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Wind speed variability between 10 and 116 m height from the regional reanalysis COSMO-REA6 compared to wind mast measurements over Northern Germany and the Netherlands

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Abstract. Hourly and monthly mean wind speed and wind speed variability from the regional reanalysis COSMO-REA6 is analysed in the range of 10 to 116 m height above ground. Comparisons with independent wind mast measurements performed between 2001 and 2010 over Northern Germany over land (Lindenberg), the North Sea (FINO platforms), and The Netherlands (Cabauw) show that the COSMO-REA6 wind fields are realistic and at least as close to the measurements as the global atmospheric reanalyses (ERA20C and ERA-Interim) on the monthly scale. The median wind profiles of the reanalyses were found to be consistent with the observed ones. The mean annual cycles of variability are generally reproduced from 10 up to 116 m in the investigated reanalyses. The mean diurnal cycle is represented qualitatively near the ground by the reanalyses. At 100 m height, there is little diurnal cycle left in the global and regional reanalyses, though a diurnal cycle is still present in the measurements over land.

Correlation coefficients between monthly means of the observations and the reanalyses range between 0.92 at 10 m and 0.99 at 116 m, with a slightly higher correlation of the regional reanalyses at Lindenberg at 10 m height which is significant only at a lower than 95 % significance level. Correlations of daily means tend to be higher for the regional reanalysis COSMO-REA6. Increasing temporal resolution further, reduces this advantage of the regional reanalysis. At around 100 m, ERA-Interim yields a higher correlation at Lindenberg and Cabauw, whereas COSMO-REA6 yields a higher correlation at FINO1 and FINO2.

1 Introduction

Global and recently also regional reanalyses are an increasingly important tool for climatological applications. A reanalysis is a physically consistent reconstruction of the atmosphere based on three equally important parts:

1. a state-of-the-art numerical weather prediction (NWP) model,
2. a comprehensive archive of various types of meteorological data including remote sensing data as well as ground based and airborne in situ measurements, and
3. the data assimilation system which brings together the data with the model in a statistically optimal way.

Global reanalyses are established for the satellite era, for which the observing system comfortably constrains the analysis. Recent work pushed the limits to covering earlier time periods by assimilating surface pressure observations only, resulting in the twentieth century reanalysis (Compo et al., 2011) ranging back to 1851 in its newest version 2c (20CRv2c); or by assimilating surface pressure observations and marine wind observations only (Poli et al., 2016), resulting in the reanalysis ERA-20C ranging back to 1900. Both 20CRv2c and ERA-20C wind profiles were compared to historical wind profile measurements (Stickler et al., 2015) which resulted in some encouraging correlations, but also illustrated the lack of constraint by the observing system in the pre-satellite era. Compared to this, the uncertainties of global reanalyses are much reduced when assimilating the modern observations of the satellite era as, e.g., done by ERA-Interim (Dee et al., 2011). These global reanalyses have been used to drive regional reanalyses (RRAs) which achieve higher spatial and temporal resolution, with demonstrated added benefit for the wind fields (Kaiser-Weiss et al., 2015). The added benefit may have arisen from the higher resolution modelled, the higher resolved output, the assimilation of more regional representative observations, or a combination of these effects.

Within the European Seventh Framework Programme (EU FP7) project Uncertainties in Ensembles of Regional ReAnalyses (UERRA) several ensembles of European RRAs are produced and their associated uncertainties estimated with a suite of various methods (Borsche et al., 2015). There are a number of different users interested in RRA data including agencies and companies involved in renewable energy production. For instance, Cannon et al. (2015) demonstrated that wind power generation statistics for the UK can be derived from MERRA (Modern-Era Retrospective Analysis for Research and Applications by NASA) reanalyses. Rose and Apt (2015) recently summarized the benefit reanalysis data can provide for wind energy applications, which are the estimation of long-term trends and variability, and characterization of extreme wind events. They also highlight the lack of verification against historical data. Kaiser-Weiss et al. (2015) showed that for Germany, the meteorological station observations of the recent years correlate highly with various reanalyses, and that the regional reanalysis COSMO-REA6 (Bollmeyer et al., 2015) adds benefit relative to ERA-Interim by which it is driven. The latter study was constrained by observations at the typical measurement height of 10 m, and the monthly scale, whereas wind energy applications require uncertainty estimation spanning the vertical range from 10 m up to the hub height of around 150 m, and much shorter time scales. Bett et al. (2015) studied the daily to inter-annual wind speed variability over Europe with special attention to wind industry applications and in heights relevant to wind turbines. They used the ERA-Interim and 20CR reanalyses, applying a statistical calibration to the 142-year long 20CR, but did not include a comparison against tower measurements, as done here. They found extremely weak trends on century timescales for many regions but large multi-decadal variability. Wijnant et al. (2014) have developed the KNW (KNMI North sea Wind) atlas which is based on ERA-Interim and is downscaled with HARMONIE (Hirlam Aladin Regional Mesoscale Operational Nwp In Europe) to 2.5 km by 2.5 km spatial resolution covering a 34-year period from 1979 to 2012. Stepek et al. (2015) have validated the KNW atlas with three off-shore wind masts including FINO1. They found very small differences between the KNW annual values and the observations of only 0.2 $\mathrm{m\,s^{-1}}$ for all masts and all measurement heights, and the occurrence of extreme events was as reliable as for the measurements. There exist various studies based on model runs without data assimilation (i.e., dynamical downscaling with either numerical weather prediction models or regional climate models like MM5 and WRF with the aim to produce a regional wind climatology (e.g., Durante et al., 2012; Hahmann et al., 2015). In contrast to these downscaling studies, which did arrive at a satisfactory climatology, regional reanalysis efforts strive to capture the actual time dependent variability (i.e., the weather), on top of a satisfactory climatology. In a successful regional reanalysis, both the climatology and the anomalies varying over time (from the hourly to the inter-annual scale) have to be realistic. To achieve the latter, a regional data assimilation is employed with the regional reanalysis.

