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Brief communication
"Spatial and temporal variation of wind power at hub height over Europe"

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Abstract. Wind power over Europe computed from two years of the new 100 m wind product from ECMWF at 16 km horizontal resolution is 20 % of maximum capacity of an exemplary wind turbine power curve. This is five percent of maximum capacity less than extrapolated from 10 m winds using model roughness in the logarithmic law, but eight percent more than multiplying 10 m winds by a constant factor of 1.28 as in a previous study. The result from the new data set happens to be very close to the actual capacity factor of 21 % for European wind turbines (Boccard, 2009). The capacity factor in high power regions between 50 and 58° N and most of northernmost Africa is almost 30 %. The aggregation of wind power over Europe smooths onshore day-to-day fluctuations to at most 7 percentage points during 80 % of the year.

1 Introduction

Wind is increasingly used as energy source for electricity generation. Some of its advantages over other energy sources are the absence of greenhouse gases and zero cost of the "fuel". Its major drawback is the intermittence of supply. One alleviating strategy is aggregating the production from an area so large that correlation between distant sites becomes small. If the region is sufficiently large, Hasche (2010) showed that the resulting smoothing of the production is only a function of the geographical area but (almost) not of the number of installed wind farms. Giebel (2007), Kiss and Jánosi (2008), and Kiss et al. (2009) evaluated the aggregated wind energy production over Europe by extrapolating 10 m winds from measurements and reanalysis data, respectively. The sparseness (60 stations) and coarseness (2.5 and 1 degree spatial resolution) of the data combined with the required vertical extrapolation to hub height around 100 m add an unknown uncertainty to their estimate. This uncertainty can be reduced with the 100 m wind product available from European Centre for Medium-Range Weather Forecasts (ECMWF) since 2010. We evaluate the European wind energy potential and variability from these new data and compare it to the potential from extrapolated 10 m winds and to the previous results. Additionally, the increased horizontal resolution permits a meaningful comparison of onshore and offshore wind energy potential.

2 Data and method

We use two years (9 November 2010 to 8 November 2012) of 3-hourly horizontal wind data at 100 m a.g.l. from analyses (00:00 and 12:00 UTC) and short-term forecasts (for the remaining times) of the ECMWF. The ECMWF interpolates this wind vertically from the two nearest model levels at approximately 67 and 111 m a.g.l. For comparison, we also use extrapolations from the 10 m wind product, which has been available for many years. The ECMWF postprocesses the 10 m wind to conditions (ECMWF, 2011, Eq. 3.94), which the World Meteorological Organization requires for wind measurements (open terrain). The horizontal grid spacing of the model is about 16 km. The selected region between 11° W and 35° E and 27° N and 67° N covers Europe and parts of North Africa. Since most offshore wind farms in operation remain close to the coast, we limited our offshore area to a two-grid-point wide strip around the ECMWF land mask. The ECMWF operational model was updated three times in the period covered (18 May 2011, 15 November 2011, and 19 June 2012). To test whether these updates have changed the statistical properties of the 10 m and 100 m wind speed analyses, we tested the data for structural changes with an ordinary-least-squares (OLS)-based CUSUM test (Ploberger and Krämer, 1992). Therefore we consider the time series of mean wind speeds over the covered region as autoregressive (ar2) process. The seasonal pattern of wind is accounted for with the sine and cosine of DayOfTheYear $\times 2\pi/365$ as additional regressors. With this test, no significant structural change can be found for the 100 m wind. However, for the 10 m wind, a change can be found towards the end of 2011 that probably corresponds to the model update of 15 November 2011 when surface roughness was changed, which led to a reduced 10 m wind over land according to ECMWF documentation . Our results confirm that. When onshore and offshore regions are tested separately, the change is significant only for onshore but not for offshore regions. Consequently, temporal variations will only be investigated with the 100 m wind but not with the 10 m wind. Note that the data period was chosen so as to avoid another model update on 9 November 2010.

The nonlinear transformation from wind to wind power proportional to the cube of the speed was done using an exemplary power curve of the VESTAS V80-2.0 MW turbine (VESTAS, access: 22 July 2012) for each grid point. We focus on the effects of meteorological variability and do not consider impacts, e.g., from differently weighted areas (Kiss and Jánosi, 2008) or transmission constraints (e.g., Giebel, 2007).

