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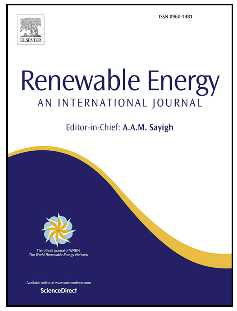

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The added value of high resolution regional reanalyses for wind power applications

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Abstract

Atmospheric reanalyses are the only source of spatial and temporal gridded wind information at wind turbine height providing data over several decades in the past. The application potential of reanalyses in the renewable energy sector depends strongly on the quality of the meteorological quantities. While global reanalyses have a resolution of typically 50 km, new regional reanalyses COSMO-REA6 and COSMO-REA2 have about 6 km and 2 km horizontal grid spacing, respectively. Here, we investigate the added value of the new regional reanalyses for the renewable energy sector, especially their application potential for site assessment. Four well established wind towers in Europe are used as reference for this purpose. We find regional reanalyses performing significantly better or at least similar to global reanalyses. Especially marginal distributions show significant improvements e.g. the most extreme temporal wind changes (ramp rates) at typical hub-heights are underrepresented by global reanalyses between -80 to -43% while COSMO-REA2 represents them with relative errors between -14 to +9%. Considering biases, mean absolute errors, and correlations most significant improvements occur close to ground and in areas with complex terrain. Moreover, vertically extrapolated wind measurements which are commonly used for site assessment show a stronger site dependency in their performance than reanalyses.

Keywords: Reanalyses, Wind speed, Renewable energy, Power law, Jackknife resampling, Site assessment

1. Introduction

Atmospheric reanalyses - best guesses of the atmospheric state in the past derived by combining numerical weather prediction models and observations - become increasingly important in the field of wind and solar energy applications (e.g. Rose and Apt, 2015; Kubik et al., 2013; Cannon et al., 2014; Staffell and Pfenninger, 2016; Pfenninger and Staffell, 2016). The importance of atmospheric reanalyses in the energy sector is driven by the need of highly resolved long-term information of atmospheric variables on a uniform grid. In this way, area resolved power simulations become possible including all variability scales of the local weather conditions - from short-term (~ hourly) till inter-annual variability. These simulations are expected to play a key role to answer many current research questions related to topics such as e.g. (1) spatial compensation potential of power production (Henckes et al., 2018), (2) planning of a sustainable power system, and closely related (3) the dimensioning of necessary storage capacities in a renewable energy dominated electricity grid (Nelson et al., 2012). These questions are currently only approachable by the use of atmospheric reanalyses. Either with global reanalyses, covering the whole globe with relatively coarse resolution, or with high resolution regional reanalyses, covering a part of the globe with finer resolution.

The main advantage of reanalyses is the provision of spatially resolved wind information on any desired height (e.g. hub-height) from hourly till climatological scales. Therefore, in the renewable energy sector reanalyses are sometimes applied in so-called measure-correlate-predict (MCP) methods where short-term measurements are related to some long-term products (e.g. reanalyses) to estimate climatological wind characteristics at a target site (Carta et al., 2013). A more general application of reanalyses provided weather data can be found in so-called re-forecasts. Here, reanalysis data are used as input to numerical weather prediction models without data assimilation. With the given reanalysis as reference, re-forecasts are a typical tool for model validation and subsequent improvements, also in terms of renewable energy related variables (Dabernig et al., 2015).

A further advantage of reanalyses in the renewable energy sector is that they provide both wind and solar radiation in a physically consistent way. This is not the case when using different sources for the quantities wind and solar radiation. Thus, reanalyses are the only way to make use of the weather dependent spatio-temporal correlations between different types of renewable energy production.

High potential of regional reanalyses lies in the field of site assessment where up to now tower measurements are vertically extrapolated to get local wind information at potential sites. Typical vertical extrapolation as for example evaluated by Gualtieri and Secci (2011) can introduce uncertainties in the derived hub-height wind speed characteristics. Nevertheless, the extrapolated wind speed information is typically used in site assessment. Thus, the resulting extrapolated wind speed quality represents a benchmark for possible alternative hub-height wind speed sources which might be provided by new high resolution regional reanalyses. Note, for Germany those towers are prescribed to have a minimum height of 2/3 (66 m) of the target height (100 m) and need to measure for at least one year (Fördergesellschaft Windenergie und andere Erneuerbare Energien, 2011). Those measurement requirements are an expensive part of site assessment studies which might be avoided.

If reanalyses became accurate enough for site assessment the costly tower measurements of local wind characteristics might be avoided. Furthermore, as reanalyses are typically multi-year products they automatically provide climatological information and therefore might solve the problem of the limited measurement periods.

Up to now most applications still use global reanalyses which cover the whole Earth with horizontal resolutions of tens of kilometers. Recently, new high resolution regional reanalyses with horizontal resolutions of a few kilometers were developed called COSMO-REA6 (Bollmeyer et al., 2015) and COSMO-REA2 (Wahl et al., 2017). One of the central questions of this work is to what extent the field of renewable energy can benefit from these new regional reanalyses.

The evaluation of the regional reanalyses COSMO-REA6 concerning hub-height wind speed is up to now only based on long-term averages. Borsche et al. (2016) studied the wind speed variability between 10 and 116 *m* height from COSMO-REA6 on the monthly scale using tower measurements. They showed that COSMO-REA6 mean winds are realistic and at least as close to the measurements as the global reanalyses ERA20C (Poli et al., 2013) and ERA-Interim (Dee et al., 2011). Considering close to ground wind validation Kaiser-Weiss et al. (2015) compared the regional reanalyses COSMO-REA6 with global reanalyses and near-surface winds in Germany. They showed that for the majority of stations the Weibull parameters of the daily mean wind speed frequency distribution match well with the ones derived from the reanalyses fields. Furthermore, Camargo et al. (2018) performed a close to ground wind assessment of the two regional reanalyses for the Czech Republic and in close cross-border regions.

Not yet investigated, is the strength of regional reanalyses - also compared to global reanalysis - to represent the actual wind speed at hub-height at hourly resolution. Moreover, to our best knowledge, there is no literature accessing new high resolution reanalysis in terms of their site assessment potentials.

The main goal of this study is to provide a comprehensive assessment of the new regional reanalyses COSMO-REA based on tower observations and its competitive performance to global reanalyses. In this way, the study investigates how reanalyses reproduce different wind characteristics relevant for the renewable energy sector. Here, the focus is put on biases, temporal wind speed changes, vertical gradients and low wind persistencies at different heights. The added value of regional reanalysis is worked out by additionally considering global reanalyses in all validation steps. Moreover, in order to judge the application potential of regional reanalysis for site assessment studies we additionally compare the uncertainty of reanalyses with that of vertical extrapolated wind measurements. In a last step we investigate how biases and uncertainties of wind simulations propagate through conversion models to the final product of wind power estimates. As reference for validation, measurements of four tall towers (>100 m) in central Europe located in different environments are used.

The structure of this paper is as follows. Section 2 describes the reanalyses and observational data sets. Vertical wind extrapolation methods and the applied method to estimate the uncertainties of later results are provided in section 3. The main part of section 4 provides a comprehensive evaluation of the different products to represent tower measurements up to 280 m, while a last part assesses the reanalyses potential to simulate power production. Section 5 provides a discussion of the results and relates it to other findings in literature.

2. Reanalyses and observations

2.1. High resolution regional reanalyses

The two reanalyses COSMO-REA6 (REA6) (Bollmeyer et al., 2015) and COSMO-REA2 (REA2) (Wahl et al., 2017) have been developed within the Climate Monitoring Branch of the Hans-Ertel-Centre for Weather Research[1]. Both, REA6 and REA2 are based on the COnsortium for Small-Scale Modelling limited-area model (COSMO 4.25.2 and COSMO 5.00.2, respectively), which is part of the operational Numerical Weather Prediction (NWP) model chain of the German Meteorological Service (DWD). The output frequency of all variables of both reanalyses is one hour for 3D variables (e.g. wind profiles) and 15 minutes for 2D variables.

COSMO-REA6 covers the European domain CORDEX EUR-11 (Jacob et al., 2014) with a horizontal resolution of about 6 km and 40 vertical layers. Currently, COSMO-REA6 is available for the period 1995-2017. The production of later periods is ongoing. COSMO-REA2 covers Germany and parts of the neighbouring countries with a horizontal resolution of about 2 km and 50 vertical layers. The reanalysis is currently available from 2007-2013 which determines the time window for the present study. At the tower sites, where the comparison of reanalyses and measurements is performed, COSMO-REA6 and COSMO-REA2 cover the lowest 350 m above ground with about seven vertical layers (Fig. 1).

The boundary conditions for the limited area reanalyses COSMO-REA6 is provided by the global reanalyses ERA-Interim (Dee et al., 2011), COSMO-REA2 is driven by COSMO-REA6. The data assimilation scheme to adjust the model state to the observations is the nudging scheme, which is a stepwise adaptation of prognostic variables towards observed values. An overview of the assimilated wind observations close to the measurement towers will be shown in section 2.4.

The main differences between the two COSMO-reanalyses are (1) the spatial resolution, (2) the deep-convection permitting in COSMO-REA2 (deep-convection is resolved explicitly), and (3) the additional assimilation of weather radar data in COSMO-REA2 (Bollmeyer et al., 2015; Stephan et al., 2008).

2.2. Global reanalyses

The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2, Gelaro et al., 2017), is the latest global reanalysis produced by the NASA Global Modeling and Assimilation Office (GMAO, Molod et al., 2015). MERRA-2 is based on the Goddard Earth Observing System Model, Version 5. Observation assimilation is performed by a three-dimensional variational data assimilation scheme (3DVAR). The MERRA-2 product is available from 1980 to present with a horizontal grid resolution of about 0.5° x 0.625° (latitude x longitude). The vertical wind profiles are available every 3 h. In the lowest 350 m above ground the output is provided at four different heights (Fig. 1). When using reanalyses for wind energy related studies MERRA-2 is most commonly used (e.g. Cannon et al., 2014; Kubik et al., 2013). This qualifies MERRA-2 to be the benchmark reanalysis in the wind energy sector.

ERA-Interim (Dee et al., 2011) is the second global reanalysis used in this study. ERA-Interim provides meteorological fields from 1979 to present. The numerical weather prediction model used to produce ERA-Interim is the Integrated Forecasting System of the European Centre for Medium-Range Weather Forecasts (ECMWF) in the operational version of 2006 (IFS release Cy31r2). The horizontal resolution of ERA-Interim is approximately 80 km. The applied data assimilation scheme is a four dimensional variational assimilation scheme. The stored output frequency of 3D variables is 3 hourly whereby the 0, 6, 12, and 18 UTC fields are analyzed and 3, 9, 15, and 21 UTC are forecast fields.