In the present study, the uncertainty of the reanalyses wind speed is characterized, covering the height range between 10 and 116 m above ground, starting from an hourly time scale frequency distribution. The height dependent variability of the reanalyses wind speed is compared against independent mast measurements in Northern Germany and The Netherlands. The ability of the reanalyses to reproduce the observed annual and diurnal cycles is investigated and correlation coefficients between reanalyses and measurements are given on an hourly, daily, and monthly scale, in order to provide uncertainty characterization for users of the RRA wind fields.

2 Data

Mast measurements of the Meteorological Observatory Lindenberg operated by Deutscher Wetterdienst (DWD), the Cabauw experimental site for atmospheric research (Cesar) observatory, and the FINO masts are used as reference data. The COSMO-REA6 RRA and two global reanalyses were used to be compared against the independent measurements.

2.1 Lindenberg measurements

As part of DWD's Meteorological Observatory Lindenberg, a mast for meteorological observations is located southeast of Berlin in Falkenberg, Germany at 52.17° latitude and 14.12° longitude. The mast is 99 m high and has anemometer instruments mounted at 5, 10, 20, 40, 60, 80, and 99 m. All but the 5 m measurements are used in this study. The measurements are available for the time period 2001 to the end of 2014 in 10 min intervals which were aggregated to hourly mean values for this study. The data used in this study have been corrected for the dampening mast effect (Leiterer et al., 2002).

2.2 Cesar measurements

The Cesar observatory is a consortium led by the Royal Netherlands Meteorological Institute (KNMI) and presently (http://www.cesar-database.nl) includes eight institutes and universities located in The Netherlands. At the observatory, located at 51.97° latitude and 4.93° longitude, a 213 m high mast is installed which is equipped with meteorological instruments at 10, 20, 40, 80, 140 and 200 m to measure wind speed and direction, temperature, and humidity. The measurements are being performed at 9.4 m long booms pointing into three directions (Monna and Bosveld, 2013). This enables measurements that are not disturbed by the mast cylinder for any wind direction (Wessel, 1983). The data was downloaded and is available for the time period April 2000 to July 2015 at 10 min intervals which were aggregated to hourly mean values for this study.

2.3 FINO measurements

The *Forschungsplattform in Nord- und Ostsee* (FINO) 1 and 2 are research platforms in the North Sea and Baltic in potentially suitable areas close to fairly large planned and proposed offshore wind farms. FINO1, located at 54.01° latitude and 6.59° longitude 45 km north of Borkum, is in operation since 2003 and operated by the R&D Centre Fachhochschule Kiel University of Applied Sciences GmbH. Data have been collected since 2007 on FINO2, located at 55.0° latitude and 13.15° longitude 40 km north-west of Rügen, and operated by Germanischer Lloyd (http://www.fino-offshore.de/en, 2016).

For this study, data from FINO1 and FINO2 were available from the top of the masts at 100 m above sea level (a.s.l.) for FINO1 and 102 m a.s.l. for FINO2. No corrections to the data were applied because the measurements on top of the mast are assumed to be undisturbed. However, the top anemometer of FINO1 is located in a lightning protection cage and Westerhellweg et al. (2012) have estimated a wind speed decrease on average of 1 % for the south and 2 % for the north wind directions compared to an undisturbed measurement on top of FINO1. This effect on the data has been neglected for this study. Also, the effect of the wind park "alpha ventus" built in the summer 2009 east of FINO1 (https://www.alpha-ventus.de/technik/, 2016) has been neglected for this study. Stepek et al. (2015) estimate the disturbance effect with up to 1 m s^{-1} for wind speed in 100 m height when considering only wind speeds for the direction of highest disturbance (East). The annual mean wind speed for all wind directions is estimated to decrease about 0.2 m s^{-1} or about 2 %. The wind speed measurements are provided as 10 min mean values which were aggregated to hourly mean values for this analysis.

2.4 Regional reanalysis data

The regional reanalysis COSMO-REA6 produced at DWD's Hans-Ertel-Centre for Weather Research (HErZ) at the University of Bonn is based on the consortium for small-scale modelling (COSMO) (http://www.cosmo-model.org/, 2016) model over a European domain (EURO-CORDEX, see Bollmeyer et al., 2015). The boundary conditions are taken from the global reanalysis ERA-Interim at six-hourly resolution. Radiosonde, aircraft, wind profiler, and surface level data are assimilated into COSMO-REA6 by using the nudging method (Schraff and Hess, 2003). The horizontal resolution of the RRA is 6.8 km nominally and analyses are stored every hour. Wind speed values are extracted for each pixel at the location of the above mentioned mast measurements. Data from the lowest four model levels were taken which provide the average wind speed at the heights centred around 10, 35, 69, and 116 m.

2.5 Global reanalysis data

Wind speed from two global reanalyses was included into the comparison. The first global reanalysis is ERA-Interim by ECMWF which is based on a 2006 release of the IFS (Integrated Forecasting System; Cy31r2). As described in Dee et al. (2011), the system includes a 4-dimensional variational analysis (4D-Var) with a 12 h analysis window. A wealth of observational data are assimilated, ranging from measurements over land, the oceans, to in situ and satellite remote sensing measurements where satellite radiance brightness observations were automatically corrected by a variational bias correction scheme. The spatial resolution of ERA-Interim is approximately 80 km (T255 spectral) on 60 vertical levels from the surface up to 0.1 hPa. Data is available since 1979 to present at four time steps a day starting at 00:00 UTC. Wind speed was extracted for the pixel at the location of the mast measurements at 10 and 100 m height. These values are provided by ECMWF as values interpolated from model levels to height above ground.