3 Results

Wind power varies most regionally and for shorter time scales, whereas interannual variations are smaller. Results are depicted in percent normalized with the maximum (= nominal) power of the turbine. This ratio is often called "capacity factor".

3.1 Spatial variations

Figure 1 shows the spatial variation of the mean capacity factor over the two years. A high-power belt with a capacity factor of about 30 % stretches zonally between approximately 50 and 58° N. Similarly large values occur over most of northernmost Africa. Offshore areas in the North Sea and the Baltic Sea as well as the Strait of Gibraltar can generate even more power. Most of the onshore regions between the two high-power belts have a potential that is half or even smaller. Increasing topographic complexity is so strongly coupled to a decreasing capacity factor that the latter effectively traces the ECMWF model topography (blueish colors in Fig. 1a). Overall minima occur over the major mountain ranges such as the Alps. The high spatial resolution of the ECMWF data allows resolving the high capacity factors provided by larger local wind systems in the Ebro Valley (NW Spain), in the Rhône Delta (S France), the Strait of Gibraltar, the Gulf of Suez and the Gulf of Aqaba.

Overall, the average capacity factor computed from daily means for the area north of 35° N is 19.5 % with a standard deviation of 7.9 %.

3.2 Temporal variations

We present results from intraday to interannual variations for the area north of 35° N. The 5 and 95 percentile of the capacity factor are 8.7 and 34.8 %, respectively. 18 days of the year are on average outside of each of these percentiles. On the longest scale resolvable with the two-year data set, the annual mean over the whole region changed little from the first year (9 November 2010 to 8 November 2011) to the second year from 19.7 % to 19.3 %. However, the spatial distribution changed noticeably between the two winters (DJF) as seen in Fig. 2. During the second winter (part b) the values are higher in the northern and middle part of Europe, while they are lower in Spain and eastern Europe compared to the first winter (part a).

Figure 3a visualizes the temporal variations on the daily scale for both years and further divides the data into onshore and offshore. The capacity factor is higher in the winter half of the year by about 15 to 20 percentage points. It is almost twice as high offshore as onshore with a capacity factor of 33.1 % versus 17.9 %. Fluctuations over the offshore area are smoothed less than over the approximately nine times larger land area. For 80 % of the year, the capacity factor changes from one day to the next by not more than 6.5 percentage points onshore and 10 points offshore, respectively (inset in Fig. 3a). Changes exceeding 20 % were nonexistent for the onshore area and very rare for the offshore area with 4 days (per year).

At a three-hourly temporal resolution, the minimum over the whole onshore region occurs around 06:00 UTC and the maximum around 15:00 UTC (not shown). Nocturnal values are lower than daytime ones. The average difference between diurnal minimum and maximum is small: 2.3 percentage points. Offshore, the minimum is at around 09:00 UTC and the diurnal range spans 3.1 percentage points.

3.3 Differences to extrapolated 10 m winds

Differences between capacity factors computed with the new 100 m wind product and with traditional extrapolations of the 10 m wind are substantial. Using a linear extrapolation (Fig. 1b) with a constant factor of 1.28 [1] as applied in a climatological study with ERA-40 data (Kiss and Jánosi, 2008) reduces the average capacity factor by a third from 19.5 % to 12.4 %. Regionally, the strongest reductions occur

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[1] equivalent to using a logarithmic wind profile with a roughness length of about 3 mm

