Mesoscale and Microscale Downscaling for the Wind Atlas of South Africa (WASA) Project: Phase 3

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Abstract

This document reports on the methods used to create and the results of the WRF-based numerical wind atlases developed for the Wind Atlas for South Africa Phase 3 (WASA3) project.

The report is divided into four main parts. In the first part, we document the method used to run the mesoscale simulations and to select the best suited WRF model configuration using the measurements from the WASA masts. In the second part, we describe the method used to generalise and downscale the WRF model wind climate. We compare the results from the downscaled numerical wind atlas against the observed wind statistics from the 19 WASA masts in the third part. In the last part we present the new wind resource maps and their long-term climatology. In WASA3, there have been many updates to the configuration of the 2018 WASA2 simulations documented in Hahmann et al. (2018). Among the most important:

1. We ran thirteen two year simulations covering the period most observed in all the WASA sites to find the WRF model configuration most suited to the simulation of the wind climatology over South Africa.

2. We used a new method of generalisation and downscaling of the WRF-derived wind climate that uses the PyWAsP engine and was demonstrated more accurate than the previous approach.

3. We produced the most extensive to date wind climatology for South Africa, 30 years (1990–2019) simulation covering all South Africa at 3.33 km 3.33 km spatial resolution and 30 minutes time output.

The final error statistics of the WASA3 wind atlas show that the WRF+PyWAsP method has a MAPE of 14.2% and 4.3% for the long-term power density and wind speed, respectively. This is improved from the same validation in WASA2. When ignoring the two more complex masts, WM09 and WM11, the WRF and WRF+PyWAsP downscaling significantly narrows the error distributions for both long-term wind speed and power density.

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Chapter 1

Introduction

1.1 Definitions and outline

The regional wind climate, i.e. the long-term spatial and temporal distribution of the wind speed and direction over an area of the earth surface, is vital information for locating optimal areas for the siting of wind power plants and for developing regional action plans for reduction of the use of fossil fuels for the generation of electricity. The output from long-term simulations using a mesoscale model is now widely used to generate the wind climatology necessary for calculating the wind energy resources of a given geographical area (Tammelin et al., 2012; Nawri et al., 2014; Hahmann et al., 2015b; Dörenkämper et al., 2020). These wind climatologies are useful when validated against measurements and serve as input to microscale models for further downscaling (Badger et al., 2014; Dörenkämper et al., 2020). With this in mind, the main objective of this report is to document the methods used and validate the model results against observations in a similar manner to that done in the mesoscale report to WASA Phase 1 (Hahmann et al., 2015a) and WASA Phase 2 (Hahmann et al., 2018).

Mesoscale model simulations using the Weather, Research and Forecasting (WRF; Skamarock et al., 2008) model are verified against measurements from the 10 masts in the first phase of the Wind Atlas of South Africa (WASA) and the 5 additional masts installed during the second phase of the project (WASA2) and 4 others during the third phase (WASA3). The verification is carried out for the raw WRF wind climatology (Chapter 3) and the downscaled WRF winds (Chapter 5) using the method described in Chapter 2.

In Chapter 6 we present the maps of mesoscale simulated winds and power densities, and the final full downscaling mean wind and power density maps. Finally in Chapter 7 we summarise the results and offer factors that contribute to the uncertainty of the results.

1.2 Glossary

AGL	Above ground level
CAM3	Radiation parameterization in the Community Atmosphere Model, Version 3 (WRF parameterization)
CEMD	Circular EMD (validation metric)
CFD	Computational fluid dynamics
CSIR	Council for Scientific and Industrial Research

DEM	Digital elevation model
DTU	Technical University of Denmark
ECMWF	European Centre for Meddium Range Forecasting
ERA5	Fifth generation ECMWF atmospheric reanalysis
EMD	Earth's movers distance (validation metric)
ESA-CCI	European Space Agency Climate Change Initiative
KAMM	Karlsruhe Atmospheric Mesoscale Model
LINCOM	fast linearised and spectral wind flow model for use over hilly terrain
LSM	Land surface model (WRF parameterization)
MAE	Mean absolute error (validation metric)
MAPE	Mean absolute percentage error (validation metric)
MYNN	Mellor-Yamada-Nakanishi-Niino PBL scheme (WRF parameterization)
M-O	Monin-Obukhov SL scheme (WRF parameterization)
NASA	National Aeronautics and Space Administration (USA)
NEWA	New European Wind Atlas
OSTIA	Operational Sea Surface Temperature and Sea Ice Analysis
PBL	Planetary boundary layer
PyWAsP	Python version of the WAsP software
RMSE	Root mean square error (validation metric)
RIX	Ruggedness index
SANEDI	South African National Energy Development Institute
SL	Surface Layer model (WRF parameterization)
SRTM	Shuttle Radar Topography Mission
UCT	University of Cape Town
USGS	United States Geological Survey (vegetation classification)
WASA	Wind Atlas for South Africa
WAsP	Wind Atlas Analysis and Application Program
WGS84	World Geodetic System 1984
WRF	Weather Research and Forecasting model
YSU	Yonsei University (YSU) PBL scheme (WRF parameterization)

Chapter 2

Methods

2.1 Model validation metrics

We used several metrics to evaluate the accuracy of the model simulations when compared to tall mast observations. These metrics were used to find the best suited model configuration used in the production simulation and the generalisation of the WRF model results.

We calculate the temporal mean of each modelled distribution, $\overline{x}_m$, and the observed distribution, $\overline{x}_o$, for identical time periods. The bias herein is defined as difference between the two means, $\overline{x}_m - \overline{x}_o$. In the case of a wind atlas, x can represent wind speed, u, or wind power density, P, defined as

$$P = \frac{1}{2}\rho u^3; \tag{2.1}$$

where ρ is the air density. If the bias of a variable is positive, the model overestimates its value compared to observations.

The bias is a popular error statistic for comparing the wind speed distributions between observations and model-simulated fields. However, since the power density is a function of the cube of the wind speed (see Eq. 2.1) the shape of the wind speed distribution is even more important. Small changes in the wind speed distribution are amplified when converted to power. Accordingly, we use the Earth Mover's Distance (EMD) to evaluate the differences in the shape of two frequency distribution. This metric was first used and introduced in the sensitivity experiments for the New European Wind Atlas (Hahmann et al., 2020). The EMD, also known as the first Wasserstein distance, is popular in image processing (EMD; Rubner et al., 2000). The EMD can be interpreted as the amount of physical work needed to move a pile of soil in the shape of one distribution to that of another distribution. For one-dimensional distributions the EMD is equivalent to the area between two cumulative distribution functions, and, this interpretation with slight modifications, can be applied also to circular variables (Rabin et al., 2008). More discussion about the EMD properties can be found in Lupu et al. (2017). The EMD was calculated using the Pyemd package (Pele and Werman, 2008). The circular EMD (CEMD; Rabin et al., 2008) extends the EMD concept to one-dimensional circular histograms, such as the frequency distribution of wind directions. An example of how to interpret the CEMD is available in the NEWA paper (Hahmann et al., 2020).