The second global reanalysis used in this study is the deterministic rerun of ERA-20C by ECMWF which is based on a 2012 version of the IFS (Cy38r1). As described by Poli et al. (2016) it is produced with a coupled Atmosphere/Land-surface/Ocean-waves model and assimilates surface and mean sea level pressures and surface marine winds with a 4D-Var data assimilation system with a 24 h analysis window. Furthermore, it is produced on 91 vertical levels between the surface and 0.01 hPa, covers the time period between 1900 and 2010, comes with a horizontal resolution of approximately 125 km (T159 spectral), and provides three-hourly time steps. Wind speed data is provided on an interpolated height level of 100 m.

3 Methods

The mast measurements were taken as a reference to compare the reanalyses against. To eliminate a constant bias (e.g., difference between the mean values) between reanalysis and observations, the wind speed anomalies (i.e., with mean over period subtracted) are compared. A constant bias can be expected because a mismatch of height assignment is likely as the measurement site may not be representative for the grid cell. With a typical wind profile (compare the various heights in Fig. 1), a constant bias could be corrected for by fitting a

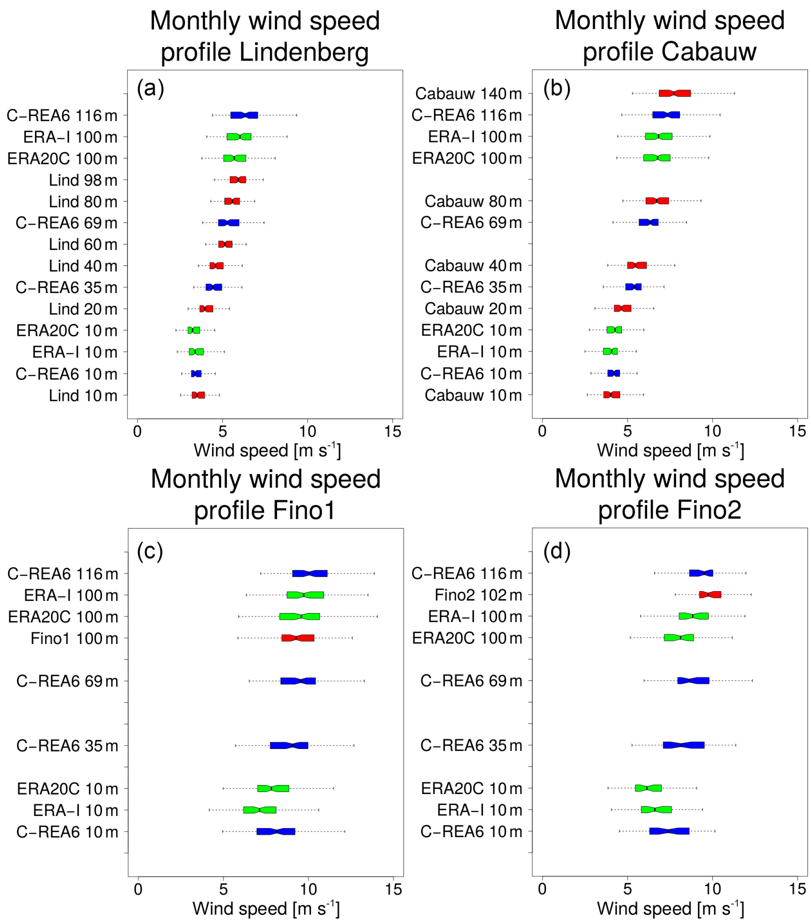

Figure 1. Box plots of monthly mean wind speed at Lindenberg (top left), Cabauw (top right), FINO1 (bottom left), and FINO2 (bottom right) at different heights between 10 and around 100 m. Mast measurements are shown in red, regional reanalysis data (COSMO-REA6) in blue, and global reanalysis data (ERA-Interim and ERA20C) in green.

height adjustment, which is, however, not the focus of this paper. Instead, here we focus on comparing the anomaly of observations versus anomaly of reanalyses. By doing so, we compare point measurements to the reanalysis grid cell values which are spatial averages. In order to reduce problems interpreting these two values we

1. pick locations with a spatial representativity likely to be larger than the grid cell size,
2. reduce potentially remaining local effects by working with anomalies, and
3. remove any short-term fluctuations specific to the point by averaging over time (daily, monthly).

For technical applications, wind speed is often characterized with a fitted Weibull distribution, thus the Weibull parameters are provided, and other statistical measures such as the mean, median, variance, Pearson's correlation, and the frequency distribution. The statistical measures depend on the time resolution chosen. To avoid sampling effects, we compare daily and monthly mean wind speeds for measurements and reanalyses. The high temporal resolution of the regional reanalysis output allows for comparison of hourly mean wind speeds to the mast measurements. The observations are aggregated to hourly mean values from the reported 10 min means (which are averages over the 1 min instrument intervals), and then further aggregated to daily and monthly means. The reported hourly and six-hourly reanalysis output are instantaneous values which are aggregated to daily and monthly means for comparison. With the aggregated temporal means, the respective anomalies, and variances were calculated and compared.

4 Results und discussion

The mast measurements are used as best estimates of truth the three reanalysis are compared against. Figure 1 shows box plots of monthly wind speed at different heights for the mast measurements at Lindenberg, Cabauw, FINO1, and FINO2 and corresponding values of the regional (COSMO-