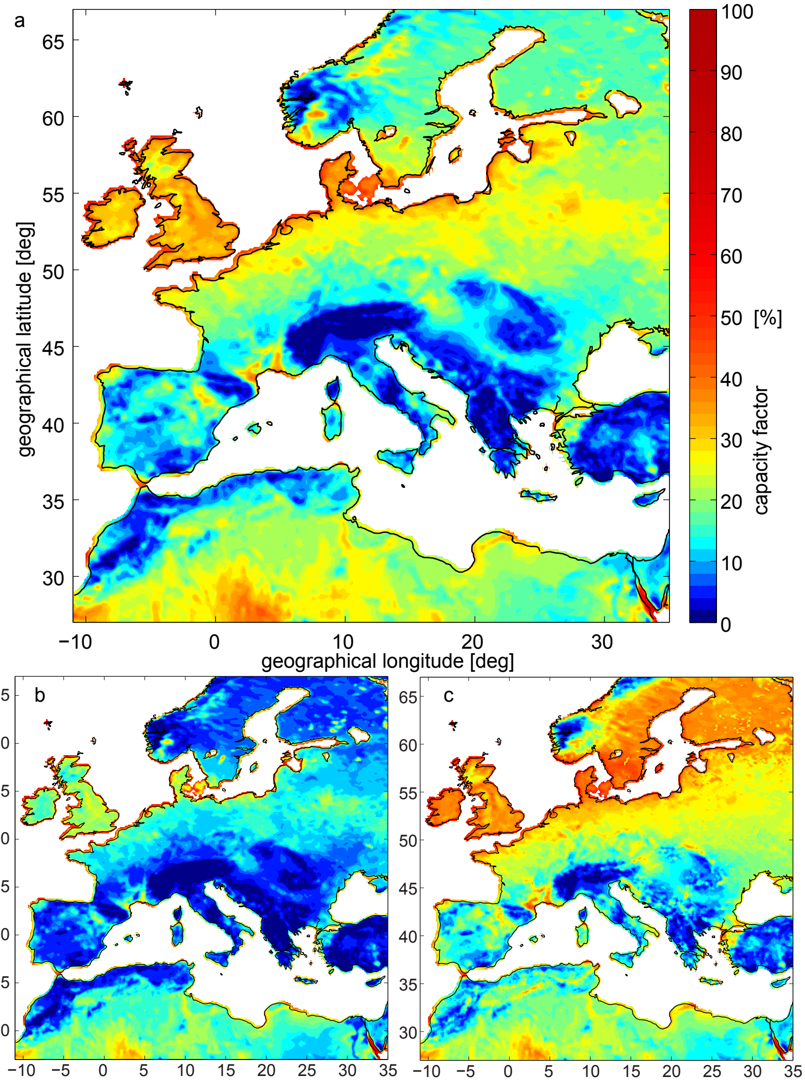

Fig. 1. Mean capacity factor (fraction of maximum capacity) using an exemplary power curve for the period 9 November 2010 through 8 November 2012 **(a)** from ECMWF 100 m wind, **(b)** from ECMWF 10 m wind multiplied by 1.28 as in Kiss and Jánosi (2008), and **(c)** from ECMWF 10 m wind extrapolated logarithmically. The capacity factor scale is logarithmic.

approximately north of 48° N in the high-power belt and northern Europe. Extrapolating the 10 m wind logarithmically with z_0 from the model, assuming neutral stratification between 10 and 100 m, on the other hand, exaggerates the capacity factor by almost a third to an average 25.2 %. Again, most pronounced differences occur north of about 48° N with especially drastic differences in the far north where stable instead of neutral stratification dominates throughout the year.

The ratio of model wind speeds at 100 m to 10 m for the area north of 35° N (Fig. 3b) varies sinusoidally with a minimum in summer when stratification is more frequently neutral and a maximum in winter when stable conditions dominate. The median over the two years is 1.56, the 25 percentile 1.50, and the 75 percentile 1.62.

4 Discussion

Using the new 100 m wind data leads to considerable differences to previously available results from extrapolated 10 m winds (e.g., Kiss and Jánosi, 2008). The annual mean capacity factor over Europe is 19.5 % from the 100 m wind with an exemplary power curve for each ECMWF grid point. A simple logarithmic extrapolation of the more commonly available 10 m wind using model surface roughness yields substantially more: 25.2 %. Clearly, the underlying assumption of neutral stratification in the lowest 100 m of the atmosphere is violated, and stable stratifications must occur frequently. They are more common at higher latitudes where solar energy input is lower. And indeed, the largest differences are found in northern Europe (cf. Fig. 1a and c). A different