The information about temporal co-variability is provided herein by the Pearson's correlation coefficient, r, a measure of dependence between two simulated and observed time series, and the root mean square error (RMSE), which estimates of systematic biases in model skill (von Storch and Zwiers, 1999). These measures are defined as

$$r = \frac{1}{\sigma_o \sigma_m} \sum_{i=1}^{N} (u_o^i - \bar{u}_o)(u_m^i - \bar{u}_m); \tag{2.2}$$

$$\text{where} \tag{2.3}$$

$$\sigma_o = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u_o^i - \bar{u}_o)^2} \text{ and } \sigma_m = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u_m^i - \bar{u}_m)^2}; \tag{2.4}$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (u_m^i - u_o^i)^2}; \tag{2.5}$$

with u_o^i and u_m^i being the i-th observed and modelled values in the time series of length N. σ_o and σ_m are the standard deviations of the observed and simulated time series.

In selection of the optimal configuration for the WASA3 wind atlas, we compared the results of an ensemble of WRF model setups against the observations at all sites. One of the ensemble members was designated to be the baseline or "BASE". To evaluate if a certain model set up from the pool performs better or worse than the BASE configuration, we define a general skill score (von Storch and Zwiers, 1999):

$$SS = 1 - M_j / M_B; \tag{2.6}$$

where M_j is the value of the metric for the j-th ensemble member and M_B is that of the baseline. The metric M can be the absolute value of the bias, the RMSE, EMD, or CEMD. For the correlation, the formula is reversed: $SS = r_j / r_B - 1$, since a perfect correlation equals 1. If $SS > 0$ the ensemble member j "improves" the metric with respect to the baseline case, if $SS < 0$ it "worsens" it. A value of $SS = 1$ means that the new simulation is perfect. The SS is easily understood and is applicable to all our evaluation metrics. However, when the BASE simulation evaluates extremely well against observations (e.g. when the bias is close to zero), the skill score can become very large. Therefore, the SS is a useful quantity for the RMSE, which is rarely close to zero, but can be misleading when used for the absolute bias or the EMD, indicating large improvements when the differences in metrics themselves are small. Accordingly, we suggest using both SS and the original metric when interpreting the results.

To facility comparisons at all masts, we average the BIAS or EMD. For the BIAS we use the mean absolute error, MAE, defined as

$$\text{MAE} = \frac{1}{M} \sum_{k=1}^{M} |\bar{u}_m^k - \bar{u}_o^k|; \tag{2.7}$$

$\bar{u}_m^k$ and $\bar{u}_o^k$ being the mean of the variable at the k-th station; and M is the number of sites. Finally, we can also define a MAE expressed in terms of a percentage by dividing by $\bar{u}_o^k$.

$$\text{MAPE} = \frac{100}{M} \sum_{k=1}^{M} \frac{|\bar{u}_m^k - \bar{u}_o^k|}{\bar{u}_o^k}; \tag{2.8}$$

2.2 WRF model simulations

The WRF model simulations follow the method used in previous wind atlases: WASA1 (Hahmann et al., 2015a) and WASA2 (Hahmann et al., 2018). The database of simulated winds and wind-energy relevant parameters for the model simulations was created by splitting the simulation period into a series of relatively short WRF model runs that, after concatenation, cover the desired time period. The simulations overlap in time during the spin-up period by 24 h, which is discarded, as described in Hahmann et al. (2015b). In this approach, the use of nudging prevents the model solution from drifting from the observed large-scale atmospheric patterns, and the multi-days simulation ensures that the mesoscale flow is fully in equilibrium with the mesoscale characteristics of the terrain (Vincent and Hahmann, 2015). The method has the added advantage that the simulations are independent of each other, and therefore, can be computed in parallel, reducing the total time needed to complete a multi-year climatology.

All mesoscale simulations in WASA3 used three nested domains with a 3.33 km horizontal grid spacing for the innermost grid and a 1:3 ratio between inner and outer domain resolution, leading to 3 different resolutions: 30 km for the outer domain, and 10 km and 3.33 km for the inner nested domains. The model top was set to 50 hPa, following the best practices recommended by the WRF developers (Wang et al., 2019). Other parameters common to all simulations are listed in Table 2.1. We explore the effect of changing various relevant parameters of the simulation set up from the base model configuration explained above to estimate the wind climatology over South Africa.

Figure 2.1 – WRF model grid configuration: D1: 140 × 160 grid points (30 km), D2: 271 × 331 grid points (10 km) and D3: 454 × 631 grid points (3.33 km)

Table 2.1 { Common WRF model setup used in all the sensitivity experiments.

option	setting
Model grid	spacing: 30 km / 10 km / 3.33 km Lambert conformal grid projection Grid centred at 15E and 28.5S, with a 10 rotation Grid sizes: 140 160 (D1), 271 331 (D2) and 454 631 (D3)
Terrain data	Global Multi-resolution Terrain Elevation Data 2010 at 30" (Danielson and Gesch, 2011)
Land use	ESA-CCI land-cover (Poulter et al., 2015), converted to USGS categories
Vertical discretisation	61 vertical levels with model top at 50 hPa
Model levels	20 model levels below 1 km
Diffusion	Simple diffusion (option 1), 2D deformation (option 4) 6th order positive definite numerical diffusion (option 2) No vertical damping Positive definite advection of moisture and scalars
Forcing data	ERA5 (Hersbach et al., 2020) reanalysis at 0.25 0.25 on 34 pressure levels
Sea surface temperature	Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA, Donlon et al., 2012) Lake temperatures from time-averaged ERA5 ground temperatures
Cloud micro-physics	WRF Single-Moment 5-class scheme (Hong et al., 2004)
Cumulus convection	Kain-Fritsch Scheme (Kain, 2004); D1 and D2
Land surface model	Unified Noah Land Surface Model (Tewari et al., 2004)
Nesting	One way nesting with smoothing (option 2)
Nudging	Spectral nudging U, V, T and q on D1 above level 20, no PBL nudging
Nudging constant	0.0003 s^{1}
Nudging wavelength	14 (x) and 10 (y) equivalent to about 400 km (synoptic wave length)

The mesoscale domain configuration, terrain elevation and dominant land use classes are shown in Figures 2.1, 2.2, and 2.3, respectively.

Figure 2.2 { Terrain elevation of the WRF D3 (3.33 km 3.33 km) domain.

Figure 2.3 { Dominant land use classification of the WRF D3 (3.33 km 3.33 km) domain.

