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Abstract:

Sub-hourly wind power fluctuations cannot be derived from Numerical Weather Predictions (NWP) as in most cases data is only provided on an hourly or even three-hourly basis. Furthermore, forecasting the timing of events (e.g. strong wind power gradients) is not reliable because the timing depends far too much on the initial conditions and physical parameterisations within the model. Thus, a new methodology has been developed to use large-scale meteorological forecasts for predicting strong wind power fluctuations at single sites. The approach is intended for single sites with high installed capacity that cannot benefit from spatial forecast error smoothing, e.g. offshore wind farms. As no data from an offshore wind farm is available, an inshore transformer station in Western Denmark is used to demonstrate the approach.
The defined metric $totalfluc_{0.1\text{-}1.}$ quantifies the occurrence of wind power gradients that exceeds 10% of rated power in a time period of six hours. The power gradient threshold of 10% was chosen because it is assumed that the majority of wind power gradients are unproblematic for the grid integration. Thus, the 96th percentile of strongest gradients is determined which is around 10% of installed power.

$totalfluc_{0.1\text{-}1}$ is related well to the average wind speed (in six hours) and the thermal stratification / stability of the atmosphere. The atmospheric stability is expressed as the temperature difference between the lowest atmospheric level (~10m) and the skin temperature. Highest wind power fluctuations occur in unstable conditions (air above is colder than the water) and average wind speeds of about 10 m/s. Look-up tables for the conditional probability that fluctuations exceed a certain threshold are derived. A case study confirms that open cellular convection that occurs in unstable atmospheric conditions leads to strong wind power fluctuations. In highly resolved mesoscale models this type of convection is simulated and leads to heterogeneous wind fields. Those wind fields shall be diagnosed in the future and the relation between spatial heterogeneity and temporal fluctuations might be a further approach for short-term forecasting of severe wind power fluctuations.

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Content

1. Introduction

In contrast to single ramp events, fluctuating wind power, i.e. series of ramps with a time scale of minutes, were investigated at University of Oldenburg (UNIOL). The knowledge about fluctuating wind power becomes highly interesting for very large-scale offshore wind farms when the range of short-term fluctuations reaches several 100 MegaWatt (MW) and poses a risk to the distribution and/or transmission grid (and requires a lot of balancing power). For instance, fluctuations of the size of 100MW have been observed for Horns Rev wind farm off Western Denmark [Akhmatov_etal2007]. As soon as many spatially distributed wind farms or wind turbines are aggregated, fluctuations on the time scale of minutes are smoothed out and the desired effect to study weather related wind power fluctuations disappears. In the future wind power density will be highest for offshore sites. Unfortunately, large offshore sites like the Horns Rev wind farm did not become a test case in SafeWind, so it was decided to study wind power fluctuations of a near-shore site where the weather conditions resemble most the offshore ones. The selection of an alternative site had to fulfil the following criteria of i) rather concentrated wind power capacity, ii) near-shore wind conditions and iii) available data in a resolution of at least 15 minutes. Thus, the chosen test case was the transformer stations of Tjaereborg where 11 turbines with 20 MW installed capacity are connected. The site is close to Esbjerg and can be considered as inshore (Figure 1). Data has been provided by Energinet.dk within the SafeWind project for the years 2006-2010.

The aim of UNIOL's task was to study under which atmospheric conditions strong wind power fluctuations occur and which variables of Numerical Weather Predictions (NWP) models can be used for characterization and forecasting. Whithin the next couple of years it is out of scope to forecast wind fluctuation precisely in amplitude, frequency and phase for any site. Even forecasts with short lead times are unlikely to be successful, as it will be impossible to gather (measure) all initial conditions accordingly. Furthermore the atmospheric models will still exhibit model errors in the dynamical core. Deficiencies in the physical representation of atmospheric processes will amplify very quickly in the model and will make any very highly resolved spatial and temporal predictions impossible.