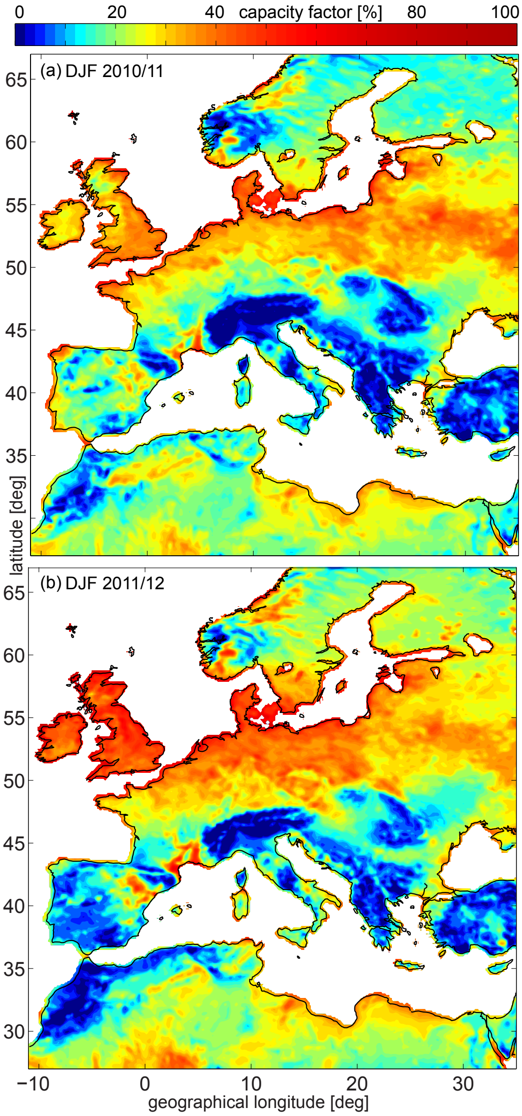

Fig. 2. Mean capacity factor from ECMWF 100 m wind and exemplary power curve for winter (DJF) of **(a)** 2010/2011 and **(b)** 2011/2012 using a logarithmic color scale.

extrapolation strategy is the multiplication of the 10 m wind by a constant factor. Kiss and Jánosi (2008) used 1.28 for the ERA-40 wind and found 13.7 % as 44 yr average for Europe. Even though the ECMWF model versions used for ERA-40 (Uppala et al., 2005) and the current study differ considerably in all aspects of the model (including a horizontal resolution increase by a factor of almost 8), the results are robust. Extrapolating the 10 m wind of the current model with a factor of 1.28 for our two-year period yields a similar capacity factor of 12.4 %. A much higher factor of 1.56 (median) is needed to produce better results for the European region. However, that factor varies by about 0.15 between summer and winter with different frequencies of neutral stratification (Fig. 3b). The jump of that factor on 15 November 2011 with the ECMWF change of surface roughness confirms our statistical tests, which point to noticeable changes only for the 10 m wind but not for the 100 m wind. A factor of 1.56 to extrapolate from 10 m to 100 m translates into a surface roughness of 0.17 m assuming neutral stratification with a logarithmic wind profile, whereas the model roughness averaged over the European region is almost four times higher (0.63 m) pointing to frequent violations of the neutral stratification assumption. If one were to extrapolate the 10 m wind with the logarithmic profile using the model roughness length, then the extrapolation factor would have to be 1.83.

These differences between the results from 100 m wind and extrapolated 10 m wind, respectively, highlight the considerable degradation of (forecasted) power production from extrapolating 10 m wind. This is supported by Drechsel et al. (2012), who compared different ways of using ECMWF winds with measurements from both tall meteorological towers and wind turbines. Logarithmically extrapolating the 10 m wind fared worst. Its bias-corrected RMSE was almost 10 percentage points higher than from the best methods, to which the linear interpolation between neighboring model levels used at ECMWF for their 100 m wind product belongs. Similarly, Motta et al. (2005) found a logarithmic extrapolation from 10 m unsatisfactory for wind energy applications. They had to add empirical stability corrections to the long-term Danish offshore measurements that they used.

Since the availability of the 100 m wind product from early 2010 on, computed capacity factors have been statistically indistinguishable across changes to the ECMWF operational model – in contrast to the 10 m product, which might be an additional advantage when using operational models instead of coarser resolution reanalyses with unchanged model formulations.

The annual capacity factor of approximately 20 % from the new data set happens to be very close to the actual capacity factor of 21 % for European wind turbines reported in Boccard (2009). We speculate that this agreement goes beyond coincidence. Two independent estimates each with different error sources lend credence to each other. Hasche (2010) supports this conclusion that for large enough areas resulting smoothing is basically unaffected by the number of installed wind farms. One can then deduce that (i) the sample size of installed wind turbines in Europe is large enough and covers a wide enough variety of terrain as to yield a representative value, and (ii) that the ECMWF wind analyses at 100 m above ground are very close to reality when aggregated over a large area like Europe.