2.3 Data processing

Wind speeds and directions are derived from the WRF model output, which represents 30-minutes instantaneous values. For evaluating the model wind speed climatology, the zonal and meridional wind components on their original staggered Arakawa-C grid were interpolated to the coordinates of the mass grid. The interpolated wind components were then used to compute the wind speed and rotated to the true north to derive the wind direction. For a given height, e.g., 100 m, wind speeds are interpolated between neighbouring model levels using linear interpolation in logarithmic height. It was found that this interpolation procedure preserves more of the original features in the model wind profile compared to other schemes (e.g., linear or polynomial interpolation of the wind components).

Chapter 3

Mesoscale modelling

3.1 Sensitivity experiments

As discussed in Hahmann et al. (2020), mesoscale models are, in general, not specifically developed for wind energy applications; however, over the last decade they have been extensively used for that purpose. Developing an optimal WRF model configuration for wind resource assessment is not a straightforward task, considering the large number of degrees of freedom in the model configuration, and the different choices of input data. Among the configuration options offered in the WRF model are, physical parameterisations such as planetary boundary layer (PBL), surface layer (SL), land surface model (LSM), cloud micro-physics, and radiation. Also numerical and technical options (e.g., domain layout, nudging options, time step), and the initial and boundary conditions of the atmosphere, sea surface, and land surface are relevant aspects to be explored before determining the set up that better fits a specific application. Arguably, an optimal configuration that performs best at all time and spatial scales cannot be expected, and we search herein for a configuration that tends to perform better at most instances within the ensemble of sensitivity experiments performed.

It is impossible to test every combination of the WRF model setup and possible parameterisations, as the number of such experiments would be in the thousands, which is unfeasible in terms of computational resources. Therefore, a compromise between available computational power and scientific soundness had to be found. The approach in WASA3 was to first define a “best practice” setup from the NEWA production run (Dörenkämper et al., 2020), and then to test the sensitivity of the results to changes in the model configuration that were not tested in previous wind atlas projects. This includes some physical options, such as PBL schemes and radiation scheme and the WRF model version, WASA1 used WRF model version 3.6.1.

All simulations for WASA3 covered two full years (2018–2019) and used similar grid parameters and modelling setup to that described in Table 2.1. What is varied in each sensitivity experiment is detailed in Table 3.1: WRF model version (WRF V3.6.1 or V3.8.1), PBL scheme (MYNN level 2.5 Nakanishi and Niino (2009) with and without mods, YSU Hong et al. (2006)), surface layer scheme (MYNN, MM5 and M-O Janjic and Zavisa (1994)). The use of a more advanced radiation parameterization (CAM3, Collins et al. (2004)) was also tested. In the “DOM” versus “MOS” experiments, we use the sub-tiling option for NOAH (Li et al., 2013), with the WASA vegetation table. The sub-tiling option generates more realistic values of surface roughness length (Figure 3.1) in areas of mixed vegetation, which could reduce the biases in wind speed (Santos-Alamillos et al., 2015).

Table 3.1 { Overview of the ensemble of simulations varying WRF model version, planetary boundary layer (PBL), surface layer (SL), radiation scheme and the use of dominant (DOM) versus mosaic (MOS) vegetation. [1] uses nudging in D01 and D02.

run name	version	PBL (#)	SL (#)	radiation (#)	veg	extras
MYNN	V3.6.1	MYNN (5)	MYNN (5)	RRTMG (4)	DOM	
MYNN-V381	V3.8.1	MYNN (5)	MYNN (5)	RRTMG (4)	DOM	
MYNN-MO	V3.6.1	MYNN (5)	MO (2)	RRTMG (4)	DOM	
MYNN-CAM3	V3.6.1	MYNN (5)	MYNN (5)	CAM3 (3)	DOM	
MYNN-V381-CAM3	V3.8.1	MYNN (5)	MYNN (5)	CAM3 (3)	DOM	
MYNN-MOS	V3.6.1	MYNN (5)	MYNN (5)	RRTMG (4)	MOS	
MYNN-V381-MOS	V3.8.1	MYNN (5)	MYNN (5)	RRTMG (4)	MOS	
YSU	V3.6.1	YSU (1)	MM5 (1)	RRTMG (4)	DOM	
YSU-V381	V3.8.1	YSU (1)	MM5 (1)	RRTMG (4)	DOM	
YSU-V381-MOS	V3.8.1	YSU (1)	MM5 (1)	RRTMG (4)	MOS	
YSU-V381-MOS-ND2	V3.8.1	YSU (1)	MM5 (1)	RRTMG (4)	MOS	[1]

Figure 3.1 { Map of surface roughness length [m] in the dominant (left; DOM) and mosaic (right; MOS) simulations. This is the D3 WRF domain.

We also performed a simulation with 4 overlapping domains instead of the very large inner domain of the other simulations. The results from this test were nearly indistinguishable from those of the control simulation, and are not used further in the validation that follows.

3.2 Evaluation of the WRF ensemble simulations

We evaluate the performance of the various sensitivity experiments in Table 3.1 against measurements from the 18 WASA masts (WM04 was discontinued before 2018).

To facilitate the intercomparison among the ensemble members, we computed all the evaluation metrics of the wind speed for each simulation (Fig. 3.2{Fig.3.6). The metrics compare the wind speed (at 62 m) and wind direction (at 60 m) observations during 2018-2019 with the corresponding WRF-simulated time series interpolated to the same height. Figure 3.2a shows the model bias at all the sites. For this metric the differences among stations are larger than differences between models in a single station, expressed in this figure as consistent colours for each line. At sites WM11 and WM19, the WRF simulations particularly overestimate the wind speed in all simulations. In terms of relative bias, the values lie between an overestimation of +17–22% at WM19 to underestimation 11–5% at WM03.

To better quantify the differences between the simulations, Fig. 3.2c shows the skill score (SS) of the bias from the MYNN simulation as defined in Chapter 2. Positive numbers (in green) show a decrease in absolute bias, which point to a more accurate simulation. Most simulations, except for YSU, improve on average the bias, but the values are small (0.1–0.2%).

Figures 3.3c and 3.3d provide further information about the sensitivity tests based on the EMD metric defined in Chapter 2 to evaluate the shape of the wind speed distributions. As with the bias, the EMD shows that the largest differences in total error are linked to the site location, with good model performance at most sites, with EMD between 0.1–0.4 m s^{-1}; at WM11 and WM19 the EMD is above 1.0 m s^{-1}. On average the YSU-V381-MOS and YSU-V381-MOS-NO2 ensembles improve this metric.

Figures 3.4e and 3.4f provide some metric of the temporal correlation between the WRF-simulated wind speed and that observed at the masts. The correlation varies between 0.86 at WM05 and 0.54 at WM12. The RMSE varies between 2.2 and 3.4 m s^{-1}. Again some relationships stand out with best RMSE at WM01 and WM03 (2.5–2.9 m s^{-1}) and worst at WM11 (3.5–4.0 m s^{-1}). The CORR and RMSE are improved by the YSU-V381-MOS-ND2 ensemble, as expected by the use of spectral nudging in both D01 and D02.