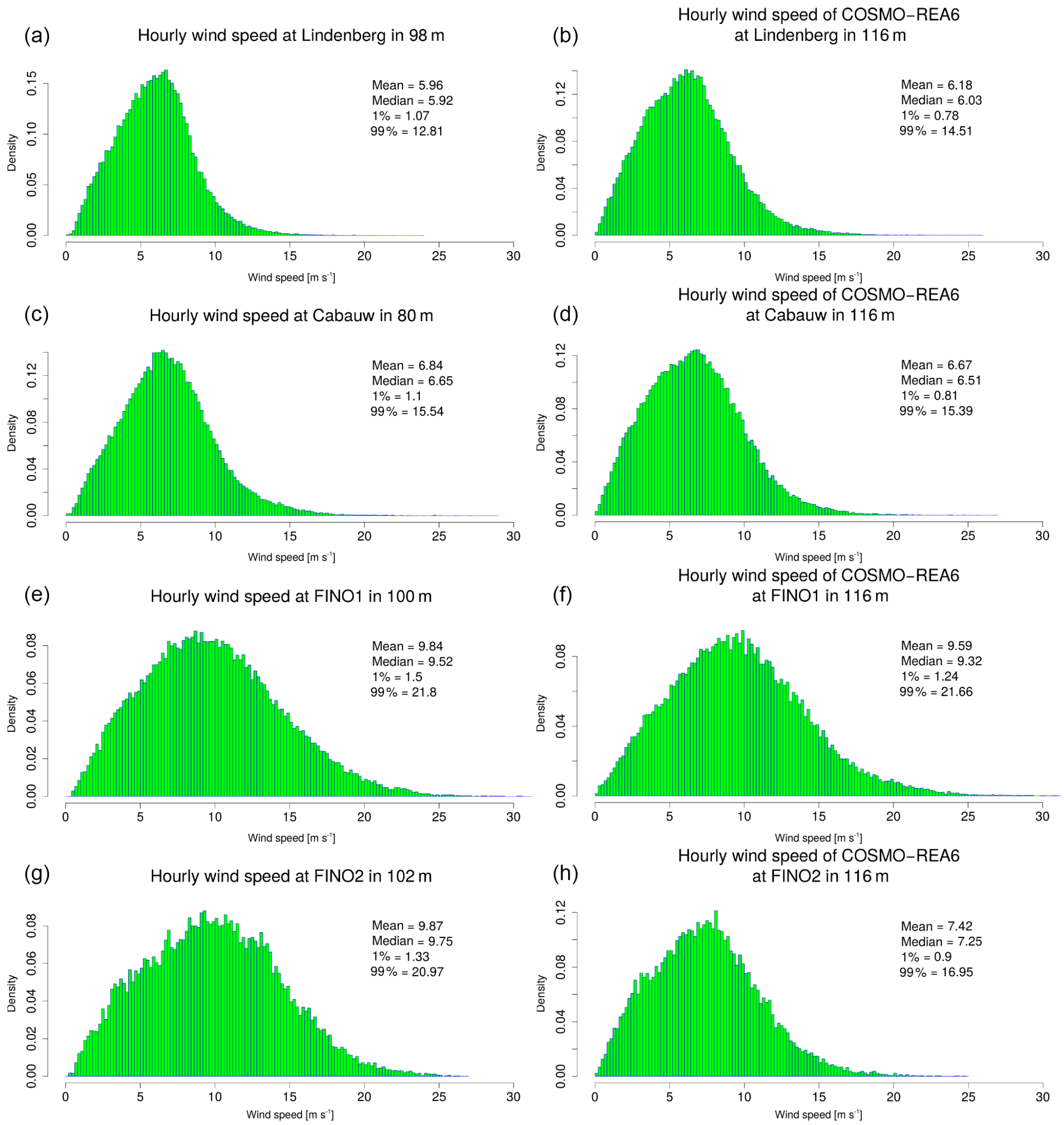

Figure 2. Histograms of the probability distributions of wind speed for Lindenberg, Cabauw, FINO1, and FINO2 measurements (left, from top to bottom, respectively) and the corresponding COSMO-REA6 histograms for the location of the measurements (right). Values on the right side of each panel describe the mean, median, 1 % percentile, and 99 % percentile for the corresponding histograms in $\mathrm{m\,s^{-1}}$.

REA6) and the global (ERA-Interim and ERA20C) reanalyses. The range of the box plot whiskers indicates 1.5 times the interquartile range. Median values of measurements and reanalyses are of comparable values throughout the height range, but the COSMO-REA6 reanalysis underestimates variability at Cabauw and overestimates it at Lindenberg. Specifically, at 10 m, the medians for Cabauw and Lindenberg measurements lie within 10 % of each other, for FINO1 and FINO2 the deviation between the reanalysis data is only slightly higher. The wind speed increases with height as expected and median values between measurements and regional reanalyses are nearly the same. However, the variability – given here as the range of the box plot whiskers – of the Cabauw measurements is more than 20 % larger than the COSMO-REA6 data at 10 m, whereas with increasing height, the difference in variability decreases. At the Lindenberg mast, the variability at 10 m as derived from COSMO-REA6 is 10 % lower than observed. However, in all heights above, the COSMO-REA6 variability is systematically larger than observed. The variability of the global reanalyses at 100 m is also larger than observed.

In Fig. 2 the probability density distributions of wind speed for the tower measurements at about 100 m height and the corresponding ones for COSMO-REA6 of the fourth model level at 116 m a.s.l. are shown. For illustration purposes the mean, median, 1 % percentile, and 99 % percentile of each distribution are given. The mean and median values for Lindenberg, Cabauw, and FINO1 are in the range

