Wind Atlas for South Africa (WASA) – Observational wind atlas for 10 met. stations in Northern, Western and Eastern Cape provinces

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Summary (max 2000 characters)

As part of the "Wind Atlas for South Africa" project, microscale modelling has been carried out for 10 meteorological stations in Northern, Western and Eastern Cape provinces.

Wind speed and direction data from the ten 60-m masts have been analysed using the Wind Atlas Analysis and Application Program (WAsP 11). The wind-climatological inputs are the observed wind climates derived from the WAsP Climate Analyst. Topographical inputs are elevation maps constructed from SRTM 3 data and roughness length maps constructed from SWBD data and Google Earth satellite imagery. Summaries are given of the data measured at the 10 masts, mainly for a 3-year reference period from October 2010 to September 2013.

The main result of the microscale modelling is observational wind atlas data sets, which can be used for verification of the mesoscale modelling. In addition, the microscale modelling itself has been verified by comparing observed and modelled vertical wind profiles at the 10 sites. WAsP generally works well, but modelling of the wind profiles can be improved by using project-specific wind atlas heights and by changing the heat flux parameters of WAsP

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Wind Atlas for South Africa (WASA)

Western Cape and parts of Northern and Eastern Cape

Observational Wind Atlas for 10 Met. Masts in Northern, Western and Eastern Cape Provinces

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WASA Observational Wind Atlas for 10 Met. Masts in Northern, Western and Eastern Cape Provinces

Contents

Preface

The present report is the third edition of the Wind Atlas for South Africa (WASA) Observational Wind Atlas. The first edition was published in March 2012, when the first years' worth of meteorological data was available. The second edition was published in December 2012, when two years' worth of data was available. The present report has been updated to include three years of data. Each edition of the report therefore reflects the status of data and analyses at the time of writing. Phase I of the WASA project ends in April 2014, so this report is the final version of the observational wind atlas.

Changes and corrections in the present version compared to the second edition are:

- Report updated to include 3 years of data
- Elevation of barometer above mean sea level (z_{baro}) used for Table 3
- Appendix with observed wind statistics and wind speed variations added
- Appendix regarding topographical data for flow modelling added

Please report any errors, omissions or suggestions to the authors.

The WASA team
April 2014

1 Introduction

The Wind Atlas for South Africa project is an initiative of the Government of South Africa (Department of Minerals and Energy, now Department of Energy) and the project is co-funded by UNDP-GEF through the South African Wind Energy Programme (SAWEP) and by the Royal Danish Embassy.

The primary objective of the project is to develop and produce numerical wind atlas methods and develop capacity to enable planning of large-scale exploitation of wind power in South Africa, including dedicated wind resource assessment and siting tools for planning purposes, i.e. a Numerical Wind Atlas and database for South Africa.

The present report describes the microscale modelling that has been carried out for 10 meteorological stations in Northern, Western and Eastern Cape provinces see Figure 1. It constitutes one of the main outputs of the projects Work Package 3: Observational Wind Atlas for Western Cape and areas of Northern and Western Cape in South Africa.

Figure 1. Overview map of the southernmost part of South Africa, showing the location of the 10 meteorological masts referred to in the text and the Wind Atlas for South Africa study area (Image © 2012 Tele Atlas, Data SIO, NOAA, US Navy, NGA, GEBCO, AfriGIS (Pty) Ltd., and Google Inc.).

The central study area is defined as the 'coastal areas of Western, Eastern and Northern Cape provinces', where coastal is interpreted here as referring to the land area between the coastline and the Great Escarpment – the plateau edge in South Africa which separates the highland interior from the lower coastal areas, see Figure 1. In administrative terms, the central study area then comprises:

- Western Cape Province – all six districts
- Eastern Cape Province – all districts except Joe Gqabi and Alfred Nzo
- North Cape Province – the coastal districts of Richtersveld, Nama Khoi and Kamiesberg; plus westernmost parts of Khâi-Ma, Hantam and Karoo Hoogland.

Because of the mesoscale modelling of the coastal area, the study area extends somewhat further inland than the Great Escarpment.

In order to assess the wind resources of such a diverse geographical region – including provision of reliable data for physical planning (national, regional or local), wind farm siting, project development, wind farm layout design and micro-siting of wind turbines – the project has adopted the framework of the wind atlas methodology developed at DTU Wind Energy (formerly Risø DTU) (Frank *et al.*, 2001; Badger *et al.*, 2006; Hansen *et al.*, 2007). Figure 2 is a schematic presentation of this framework.