2.3. Tower measurements

Tower measurements are the only in-situ observations at hub-height with high quality and high temporal resolution. However, publicly accessible tower measurements of high quality over long time periods are limited to a very small number of locations. Here, we make use of four well established meteorological towers between 98 m and 280 m height in central Europe (joint region of all reanalyses). All towers used are onshore, since the added value of regional

[1]https://www.herz-tb4.uni-bonn.de

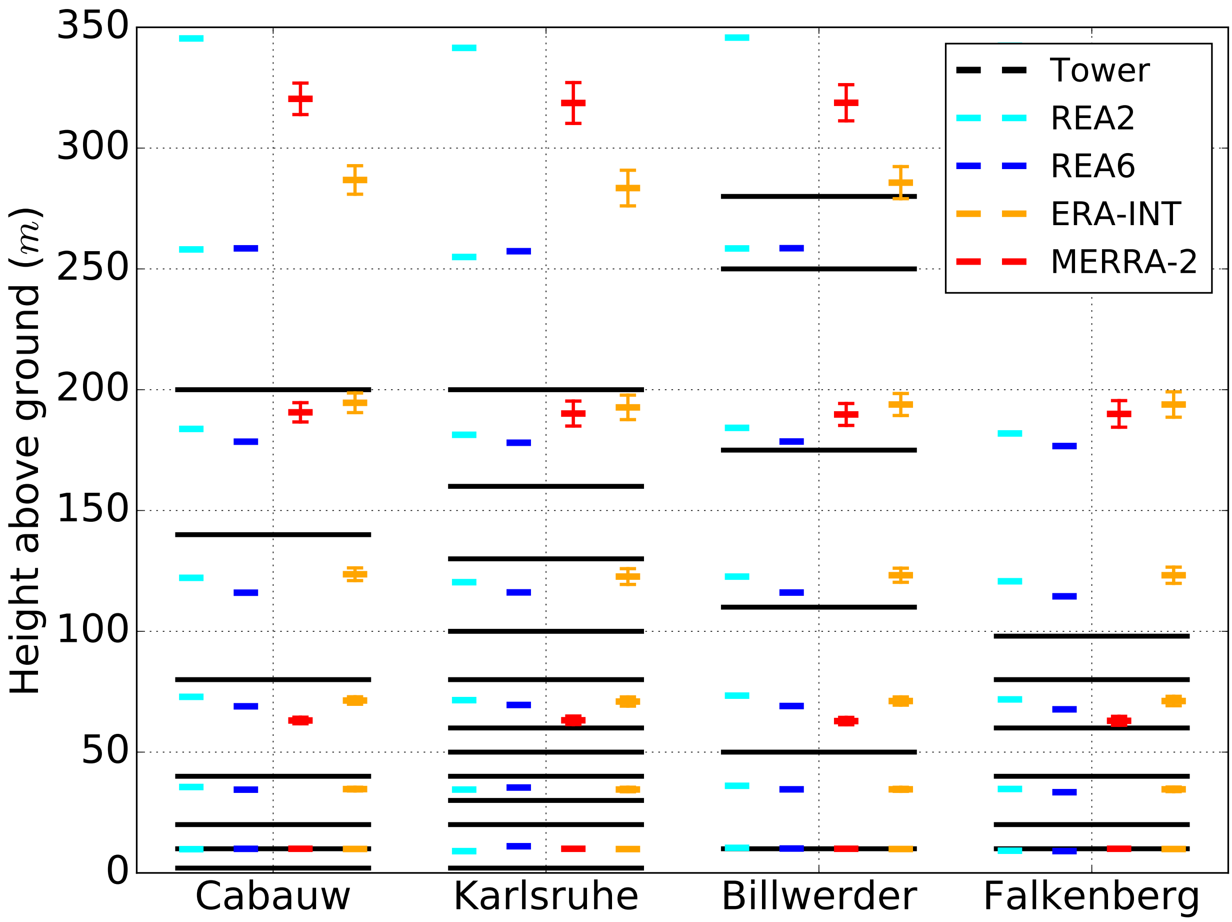


Figure 1: Vertical levels of reanalyses products and wind measurements at the different tower sites. Measurement heights are depicted as horizontal lines. Model height levels are drawn as short lines. ERA-Interim and MERRA-2 levels are shown with standard deviations, since their model level heights depend on pressure.

Table 1: Meteorological tower locations and number of considered data points, i.e. the number of considered time steps. Only time steps with measurements on all tower heights available are considered. The evaluation time span in total is 7 years from 2007-2013. Beside the number of data, the year equivalent indicates the data availability in terms of years.

Tower	Latitude	Longitude	Height a.s.l (m)	# Data	Year equivalent
Cabauw, Netherlands	51.970	4.926	-0.7	20455	7.0
Hamburg, Germany	53.519	10.103	0.3	15366	5.3
Karlsruhe, Germany	49.093	8.426	110.4	18465	6.3
Lindenberg, Germany	52.166	14.122	73	19914	6.8

reanalyses is expected to be more prominent in complex environments. The four towers are located in rather different wind climate conditions. The mean wind speed at 100 m varies between 4 ms^{-1} in Karlsruhe and 7 ms^{-1} in Cabauw (see Fig. 2).

The KNMI-Cabauw tower is part of the Cabauw Experimental site for atmospheric research (CESAR) observatory located in the western part of the Netherlands in flat grass land (Van Ulden and Wieringa, 1996). The weather tower Hamburg is the observation site of the University of Hamburg and the Max-Planck-Institute for Meteorology (Brümmer et al., 2012). The tower is located in a surrounding of agricultural fields, close to flat suburban buildings, and to industry in the west. The Lindenberg tower is operated by the Meteorological Observatory Lindenberg (Richard Aßmann Observatory) of the DWD in a region of grass, fields and forest (in the surrounding area of $< 10\,km$) (Beyrich and Adam, 2007). The fourth tower operated by the Karlsruhe Institute for Technologie (KIT) is located directly within a 40 m high forest (Kohler et al., 2018). For the measurements in Lindenberg, Cabauw, and Hamburg comprehensive quality control is performed by Petrik et al. (2019). The quality control applied to measurements in Karlsruhe is described in Kohler et al. (2018).

Each site provides wind speed and direction at individual heights and for individual time periods. At all sites cup-anemometers are installed to measure the wind speed. For our study 10 min averages are taken. We only use time steps for which measurements are available at all measurement heights. For reasons of temporal matching we use a frequency of 3 hours which is the output interval of the global reanalyses. The general data availability per site in the evaluation period 2007-2013 is 5-7 years. An overview on data availability of the towers and site specific characteristics is given in Tab. 1 and figure 1. Note, that for Hamburg measurements at 280 m are less frequent (7266 data points $\sim$ 2.5 years), since measurements at that level only started in 2010. To avoid disturbances by the tower itself the lowest measurements are often performed at small separate towers. The 10 and 20 m measurements in Cabauw for example are performed on two separate small towers in the north and the south of the main tower. In Karlsruhe and Hamburg towers in a distance of 50 m (outside the forest) and 30 m, respectively, are used to measure close to ground variables.

For a later classification of the data into different stability regimes, additional measurements of temperature and global radiation are used (see sec. 3).

2.4. Assimilated observations

To guarantee a fair comparison between the different reanalyses it is important to know if wind measurements from the reference towers or any other wind related observations close to the towers were used in the assimilation process. If specific observations are assimilated into one, but not into the other reanalyses, a different performance is expected. Generally, none of the tower measurements themselves were assimilated into any of the reanalyses.

However, since most of the towers are located close to meteorological supersites, other data were used for assimilation. An overview of assimilated wind observations close to the tower sites is given in Tab. 2. In Cabauw and in Lindenberg wind profiler observations in heights above at least 500 m are assimilated. Thus, although the assimilation height is not equal to the tower measurement height care should be taken when interpreting the performance of the reanalyses at those sites, since reanalyses data are spatially coupled. Although the minimum distance between towers and the next 10 m wind measurement is 5 km, it is worth mention that only ERA-Interim does not assimilate 10 m wind at all. Thus, one could expect that all other reanalyses perform a bit better in representing the tower measurements.

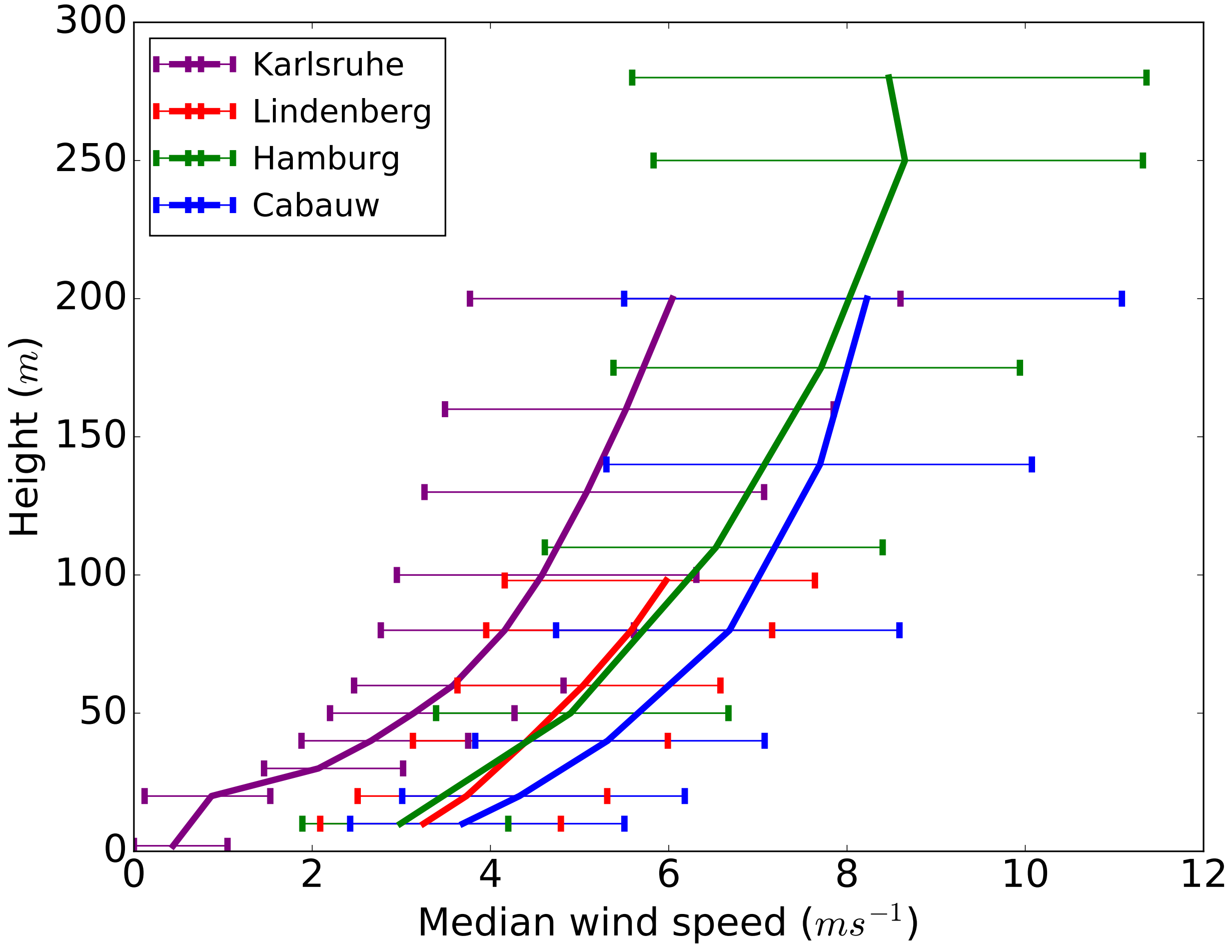


Figure 2: Measured wind speed at the different tower locations and heights. Shown are the 25, 50, and 75th percentiles.

Table 2: Wind observations used for data assimilation in the four considered reanalyses.

