cycloic activity during winter months (see Ref. [43]). Further areas with higher frequencies are to the West of Cyprus and over the Black Sea. A comprehensive overview and explanation of cyclogenesis regions in the Mediterranean Basin is given by e.g. Ref. [11].

The above listed observations confirm, that the cyclone detection algorithm is able to correctly capture areas of high cyclonic influence.

### 5.2. Cyclone frequency during large power forecast errors

The method of computing a cyclone frequency $f_c$ as described in section 5.1, is now applied to the three year time period between 2012 and 2014. Three-hourly COSMO-EU analysis data are the basis for computing $f_c$. Additionally, the cyclone frequency is exclusively evaluated for the days with the largest wind power forecast errors as listed in Table 1 and is named $f_c\text{err}$. In Fig. 8, the difference between this conditional cyclone frequency $f_c\text{err}$ and $f_c$ for the entire time period is depicted. Red shading indicates a higher cyclone intensity during the days with largest wind power forecast errors.

An increased cyclone activity can be observed in the North of Germany, the North- and Baltic Sea and particularly in the area of Denmark for the days with largest errors. These cyclones potentially influence the NWP forecast quality and subsequently the quality of power forecasts for Germany. Cyclones in the Baltic- and North Sea often induce an approaching southeasterly or southerly flow at the Scandinavian Mountains, which causes lee effects. Due to their quasi-stationary nature, these are particularly predominant when evaluating 3 hourly NWP analyses. A third area of increased cyclonic frequency is located over Scotland. Larger cyclones with their center in this region can steer smaller, secondary cyclones through the North Sea. This objective evaluation underlines the relationship between large wind power forecast errors in Germany and the occurrence of cyclones or troughs in the area of the North Sea, the Baltic Sea and Germany. Automatically identifying such synoptic weather situations helps to call the grid operator’s attention to such critical weather developments well in advance.

### 5.3. Products for end-users

For the day to day business of grid operators, or more generally for wind energy trading, a comprehensive and short representation of weather related information and especially indications of critical weather patterns is of great importance.

An automated weather information tool with focus on wind energy applications in Germany is constructed by applying the cyclone detection algorithm to the day-ahead NWP forecasts. The purpose of such a product, as shown in Fig. 9, is twofold. First, it serves as a visualization tool where valuable meteorological information is condensed to a minimum. Higher or lower wind speeds are indicated by the tightness of MSLP isobars. Areas of fast varying
winds, as induced by cyclones and troughs, are highlighted by red shading and are easy to perceive (see Fig. 9(b)). By looping over the 24 forecast hours, major weather events can be realized in a very short time, which becomes especially important in decision making processes with sharp time constraints. The second scope is to derive automated indications of challenging weather situations which were demonstrated to accompany high forecast errors. Therefore, areas of high influence are defined (red rectangles in Fig. 9). A cyclone or trough that moves through these areas is likely to influence the wind power production in Germany directly, as the trough in Fig. 9(b), or indirectly, as for example the cyclone center in the North Sea in Fig. 9(a). If a recognized cyclone center or an intensive trough is identified to pass through these predefined areas, an automated indication or warning is issued. Such a warning has to be interpreted as a low-level warning, comparable with the yellow traffic light. It points out a challenging weather situation and advises the user to consult further information about the underlying forecast uncertainty in his decision process.

In the following, the application of the automated weather information tool to all day-ahead forecasts of the NWP model COSMO-EU (00:00 UTC model runs) in 2014 is evaluated. Warnings are computed for every forecast hour, but for the following evaluation, the warnings are considered on a daily basis. Days with special weather developments are defined if a cyclone center remains for at least 6 h in predefined areas of high influence (red rectangles in Fig. 9), or if curvature values exceed the subjective threshold of 6 hPa m−2 in more than one quarter of these areas. The second criterion allows to also consider troughs that are passing through.

In 38% of all days, a critical weather development was identified. Fig. 10 illustrates the result for the months September to November. Periods with identified significant low pressure influence (red marks) alternate with periods of less cyclonic activity (green marks).

In Fig. 11, the frequency distribution of all day-ahead wind power forecast errors in 2014 is depicted. The blue curve includes all 15 min forecast errors, whereas the red curve is based solely on those days with a significant weather indication from the automated weather information tool. The green curve is based on the remaining days. The error distribution for days with significant weather influence is broader and covers all negative forecast errors larger than −11.8% of installed capacity. The distributions for hourly and 6-hourly averaged errors show a similar behavior. The mean absolute forecast error during the days with cyclonic influence is higher by 0.77% of the installed capacity than during the remaining days and the root mean square error increases by roughly 1% of the installed capacity (see Table 2). Note, that the automated weather information tool can identify cyclonic developments and their related forecast uncertainties also during days with lower wind speeds. Only 57% of days with indicated cyclonic influence coincide with the days of largest wind power production.