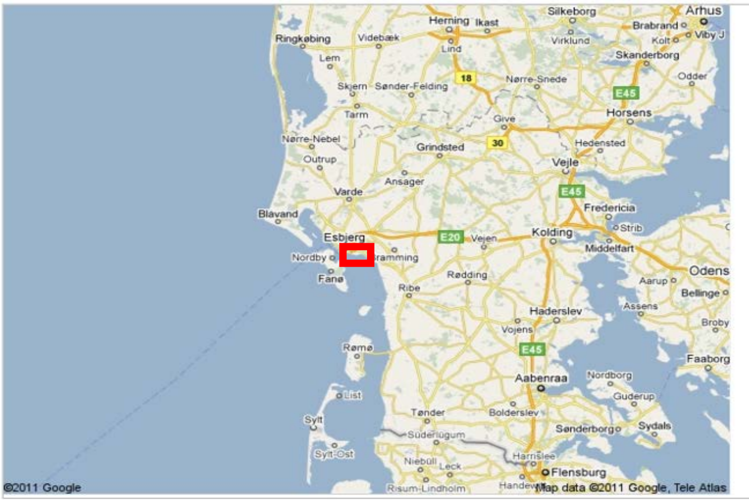


Figure 1: Location of the transformer station TJAe (Tjaereborg)

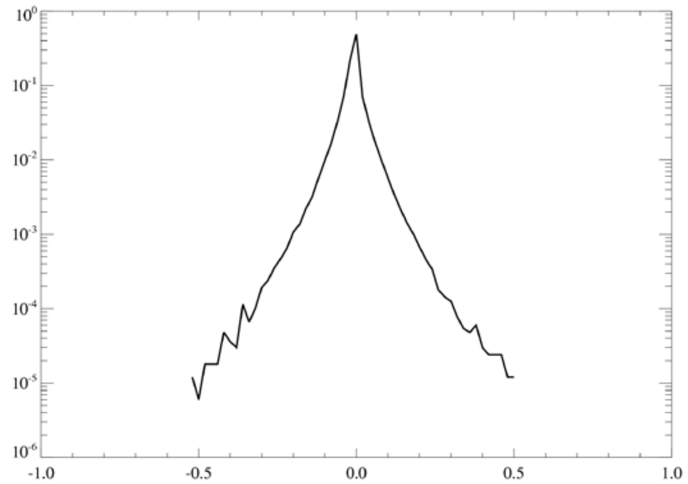
2. Definition of a metric for fluctuation

The distinct forecast of frequency and amplitude of wind (power) fluctuations is not only impossible but is also not the type of information that transmission system operators (TSO) ask for. It is more important to quantify the amount of secondary reserve required within a certain time period to level the fluctuating feed-in of a specific wind farm. In the upcoming years, high offshore installation densities combined with little spatial separation will force the transmission operators to keep high shares of balancing power and to spend a high share of balancing energy in case a large offshore wind farm enters a period of high wind power fluctuations.

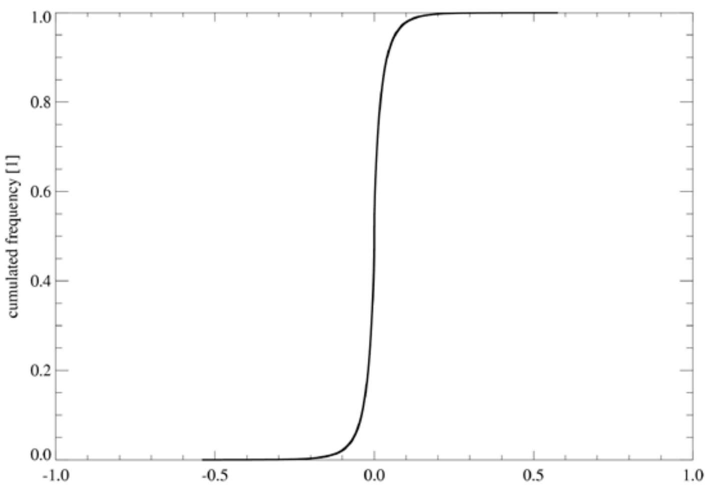
The analysis of short-term wind power fluctuations requires a proper metric to quantify fluctuations. [Davy_etal2010] and [Vincent_etal2010a] have developed metrics for fluctuating wind speeds. [Davy_etal2010] used a low-pass filtered wind speed time series to compute the standard deviation of wind speeds as proxy for high fluctuating winds. [Vincent_etal2010a] applied the Hilbert-Huang Transformation to analyse different frequencies and amplitudes in the wind speed time series. In contrast to metrics for variable wind, the metric needed in this task should have a relation to required balancing energy that is needed for the integration of wind power into the electrical grid. Therefore the metric should accommodate the impact of wind power gradients during a certain time interval/period. However, not all wind power gradients are relevant to consider as wind power fluctuations that might harm the integration of wind power. The analysis of the distribution of temporal wind power gradients at Tjaereborg shows that only 4% of all 15 minute gradients exceed the size of 10% of rated power