Reanalysis	Site name	Instrument/Product	Location	Temporal frequency
All	Cabauw	Wind profiler above ∼500 m	300 m south	Hourly or 30 min
All	Lindenberg	Wind profiler above ∼500 m	5 km	Hourly or 30 min
MERRA-2, ERA-Int	All	Satellite derived cloud motion vectors	-	-
MERRA-2, REA6, REA2	Lindenberg	10 m wind	5 km	-
MERRA-2, REA6, REA2	Hamburg	10 m wind	∼ 10 km	-
MERRA-2, REA6, REA2	Cabauw	10 m wind	20 km, De Bilt	-
All	Lindenberg	Radiosonde	5 km	4/day at 0,6... UTC
All	Cabauw	Radiosonde	20 km, De Bilt	1/day at 0 UTC

3. Methods

3.1. Matching of model and measurements

All reanalyses have different vertical grids (Fig. 1). In order to compare the reanalyses wind speed with tower measurements a linear interpolation from model levels to the tower heights (Fig. 1) is applied. In cases of nonlinear vertical profiles this approach induces errors whose magnitude depends on the specific wind profile and the vertical resolution of the model. Since the vertical model resolution close to ground is quite high for the used reanalyses (between 30 and 80 m for REA2, REA6, and ERA-Interim and between 50 and 150 m for MERRA-2, see Fig. 1) this issue is ignored here.

The horizontal matching of gridded reanalyses data with point measurements is done by the nearest neighbour approach. Temporally, the different data products are analysed every 3 h, determined by the output interval of the global reanalyses. In contrast to reanalyses which provide domain representative values, tower measurements are point values. The matching of spatially representative values with point values is not exactly possible, but the differences can be reduced by temporal averaging of the point values under consideration of meteorological processes and associated scales. Considering a typical horizontal wind speed of $U = 10\,ms^{-1}$ in a $L = 6\,km$ grid box it would need $T = L/U = 600\,s$ to cross the whole spatial length of the grid box (Stull, 1988a). Thus, the 10 min averages of point measurements compare best with instantaneous values of a reanalysis with 6 km horizontal grid spacing. This seems to be an advantage for the regional reanalyses because global reanalyses are not expected to resolve phenomena close to the 6 km scale. Nevertheless, many renewable energy applications benefit from higher resolution.

3.2. Uncertainty estimates

When comparing statistical parameters, such as median or RMSE, a confidence level is calculated. The confidence intervals are derived by the use of the Block-Jackknife method (Kaigh, 1983). Similar to the Bootstrap method, the Jackknife method is a resampling technique to estimate confidence intervals of a statistical parameter $\theta(x)$ derived from one sample x with unknown underlying distribution (non-parametric estimator) (von Storch and Zwiers, 2001). The confidence intervals of the arbitrary statistical parameter θ are estimated based on the statistical parameter distribution $F(\theta(x^\star))$ derived from n_J sub-samples $(x^\star)$ from x. It has been found that the distribution constructed by the n_J values $\theta(x^\star)$ reasonably represents the sampling distribution of $\theta(x)$ (Kaigh, 1983).

The difference of the Bootstrap and the Jackknife methods is the technique of sub-sampling. While in the Bootstrap approach the sub-samples are chosen by random sampling with replacement, Jackknifing is based on the leave-one-out idea (Efron and Tibshirani, 1994). For a sample x consisting of independent and identically distributed entries the bootstrap method was found to work well. For the case of correlated data (entries of sample x are not independently distributed) the Jackknife sampling method is preferable. By leaving-one-out the sub-samples remain in the correct temporal order. Since temporal correlations often last longer than one time step the leaving-one-out method does not result in independent sub-samples. To solve that problem we apply the Block-Jackknifing where temporal blocks are skipped in each sub-sample.

Applying the Block-Jackknifing to temporally correlated data, in our case the time series of wind speed, we still need to consider the remaining problem of temporally correlated entries within each sub-sample. This problem leads to an underestimation of variance in the individual sub-samples (caused by the violation of the independency assumption). In accordance to von Storch and Zwiers (2001) this issue can be statistically corrected by the use of the equivalent sample size n_e

$$n_e = n/D \tag{1}$$

with n the length of the sample and D the variance inflation factor, also known as decorrelation length, which is the time between effectively independent sample-entries. The decorrelation length D is defined as

$$D = 1 + 2\sum_{k=1}^{n-1}(1 - k/n)r_k \tag{2}$$

with r_k being estimates of the autocorrelation of wind speed at lags k.

The central argument for non-parametric methods as Jackknifing can be found in the mathematical expression of the variance of estimators (von Storch and Zwiers, 2001) which is defined as

$$Var(\theta) = \frac{1}{n}\sigma(\theta)^2 \tag{3}$$

with θ the statistical parameter to be estimated and its variance σ. As stated above the statistical parameter θ is reasonably represented by the distribution of $\theta(x^\star)$. Thus, the left site of equation 3 can be substituted by e.g. the median minus the 5th percentile of $\theta(x^\star)$ for the left hand uncertainty and the 95th percentile minus the median of $\theta(x^\star)$ for the right hand uncertainty. Thus, the confidence interval is estimated by the calculation of a left hand and right hand $\sigma_{l,r}$ calculated with

$$\sigma_{l,r}(\theta) = (Var(\theta)_{l,r}\, n_e)^{0.5}. \tag{4}$$

Decorrelation lengths used in this study are derived by applying eq. 2 for each tower wind time series individually. Using measurements between 50 m and 280 m we found the derived decorrelation length just slightly varying with height (±2 - 14%). Thus, for simplicity we use one averaged decorrelation length per site. This simplification leads to an underestimation of the uncertainty intervals close to ground and to an overestimation in the highest heights with errors up to 7%. The estimated decorrelation lengths are 4, 3, 2.5, and 3 days for Cabauw, Karlsruhe, Hamburg, and Lindenberg, respectively. The block length used in the Block-Jackknife procedure is set to 5 days. For each sub-sample (in total 200) the number of blocks ignored is determined by the condition to retain 95% of the original data in each sub-sample.

3.3. Vertical extrapolation of measurements

Practical and financial reasons motivate small tower measurements which need subsequent vertical extrapolation to estimate hub-height wind speed. In order to extrapolate measured wind speed to hub-height sundry mathematical expressions exists. Among these are the logarithmic law, log-linear law (also known as Monin-Obukhov relation) and the power law (Irwin, 1979; Stull, 1988b).

As the logarithmic laws are "difficult to use for engineering studies" (Bañuelos-Ruedas et al., 2010), the more simple power law is widely used. Although being the one method without physical basis (Gualtieri and Secci, 2011), it seems to give a better fit to most of the data over a greater height range and for higher wind conditions (Hadi, 2015). The general power law may be written as:

$$v_2 = v_1\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{5}$$

with v_1 and v_2 being the wind speed in measuring height z_1 and target height z_2, respectively. The power law exponent α is known as Hellmann (or friction) exponent. It is found to be a function of atmospheric stability, wind speed, surface features (roughness length), and the extrapolation height interval (e.g. Irwin, 1979; Gualtieri and Secci, 2011). For practical use lookup tables of α as function of terrain type were collected e.g. by Masters (2004). The values vary between 0.4 in urban areas with high buildings to 0.1 over smooth ground or water. Further studies reveal a high diurnal variability changing from less than 1/7 (~0.14) during daytime to more than 1/5 (~0.2) at night over the same terrain (Spera, 1994). The Hellmann exponent α can also be directly determined if measurements of v_1 and v_2 are available:

Table 3: Reference heights (h_1 and h_2) and roughness lengths (z_0) used for the different vertical extrapolation methods per site.

Site	h_1 (m)	h_2 (m)	z_0 (m)
Cabauw	10	40	0.1
Karlsruhe	40	60	0.25
Hamburg	10	50	0.1
Lindenberg	10	40	0.1

$$\alpha = \frac{ln\, v_2 - ln\, v_1}{ln\, z_2 - ln\, z_1} \tag{6}$$

The high variability of α led to the development of various methods to estimate an appropriate exponent based on surface measurements. Gualtieri and Secci (2011) performed a comprehensive evaluation of some of the most commonly used methods to extrapolate 10 m wind to 50 m wind at one location close to the coastline and one industrial location in Southern Italy. They compared the logarithmic approaches with four different power law approaches (meaning 4 different approaches to estimate the exponent α). They found the power law approach of Smedman-Högström and Högström (1978) (PL_SH) performing best compared to all other methods. Here, we chose three different methods for α with increasing level of complexity:

PL_const: This approach assumes a constant value for the Hellmann exponent. According to the international standards for wind turbine design provided by the International Electrotechnical Commission (IEC) the constant Hellmann exponent is set to $\alpha = 0.2$ (IEC, 2005).

PL_2L: This two level measurement based extrapolation method uses a temporal adapted Hellman exponent. Using wind measurements of two height levels in eq. 6 the Hellmann exponent is estimated for each time step and subsequently applied to extrapolate to higher heights.

PL_SH: The Smedman-Högström and Högström (1978) approach estimates the Hellmann exponent by the use of an empirical relation using both surface roughness and atmospheric stability. The relation was derived from wind measurements from three 100 m masts in Southern Sweden:

$$\alpha = c_0 + c_1 log(z_0) + c_2[log(z_0)]^2 \tag{7}$$

where coefficients c_0, c_1 and c_2 are stability dependent coefficients as defined by Smedman-Högström and Högström (1978) and z_0 is the roughness length. To estimate the Pasquill-Gifford stability category for each time step, the short wave radiation and temperature gradient (SRDT) method is applied (EPA, 1994; Bowen et al., 1983). Similar as (Mohan and Siddiqui, 1998), we applied a slight modification of the proposed SRDT method by adding an additional category beyond the most stable Pasquill-Gifford class. This additional class corresponds to a stable nighttime situation for wind speeds lower than 0.5 ms^{-1} (the adopted categorization scheme can be found in the supplementary material in Tab. S1).

3.3.1. Wind extrapolation set-up

The vertical wind speed extrapolation methods (sec. 3.3) are based on wind speed measurements at reference height(s) and additional information to specify atmospheric stability. In general, the used reference height is 10 m but in Karlsruhe a forest with an approximately height of 40 m forced the used reference height to 40 m.

In case of the PL_2L extrapolation a second reference height is necessary to estimate the Hellmann exponent. This second height is in generally set to 40 m motivated by the standard height of tilt-up towers (Lubitz, 2006). In Hamburg the second height is set to 50 m because in 40 m no measurements are available. In Karlsruhe the 60 m measurements are chosen as second height, as it is the height of the large tilt-up towers.

For the PL_SH extrapolation method the roughness length is used to consider local surface conditions. We roughly estimated the roughness length according to pictures and the suggestions of the WMO guide to 0.1 except for Karlsruhe with 0.25 (WMO, 2008, Chap. I.5-13). For an overview of these set-up parameters see Tab. 3.

4. Results

This section addresses the central questions (1) if regional reanalyses perform better in representing measured wind speed compared to global reanalyses and (2) whether reanalyses are advantageous in representing the wind speed on hub-height compared to extrapolated wind speed (based on 10 m extrapolations and/or based on measurements from two different heights). The quality of different reanalyses and extrapolation methods, together called products later on, is assessed by ranking.

The section is structured in three parts: Firstly, the marginal distributions (time independent statistics) are compared in order to assess whether the products are able to represent realistic frequency distributions of typical wind metrics on hub-height. Secondly, the joint distributions are compared in order to assess the temporal and spatial representation of measurements and products, combined. The third part provides an outlook on the performance of the products after conversion into theoretical power yields.

4.1. Marginal distributions

Marginal distributions provide the frequency occurrence of a quantity by ignoring temporal similarity of the different data products. In the context of site assessment for wind power plants marginal distributions are of particular importance, since they provide the information of wind speed frequency distribution at a site.