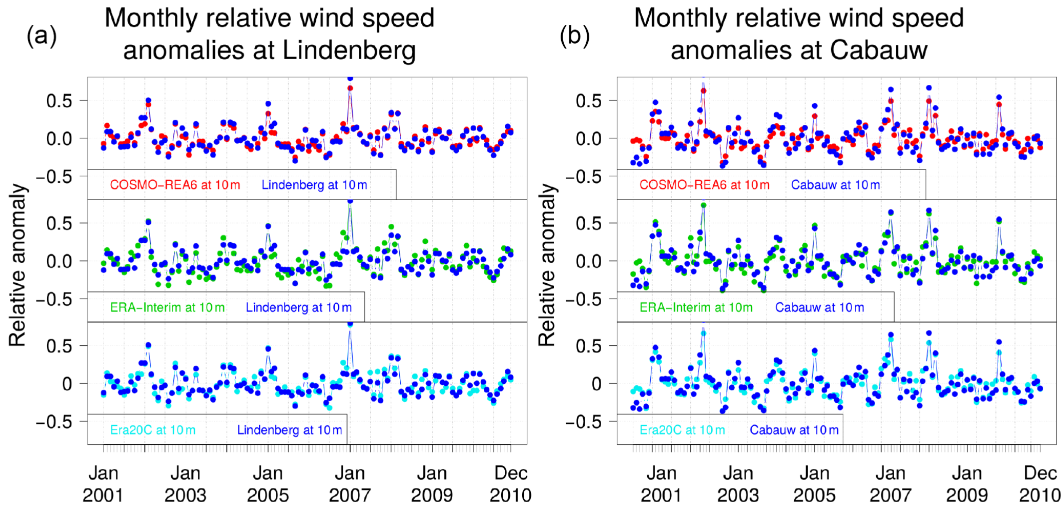

Figure 3. Time series of relative anomalies in monthly mean wind speed at Lindenberg (left) and Cabauw (right) mast measurements at 10 m height against regional reanalysis (COSMO-REA6) and global reanalyses (ERA-Interim and ERA20C).

of $0.2\,\mathrm{m\,s^{-1}}$ within the corresponding COSMO-REA6 values. Only for Lindenberg, the COSMO-REA6 mean and median values are higher than the measurements. The 1 % percentile values are lower for all three COSMO-REA6 sites, whereas the 99 % percentile values are similar between measurements and COSMO-REA6 for Cabauw and FINO1 but higher for COSMO-REA6 at Lindenberg. For FINO2, the measurements yield mean and median values which are about $2.5\,\mathrm{m\,s^{-1}}$ higher than COSMO-REA6; also the 99 % percentile is higher by $4\,\mathrm{m\,s^{-1}}$. This finding is in-line with Durante et al. (2012) and Hahmann et al. (2015) who also found an under-prediction of wind speed by their meso-scale model compared to FINO2 measurements.

A direct comparison of absolute values between mast measurements and COSMO-REA6 output on a specific height level is not recommended because these are influenced by biases which could be caused by insufficient representativity, mismatching heights, and mismatching surface roughness. This is especially true for comparisons over land where height mismatch might be large due to differences between model and real orography. Note further that surface roughness is kept constant with time in COSMO-REA6. For these reasons we recommend using the anomalies when working with reanalysis data, as presented below.

Figures 3 and 4 show the time series of the reanalysis versus observed monthly wind speed anomalies. Figure 3 shows the time series of the monthly mean anomalies at 10 m for Lindenberg and Cabauw and Fig. 4 shows the monthly mean anomalies at around 100 m height for Lindenberg, Cabauw, FINO1, and FINO2. The corresponding correlation coefficients of the monthly means from Figs. 3 and 4 are shown in Fig. 5 (top left) together with their 95 % confidence intervals.

At the height of around 100 m on a monthly scale there seems to be hardly any difference between regional and global reanalysis correlation with observations, regardless whether the location is over the sea (FINO1 and FINO2), close to the sea (Cabauw), or a representative inland site. The only exception is Lindenberg at 10 m height, where COSMO-REA6 correlation is higher than the global reanalyses, albeit for a confidence smaller than 95 % (note that in Fig. 5 (top left) the 95 % confidence intervals are nearly adjacent).

Daily time series were calculated from the native temporal resolution (i.e., hourly for observations and COSMO-REA6, three-hourly for ERA20C, and six-hourly for ERA-Interim) and correlations are shown in Fig. 5 (top right). In this case, the regional reanalysis has significantly higher correlations with the measurements than the global reanalyses, for nearly all locations. To exclude the effect of different temporal sampling for the daily means, the daily values are calculated again by using six-hourly values only for each reanalysis and observation time series and correlations are shown in Fig. 5 (bottom left). In this case, the overall correlation decreases. The advantage of COSMO-REA6 is reduced and in Lindenberg at 98 m ERA-Interim has a higher correlation. Figure 5 (bottom right) shows the correlations based on the instantaneous values sampled six-hourly. At this high temporal resolution, the correlations generally reduce compared to the daily ones. At FINO1 and FINO2 the advantage of COSMO-REA6 slightly increases, whereas at Lindenberg and Cabauw 10 m it is clearly reduced. At Lindenberg in 98 m and Cabauw 140 m the advantage of ERA-Interim increases. For daily and hourly correlations, the highest values are found for COSMO-REA6 at FINO1 and FINO2.

Figure 6 shows the annual cycle of relative monthly wind speed at Lindenberg, Cabauw, FINO1, and FINO2 for 10 and around 100 m. At Lindenberg, the COSMO-REA6 exhibits an increasing variability with height ranging between 20 % at 10 m and 35 % at 116 m. ERA20C shows similar variabil-