Figure 2, bottom). Thus, it was assumed that during normal operations, i.e. in 96% of time intervals no awareness of gradients is needed. Consequently, in 4% of time intervals attention must be given to fluctuations. [Bremen_etal2010a] developed a simple metric to quantify the strength and the occurrence of wind power fluctuations with gradients higher than 10% of rated wind power capacity by adding up the absolute value of gradients, e.g. in a 6h time period

$$totalfluc_{0.1-1} = \sum_{i}^{6h} \left|P_i - P_{i-1}\right| \text{ with } \left|P_i - P_{i-1}\right| > 0.1$$



wind power gradient normalized with installed capacity [1]



wind power gradient normalized with installed capacity[1]

Figure 2: Distribution (top) and cumulated distribution (bottom) of wind power gradients normalized with rated power at transformer station TJAe (Tjaereborg).

Figure 3 shows the time series of $totalfluc_{0-0.1}$ (right) with very small gradients (<0.1) and $totalfluc_{0.1-1}$ (left) that summarizes all gradients exceeding 0.1. It can be seen that fluctuations with gradients <10% of rated power are distributed quite equally during the seasons and no exceptionally high values occur. Conclusively, gradient <10% of rated power are basically occuring very frequently and do not require special attention. This is different for $totalfluc_{0.1-1}$ which is largest in autumn and beginning of winter, but is smallest in summer.

Totalfluc can be interpreted as the amount of required balancing energy to compensate for the loss or surplus of wind energy in the subsequent time step with respect to the preceeding time step.
The maximal value of $totalfluc_{0.0-1.0}$ (all gradients) in a six hour period that is discretized with 24 15 minutes intervals is 24. In the absolute extreme case the power bounces between 100% load and zero load (=maximal gradient) every 15 minutes. In this case, the balancing energy (negative or positive) to adjust to the power level of the previous time step is the installed power multiplied with 15 minutes (=1/4 h), i.e. 1/4h x 20 MW=5 MWh for Tjaereborg (20 MW). In case of 24 of these power ramps, 120MWh (=5MWh x 24) would be required as balancing energy to keep the grid frequency in balance (within a 6 hours period). As a general rule, 1/4 of $totalfluc_{0.0-1.0}$ multiplied with the capacity (in MW) can be regarded as the absolute maximum of balancing energy (in MWh) required in 6 hours. The wind power fluctuations shown in Figure 6 (right) lead to $totalfluc_{0.0-1}$ =3. Thus, 15MWh of balancing energy is necessary in 6h to adjust the power to the power of the previous timestep.