An automated weather information tool, such as the presented, can be implemented efficiently and can easily be adapted to the user’s needs. For example, constraints for recognizing days with special weather developments can simply be strengthened or weakened. Within the project EWeLiNE it will be supplied to three German TSOs and shall help to facilitate the incorporation of meteorological information into weather dependent processes. The information provided by the automated weather information tool is based on deterministic forecasts and follows a physical interpretation of the forecasted weather situation on a larger, synoptic scale. It can help to perceive major atmospheric motions and points out areas of high variability, e.g. in wind speed. Complementary to this qualitative representation of forecast uncertainty, the warning advises the user to consult additional information about the underlying NWP forecast uncertainty, for example as estimated by

**Table 2**

|                         | All days | “Cyclone days” | Remaining days |
|-------------------------|----------|----------------|---------------|
| MAE                     | 2.26     | 2.73           | 1.96          |
| RMSE                    | 3.09     | 3.69           | 2.65          |

Fig. 9. Visualization of two situations with potentially higher forecast uncertainty. a) For 09-08-2014 12:00 UTC, as explained in section 3.1, and b) for 27-12-2014 00:00 UTC. Red rectangles mark areas which were defined as areas with high impact on the wind energy production in Germany and yellow cyclone centers indicate cyclones with core pressure lower than 970 hPa. Red shading indicates cyclonic movement (lows or troughs), blue shading marks high pressure areas.

Fig. 10. Result of the automated weather information tool for September to November 2014 (applied to 00:00 UTC NWP model runs). Days when a significant cyclonic influence could be identified are marked in red, the other days are marked in green.

Fig. 11. Frequency distribution of day-ahead wind power forecast errors for Germany in 2014. The blue line includes all days, the red line days with a significant weather indication from the automated weather information tool and the green line the rest of the days. For computing the whiskers in the box-plots, 1.5 times the interquartile range was used. The thin line underneath each box-plot marks the range of forecast errors during all days.
Ensuring effective and comprehensive probabilistic forecasts is essential for effective grid operations. Within this paper, we analyze German grid operation requirements on wind power forecast errors and their co-occurrence with special weather situations. A connection with cyclones and troughs in the North Atlantic and the Baltic Sea was identified. Hence, a cyclone detection algorithm was introduced, which can automatically identify and indicate upcoming days with significant weather development and potentially higher wind power forecast errors to end-users such as TSOs.

The analyzed Germany-wide day-ahead wind power forecast errors for the three year period of 2012–2014 show a seasonal dependency with larger or more frequent errors during colder months and a mean absolute error of 2.31% of installed capacity. The number of independent days with large forecast errors was extracted, which show the same seasonal dependency. Subjective analysis on the synoptic scale revealed that in 60.2% of these days with large wind power forecast errors a cyclone or a trough moved over the North Sea, the Baltic Sea or directly over Germany.

An automated cyclone detection algorithm has been developed in order to recognize these challenging weather situations. The presented method uses COSMO-EU day-ahead forecast and analysis fields, but it is universally applicable to NWP model forecasts. The cyclone detection is based on long-term sea level pressure and uses the Laplacian of the MSLP field as a proxy for the quasi-geostrophic relative vorticity to indicate areas of cyclonic influence. Subjectively chosen thresholds for curvature values as well as for spatiotemporal movement complete the automated cyclone detection algorithm.

A long-term application proved the algorithm to be able to correctly recognize areas of high cyclonic influence and intra-annual variations. By computing a conditional cyclone frequency for the 88 days with largest power forecast errors, an above-average cyclone activity over Northern Germany, the North Sea, the Baltic Sea and over Denmark can be found. The cyclone detection algorithm and the gathered information is also used to design an automated weather information tool for end-users such as German TSOs. Its comprehensive and short representation of relevant weather information is essential to ensure an efficient use in complex decision processes. Furthermore, by defining areas of high influence, users can automatically be alerted to critical weather developments. An application of the automated weather information tool to day-ahead forecasts in 2014 indicated a special weather development in 38% of all days. During these days, the MAE of wind power forecasts increased by 0.77% of installed capacity in comparison to days without a significant weather development and the RMSE increased by 1% of the installed capacity. Especially the largest, negative errors occurred during those indicated days with higher cyclonic influence.

In the renewable energy business, the awareness of the apparent multidisciplinary challenges is high and the use of weather related data is promoted. Nevertheless, meteorological information needs to be prepared in an easily perceivable, compact and automated way to guarantee a time efficient use in complex decision processes such as energy balancing and trading. The automated weather information tool is currently being implemented in a real time suite at the German Weather Service. Within the project EWeLiNE, it will be made available to three German TSOs which will be testing the apriori-indications of critical weather situations in their decision making processes. Furthermore, the automated alert could be used as a trigger for further post processing procedures, or may be useful as input in wind power forecast models. Also, the project EWeLiNE incorporates photovoltaic (PV) power production forecasts. Thus, in an associated article [46], critical weather situations concerning PV power production are analyzed. Low stratus clouds represent such a critical weather element and an automated tool to assess the low stratus risk is designed.

The share of renewable energy sources is constantly increasing. Automatically indicating critical weather developments as well as a short and comprehensive representation of these will help to maintain and guarantee a secure and efficient integration of renewable energies also in the future.

7. Disclaimer

Due to the missing expertise of the presented models, the co-author 50 Hertz, TenneT and Amprion disclaim any liability for the shown results.

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