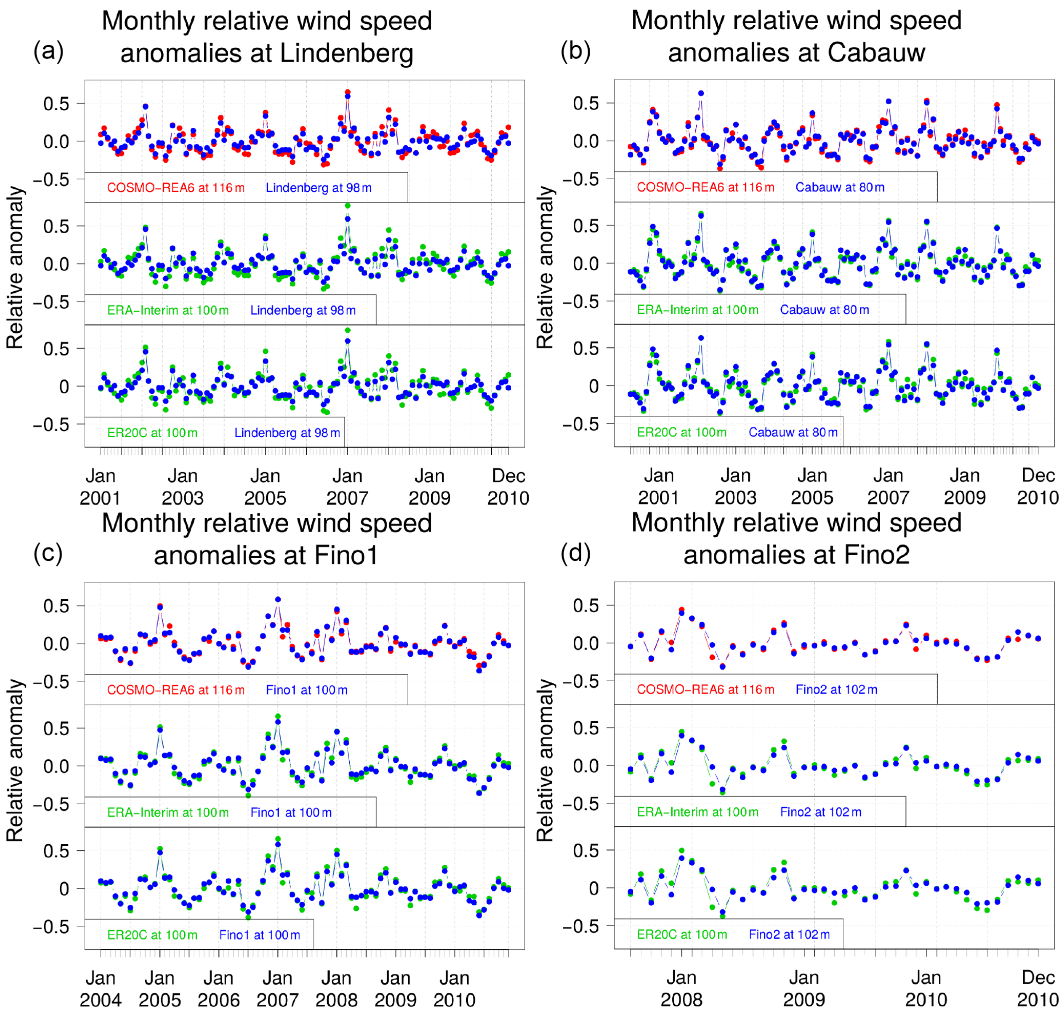

Figure 4. Same as Fig. 3 for Lindenberg (top left), Cabauw (top right), FINO1 (bottom left), and FINO2 (bottom right) at around 100 m height.

ity (25 and 35 %, respectively). ERA-Interim variability is larger at the 10 m with 30 % and the same as the other reanalyses at 100 m with 35 %. The measurements, however, contain a much lower variability at 98 m of only 20 %. At 10 m the variability of the measurements is about 25 %. For Cabauw, the measurements again show a lower variability at 10 m (25 %) than at 80 and 140 m (40 %) whereas this time the COSMO-REA6 RRA exhibits for both heights (10 and 116 m) a very similar variability of about 45 %. The global reanalyses show also a very similar variability at both heights (10 and 100 m) of about 40 %. At FINO1 and FINO2, the variability in COSMO-REA6 is larger at 10 m (45 %) than at 116 m (40 %), the latter matching the observed variability at 100 m. There is hardly any difference between 10 and 100 m variability in the global reanalyses and it is similar to that of the RRA at 10 m.

For all observations and reanalysis data and every height level a well developed annual cycle is visible with the minimum occurring in summer and the maximum in winter. There are contradicting results concerning the height dependency of the annual cycle of the wind speed variability. On the one hand, the annual cycle is growing with height for COSMO-REA6 at Lindenberg and, to a lesser extent, for ERA20C, which is hardly confirmed by the measurements where no height dependency is present. In contrast, at Cabauw, the measurements show a clear height dependency, whereas no height dependency is present in the reanalyses' annual cycles of wind speed variability. Over the ocean at the FINO platforms (only 100 m measurements were used), COSMO-REA6 shows a slight height dependence of wind speed variability, which cannot be detected in the ERA20C wind fields.

Figure 7 shows the diurnal cycle of mean hourly wind speed at each Lindenberg and Cabauw measurement level and the model level output of the reanalyses. At both locations at 10 m height, measurements and reanalyses show a diurnal cycle with a maximum in the early afternoon. For