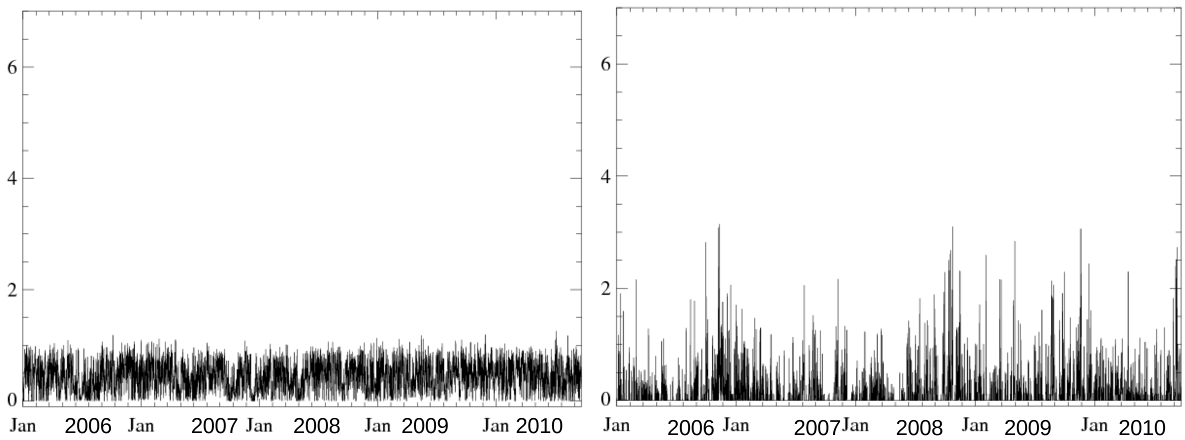


Figure 3: Time series of $totalfluc_{0.0-0.1}$ (left) and $totalfluc_{0.1-1}$ (right) at transformer station TJAe (Tjaereborg) 2006-2010.

3. Fluctuations related to large scale meteorological parameters

In [Bremen_etal2010] and [Vincent_Hah2011, Vincent_etal2010] it has been shown that the highest wind power fluctuations occur in north-western flow conditions. Northwestern flow is often connected with cold-air outbreaks from the polar ice caps. As these air masses are very cold, the stratification is unstable over the comparatively warm North Sea. For the choice to describe atmospheric stability it is important to consider that related parameters, describing atmospheric stability, are available from NWP models. Unfortunately, parameters like Monin-Obhukov length or Richardson number that are usually used to determine atmospheric stability are not available from NWP. The temperature difference between the underground (sea surface) and the entire air mass either enhances or suppresses the lifting of air parcels. In particular, cold-air outbreaks over the open North Sea lead to organized convection [Brümmer_1997]. Open cellular convection (OCC) [Noteboom_2006] can be considered as a source of wind fluctuations due to local wind conditions that develop in the downdrafts and updrafts of these clouds. In this study the air temperature difference between the lowest atmospheric model level from ECMWF (level T91) (10m) and the (surface) skin temperature (SKT) is used as a proxy to characterize whether the stratification is stable or unstable. As Tjaereborg can be considered inshore the sea surface temperature closest to this site has been used. A case study of

September 18th, 2010 illustrates the very heterogeneous wind field during a cold air outbreak that leads to open cellular convection (Section 4).

Figure 4 shows the relation between wind power fluctuation (*totalfluc*$_{0.1—1.}$) 70 m wind speed and the temperature difference T91-SKT. All meteorological parameters are taken from 6 hourly ECMWF analyses. The black dots indicate that no wind power fluctuations with gradients >10% occur for low wind speeds. The highest fluctuations occur for wind speeds between 8-12 m/s and negative differences of air and skin temperature. In case the sea surface skin temperature is higher than the air temperature an unstable stratification exists. It is obvious that the characterization of the meteorological condition is not strong enough to determine perfectly whether convection and related wind fluctuations will occur. Occasionally, high fluctuations (>1.9) also occur in stable conditions and occasionally almost no fluctuations (blue points) occur in very unstable conditions and wind speeds of around 10m/s. It can be concluded that dependencies on other variables exist. However, the general relationship of *totalfluc*$_{0.1\text{-}1}$ between wind speed and stability remains and can be used to quantify the conditional risk for severe wind power fluctuations, i.e. for given (forecasted) weather conditions, the risk that fluctuations exceed a certain threshold.