The performance of the model with respect to the wind direction is shown in Fig. 3.6. The best simulated site is WM01 (CEMD: 1.0–5.0) and the worst WM11 with CEMD above 10 in most ensembles. Here all ensemble members seem to make the CEMD worse with respect to MYNN, except for the YSU simulation.

In conclusion: The BIAS is improved by all simulations, except for YSU. The EMD is improved by the YSU-V381-MOS and YSU-V381-MOS-NO2 ensembles. No simulation, except for YSU-V381-MOS-NO2, improves on average the CORR and RMSE. Finally, no simulation improves on average the circular EMD, but it is not worsen by the MYNN-V381-MOS and YSU ensembles.

(a)

(b)

(c)

Figure 3.2 { Evaluation metrics: (a) bias [m s^{1}], (b) relative bias [%] and (c) bias SS [-] between the observed and simulated wind speed at the 18 WASA sites and 62 m height and the various sensitivity studies in the ensemble (Table 3.1). All SS are relative to the MYNN simulation. The last line shows the mean absolute bias (MAE) for all sites.

(a) (b)

Figure 3.3 { As for Fig. 3.2 but for the (a) EMD and (b) EMD SS.

(a) (b)

Figure 3.4 { As for Fig. 3.2 but for the synchronous correlation (r) between the wind speed in the model and the observations.

(a) (b)

Figure 3.5 { As for Fig. 3.2 but for the (a) RMSE and (b) RMSE SS.

(a) (b)

Figure 3.6 { As for Fig. 3.2 but for the (a) circular EMD and (b) CEMD SS.

Chapter 4

Microscale modelling

For the first time both mesoscale modelling and microscale sensitivity studies were performed. This was done by testing three different descriptions of the roughness length and two different generalization procedures.

4.1 Generalisation

According to the Numerical Wind Atlas concept, a generalized wind climate can be obtained by removing the effects of terrain and roughness from the mesoscale model grid (Badger et al., 2014; Lennard et al., 2015). Two approaches are used and compared in this report.

An identical generalization approach to that described in Dörenkämper et al. (2020) is deployed here, which relies on the linearized flow model LINCOM to compute orographic speedups and is hence labelled 'LINCOM' throughout the rest of this report. The roughness speedups of the WRF grid are calculated using the same routines as in WAsP. Finally the geostrophic drag law is used to compute geostrophic wind according the procedure outlined in (Badger et al., 2014).

The second generalization procedure solely relies on the WAsP model engine: it could be argued that it is more consistent to use the same models for removing the mesoscale effects and applying the microscale effects. The generalization was performed with PyWAsP version 0.4.1, with default wind profile setting and the baroclinicity model switched off Floors et al. (2015, 2018). At present there is no method to obtain geostrophic shear from the WRF model and using it from another source such as ERA5 would have introduced issues with the ERA5 tiles being visible in the output. A new stability model that has been implemented in WAsP was tested as well (Floors et al., 2021b). This model uses a temperature scale derived from the WRF time series which was then converted into a histogram based on the wind speed at 100 m. The mean and standard deviation from this temperature scale were then obtained at the highest 50% of the wind speeds. This procedure was applied because higher wind speeds are most important when extrapolating Weibull distributions. The boundary layer height was obtained in a similar fashion.

For the topography modelling the 'spider-grid' roughness analysis was used, which keeps the terrain description in it's original land cover classes together with a lookup table when processing the zooming grid around the point of interest (Floors et al., 2021a). The first grid cell is 25 m and this distance increases with 5% for each next radial grid cell. For the computation of the orographic speedups the Bessel expansion on a zooming grid (BZ) model was used. The BZ model is extensively described in Ch. 8.5 in Troen and Petersen (1989). Although it gives generally good results in simple terrain, it is known to have issues in complex terrain. Due to it's linearized nature, flow separation that occurs when the terrain slopes are more than ≈30% (17°) cannot be modelled. This results in the calculation of too high speedup effects at sites that are located near the top of a hill or mountain. Therefore, the ruggedness index (RIX) is used to identify the ability of the BZ model to correctly calculate orographic speedups Mortensen et al. (2006). It is defined as the percentage of slopes that is steeper than 30% in a circle of 3.5 km around the point of interest.

4.2 Downscaling

The downscaling was performed with PyWAsP version 0.4.1 with the same settings as the generalization procedure. The simulation that used the PyWAsP updated stability model (see Sec. 4.1) also needs to have information about the stability for the downscaling. Therefore the same stability histogram was used for the downscaling for this model, i.e. by applying the WRF temperature scale and boundary layer height in the profile model. Note that the offshore stability parameters are applied based on the ESA-CCI land mask with 300 m resolution.

The same setup for the microscale topography modelling was used as in the generalization (see previous section). For the computation of the orographic speedups the high resolution elevation data were used as input.

The elevation data were obtained from NASA's Shuttle Radar Topography Mission (SRTM) version 3. The data were void-filled with the Viewfinder DEM data De Ferranti (2012). These elevation data have a resolution of 3" (≈90 m).

microscale mode	land cover table
PyWAsP	DTU
PyWAsP	EMD
PyWAsP	WRF
PyWAsP stab.	DTU
PyWAsP stab.	EMD
PyWAsP stab.	WRF

Table 4.1 – Overview of the different microscale model runs that were evaluated.

All versions used the same land cover data, namely the ESA-CCI land cover produced in 2015 (Poulter et al., 2015) (Table C.2). The way that lookup tables are generated is subjective, where the z_0 values are estimated based on knowledge of the behaviour of the logarithmic wind profile over different types of surfaces. Three versions of the land cover tables were used (see Table 4.1). The land cover labelled 'DTU' was developed at DTU wind energy and has been used in the Global Wind Atlas (Badger et al., 2015). The 'EMD' lookup table is used in the windPRO software and was obtained from their website Thøgersen (2020). Finally, a lookup table was generated by using the corresponding roughness that was used in the WRF model setup, which is labelled as 'WRF'. In previous modelling studies it was found that the generalization procedure performed better when using similar values as WRF (Dörenkämper et al., 2020).

Because the downscaled results obtained from both methods are given as sector wise Weibull A and k parameters, they cannot be directly compared to the histograms. Therefore the distributions were transformed to histograms with 12 30 wide sectors and 30 wind speed bins.