4.1.1. Wind speed

The realistic representation of absolute wind speed values is vital for wind assessment studies. A relative frequency histogram (Fig. 3) shows the capability of the different data products to match the general occurrence of specific wind speed values. Due to the height dependence of the wind speed the marginal distributions are shown on different height levels. For a quantitative comparison of the distribution differences the Earth Mover's Distance (EMD, Rabin et al., 2008) is calculated. The EMD score describes the number of values which need to be rearranged to match the measured distribution perfectly and is given in percent. The smaller the EMD the better the agreement. The uncertainty estimates of the EMD scores are the 5th and 95th percentiles derived by Block-Jackknifing (see sec. 3.2).

The reanalyses distributions follow the measured ones in general better in higher heights than in lower heights where local conditions become more and more important (Fig. 3). As reanalyses products represent grid cells they are per definition not able to resolve and represent sub-grid influences to the wind field. A most evident feature is the overestimation of wind speed by MERRA-2 which was also found for 10 m wind in the UK by Cannon et al. (2014) especially for a wind speed above 20 ms^{-1}.

The extrapolation methods PL_const and PL_SH tend to underestimate the broadening of the wind speed distribution with height significantly for all considered measurement sites. Thus, a systematic underestimation of wind speed occurs with increasing extrapolation height. The extrapolation method PL_2L represents the measured distributions better than the other two methods but overestimates wind speed significantly in Karlsruhe. This overestimation in Karlsruhe is expected to be caused by significantly differing 40 and 60 m measurements due to forest disturbed 40 m measurements.

In order to rank the reanalyses and extrapolation methods the EMD scores are shown for each height and site (Fig. 3). COSMO-REA6 performs most often significantly better in representing the measured distribution. Only in Hamburg at 175 and 280 m height, ERA-Interim performs better. Here, the REA6 distribution is slightly too broad with a slight shift to higher wind speed values. Thus, the wind speed seems to be overestimated by REA6 (in accordance with bias scores derived later in section 4.2.1). Furthermore, the EMD ranking shows REA2 being frequently ranked between the two global reanalyses which might be caused by the slight shift of the REA2 distribution towards higher wind speeds. In general, regional reanalyses outperform the global ones as demonstrated with their persistent occurrence among the first three ranks when comparing just the four reanalyses products.

Comparing the reanalyses with extrapolations only PL_2L which requires a second wind speed measurement seems to be able to represent the measured wind speed distributions for all heights with similar quality like the reanalyses. Only in Karlsruhe the PL_2L method shows deficits.

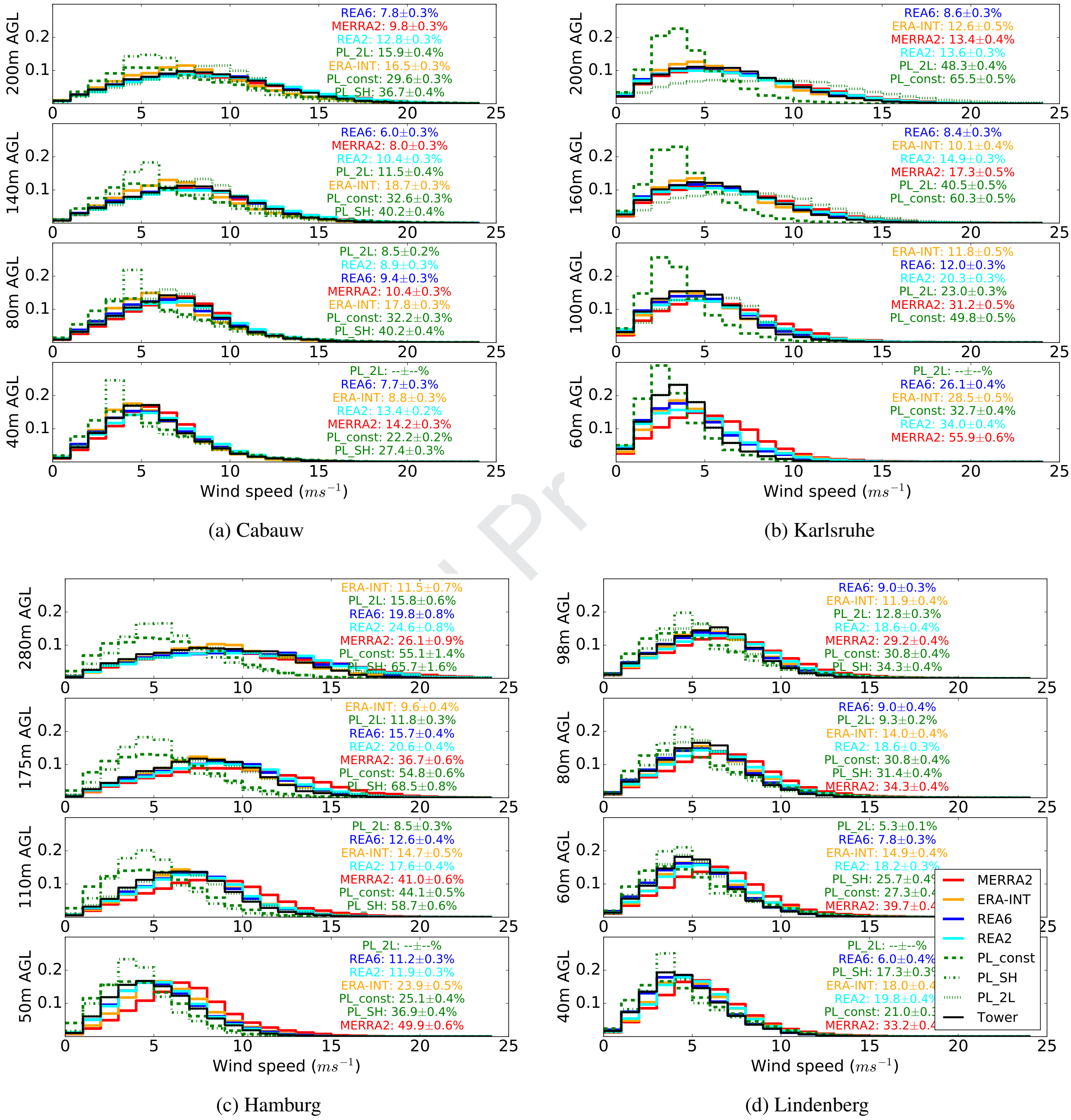


Figure 3: Marginal distribution of wind speed at different tower heights. The EMD scores, quantifying the distribution difference relative to the measured distribution, are ranked with best performance listed first (Best score: EMD = 0%). Reanalyses data are vertically linear interpolated to the tower levels. The number of considered data per tower is shown in Tab. 1.

4.1.2. Temporal wind speed changes

Wind speed changes per time interval, often called ramp rates, cause wind power generation changes over time. Since supply and demand in a power system always have to be balanced the weather-induced uncontrollable generation changes causes compensation costs i.e. flexible power plants need to be turned on/off or electricity storage is needed (Graabak and Korpås, 2016). As ramp rates are the driving process leading to the balancing efforts it is important to know their statistical characteristics as accurately as possible.

In order to quantify the ability of the different products to represent the ramp rates the marginal distributions are shown relative to the measured ramp rates (Fig. 4). The global reanalyses systematically underestimate the occurrence of more intense ramp rates and overestimate that of weak ramp rates. These problems are significantly reduced in regional reanalyses as their marginal distributions are much closer to the measured ones. The slightly different result close to ground in Karlsruhe is probably caused by the general overestimation of the wind speed in the reanalyses at this location causing probably more intense ramp rates.

Considering the most extreme measured ramp rates (lowest 5% + highest 5%) at levels above 98 m global reanalyses underrepresent them by -80 to -43%. The regional reanalyses COSMO-REA6 and COSMO-REA2 show significant improved extreme ramp rate representation with relative errors between -28 to +2% and -14 to +9%, respectively.

The vertical extrapolation methods vary strongly with site, height and the method applied. Only the PL_2L method performs more robust with strong overestimation of extreme ramp rates for all heights and sites except for Hamburg at 10 m above reference height.

4.1.3. Vertical wind speed gradients

The vertical wind speed gradient is important when considering shear stress on wind-blades (Fernandez et al., 2018). In order to investigate which reanalyses represents vertical gradients on typical hub-heights more accurately the frequency distribution of wind speed differences from one tower level to the next are investigated (Fig. 5). As already used in Fig. 3 the EMD is used to get a quantitative measure for the difference of the distributions. According to the EMD score the regional reanalyses perform about twice as good as the global reanalyses in representing the distributions of vertical wind gradients. With more narrow distributions global reanalyses and especially the vertical extrapolation methods underestimate the occurrence of high wind speed gradients. This effect is significantly reduced in the regional reanalyses.

Applying the analysis for different thermal stability conditions we found that the improvement in the regional reanalyses is caused by a better representation of vertical wind speed gradients especially during stable atmospheric conditions (not shown). For all well-mixed and neutral conditions regional and global reanalyses perform more or less similarly.

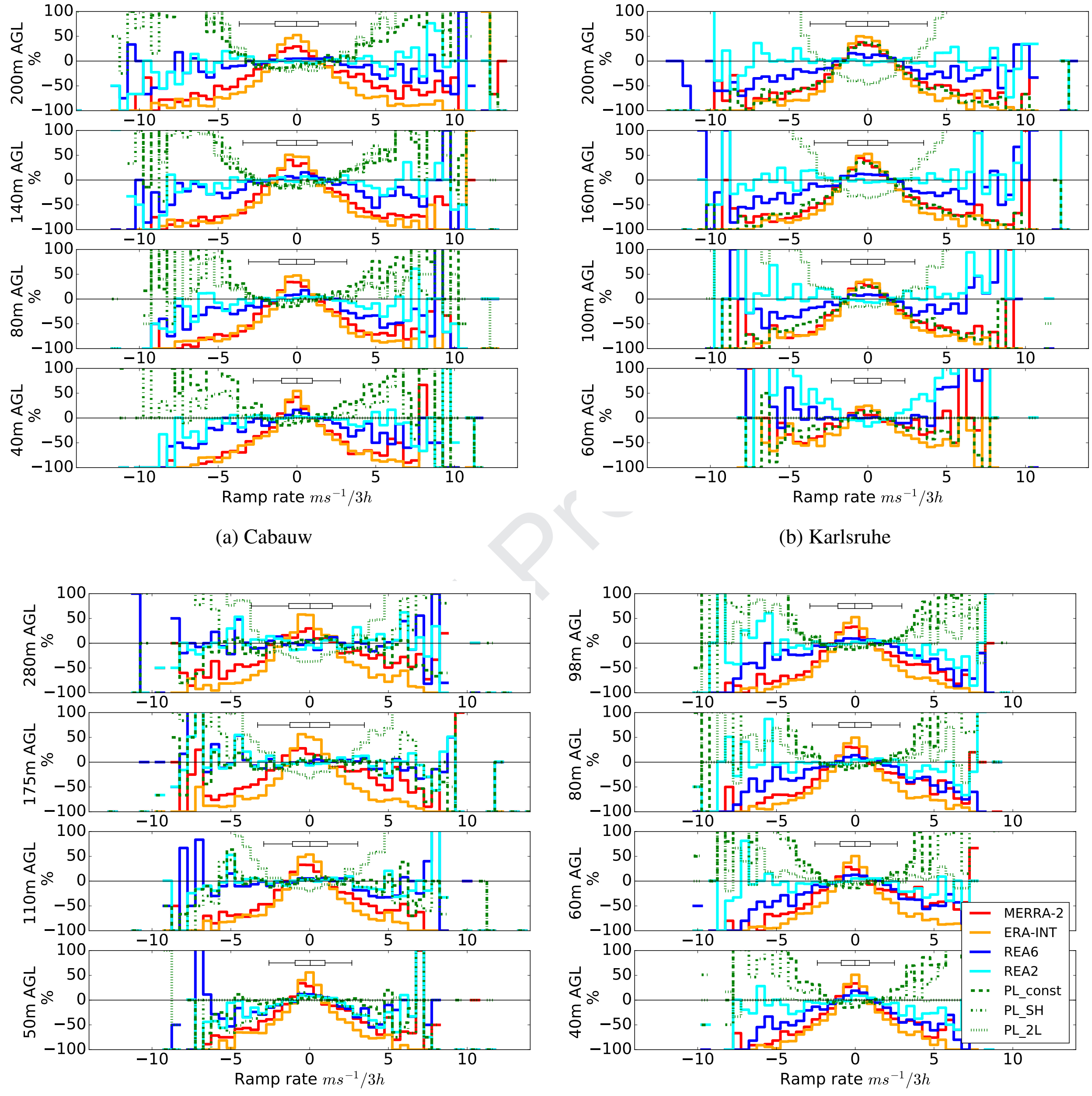
4.1.4. Low wind persistence

Statistics of weak wind situations and especially persistent low wind situations are of great importance for the energy sector, as electricity production shortages can occur during these times. Thus, persistent situations should be represented as accurately as possible.