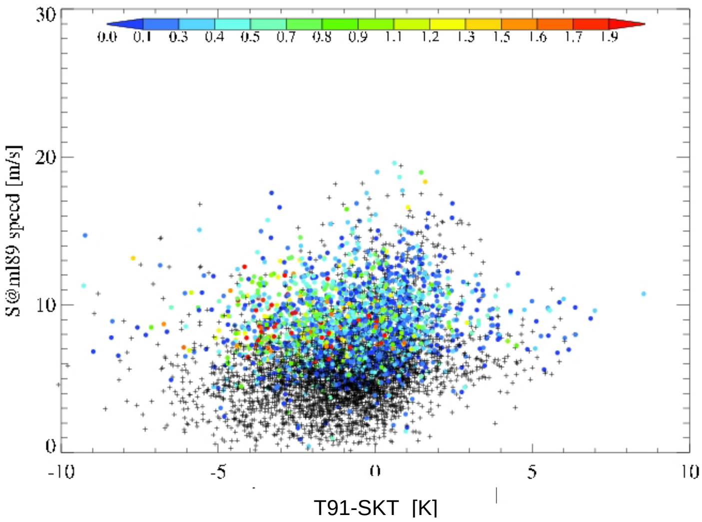


Figure 4: Wind power fluctuations expressed as *totalfluc*$_{0.1\text{-}1.}$ over 70 m wind speed (ECMWF analysis) and thermal stability of the atmosphere (T91-SKT) for the years 2006-2009 at transformer station TJAe (Tjaereborg).

Figure 5 shows the 50th, 80th, 90th and 95th percentile of *totalfluc*$_{0.1—1.}$ conditioned on 70 m wind speed and stability (T91-SKT). The highest fluctuations occur for wind speeds of 8-12 m/s and temperature differences between air and surface skin temperature of -2 to -4 K. Under these conditions, with a probability of 10% *totalfluc*$_{0.1—1.}$ is larger than 1.5 (Figure 5, top right) and with a probability of 5% *totalfluc*$_{0.1—1.}$ exeeds 1.9 (Figure 5, bottom right). As can be seen from Figure 3 (right) *totalfluc*$_{0.1—1.}$ =1.9 is rather rare and can be regarded as very strong fluctuations. An example of time series with very strong wind power fluctuations of 2.58 is shown in Figure 6.

The maps of derived quantiles can be used as look-up tables to estimate the risk of fluctuations that exeed a certain strength. In an operational environment to warn against strong fluctuations, forecasted wind speeds and forecasted stability are required to make use of the look-up table. However, such a look-up table is needed for each individual wind farm (transformer station) as the relation between observed fluctuation and wind speed. In addition, stability is usually described by other parameters which have not been considered here. Thus, it is advised that more stability measures are investigated and the general quality of stability forecasts by NWP is assessed. In particular, the use of probabilistic forecasts for stability and wind speeds should be analysed since the sensitivity of fluctuations on both parameters is very high.