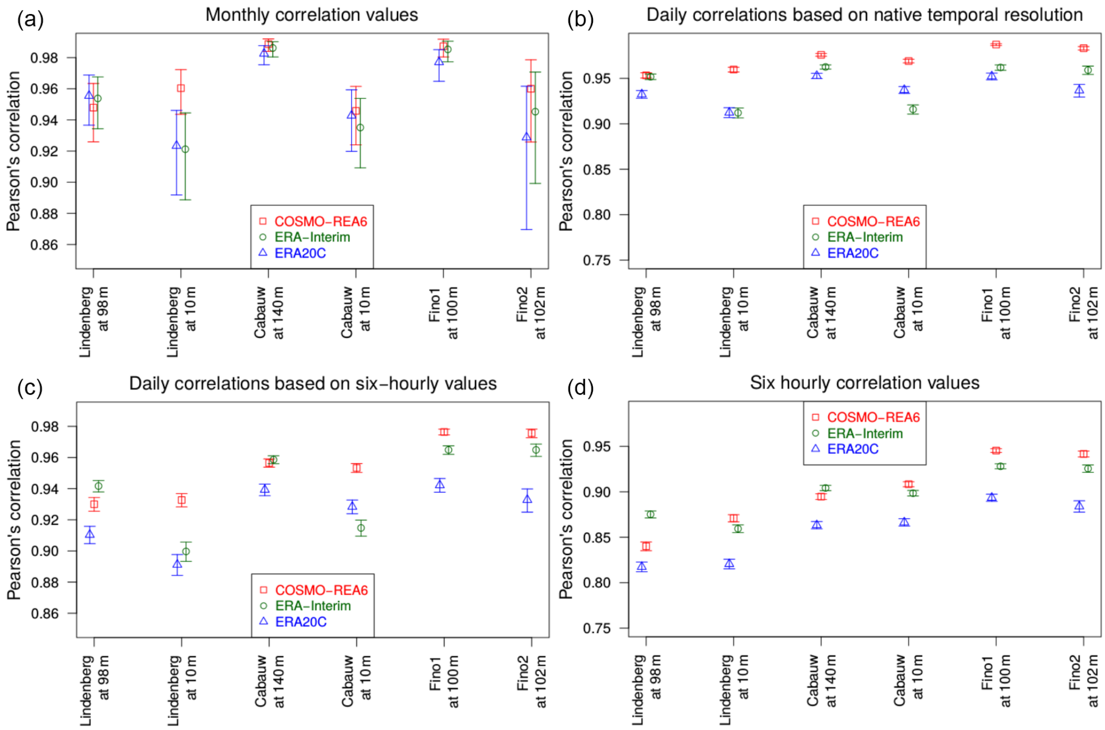

Figure 5. Pearson's correlation for monthly mean wind speed (top left), for daily mean wind speed on the native temporal resolution (top right), for daily mean wind speed of six-hourly values (bottom left), and for six-hourly mean wind speed (bottom right) between tower measurements and reanalyses. Shown is the 95 % confidence interval for each correlation value.

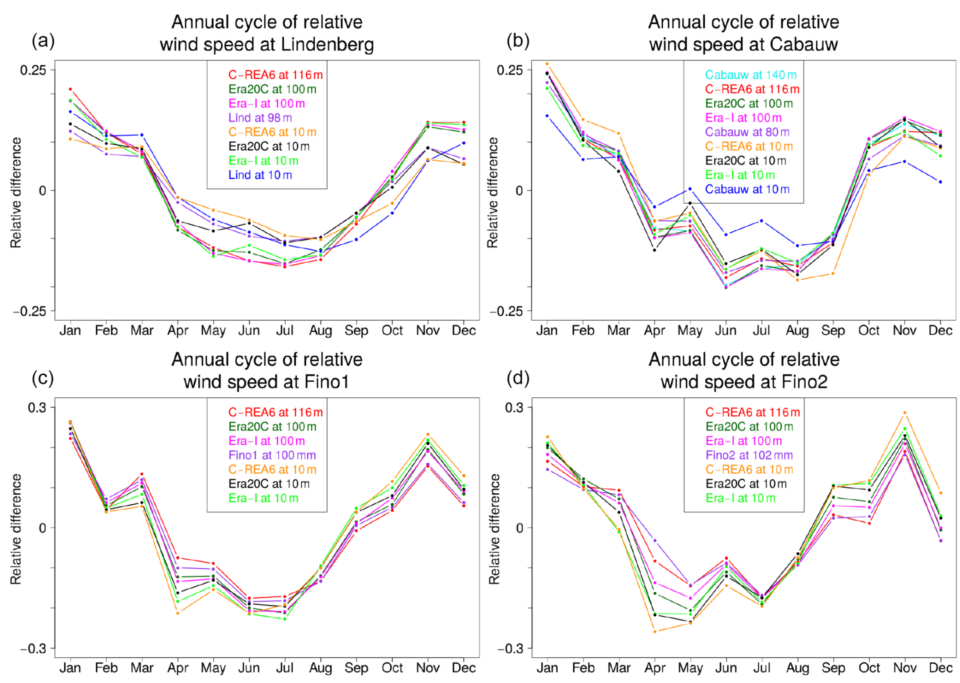

Figure 6. Annual cycle of relative monthly wind speed (anomaly) of 10 and 100 m at Lindenberg (top left), Cabauw (top right), FINO1 (bottom left), and FINO2 (bottom right).