In our study (Fig. 6) the weak wind persistence is determined by the number of successive time steps with a wind speed below a typical cut-in velocity of $3.5\,ms^{-1}$. The considered time steps are 3 hourly, as it is the resolution of the global reanalyses. In order to get similar results in model and measurements only the 10 min averages of the measurements around the considered 3 hourly interval are used to determine the measured persistence. In case of the reanalyses the instantaneous 3 hourly values are checked if they meet the low wind criteria (lower than cut-in velocity).

The longest persistencies of weak wind situations (up to 21 hours) occur in Karlsruhe which is in accordance with the general weaker wind speed at this location compared to the other sites as was already shown in Fig. 2.

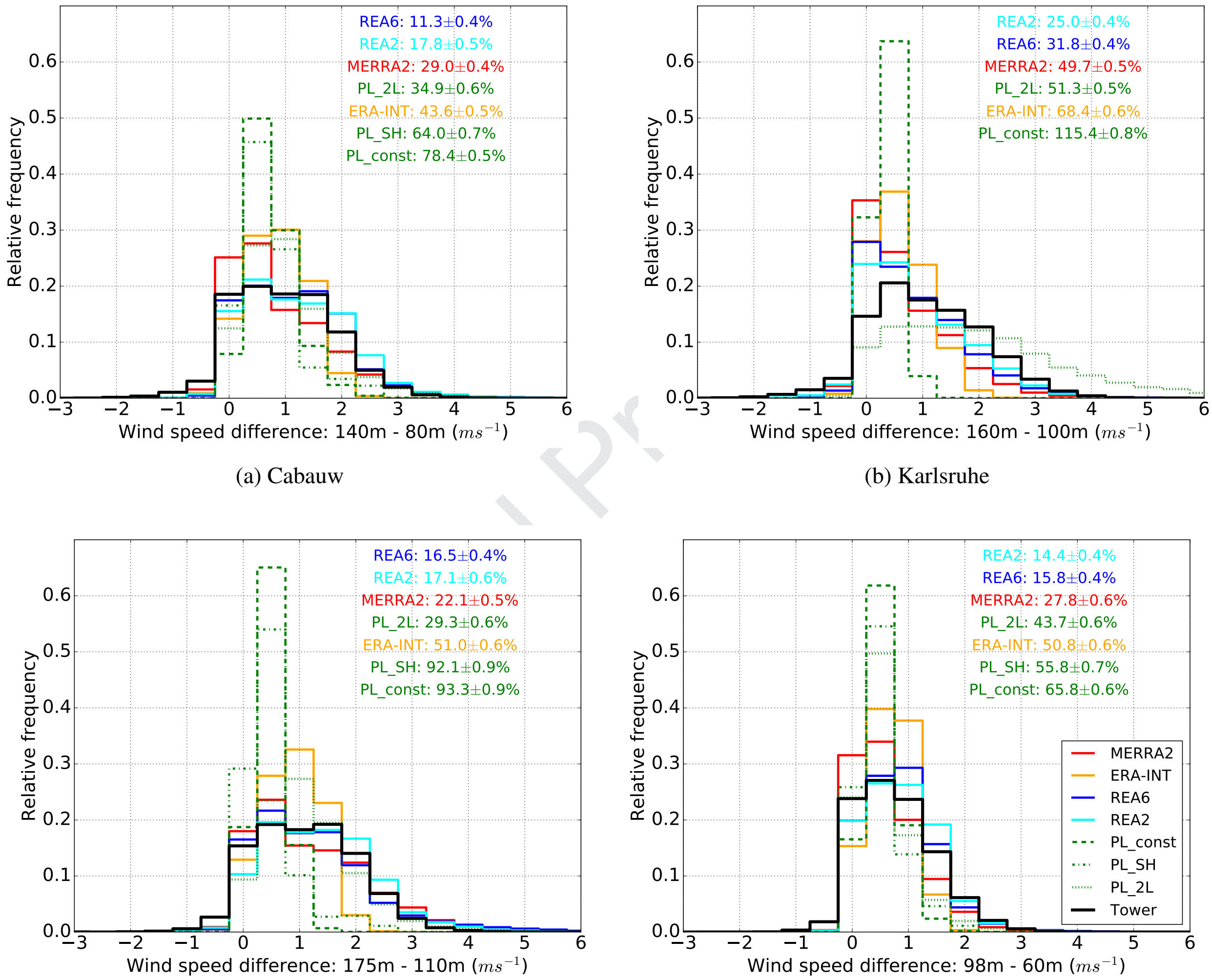
The relative error of persistent low wind events derived from reanalyses varies in general between −80% and +80%. In most cases, especially in the lower heights, MERRA-2 underestimates the number of persistent low wind events, which is consistent with the general overestimation of the wind speed by MERRA-2 (see bias in Fig. 7). Although MERRA-2 also shows positive wind speed biases at the higher tower levels it is not leading necessarily to underestimations of low wind persistence at that heights. This is in accordance with the marginal distributions of



(a) Cabauw (b) Karlsruhe

(c) Hamburg (d) Lindenberg

Figure 4: Relative deviation of ramp rate occurrence with respect to tower measurements for different tower heights. The reference distribution is derived from the 10 min tower measurements considered every 3 hours. Ramp rates of the reanalyses are based on the instantaneous wind speed values every 3 hours. The horizontal box plot shows the 5, 25, 50, 75, 95th percentiles of the reference distributions. The number of considered data per tower is shown in Tab. 1.



(a) Cabauw

(b) Karlsruhe

(c) Hamburg

(d) Lindenberg

Figure 5: Vertical wind speed gradient between site specific measurement heights. The EMD scores, quantifying the distribution difference relative to the measured distribution, are ranked with best performance listed first (Best score: EMD = 0%).

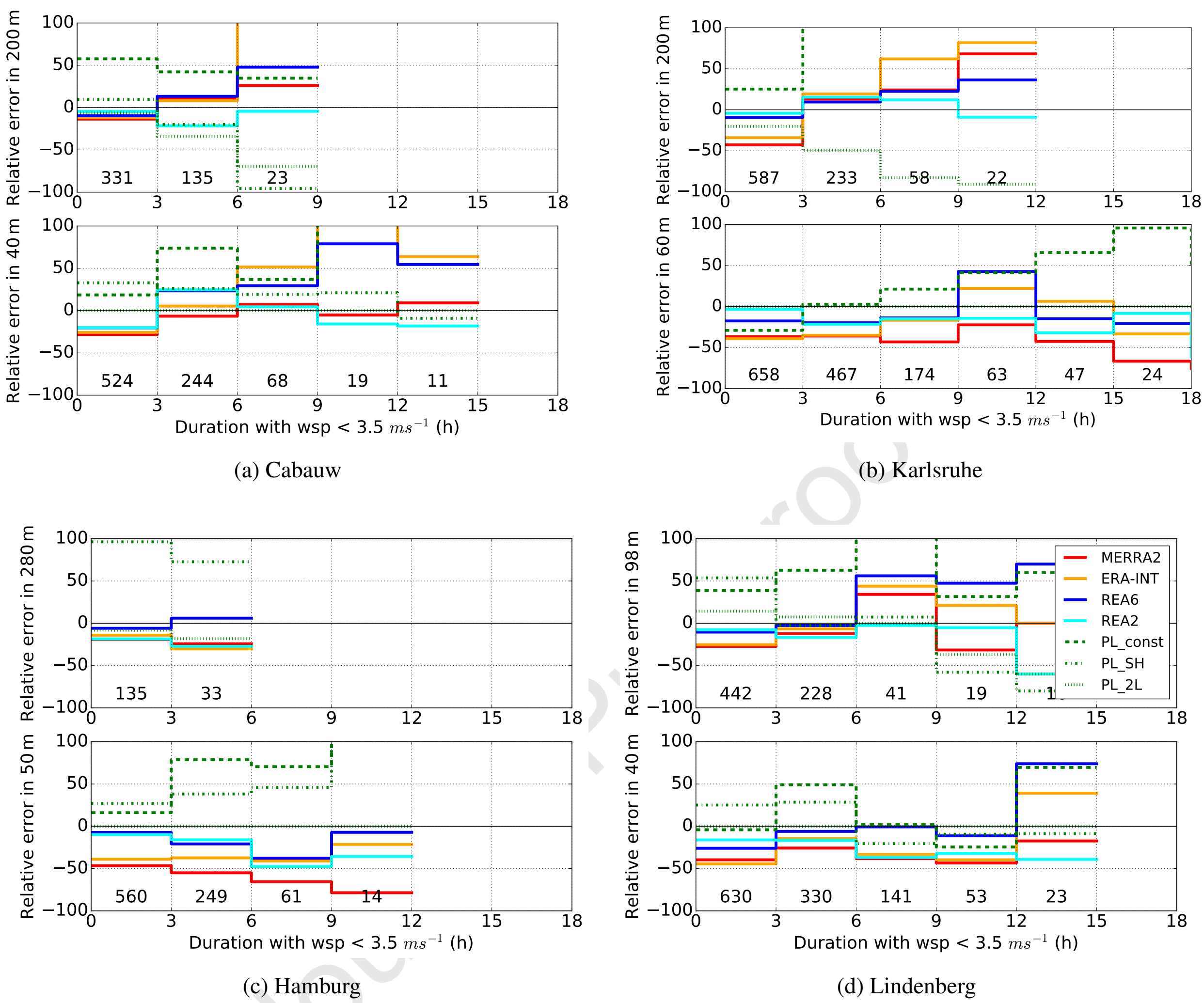


Figure 6: Relative error of low wind persistence at different heights. The numbers provide the total occurrence of measured persistencies per class (3 hourly binned classes). The lines show the relative error of the different products in representing the measured number per class. Direct site-to-site comparisons are not possible since the number of measurements varies with site (Tab. 1).

MERRA-2 which show an increasing agreement with the measurements with increasing height. At the upper tower levels the regional reanalyses show typically a slight underestimation of the 3 h persistence turning to overestimation for longer persistence.

The relative error of persistent low wind events derived from extrapolated wind speed varies strongly. While relative errors from reanalyses typically remain below 80%, the relative errors of extrapolated wind speed often exceed this value. Thus, reanalyses clearly outperform the extrapolation methods in representing the number of persistent low wind events.