Mesoscale	**Pre-processing** Wind classes Terrain elevation Terrain roughness Input specifications Model setup	**Modelling** Mesoscale model; e.g. KAMM, WRF, MC2, MM5 or similar.	**Post-processing** Predicted wind climate Regional wind climate Predicted wind resource for selected terrain site coordinates	**Numerical WA** Mesoscale maps Database of results WAsP *.LIB files Uncertainties Parameters
Measurements	**Met. stations** Siting Design Construction Installation Operation	**Wind data** Data collection Quality control Wind database Wind statistics Observed wind climate	**Verification** Meso- and microscale results vs. measured data Adjust model and model parameters to fit data Satellite imagery (offshore sites only)	**Applications** Best practices Courses and training Microscale flow model Wind farm wake model ⇒ **Wind farm AEP**
Microscale	**Pre-processing** Wind speed distributions Wind direction distribution Terrain elevation Terrain roughness Sheltering obstacles	**Modelling** Microscale model: Linearised, e.g. WAsP, MS-Micro or similar. Non-linear, e.g. CFD (Computational Fluid Dynamics).	**Post-processing** Regional wind climate Predicted wind climate Predicted wind resource for selected terrain site coordinates	**Observational WA** Microscale maps Database of results WAsP *.LIB files Uncertainties Parameters © 2006-08 Risoe DTU

Figure 2. Overview of wind atlas methodologies (Hansen et al., 2007). This graphic also illustrates the overall design and contents of the "Wind Atlas for South Africa" project.

The "Wind Atlas for South Africa" project has been implemented in six work packages: 1) Mesoscale modelling, 2) Measurements, 3) Microscale modelling, 4) Applications, 5) Extreme winds, and 6) Documentation and dissemination; each associated with extensive capacity building and R&D.

The contents of and relations between these six work packages are shown in schematic form in Figure 2 and the methodology is described further by e.g. Hansen *et al.* (2007) and Mortensen *et al.* (2008).

The present report is thus concerned mainly with the 'green part' of Figure 2, microscale modelling, and constitutes one of the main outputs of this work package. Additional outputs are given in electronic form as WAsP workspace files (Mortensen *et al.*, 2012). Results from the other work packages are reported separately.

The WAsP modelling results reported here were obtained using the most recent version of the Wind Atlas Analysis and Application Program, WAsP version 10.02.0010 (2012). This program, as well as the underlying wind atlas methodology, is described in some detail by Troen and Petersen (1989). Details of setting up and running the software are given by Mortensen *et al.* (2013). The standard configuration of the WAsP program has been used throughout the report unless stated otherwise. In addition, the WAsP Climate Analyst version 2.00.0086 and the WAsP Map Editor version 10.1.0.320 have been used. Surfer 10 was used to generate the height contour maps from SRTM 3 data.

The current WAsP best practices and checklist are given in Appendix B.

2 Preliminary wind atlas analysis

The Wind Atlas for South Africa project is divided into two phases. The overall purpose of the microscale modelling in Phase I is three-fold, cf. Figure 2:

- Verification of the mesoscale modelling at the met. station sites
- Verification of the microscale modelling at the met. station sites
- Establishment of an observational wind atlas for parts of South Africa

The verification activities also include study of modelling sensitivities and uncertainties, and possible adaptations of the methodology and models to South Africa. The main purpose of this first version of the observational wind atlas is to provide verification data for the mesoscale modelling using the Karlsruhe Atmospheric Mesoscale Model.

The main inputs to the microscale modelling are the observed wind climates from the 10 meteorological stations, see Figure 1. In addition to the purposes mentioned above, these masts may also serve as reference stations for wind resource calculations at wind farm sites in the vicinity of the masts, and as test beds for comparison of wind sensors and mounting arrangements.

2.1 Summary of measurements

More than two-years-worth of data is available from the 10 met. stations. The period from 1 October 2010 to 30 September 2012 has been selected as the two-year reference period for the wind atlas analyses and modelling. Table 1 provides a summary of some weather observations for this period and of some site characteristics at the stations.

Table 1. Summary of weather observations at the 10 meteorological stations for a 3-year period: absolute minimum air temperature (T_{min}), absolute maximum air temperature (T_{max}), mean air temperature (T_{mean}), mean barometric pressure (B). Site characteristics are site elevation above mean sea level (z) and mean air density (ρ).

Mast	$T_{\min}$ [°C]	$T_{\max}$ [°C]	T_{mean} [°C]	B [hPa]	z [m]	ρ [kg m^{-3}]
WM01	5.4	37.7	16.7	997.5	152	1.199
WM02	−0.3	37.7	16.4	922.2	824	1.110
WM03	5.1	40.5	16.9	987.6	242	1.186
WM04*	5.0	38.9	16.9	1013.3	22	1.217
WM05	4.6	33.2	14.9	983.4	288	1.189
WM06	−4.3	30.4	11.8	843.3	1581	1.031
WM07	−0.3	36.0	15.2	898.4	1047	1.085
WM08*	6.7	37.8	17.1	1004.1	110	1.205
WM09*	−6.0	30.4	12.7	821.7	1806	1.001
WM10*	2.0	34.6	15.4	908.7	925	1.097

* Results are given for the three-year period from 2010-10-01 to 2013-09-30; except for
WM04, where the period is 3 years: from 2010-06-01 to 2013-06-01;
WM08, where the period is 2 years: from 2010-10-01 to 2012-09-30.
WM09, where the period is 2 years: the calendar year 2011 is missing;
WM10, where the period is 2 years: from 2011-03 to 2012-02 + 2012-10 to 2013-09.