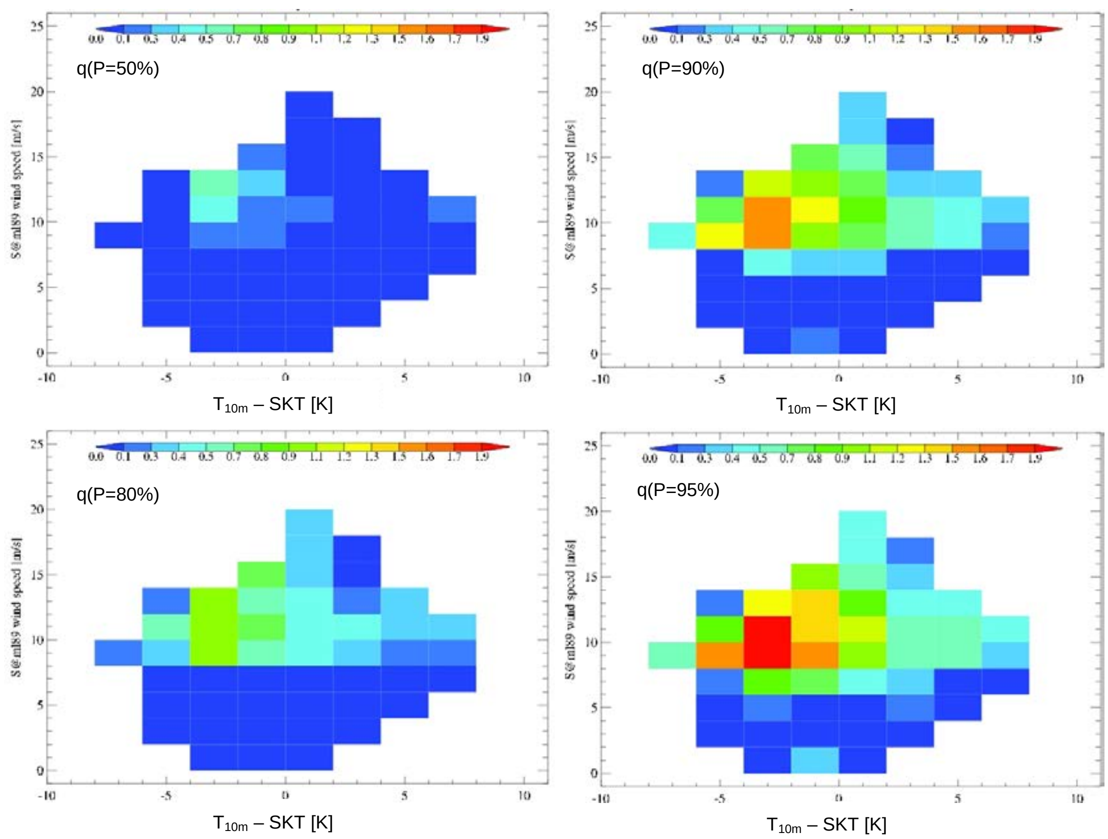


Figure 5: Quantiles of *totalfluc*$_{0.1\text{-}1.}$ depending on 70 m wind speed (ECMWF analysis) and thermal stability of the atmosphere (T91-SKT) for the years 2006-2009 at transformer station TJAe (Tjaereborg).

4. Case study 18 September 2010, 12UTC

The Meteosat 9 satellite image (Figure 6) of September 18th, 2010 at 12 UTC shows that vast expanses of the North Sea are covered with open cellular convection. Very strong fluctuations in wind power at Tjaereborg are observed (Figure 6). The 850hPa temperature (Figure 8, left) illustrates nicely the pool of cold air that reaches West-Denmark in a northwestern flow (Figure 8, right).

Figure 6: Observed wind power fluctuations at transformer station TJAe (Tjaereborg) in 15 minute resolution (18 September 2010). totalfluc$_{0\text{-}0.1}$ with very small gradients (<10% of installed capacity) is 0.42 and totalfluc$_{0.1\text{-}1}$ for all gradients exceeding 10% of installed capacity is 2.58.

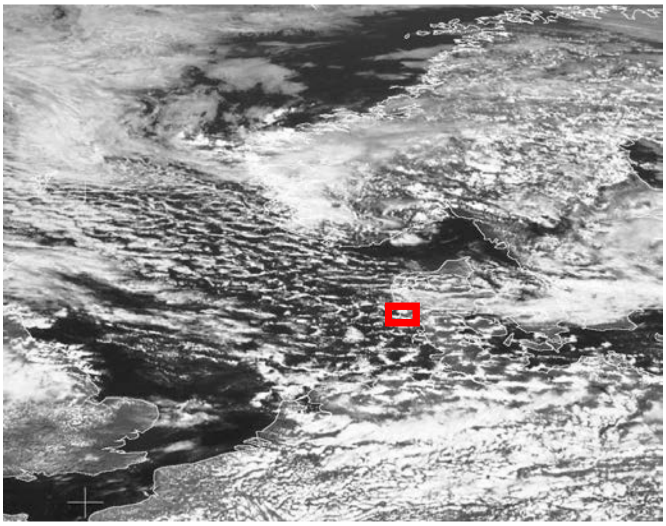


Figure 7: Open cellular convection over the North Sea observed by Meteosat 9 (visible channel) at 18 September 2010, 12UTC. The location of the transformer station TJAe (Tjaereborg) is marked.