4.2. Joint distributions

In order to assess the wind products ability to represent measurements in space and time exactly the joint distributions are analyzed. Related to site assessment studies joint distributions are important, since MCP methods often rely on scores like bias, mean absolute errors (MAE), and correlations (Carta et al., 2013).

4.2.1. Bias and bias corrected MAE

Regional reanalyses turn out to be the best products for representing the local wind speed by looking at profiles of wind speed bias and mean absolute error (Fig. 7). The bias shows the systematic under- or overestimation of the different products, while the BC_MAE describes the ability of a product to reproduce the variability of the measurements. Comparing the reanalyses products in terms of bias and BC_MAE, most of the significant differences are in favor of the regional reanalyses, especially REA6. The only exception can be found at Hamburg where the bias of ERA-Interim is lowest with less than 0.5 ms^{-1} in heights above 150 m.

Largest bias values occur close to the ground in Karlsruhe. The domain averaging reanalyses products are not able to represent the strong influence of the local forest. Thus, all reanalyses overestimate the wind speed at this location. Especially at sites like Karlsruhe, where local small scale conditions predominate the wind characteristics, regional reanalyses are expected to outperform the global ones. This outperforming is confirmed by significantly improved bias as well as BC_MAE scores in the regional reanalyses (e.g. in 40 m height the bias reduced from 1.5±0.3 ms^{-1} to about 1 ms^{-1}).

PL_const and PL_SH are based on 10 m wind measurements. Evidently, their performance decreases with increasing extrapolation height. The height of equal performance of the extrapolated wind speed and the reanalyses is 50 – 100 m above reference height. Above that height the reanalyses perform better. Except for Karlsruhe, the PL_2L MAE is comparable to that of the reanalyses in a height of about 100 m above reference height which is roughly 2-3 times the upper measurement height. PL_2L seems to be more dependent on local conditions compared to the other extrapolation methods (best performance in flat regions).

4.2.2. Correlations

The correlation shows the ability of the different products to follow measured temporal tendencies. The wind speed correlation of the different products with the towers are in general quite similar from one to the other tower location (Fig. 8). As expected the reanalyses correlation increases slightly with height, as local effects decrease with height and large scale processes become the driving process. In contrast, the correlation of the extrapolation method decreases with increasing distance to the measurement height.

Among the reanalyses COSMO-REA6 and COSMO-REA2 generally outperform the global reanalyses, significant outperforming can be found in Karlsruhe where the spatial resolution becomes more important in order to represent the local conditions. The correlation of extrapolated wind speed and reanalyses wind speed become similar in a height range between 80 to 150 m above the measurement height. The exact height depends on the tower location, the reanalyses, and on the used extrapolation method. One main exception can be found for Karlsruhe, where the PL_2L extrapolation method leads to drastically decreasing correlation scores with height. Here, reanalyses outperform the extrapolations in just a few meter above reference height. Similar to the bias also the correlation score indicates the PL_2L extrapolation method to be the one most dependent on local conditions.

4.2.3. Stability dependent validation

The vertical wind speed profile strongly depends on the thermal stability of the atmosphere. Thus, the performance of the different extrapolation methods and reanalyses are studied under the different atmospheric stability conditions. The thermal conditions are determined by the use of the temperature differences between top of the tower (except Hamburg where we chose 175 m) and 10 m (except Karlsruhe with 30 m). Cases with temperature decreases of more/less than 1 $K/0.5\,K$ per 100 m are assigned to unstable/stable conditions. Note, the representation of the different stability conditions by COSMO-REA6 is validated in detail by Petrik et al. (2019).

Both, reanalyses and extrapolation methods perform better under unstable conditions, especially above 50 m (see Fig. 9 and for all sites S1). This behaviour is also found considering diurnal cycle investigations where stable conditions mostly prevail during night and unstable conditions during daytime (not shown here). The weaker performance during stable conditions is closely connected to the more intensive vertical wind speed gradients (more vertical variability due to thermal inversions) which increase local extrapolation uncertainties Gualtieri and Secci (2011).

Comparing the different reanalyses in terms of the bias we find for both stability conditions that the regional reanalyses have a smaller or equal bias than the global reanalyses. Thus, the largest bias values can always be found in global reanalyses.

Considering the BC_MAE under stable conditions we find similar or better performance of regional reanalyses compared to global reanalyses for all sites with the only significant improvement in Karlsruhe. Although we find the

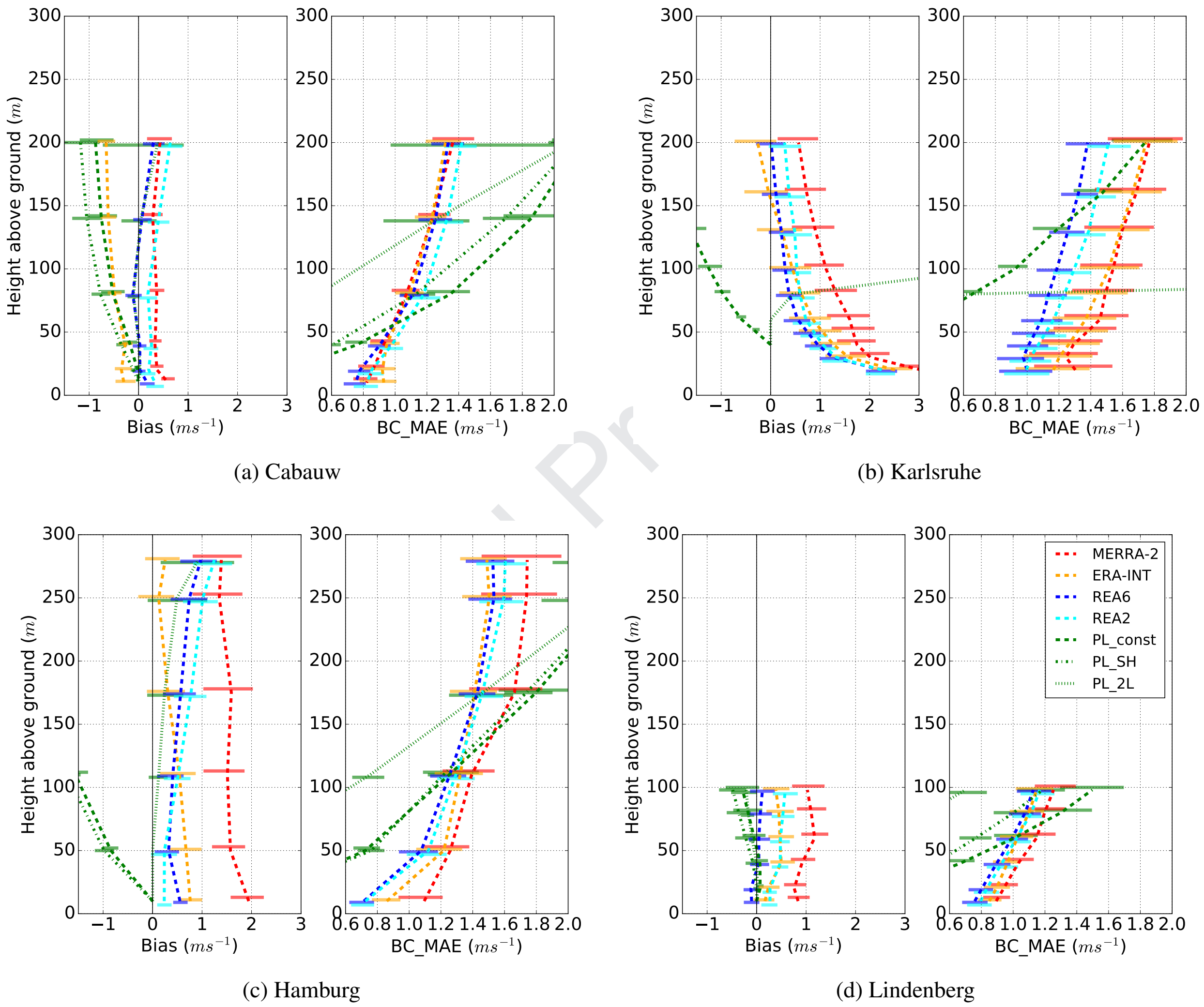
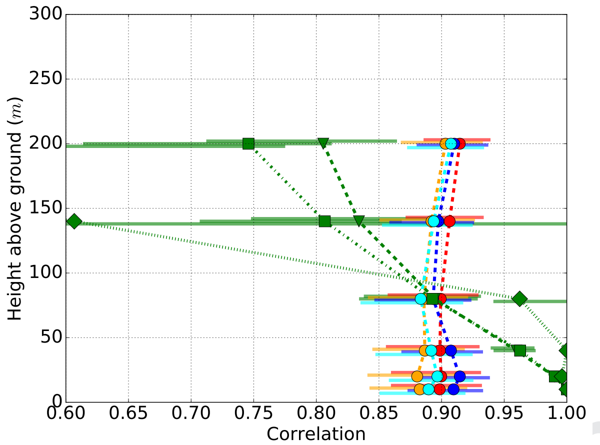
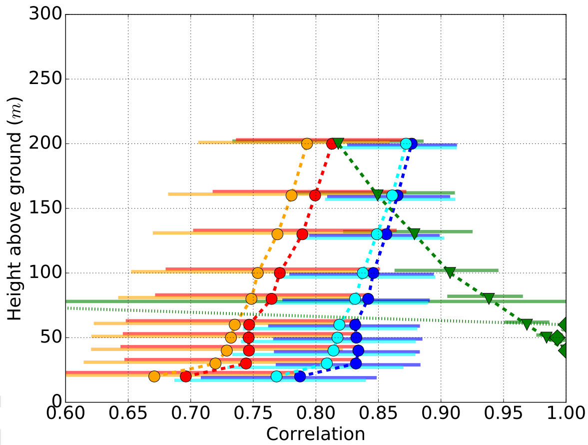


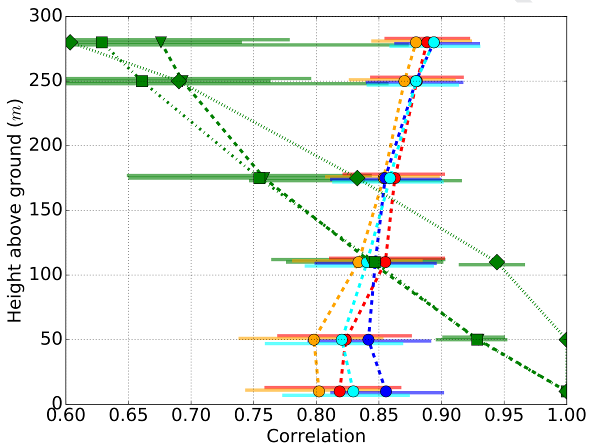
Figure 7: Bias and bias corrected mean absolute error (BC_MAE) profiles of instantaneous wind speed compared to 10 min averaged tower measurements. The vertical matching is done by linear interpolation of all products to the tower heights. The number of considered data per tower can be seen in Tab. 1.