Chapter 5

Wind atlas validation

5.1 Evaluation of WRF ensemble including downscaling

In previous validations of WASA1 and WASA2, only the best performing WRF simulation was selected for creating the final long-term simulations and further downscaling and validation. In this report another approach is taken: all WRF sensitivity experiments were downscaled using the two microscale model chains. These are based on the LINCOM and PyWAsP model for the generalization procedure (see Section 4.1) and using three different lookup tables for the land cover classes in the downscaling procedure (see Section 4.2). For simplicity, and because these were used for the final downscaling result (Table 5.1), we only discuss the results from the PyWAsP procedure and DTU lookup table here. However, the order of the WRF simulations in terms of the MAPE in power density and wind speed did not change from that of the raw mesoscale validation presented in Section 3.2. The validation presented in this section is only for the two years (2018–2019) of the WRF sensitivity experiments.

From Table 5.1, the YSU-V381-MOS WRF simulation gives the lowest MAPE in terms of mean power density. The MYNN simulation gives a slightly lower MAPE in U, but the power density is generally more important for wind energy applications. Thus the YSU-V381-MOS configuration was chosen for the production run for the full 30 year period (1990–2019). When comparing simulations that are identical except for the PBL scheme (YSU-

Table 5.1 – The MAPE in power density (P) and wind speed (U) at all masts with RIX of 0.0 using the PyWAsP microscale model chain and the DTU land cover table for different mesoscale WRF experiments. The MAPE are relative to the 2018–2019 period in simulations and observations.

WRF experiment	MAPE P [%]	MAPE U [%]
YSU-V381-MOS	13.01	4.27
YSU-V381	14.58	4.44
MYNN	14.73	4.22
MYNN-V381-MOS	15.44	4.82
MYNN-CAM3	15.53	4.89
YSU	16.02	6.58
MYNN-V381-CAM3-MOS	16.03	5.00
MYNN-V381	16.74	5.43
MYNN-V381-CAM3	17.60	5.67

V381 versus MYNN-V381 and YSU-V381-MOS versus MYNN-V381-MOS) it appears that the YSU scheme performance is slightly better than that of the MYNN scheme. Using the CAM3 radiation scheme resulted in higher MAPE compared to the default radiation scheme.

5.2 Evaluation of downscaling methods

NWP model	micro model	landcover	MAPE P [%]	MAPE U [%]
YSU-V381-MOS	PyWAsP stab.	EMD	11.79	3.49
YSU-V381-MOS	PyWAsP	EMD	12.10	3.64
YSU-V381-MOS	PyWAsP stab.	DTU	13.71	4.13
YSU-V381-MOS	PyWAsP	DTU	14.21	4.30
YSU-V381-MOS	none	WRF	15.62	4.66
YSU-V381-MOS	PyWAsP stab.	WRF	16.35	6.02
YSU-V381-MOS	PyWAsP	WRF	16.56	6.13
YSU-V381-MOS	LINCOM	EMD	17.01	6.66
YSU-V381-MOS	LINCOM	WRF	17.73	4.77
YSU-V381-MOS	LINCOM	DTU	18.35	6.77
ERA5	none	ERA5	54.01	24.76

Table 5.2 – Comparison of the MAPE in power density P and wind speed U for the raw output of the NWP models and for the different microscale model options (see Table 4.1). Only flat sites (RIX=0) are considered and the results are ordered by the MAPE of power density order.

Based on the previous section, the YSU-V381-MOS WRF configuration (the namelists can be found in appendix A) was chosen to model the full 30 year period. A verification of the microscale modelling was performed, comparing the downscaled with the full set of measurements from all sites. We note that the period with available measurements is about 10, 5 and 1.5 years for masts WM01–WM10, WM11–WM15 and WM16–WM19, respectively. Therefore, it is not uniform across all sites. The half-hourly WRF output were matched with the corresponding available time stamps that were available for each mast. The observations are compared with the WRF model output (YSU-V381-MOS) from the nearest model grid cell (denoted as ‘Raw WRF‘). In addition, the nearest grid cell from the ERA5 reanalysis, which is used as boundary conditions for the WRF model simulations, is also used in the verification (denoted as ‘Raw ERA5‘). The WRF-derived climatologies are further generalized and downscaled to 62 m AGL using the two procedures outlined in Chapter 4.

The values of mean wind speed and power density are compared in Table 5.2. The ERA5 output from the nearest grid cell clearly fails to accurately estimate the MAPE in P and U, with errors of 54% and 25%, respectively. The LINCOM generalization has a MAPE in P of about 17%. Notably the LINCOM simulation using the same z_0 as WRF performs relatively well in terms of MAPE in U, as previously found in Dörenkämper et al. (2020). On the contrary the downscaled PyWAsP and PyWAsP stab. simulations perform relatively poorly when using the same land cover table as WRF with a MAPE in P 16%. The raw WRF output of the nearest grid point performs quite well and P 16%. This might be related to the relatively simple terrain that is present around the masts, which causes the roughness and orographic speedups to be generally quite small (not shown). It is possible that in areas with complex land cover the WRF raw output might not do quite as well.

The PyWAsP simulations with the EMD land cover table resulted in the lowest MAPE in P and U. PyWAsP with the new stability model (PyWAsP stab.) outperformed the simulations that adopt the default WAsP heat fluxes (PyWAsP) for all land cover tables. The stability performance will be further evaluated in future studies, but for the final high-resolution wind resource map the standard PyWAsP stability approach was used, because otherwise the results would show tiles with the size of the WRF data that was used to create the stability histograms. In the PyWAsP downscaling tiling artefacts are avoided by using a natural neighbour interpolation of the generalized wind climates.

5.3 Validation at all sites of the WRF production run and PyWAsP downscaling

A comparison between the observed wind climatology at the 62 m level of the masts and both WRF and downscaled WRF results is presented in Table 5.3. For comparison, the same results are also graphically shown in Fig. 5.1. Mast WM09 and WM11 have a RIX higher than 0.0 and are therefore not included in the overall summary. The LINCOM model chain does not perform

mast	u_o (m s ^{1})	RIX	u_m (m s ^{1}) LINCOM	PyWAsP	WRF	Abs. bias, u_m u_o (%) LINCOM	PyWAsP	WRF
WM01	6.20	0.0	5.37	5.88	6.19	13.34	5.10	0.08
WM02	6.19	0.0	6.09	6.38	6.74	1.50	3.19	8.96
WM03	7.13	0.0	6.09	6.49	6.62	14.65	9.02	7.22
WM04	6.70	0.0	6.00	6.57	6.85	10.50	1.99	2.19
WM05	8.42	0.0	7.39	8.07	8.22	12.31	4.22	2.37
WM06	7.40	0.0	7.05	7.49	8.06	4.73	1.19	8.98
WM07	6.98	0.0	6.57	6.76	7.34	5.85	3.17	5.18
WM08	7.27	0.0	6.51	7.37	7.39	10.46	1.39	1.57
WM09	8.01	3.0	7.50	7.80	8.34	6.42	2.66	4.06
WM10	6.66	0.0	6.49	6.83	6.71	2.53	2.43	0.74
WM11	7.80	1.0	8.82	9.76	9.11	13.14	25.24	16.88
WM12	5.12	0.0	4.88	5.15	5.27	4.61	0.56	3.02
WM13	5.08	0.0	5.18	5.50	5.67	1.97	8.32	11.61
WM14	7.45	0.0	7.62	7.84	7.50	2.26	5.23	0.66
WM15	6.13	0.0	6.00	6.40	6.04	2.13	4.31	1.52
WM16	7.05	0.0	6.46	6.74	7.18	8.36	4.33	1.94
WM17	6.95	0.0	6.58	6.65	7.17	5.28	4.31	3.11
WM18	6.62	0.0	6.02	6.23	6.77	8.97	5.82	2.32
WM19	5.73	0.0	6.06	6.23	6.75	5.74	8.61	17.74
all (RIX=0.0)	6.65	0.0	6.26	6.62	6.85	6.77	4.30	4.66