The higher capacity factor in winter is caused by a jet stream that is both stronger and also located further south. The difference of the spatial distribution between the two winters (Fig. 2) can be explained by the different large-scale circulation patterns, which, e.g., the North Atlantic Oscillation (NAO) index summarizes. This index was negative for DJF the first winter (2010/2011), and positive for the second winter. A positive NAO index implies stronger westerlies

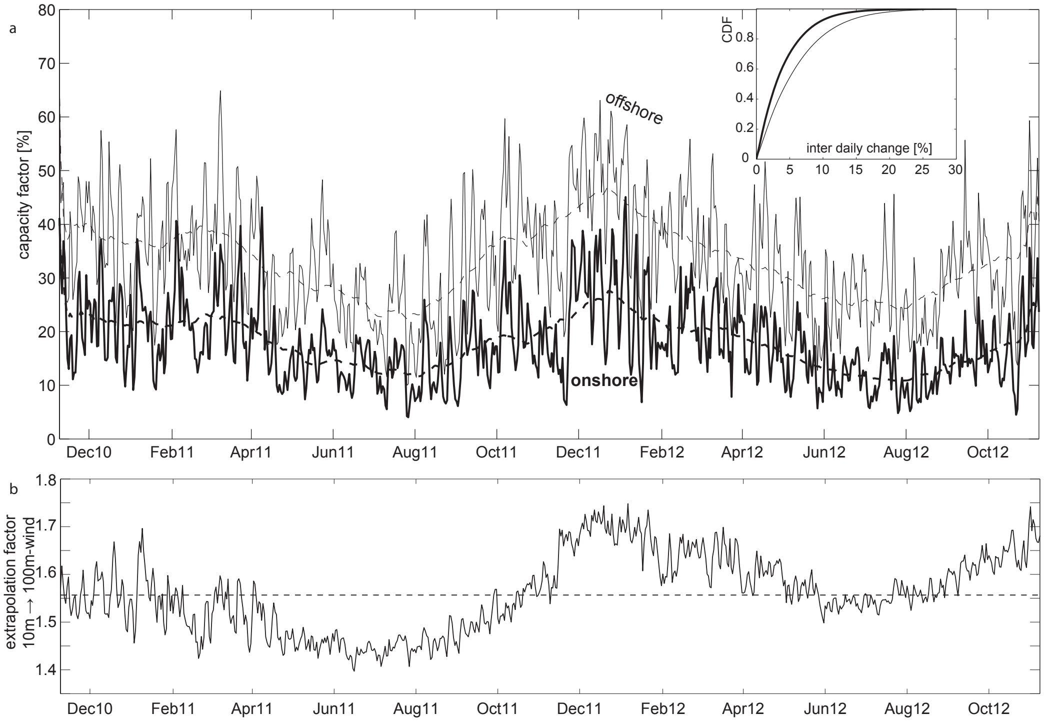

Fig. 3. **(a)** Time series of mean daily capacity factor for the area north of 35° N for offshore (thin line) and onshore (bold) regions, with overlaid 61-day running mean (dashed). Inset: cumulative distribution function (CDF) of day-to-day difference of capacity factor. **(b)** Time series of extrapolation factor from 10 m to 100 m wind speeds with median value (dashed).

over the eastern North Atlantic and the European continent (Wanner et al., 2001). The second winter had a positive NAO index and also a higher capacity factor, most pronouncedly so in the northern high-power belt.

Our study focused on the meteorological variability of wind energy and found that aggregating wind power over Europe drastically reduces volatility, one of its main drawbacks compared to electricity generation from conventional sources. In 80 % of the time the change from one day to the next is no more than 6.5 %. However, limited transmission line capacity makes it currently impossible to truly aggregate European (and northernmost African) wind power. Giebel (2007) and Roques et al. (2010) examine consequences of this limitation.

One of the appeals of wind energy is its potential to replace some greenhouse-gas-producing thermal electricity generation. It would be most valuable if the availability were high at the peak times of the electricity load curve (morning, noon, evening) as Boccard (2010) studied in detail for several European countries using actual production data. Aggregated over all of Europe, our results show that wind power is indeed close to its diurnal maximum at the time of the noon and evening peaks and lower throughout the night, but also lower during the morning load peak. Drechsel et al. (2012) found the range of 60–100 m, where hub heights are commonly found, to be the one with smallest diurnal differences. As hub heights increase, diurnal amplitude of electricity produced from such turbines will increase and the time of the onshore maximum should shift towards the second half of the night due to the influence of the so-called low-level nocturnal jet (Baas et al., 2009; Drechsel et al., 2012).

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