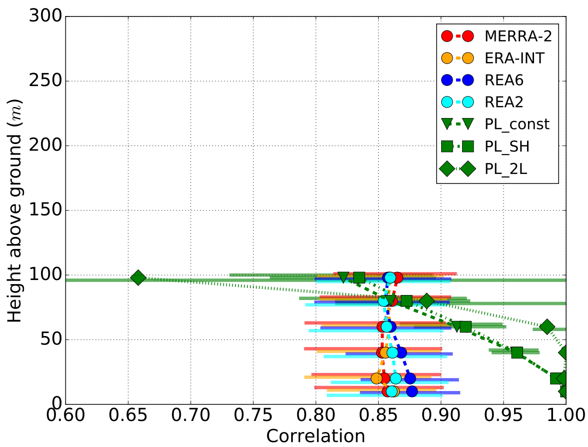
(a) Cabauw



(b) Karlsruhe

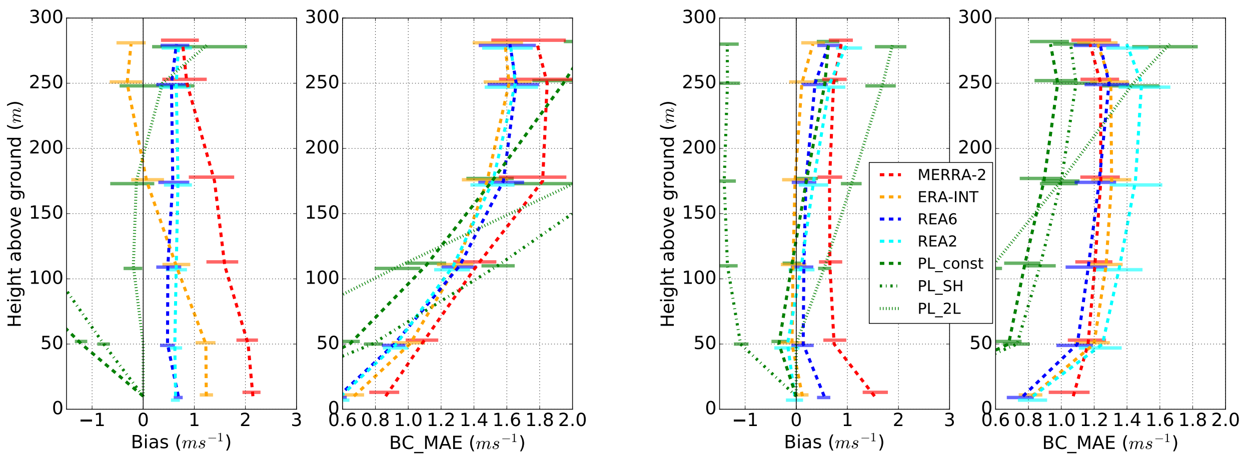


(c) Hamburg



(d) Lindenberg

Figure 8: Pearson correlations based on 3 hourly values. 10 min averaged measurements are used as reference. The number of considered data per tower can be seen in Tab. 1.



(a) Stable

(b) Unstable

Figure 9: Bias and bias corrected mean absolute errors (BC_MAE) under stable (9a) and unstable (9b) thermal conditions for the example site Hamburg. The scores are based on 3 hourly values. 10 min averaged tower measurements considered every third hour are used as reference.

same for COSMO-REA6 under unstable conditions this is not the case for COSMO-REA2. At two of the four sites the COSMO-REA2 BC_MAE scores are similar or significantly better than that of the global reanalyses, but at the other two locations we find significant degradation compared to the global reanalyses and COSMO-REA6.

Considering the extrapolation methods under stable conditions the quality decreases rapidly with height. From all sites we obtained: When extrapolating wind characteristics based on 10 m measurements, reanalyses outperform the extrapolated ones in heights above 70 m. Using two measurement levels for extrapolations, reanalyses outperform the extrapolated wind in heights above 3 times the higher measurement level.

Under unstable conditions it is always one of the extrapolation methods producing best wind speed estimates at all height levels. But considering the MAE (combining the effects of bias and BC_MAE) at least one of the extrapolation methods produces worse estimates as the reanalyses in heights above 80 m above ground. The method which performs "worse" is different from site-to-site. Thus, we can not find the one extrapolation method being superior to all reanalyses for all sites. Again we can note that reanalyses perform less site dependent.

4.3. Power estimates

Finally, a first assessment of the reanalyses potential to simulate the power yields of wind turbines is presented.

4.3.1. Accumulated relative power estimates

The ultimate product of interest from an economic perspective is the power yield of an installed wind power plant. Thus, a central question is if the products are able to represent realistic power estimates. In this study, we investigate the total power generation of the considered seven years and compare the different reanalyses and extrapolation methods with measurement based power estimates.

The power generation estimates E_{out} are calculated by the use of turbine characteristics of a 2.5 MW wind turbine from General Electric (General Electric 2010 [2]). The turbine does not generate electricity below cut-in velocity (3.0 ms^{-1}) and above the cut-out wind velocity (25 ms^{-1}). Between the cut-in and the rated wind speed (about 12.5 ms^{-1}) the estimated power is proportional to the wind speed:

$$E_{out} = \frac{1}{2} c_p \rho \pi R^2 v^3 \quad (8)$$

[2]https://wind-turbine.com/windkraftanlagen/9813/ge-2-5-100.html

with a constant power coefficient c_p of 0.35 and a rotor diameter of 100 m. The air density is assumed to be a constant standard value of 1.225 $kg\,m^{-3}$. The maximum power production is constant between rated wind speed and cut-out wind speed.

In order to estimate comparable power estimates derived from measurements and reanalyses only the 3 hourly values (10 min averages in case of measurements and instantaneous values in case of reanalyses) which are available for all products per site are used to derive the total power generation. The number of considered time steps is shown in Tab. 1.

The power estimates derived from reanalyses are too high for most heights and sites by roughly 10-50% (Fig. 10). The only underestimations occur with REA6 in Lindenberg and ERA-Interim in Cabauw. While the relative errors of the regional reanalyses in 100 m AGL are usually lower than 25% the global reanalyses reach values of about 60%. Closely connected, we find the performance of the power estimates derived from regional reanalyses to be less variable from site-to-site than those derived from global reanalyses.

The performance of extrapolation methods varies strongly with site, method and height. The estimates based on the extrapolation methods PL_const and PL_SH lead after about 50 m extrapolation height to comparable uncertainties like the reanalyses products. Above that height reanalyses perform better and below they perform worse than extrapolation based estimates of the power generation. In contrast, the PL_2L method leads for all sites (but Karlsruhe) and heights to better or comparable power estimates than the reanalyses do.

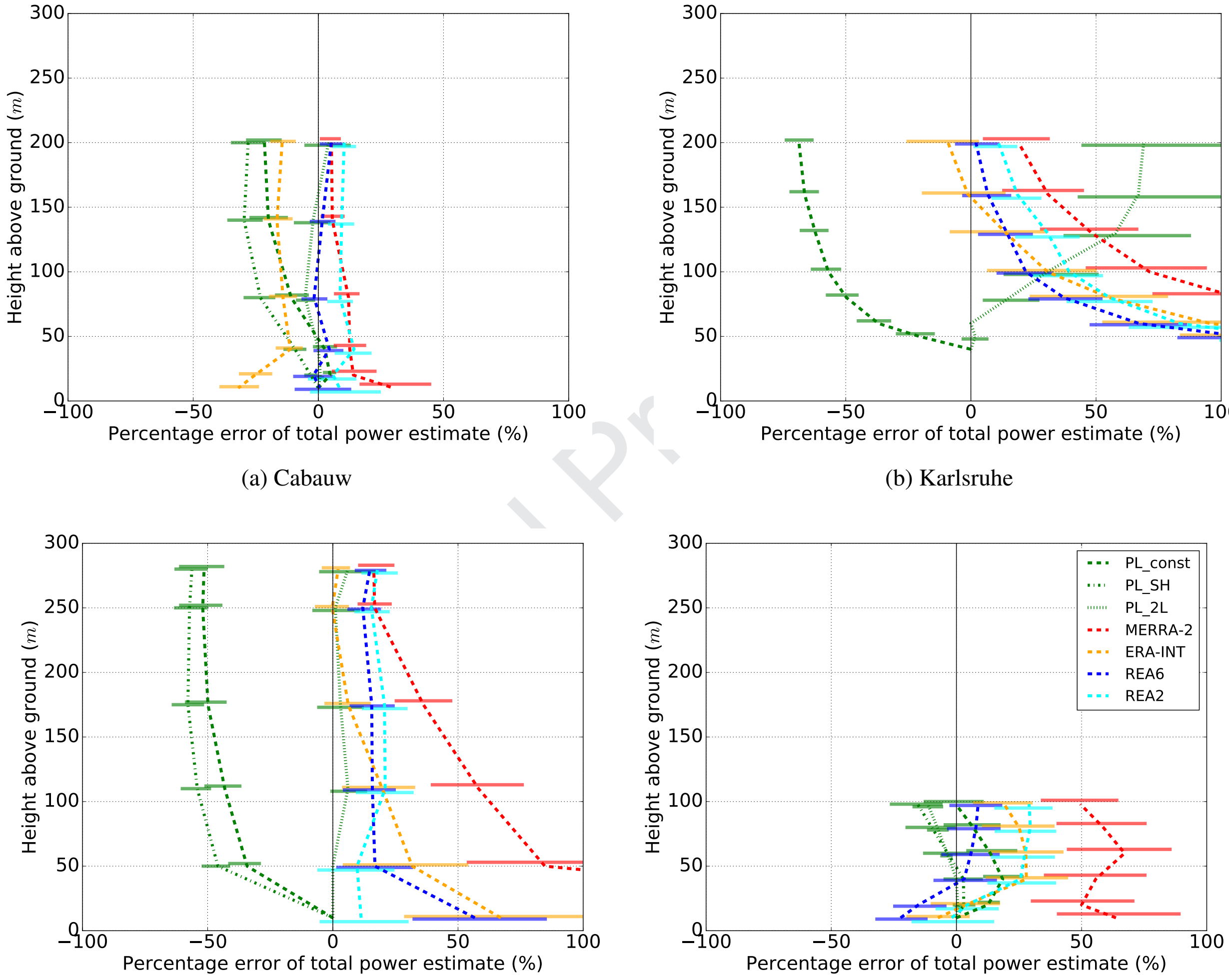
Considering the uncertainty estimates (derived by Jackknifing see sec. 3.2) of the power generation estimates we find increasing uncertainties with height for the estimates based on extrapolated wind speed and decreasing uncertainties with height for estimates based on reanalyses. The decrease with height in case of reanalyses based estimates might be a result of the non-linear conversion to power generation. While wind speeds above rated-velocity yield to a constant full power generation the low wind speed values (between cut-in and rated velocity) are expected to introduce more uncertainty to the estimates. Thus, the uncertainties close to ground appear higher as shown in Fig. 10. In the case of extrapolation based estimates the general uncertainty increases with height, see e.g. BC_MAE of the wind speed, seems to dominate the compensating non-linearity effect of the power curve.

5. Discussion

We found that regional reanalyses often outperform global reanalyses in terms of their quality to represent measured wind speed. Especially marginal distributions of wind speed metrics are found to be significantly improved (see 4.1). Joint validation metrics e.g. the bias corrected mean absolute error revealed the added value of regional reanalyses predominantly in more complex terrains and close to ground, as expected. Nevertheless, in a few cases some metrics at specific heights and sites also show global reanalyses performing significantly better e.g. the ERA-Interim bias above 250 m in Hamburg (Fig. 7c). This is not unexpected since the results can be influenced by coincidentally better guesses of the local conditions by the coarser resolution than by the finer which depends strongly on the exact location of the measurement. Moreover, joint distribution scores are sometimes degraded by finer resolutions caused by spatiotemporal mis matching combined with increased variance representation in the finer resolved models (Gilleland et al., 2009). Nevertheless, most metrics show regional reanalyses outperforming the global reanalyses ERA-Interim and MERRA-2, which is consistent with the findings of Borsche et al. (2016) and Kaiser-Weiss et al. (2015) who investigated reanalysis performance on aggregated scales and/or close to ground.