Table 5.3 { Comparison of the mean wind speed at 62 m AGL for all WASA masts for the observations (u_o) and both raw WRF and downscaled models (LINCOM and PyWAsP) (u_m). All concurrent observations are used.

very well for the first 10 masts, with WM01, WM03, WM04, WM05 and WM08 having wind speed error that exceed 10%. WM11 is a highly complex site at high elevation south of the elevated terrain of Lesotho. Both WRF and PyWAsP show large overestimation of wind speed there, whereas LINCOM has a slightly smaller error. In most sites, WRF does generally have low errors in wind speed, but largely overestimate the wind speed at WM19. The reason for this is unknown, since the surrounding terrain is not very complex. We speculate that strong stability changes occur at this site.

Figure 5.1 { MAPE in the long-term wind speed at 62 m AGL for all sites.

All sites shown in Fig. 5.1 capture the overall error distribution for whole South Africa. Because of the special behaviour of the microscale models in complex terrain and the fact that it is usually recommended to run CFD simulations there, we analyzed the results both with and without the sites with a non-zero RIX. The error distribution of the mean wind speed and power density biases is shown in the top and bottom left panel in Fig. 5.2, respectively. The large underestimation in the ERA5 data is very obvious. Both the WRF and downscaled simulations perform much better. The downscaled simulations have the lowest spread and an overall mean bias close to zero.

The outlier in these panels is the very complex WM11 site and the results with the high RIX sites removed is shown in the top and bottom right figures. The error distribution is now becoming increasingly centred around zero and the spread is significantly reduced. These figures indicate that there is a clearly value of applying a full meso- and microscale model chain in non-complex terrain.

Figure 5.2 { Distribution of the bias in wind speed (top) and power density (bottom) for the ERA5, ERA5+WRF and ERA5+WRF+PyWAsP downscaling at all 19 sites WASA (left) and the 17 at sites (RIX=0, right).

5.4 Validation at each site

To exemplify the sensitivity of the simulations to the microscale model setup, a more extensive validation at each site is performed. For illustrative purpose we shortly present the WRF roughness map and the microscale roughness maps that were used in the sensitivity study. These maps were also used to ensure that all computations related to the transformation of map projections were performed correctly. For example, an error with the projection string of the WRF data was detected and corrected. Also the mast coordinates of masts 1{10 were initially slightly off, causing the WRF variables to be extracted from the wrong grid point.

First we introduce an aerial overview of all sites to get an impression of the position of the mast in the landscape. In addition it can be seen how complex the landscape is in terms of land cover and orography, which is recommend when doing a wind resource assessment using the WAsP software.

The observed wind climatology of the measurements from the masts are compared with values of the corresponding model grid cell in the WRF simulations and the ERA5 reanalysis data. The WRF-derived climatologies are further generalised and downscaled to 62 m AGL using the two procedure outlined in Chapter 4 (LINCOM and PyWASP). Here we compare the wind roses from the observations, the coarse reanalysis data from ERA5, the WRF production run and the two downscaled WRF results. As the wind rose results are presented above, we focus on the differences between the raw WRF output and the downscaled WRF results to highlight where the downscaling is important and what type of value the downscaling adds in these cases.

Figure 5.3 { Location of all the validation sites. The blue outline is the outer edge of the WRF D3 domain.

The comparison continues by comparing the wind all-sector wind distribution between the observations and the WRF production run. Finally, we compare the diurnal and annual cycle of wind speed at each site. Heatmaps for the seasonal versus diurnal wind speed are compared in the observations and the WRF model simulations.

In all the following figures and descriptions, the complete available observed dataset ending on 31 December 2019 is used. Also, the measurements and WRF model simulations (at 30 minutes frequency) are synchronised and always contain the same amount of samples. No effort has been made to include complete years, and all available measurements are taken. Caution should be taken in interpreting the results from masts WM16{WM19, where a short period of measurements (1{2 years) is available.

5.4.1 Alexander Bay (WM01)

The first mast of WASA phase 1 is located near Alexander Bay in the northwest of South Africa. The terrain is dry and the climate arid (Fig. 5.4). In WRF (5.4a) the roughness length is low and generally around 0.01 m in the northwesterly direction of the mast and 0.03 m to the south easterly direction. In the DTU lookup table the area towards the northwest has a roughness length of 0.005 m and to the southeast it is 0.1 m. The latter is probably too high as the area is very sparsely vegetated. There is more vegetation in the river valley, where all microscale maps correctly show a higher z_0.

Figure 5.4 { Roughness maps around mast WM01 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climates at WM01 are shown in Fig. 5.5. The predominant wind direction is from the southwest. Both downscaling methods degrade the raw WRF result as it produces a lower wind speed climatology compared to the raw WRF data. The ERA5 data largely underestimate the wind speed in all directions. The directional frequency distribution is captured quite well by both WRF and the downscaled results.

The wind speed distribution at WM01 is very well simulated by the raw WRF data

Figure 5.5 { Observed and simulated wind climatologies at 62 m AGL at site WM01: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.6 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM01.

Figure 5.7 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM01.

(Fig.5.6). The very marked annual cycle in wind speed (Fig.5.7) is well simulated by WRF, with minimum wind speed in the winter months, and higher winds in November to February. The amplitude of the diurnal cycle during summer, with maximum winds in the late afternoon, is very well simulated by WRF, but with a phase error of about 1.5 hours, with the WRF maximum wind speed being too early in relation to that of the observations.

5.4.2 Calvinia (WM02)

Site WM02 is located at an elevation of about 800 m. There is more vegetation than in WM01, but the climate is still dry and arid $z_0 = 0.03$ m in the WRF simulations, whereas it is somewhat higher ($z_0 = 0.07$ m) in the EMD microscale maps and even higher in the DTU maps ($z_0 = 0.1$ m). To the west of the mast there is a ridge where the elevation drops about 50 m.