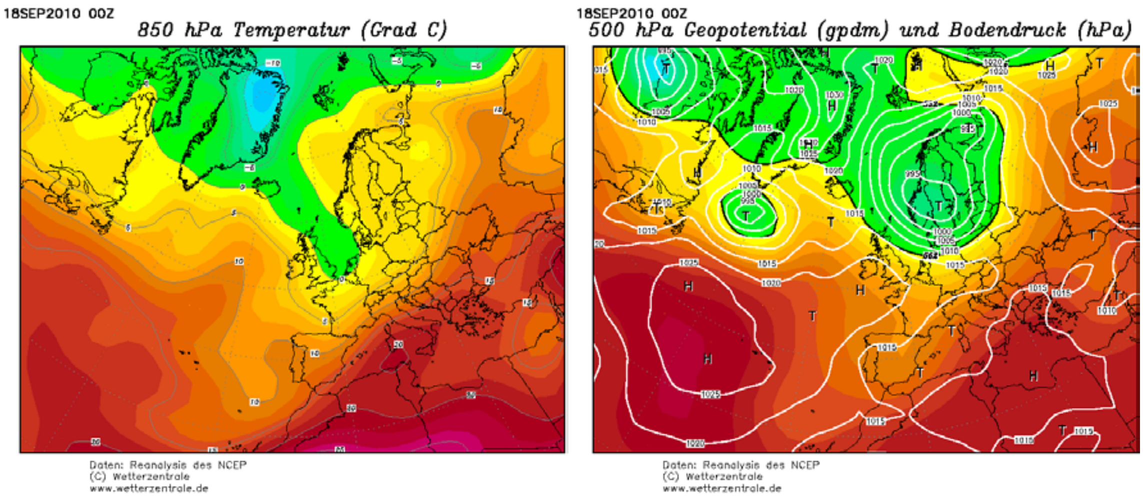


Figure 8: 850hPa temperature (left) and 500hPa geopotential height and surface pressure (right) on Sept 18th, 2010 00UTC.

The horizontal resolution of mesoscale models has improved considerably over the last decade. Hence, to a certain extent small-scale flow in the atmosphere is captured, however it is currently impossible to match the timing of the model with observations. Here, forecasts from the COSMO-DE model of the German Weather Service (DWD) are analysed to determine whether the cold-air outbreak leads to a heterogeneous wind field and whether up and downdrafts are resolved. The spatial resolution is 2.8x1.7 km and forecasts are available in hourly resolution.

Figure 9 (top) shows the heterogeneous wind field 73 m above ground as a +12h and +13h forecast. Rolls of convection that are stretched from North-West to South-East pass Tjaereborg. The heterogeneity of the horizontal wind field is coupled to up and downdrafts of clouds. Vertical updrafts exceeding 0.35 m/s occur at cloud base height (around 1000 m) (Figure 9, bottom). Downdrafts of similar strength occur as well. In future studies the spatial heterogeneity of the surface wind field or the heterogeneity of the vertical wind speed can be tested to serve as an indicator of wind speed and power fluctuation in time.