Comparing the two regional reanalyses the results imply COSMO-REA6 being slightly better in representing the real wind speed compared to COSMO-REA2 in terms of bias and mean absolute errors. A similar result is found by Steinke et al. (2019) who could not find an added value of COSMO-REA2 compared to COSMO-REA6 in terms of the integrated water vapor. This unexpected results might be explained by the slightly different underlying NWP models of the two regional reanalyses. One reason for model differences is e.g. an applied optimization of COSMO-REA2 with respect to precipitation (Wahl et al., 2017). Thus, other model variables might be slightly degraded (e.g. the quality of wind speed) leading to compensation of the expected added value by increasing the resolution. Nevertheless, the temporal ramp rate study and vertical wind speed gradient study show better statistical representation of variability scores by COSMO-REA2 (see Fig. 4 and 5).

The comparison of reanalyses with vertical extrapolations revealed more realistic wind representation by extrapolation methods close to reference height and degradation with increasing height. The height where reanalyses and



(a) Cabauw

(b) Karlsruhe

(c) Hamburg

(d) Lindenberg

Figure 10: Mean relative error of estimated power generation. The reference power estimates are derived from tower measurements (2007-2013). The number of considered data per tower can be seen in Tab. 1.

extrapolations perform similar varies with site, method, and stability. Nevertheless, the height of similar performance is found in roughly 50-100 m above reference height if extrapolations are based on one level (see e.g. 7 and 8). For the two level based extrapolation method the results imply the level of similar performance a bit higher than 100 m above reference height (2-3 times the upper measurement height) but the method seems to be even more site dependent than the other extrapolation methods.

In contrast to the general statement of Gualtieri and Secci (2011) who found the PL_SH to be the best extrapolation method (tested for two sites), we could not identify a single extrapolation method which systematically outperforms the other extrapolation methods (see e.g. Fig. 7, S1).

Kubik et al. (2013) already showed that the global reanalysis MERRA provides comparable power estimates in 60 m height when comparing to power estimates based on vertically extrapolated 10 m measurements. Since Kubik et al. (2013) used the PL_const method with a calibration eliminating systematic errors, their derived results for Northern Ireland can be compared to our PL_const bias corrected MAE score in Fig. 7. For two of our sites, Cabauw and Lindenberg, we find exactly the same height (60 m) where reanalyses and extrapolation become more or less equal realistic. For Hamburg and Karlsruhe this height is slightly higher in about 100 m above reference height. Finding the reasons for the different heights of common quality is a difficult task, since many parameters influence the performance of the reanalyses and extrapolation methods as e.g. the different climatologies and different representation of stable, neutral and mixed situations etc. .

Comparing the site-to-site performance of reanalyses and vertical extrapolation products we found extrapolated wind profiles to be more variable. Thus, reanalyses represent the real wind profiles spatially more robust than extrapolation methods, e.g. the bias corrected mean absolute error in 100 m of the regional reanalyses varies for all sites between 1.1 and 1.25 ms^{-1} while the extrapolations varies between 0.6 and 1.5 ms^{-1}.

The extrapolation methods as well as the reanalyses show better performance under unstable conditions. Under this condition there is for each investigated site at least one extrapolation method outperforming the reanalyses products, but the best method varies from site-to-site significantly and the least performing extrapolation method (also more or less random from site-to-site) is typically outperformed by the reanalyses in heights above 50 m above reference height. Again, reanalyses and in particular the regional reanalyses come up with more site independent representativity scores.

6. Conclusion

The high resolution regional reanalyses COSMO-REA6 and COSMO-REA2 are evaluated in the context of wind energy applications to quantify their added value compared to established global reanalyses. Using in-situ tower measurements as reference, the reanalyses are also compared to extrapolated wind profiles based on small tower measurements (up to 60 m) which are commonly used as reference for site assessment studies.

Using wind measurements at four tall towers (up to 280 m) regional reanalyses are proven to better represent the measured wind speed or at least perform equally well (depending on the considered validation metric and site) compared to the global reanalyses ERA-Interim and MERRA-2. Especially, close to ground wind speed is better represented by the regional reanalyses due to the enhanced horizontal resolution and better representation of land-surface interaction and orographic effects.

In particular the variability scores, namely for vertical wind gradients and temporal wind speed changes (ramp rates), are shown to be significantly improved in regional reanalyses. For example, global reanalyses underrepresent the extreme ramp rates (upper 10% in heights above 98 m) by up to 80%, while COSMO-REA2 represents them by ±14% (Fig. 4).

In economics, reanalyses are sometimes used in combination with short-term tower measurements in order to estimate climatological wind characteristics at a specific site (MCP methods, Carta et al., 2013). For this task we highly recommend to move from the global reanalyses to the regional reanalyses especially due to their improved representation of marginal distributions (see sec 4.1). The better representation of marginal distribution is particularly important when investigating occurrences of specific events as for example low wind situations or ramp rates. For this purpose, COSMO-REA6 already provides 23 years for whole Europe on a 6 km grid and is constantly extended in time.

However, the new regional reanalyses are still not accurate enough to replace the costly tower measurements for site assessment studies completely. Instead of reaching the extrapolation accuracy in heights of 3/2 above the measurement height (minimum prescribed height by site assessment guidelines in Germany) reanalyses become equal in heights of roughly 2-3 times above the upper reference height, at least for three out of four considered towers.

At this point we would like to remind the reader that all results are based on the finite number of considered validation metrics and on just four tower sites in central Europe. The site-to-site variability already indicates the local dependency and often reduces the ”general validity” of results. For the future we recommend to use a larger number of reference towers to get more robust results. The collection of uniform tower measurements within e.g. the INDECIS project of the European Reasearch Area for Climate Services (ERA4CS) will provide opportunities for validation across a wider geographical region and with more towers.

Despite the uncertainties and shortcomings discussed above, the regional reanalyses COSMO-REA6 and COSMO-REA2 have demonstrated their improved skill to estimate wind energy compared to commonly used reanalyses. Together with the post-processed radiation by Frank et al. (2018), COSMO-REA6 provides a solid data foundation of hybrid wind-solar assessments in terms of country based smoothing and compensation potentials on a European scale.

Acknowledgments

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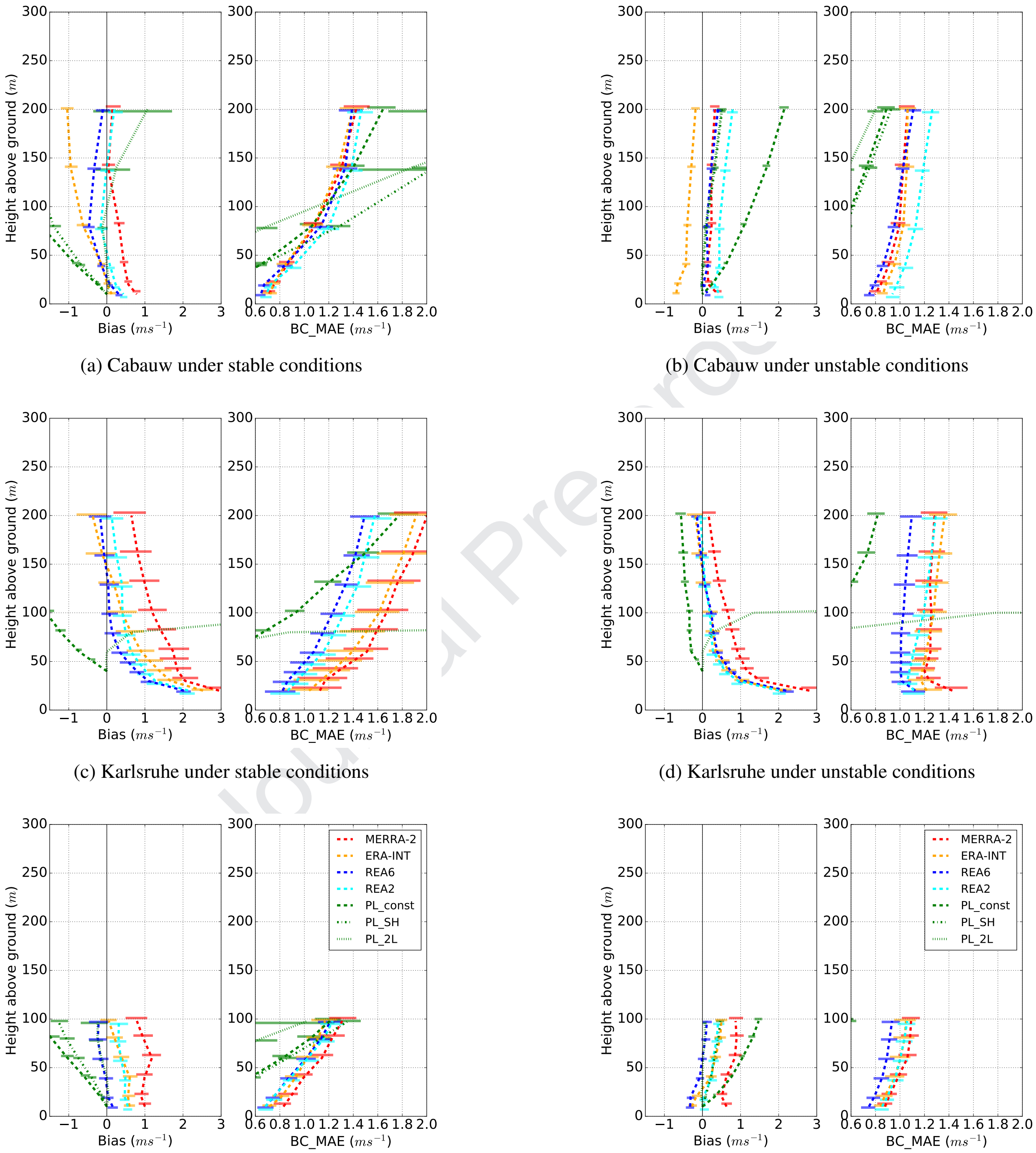
7. Supplementary Material

Table S1: Insolation-based key to Pasquill-Gifford stability categories. The reference wind speed (v_{10}) is the average wind speed, measured at 10 m above ground level.

Daytime					Nighttime		
	Global radiation (Wm^{-2})					2-10m △T (°Cm^{-1})	
v_{10} (ms^{-1})	>=925	925-675	675-175	<175	v_{10} (ms^{-1})	<0	>=0
< 2	A	A	B	D	<0.5	E	G
2-3	A	B	C	D	0.5-2.0	E	F
3-5	B	B	C	D	2.0-2.5	D	E
5-6	C	C	D	D	>=2.5	D	D
>=6	C	D	D	D			



(a) Cabauw under stable conditions

(b) Cabauw under unstable conditions

(c) Karlsruhe under stable conditions

(d) Karlsruhe under unstable conditions

(e) Lindenberg under stable conditions

(f) Lindenberg under unstable conditions

Figure S1: Bias and bias corrected mean absolute error (BC_MAE) of the different products under stable (left) and unstable (right) thermal conditions.

Three to five points collecting the highlights of the paper:

- Reanalyses (REA) are a valuable tool for providing gridded wind speed at hub-height
- Low level wind profiles from regional reanalyses outperform global reanalyses
- COSMO-REA2 represents extreme ramp rate occurrences at hub-height best
- The performance of REA is more robust than those of vertical extrapolation methods