Figure 5.8 – Roughness maps around mast WM02 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climate at WM02 are shown in Fig. 5.9. Again the ERA5 reanalysis largely underestimates the wind speed in all directions. In addition the very frequent occurrence of southeasterly wind is not present in the ERA5 wind rose. The WRF, LINCOM and PyWAsP wind roses agree fairly well, although the frequent winds from the SSE are spread slightly to the neighbouring sectors in PyWAsP and LINCOM. LINCOM has the lowest error in mean wind speed and has a bias of 1.5%.

The annual and seasonal cycles (Fig.5.11) are exaggerated by the WRF simulations at WM02, and in opposition to WM01, the late afternoon peak occurs later in the WRF simulations than in the observations during the summer months. Winds are strongest in winter and overestimated by WRF in all seasons (Fig.5.10).

Figure 5.9 { Observed and simulated wind climatologies at 62 m AGL at site WM02: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.10 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM02.

Figure 5.11 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM02.

5.4.3 Vredendal (WM03)

The WM03 mast is located in a sparsely vegetated landscape. The ocean is located to the southeast, resulting in lower effective roughness in that direction. In the WRF roughness map z_0 0:03 m. The roughness in the DTU map is significantly higher, z_0 0:1 m and the EMD map is in between, z_0 0:07 m. There is a river towards the each which has higher z_0. The observed and simulated wind climate at WM03 are shown in Fig. 5.13. ERA5 largely underestimate the wind speeds in all directions. The wind rose is captured well by both the WRF, PyWAsP and LINCOM simulations. The PyWAsP and LINCOM simulation underestimate the wind and WRF has the lowest MAPE with 7.2%.

Figure 5.12 { Roughness maps around mast WM03 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

At WM03, winds are stronger during the summer season from October to February, with a clear peak in early evening. The wind speed distribution is very well simulated by WRF (Fig. 5.14). The annual and diurnal cycles are also well represented, with a small underestimation (0.5 m s^{1}) of the wind speed in all seasons (Fig. 5.15). The peak of the diurnal cycle in the afternoon is also well simulated.

Figure 5.13 { Observed and simulated wind climatologies at 62 m AGL at site WM03: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.14 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM03.

Figure 5.15 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM03.

5.4.4 Vredenburg (WM04)

The WM04 mast is located close to a peninsula near the west coast of South Africa. The land cover is slightly complex, with agricultural areas mixed with forests and grassy plains (Fig. 5.16). The sea has some influence from the westerly sectors and mostly from the northerly sector. The roughness is quite low in all roughness map, z_0 0:02 in the WRF maps and z_0 0:06, with the highest roughnesses occuring in the southeasterly sector. It should be noted that mast WM04 was vandalised and cut down in 2013 so only three years of data are available for comparison.

Figure 5.16 { Roughness maps around mast WM04 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climate at WM04 are shown in Fig. 5.17. The wind speeds in ERA5 are not underestimated as much as at WM01{WM03, perhaps because the site is close to the coast. WRF captures the observed wind rose quite well, but has slightly too many southerly winds. The PyWAsP wind rose is closest to the observations.

As other sites in the west part of South Africa, WM04 shows the strongest winds during the summer months and in the early evening hours. These dominant annual and diurnal cycles

Figure 5.17 { Observed and simulated wind climatologies at 62 m AGL at site WM04: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.18 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM04.

Figure 5.19 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM04.

are well simulated by WRF, with excellent timing, but slight underestimation of the amplitude by WRF compared to observations (Fig. 5.19).

5.4.5 Napier (WM05)

WM05 is the southernmost mast in the WASA project. The terrain around WM05 is more vegetated than around masts WM01–WM04. In the WRF roughness map, z_0 0.07 but it varies with wind direction. The WRF roughness map shows that z_0 0.03 m, whereas z_0 0.08 m and z_0 0.13 m for the EMD and DTU roughness maps, respectively. The forests in the DTU landcover table have z_0 1 m, which is too high for the type of forest observed around mast WM05. The EMD and WRF landcover tables appear more realistic. The observed and simulated wind climate at WM05 are shown in Fig. 5.21. Wind speeds from the east are underestimated in all simulations. ERA5 underestimates wind speeds from all directions. The wind roses are well captured by both WRF, PyWAsP and LINCOM. As with all other sites, ERA5 has the correct wind distribution, but underestimates wind speeds in all sectors.

Figure 5.20 – Roughness maps around mast WM05 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

At WM05, the WRF-simulated wind speed distribution matches nearly perfectly that observed (Fig. 5.21). Here the annual and diurnal cycles show in Fig. 5.23 are less pronounced

Figure 5.21 { Observed and simulated wind climatologies at 62 m AGL at site WM05: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.22 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM05.

Figure 5.23 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM05.

that in the stations further north, but very well captured by the WRF simulation. Even the strange observed local maximum during June compared to May and July is clear in the annual cycle. The timing of the diurnal cycle in the WRF simulations is good both in amplitude and phase. The maximum summer wind speed occurs earlier here that at the stations further north.

5.4.6 Sutherland (WM06)

WM06 is located on a plateau at an elevation of about 1500 m AMSL. The surrounding landscape is open and arid, with z_0 0.03 in the WRF model. The EMD roughness maps shows z_0 0.07 m whereas the DTU shows z_0 0.1 m. The observed and simulated wind climate at WM06 are shown in Fig. 5.25. ERA5 again shows too low wind speeds compared to the observations. The observations have slightly more winds from the west than the WRF, PyWAsP and LINCOM simulations, but otherwise the wind direction distribution is represented well.

Figure 5.24 – Roughness maps around mast WM06 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The winds in the WRF simulation are overestimated compared to the observations (Fig. 5.26) at WM06. But the timing of the diurnal and seasonal cycle are well captured by the WRF simulation (Fig. 5.27). Here the wind speed are highest during the winter months, including much stronger winds during June, similar to what is observed at WM05. The amplitude of the diurnal cycle of summer wind speed is exaggerated in the WRF simulations compared to that of the observations.

Figure 5.25 { Observed and simulated wind climatologies at 62 m AGL at site WM06: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.26 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM06.

Figure 5.27 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM06.

5.4.7 Beaufort West (WM07)

Beaufort West is an inland site located at a plateau at above 1000 m. It is sparsely vegetated and very homogeneous, with z_0 0.04 m using the EMD lookup table, z_0 0.07 m using the DTU lookup table and z_0 0.01 m using the WRF lookup table.

Figure 5.28 – Roughness maps around mast WM07 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climate at WM07 are shown in Fig. 5.29. All simulations show too little winds from the easterly sector and ERA5 shows low wind speeds from all directions. WRF overestimates wind speeds from the westerly sector.

The frequency distribution of wind speed (Fig. 5.30) and the comparison of the diurnal and seasonal cycles, show an overall overestimation of the wind speed. The timing of the diurnal and annual cycles are well represented in the WRF simulations. At this site there is a double maximum in wind speed in summer in early evening and during the winter months.