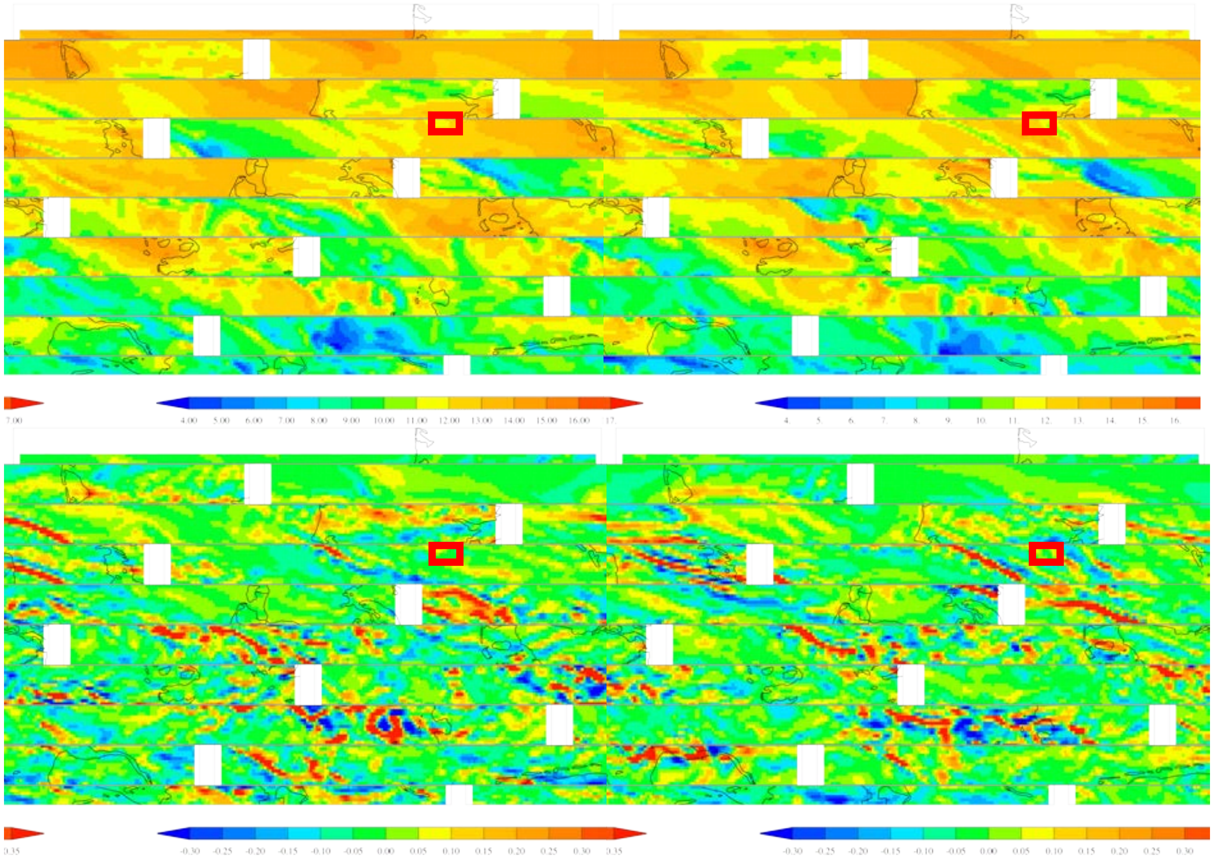


Figure 9: +12h (left) and +13h (right) forecast of wind speed [m/s] (top) at 73 m height and vertical wind speed [m/s] (bottom) at 1072 m height from COSMO-DE initialized 18 September 2010 0UTC.

5. Conclusion

Sub-hourly wind power fluctuations cannot be derived from Numerical Weather Predictions (NWP) as in most cases data is only provided on an hourly or even three-hourly basis. Furthermore, forecasting the timing of events (e.g. strong wind power gradients) is not reliable because the timing depends far too much on the initial conditions and physical parameterisations in the model. Thus, a new methodology has been developed to use large-scale meteorological forecasts for predicting strong wind power fluctuations at single sites. The approach is intended for single sites with high installed capacity that cannot benefit from spatial forecast error smoothing, e.g. offshore wind farms. As no data from an offshore wind farm is available within the project, a inshore transformer station in Western Denmark is used to demonstrate the approach.

The defined metric $totalfluc_{0.1\text{-}1.}$ quantifies the occurrence of wind power gradients that exceeds 10% of rated power in a time period of six hours. The power gradient threshold of 10% was chosen because it is assumed that the majority of wind power gradients are unproblematic for grid integration. Thus, the 96% quantile of strongest gradients is determined which is around 10% of installed power.

$totalfluc_{0.1\text{-}1}$ is related well to the average wind speed (in six hours) and the thermal stratification of the atmosphere. Atmospheric stability is expressed as the temperature difference between the model's lowest atmospheric level (~10m) and the skin temperature. Highest wind power fluctuations occur in unstable conditions (the air is colder than the water) and average wind speeds of about 10 m/s. Under those conditions air that has been warmed at the surface starts to rise up, because it is lighter than the surrounding air, i.e. convection develops. The convection in cold-air outbreaks leads to well organised cloud patterns (open cellular convection) and to a local wind field with high spatial wind gradients. Stable stratification suppresses convection and wind (power) fluctuations are very unlikely.

Furthermore it was found that the risk for strong wind power fluctuations decreases for very strong wind speeds due to the saturation effect of the power curve (as long as the cut-off wind speed is not exceeded). Also in case of very low average wind speeds the risk for strong wind power fluctuations is low, because the power curve is not very steep.

Look-up tables for the conditional probability that fluctuations exceed a certain threshold are derived. A case study confirms that open cellular convection that occurs in unstable atmospheric conditions leads to strong wind power fluctuations. In highly resolved mesoscale models this type of convection is simulated and leads to heterogeneous wind fields. Those wind fields shall be diagnosed in the future and the relation between spatial heterogeneity and temporal fluctuations will be explored for the purpose of short-term forecasting of severe wind power fluctuations.

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