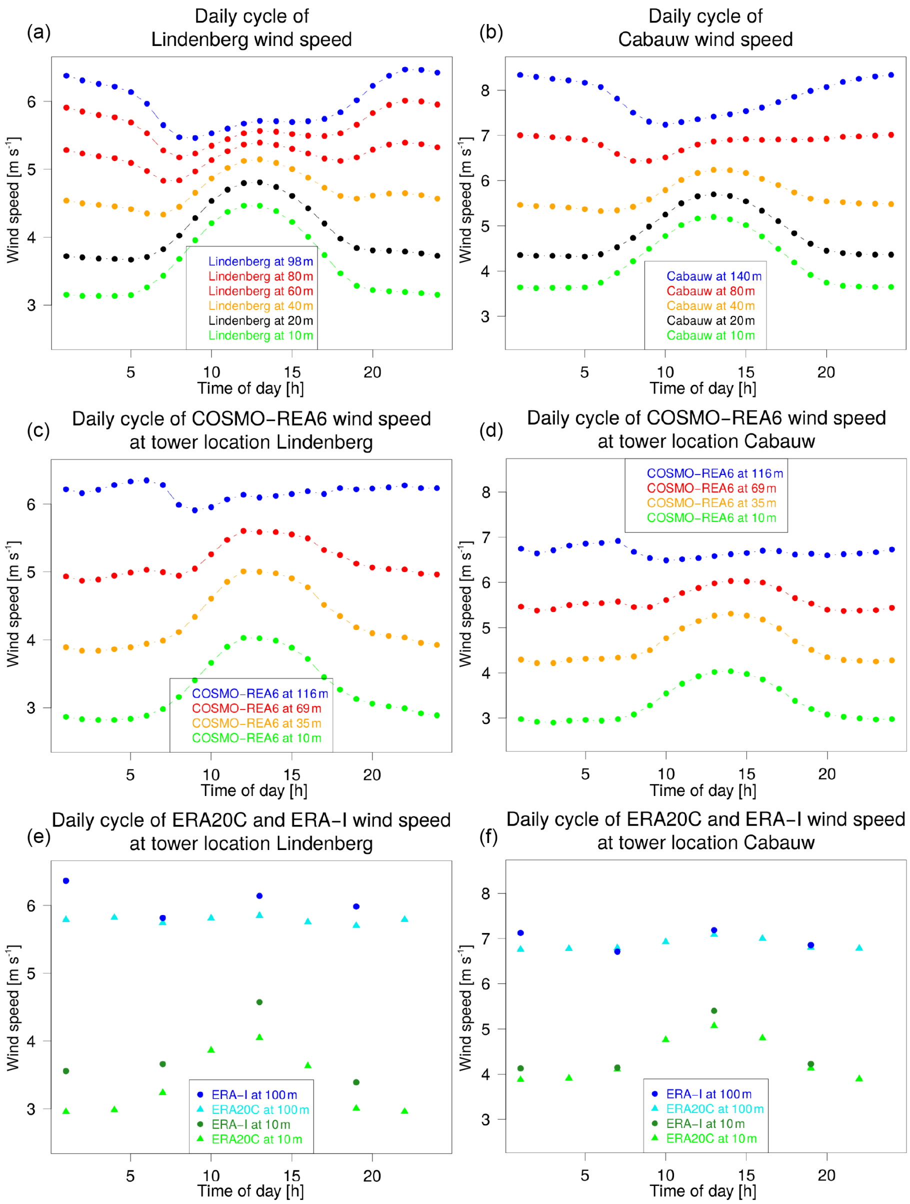

Figure 7. Diurnal cycle of wind speed at the location of Lindenberg (left) and Cabauw (right). Mast measurements are shown at the top, COSMO-REA6 values in the middle, and global reanalyses in 10 and 100 m height at the bottom.

COSMO-REA6 the diurnal cycle remains pronounced up to 40 m and degrades from 60 m height onwards. The observed reversal with height is not captured. The amplitude of the diurnal cycle in COSMO-REA6 is generally smaller than observed. For instance, at 10 m, the COSMO-REA6 mean diurnal cycle is about 33 % with respect to the minimum, whereas the mast measurements record about 50 %. The relatively good match of COSMO-REA6 with observations at the ground and mismatch above can be explained by the parametrizations of the boundary layer and the sub-grid scale orography which were particularly optimized with respect to the observed 10 m wind speed statistics (Schulz, 2008).

5 Conclusions

In this study we have compared the wind speed of the regional reanalysis (COSMO-REA6) against mast measurements in Northern Germany (Lindenberg, FINO1, FINO2) and in The Netherlands (Cabauw). We compared the results with the ones obtained with two global reanalyses (ERA-Interim and ERA20C). The reanalyses' median wind profiles are generally consistent to the observed ones.

The FINO platforms are located over the sea. Their mean winds and their variability are higher, and their height dependency less pronounced than for the stations over land. These effects are captured by the reanalyses.

The correlation coefficient of observed long-term monthly mean time series against the reanalyses range between 0.92 (within a 95 % confidence interval of $<0.892,\ 0.946>$) at 10 m and 0.99 $<0.982,\ 0.991>$ at 116 m. At Lindenberg at 10 m the regional reanalysis is correlated significantly higher $<0.945,\ 0.972>$ than ERA-Interim $<0.889,\ 0.945>$ and ERA20C $<0.892,\ 0.946>$. At Cabauw at 10 m the differences are not significant. In 100 m, at all sites, there is no difference in the correlations of the monthly measurements against the global and regional reanalyses, respectively.

The correlation coefficient of observed long-term daily mean time series against the reanalyses have much reduced confidence intervals, due to the higher number of data points. With the daily means, the correlations for the regional reanalysis COSMO-REA6 are significantly higher than for the global ones, except for Lindenberg at 100 m and Cabauw at 140 m.

The contrast between the daily and monthly results is striking, especially the clearly significant advantage of the regional reanalysis in the daily correlations caused partly by the higher temporal resolution of COSMO-REA6. More research is needed to pinpoint the cause of the remaining gain. It could possibly be due to the higher resolution, or the favourable tuning of the COSMO-model in this area, or due to the data assimilation, especially of the 10 m synoptic winds in the surroundings. Increasing temporal resolution further, reduces the advantage of the regional reanalysis. At around 100 m, ERA-Interim yields a higher correlation at Lindenberg and Cabauw, whereas COSMO-REA6 yields a higher correlation at FINO1 and FINO2.

In the investigated area, the observed annual cycle of wind speed is reproduced in the three reanalyses. Wind speed is highest in January and smallest in the summer months.

The annual cycles of variability are generally reproduced from 10 up to 116 m.

At 10 m, all investigated reanalyses yield a realistic diurnal cycle. In COSMO-REA6, the diurnal cycle is qualitatively captured up to approximately 40 m. Aloft, the ability of COSMO-REA6 to capture the diurnal cycle degrades. At 100 m height, there is a distinct diurnal cycle left in the measurements over land, which is not reproduced by the three reanalyses.

These numbers reflect the accordance of observations and reanalyses in an area of favourable conditions, i.e., over sea and over flat land. Though even over flat terrains there remain differences, which could be caused e.g., by shortcomings in model parametrization, model orography, land use, surface roughness or stability representation. In addition, there might be local processes which are not modelled. Also, we compare here point measurements with grid cell values, i.e., different spatial resolutions, the effect should be mitigated by analysing time averages.

We expect that in more hilly terrain orographic effects will degrade the congruence between the measurements and reanalyses.

6 Data availability

The Cabauw data is publicly available at http://www.cesar-database.nl, the FINO data are available at http://fino.bsh.de, the Lindenberg data are available through the providing organization only. The regional reanalysis COSMO-REA6 has been made available for some parameters (including wind speed) through https://www.herz-tb4.uni-bonn.de/ and the global reanalyses ERA-Interim and ERA20C are available through ECMWF (http://apps.ecmwf.int/datasets/).

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