Figure 5.29 { Observed and simulated wind climatologies at 62 m AGL at site WM07: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.30 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM07.

Figure 5.31 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM07.

5.4.8 Humansdorp (WM08)

The mast at Humansdorp is located close to the coast and is characterized by a much more complex landcover than the other sites. The mast is surrounded by agricultural areas and low forest patches. A ridge is located to the northwest and the sea is in the southwesterly directions. The large-scale roughness is highest in the northwesterly sector and z_0 0.1 m, whereas it is much lower towards the southwest. Significant speed downs from the internal boundary layer located towards the southeast are expected for all landcover maps. The

Figure 5.32 { Roughness maps around mast WM08 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

observed and simulated wind climate at WM08 are shown in Fig. 5.33. ERA5 has too many southwesterly winds and too low wind speeds. The WRF-simulated wind rose looks similar to that observed, but lacks wind directions from the WNW. The PyWAsP wind rose agrees best with the observations, whereas the LINCOM wind rose shows too many winds from the west.

The observed and WRF-simulated wind speed distribution agree very well with each other as it is seen in Fig. 5.34. The amplitude of the diurnal cycle is too weak in the WRF simulations (Fig. 5.35, but its phase compares well with that measured at this site. The

Figure 5.33 { Observed and simulated wind climatologies at 62 m AGL at site WM08: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.34 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM08.

Figure 5.35 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM08.

seasonal cycle at this site is modest, with only about 1 m s^{-1} difference between minimum and maximum annual mean wind speed. Monthly mean wind speeds are above 6 m s^{-1} all year around. The maximum summer wind speed occurs earlier in the day than in previous mast locations, even taking into account that this mast is located further east.

5.4.9 Noupoort (WM09)

Noupoort is situated on a plateau at high elevation (above 1800 m AMSL). The roughness length is low in all directions, thanks to the open and homogeneous landscape, but the terrain is complex with a RIX index of 3.0%. The observed and simulated wind climate at WM09 are shown in Fig. 5.37. The wind rose is well captured by all models. The WRF model simulation shows slightly too high winds from the northwesterly sector. ERA5 underestimates wind speeds as usual. LINCOM captures the wind direction distribution from the northwest very well.

Figure 5.36 { Roughness maps around mast WM09 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

Wind speeds at WM09 are strong during the winter months, with a maximum above 9 m s ^{1} in June and July, but wind speeds are strong all year round with a long-term average of 8 m s ^{1}. The WRF simulations exaggerate the winter maxima by about 1 m s ^{1}, but the timing of the maximum and minimum agree very well with the observations. The amplitude and timing of the diurnal cycle during the summer months is well captured by the WRF-derived wind speeds.

Figure 5.37 { Observed and simulated wind climatologies at 62 m AGL at site WM09: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.38 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM09.

Figure 5.39 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM09.

5.4.10 Butterworth (WM10)

Butterworth is located in a hilly region, z_0 0.07 m in the WRF land cover table, z_0 0.1 m in the DTU table and z_0 0.13 m in the EMD table. The highest z_0 is observed for northerly and northwesterly winds. The DTU land cover tables shows some forest with too z_0 high whereas the EMD table has higher z_0 for shrubs.

Figure 5.40 { Roughness maps around mast WM10 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climate at WM10 are shown in Fig. 5.41. The wind rose at WM10 is quite omnidirectional, with all direction occurring around 10% of the time. ERA5 has too low wind speeds and no winds from the northerly sector. The WRF wind rose resembles the observations best, whereas the LINCOM wind rose shows too many winds from the south and the ENE.

Despite a poor representation of the wind rose, the wind speed distribution and the amplitude of the diurnal and seasonal cycles are captured relatively well by the WRF simulation. Wind are strongest during the winter months and the diurnal cycle is more apparent during the summer as in many other WASA masts.

Figure 5.41 { Observed and simulated wind climatologies at 62 m AGL at site WM10: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.42 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM10.

Figure 5.43 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM10.

5.4.11 Rhodes (WM11)

WM11 is a complex site with a RIX of around 4%. It is located at very high elevation, z 2600 m, south of elevated terrain of Lesotho. The roughness is highest in the EMD landcover table z_0 0.07. For all other landcover tables z_0 0.03. There are very large orographic speedups in the northwesterly sector for all microscale simulations.

Figure 5.44 – Roughness maps around mast WM11 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

The observed and simulated wind climate at WM11 are shown in Fig. 5.45. Here, the raw WRF has the largest wind speed climatology error. The LINCOM downscaling reduces the over-speed error from 16.88 to 13.1%. However, the PyWAsP downscaling increases the mean wind speed bias to 25%. It is clear that none of the models performs very well at this very complex site. The overestimation from the WRF model simulations cannot be corrected by the orography and roughness effects. However, the wind direction distribution is relatively well captured by all models.

At WM11 wind speeds are strongest from July to September, and this timing is well captured by the WRF simulations, but with a bias of 1–1.5 m s^{-1} in all months. During the

Figure 5.45 { Observed and simulated wind climatologies at 62 m AGL at site WM11: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.46 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM11.

Figure 5.47 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM11.

summer months, there is also a very strong diurnal cycle in wind speed, with a maximum that is about 1{2 hours too early in the WRF simulations compared to the observations. These summer winds are also overestimated by the WRF simulations.

5.4.12 Eston (WM12)

The terrain at mast 12 is more vegetated than many of the other sites, with low shrubs in all directions. This leads to a more challenging estimation of the roughness length, with the DTU lookup table yielding z_0 1 m in many directions, whereas the WRF and EMD lookup tables are more alike and z_0 0:4, but the WRF roughness map has smaller z_0 directly around the mast. The observed and simulated wind climate at WM12 are shown in Fig. 5.49. The observed and simulated wind roses agree reasonable well, in particular that from the raw WRF simulation and PyWAsP.

Figure 5.48 { Roughness maps around mast WM12 obtained from the WRF simulations (a), and from the high-resolution ESA-CCI landcover generated with the EMD (b), DTU (c) and WRF lookup table (d).

Winds at WM12 are relatively low, with an annual average of 5.12 m s^{1}, the lowest of all WASA masts. Winds are strongest in the summer months in late afternoon. This diurnal cycle is well represented in the WRF simulations as seen in Fig. 5.51. There is also a good agreement between the frequency distribution of the wind speed in WRF and the observations (Fig. 5.50).

Figure 5.49 { Observed and simulated wind climatologies at 62 m AGL at site WM12: (a) observed, (b) ERA5, (c) raw WRF production run, (d) PyWAsP downscaling, (e) LINCOM downscaling.

Figure 5.50 { Observed and WRF-simulated frequency distribution of wind speed at 62 m AGL at site WM12.

Figure 5.51 { Observed and WRF-simulated seasonal and diurnal cycle of wind speed at 62 m AGL at site WM12.