Table 2 provides a summary of the wind observations at the stations, for the top level (62 m) of the masts. Data from WM09 and WM10 are given for two-year periods only.

Table 2. Summary of wind observations 62 m above ground level at the meteorological stations: data recovery rate (R), Weibull A- and k-parameters, Weibull-derived mean wind speed (U) and power density (E), and the direction (D_U) and magnitude (|U|) of the mean wind vector. The site ruggedness index is given in the right-most column.

Mast	***R*** [%]	***A*** [ms^{-1}]	***k***	***U*** [ms^{-1}]	***E*** [Wm^{-2}]	D_U [deg]	$\lvert U \rvert$ [ms^{-1}]	**RIX** [%]
WM01	100.0	6.8	1.68	6.07	313	180	3.34	0
WM02	93.4	6.9	2.09	6.15	238	206	0.73	0
WM03	100.0	8.1	2.33	7.15	365	195	2.68	0
WM04	100.0	7.7	2.22	6.69	327	203	3.24	0
WM05	98.6	9.7	2.21	8.63	648	180	0.83	0
WM06	99.9	8.2	2.03	7.31	371	309	2.09	0
WM07	100.0	7.9	2.47	6.95	302	159	0.55	0
WM08	100.0	8.3	2.06	7.38	449	285	2.37	0
WM09	99.7	9.2	2.20	8.16	470	306	2.61	4
WM10	98.8	7.4	1.91	6.58	304	310	0.26	0

The site ruggedness index is 0% for nine of the stations and 4% for station WM09; the nine stations are therefore within the operational envelope of the WAsP model and WM09 only slightly outside. Based on experience from many other met. station and wind farm sites, we would expect the WAsP models to work well at these sites.

2.2 Wind-climatological inputs

Observed wind climates, i.e. the wind rose and sector-wise wind speed distributions, were constructed for each station using the WAsP Climate Analyst, version 2.0. The observed wind climates are used as input to a microscale model which is able to model the influence of the nearby terrain on the measurements. Employing detailed descriptions of terrain elevation, land cover and the occurrence of sheltering obstacles around each meteorological station, the observed wind climate is transformed into what would have been measured at the location of the station if the surroundings were completely flat and uniform with a certain roughness length value, and the wind measurements had been taken at certain standard heights. Through this transformation procedure, the observed wind climate is freed from the influence of local topography to become regionally representative. These generalised wind climates, as well as other results of the microscale modelling, are given in Chapter 3.

The microscale model used for the analysis is the Wind Atlas Analysis and Application Program (WAsP); a description of the model is given by Mortensen *et al*. (2012). A general introduction to the wind atlas methodology is given by Troen & Petersen (1989). How to set up and run the WAsP model is described by Mortensen *et al*. (2012) and the current best practices for WAsP-related work is given in Appendix B.

2.3 Meteorological stations and masts

The 10 sites were selected not only to cover the WASA modelling domain, but also to represent different types of terrain and climatology. A main objective has been to provide reliable data for verification of the mesoscale and microscale modelling. The locations of the meteorological stations are shown in Figure 1.

The design and characteristics of the 60-m masts and instrumentation are described briefly by Mortensen *et al*. (2012). Photos taken during the site inspection trip serve to verify that actual installations are done according to this master design. The *Station and Site Description report* contains information for each met. station regarding

- Position and elevation of the mast site
- Boom and instrument heights above ground level
- Magnetic declination and meridian convergence at the site
- Sensor boom and lightning rod directions
- Photographic documentation of mast design and installation
- Photographic documentation of mast surroundings (panoramic view)

The report, as well as the meteorological data measured at the stations, is available from the WASA web site wasadata.csir.co.za/wasa1/WASAData.

2.4 Topographical inputs

For a general impression of the setting, the terrain surrounding each mast is shown in panoramic photographs taken during the site inspection trip (Mortensen *et al*., 2012).

Elevation maps

Elevation maps for each site were constructed from Shuttle Radar Topography Mission (SRTM) 3 arc-second data, using Surfer. The maps cover 40×40 km^2, with 20- or 10-m height contours; but are detailed with 5-m contours in an area of 10×10 km^2 close to the station. Overview maps are shown for each station in the descriptions in Chapter 3; the maps used for the flow modelling are given in the WAsP workspaces.

The elevation information was obtained from version 2.1 (the 'finished' version) of the SRTM data set. Additional information was in some cases obtained from standard South African topographical maps. Information on land cover and thereby roughness length of the terrain surface was obtained from satellite imagery (e.g. Google Earth), topographical maps and from field visits to the sites.

Land cover maps

During a site inspection trip (Mortensen *et al*., 2012) the land cover around each station was compared to print-outs of Google Earth imagery and sector-wise photos were taken of characteristic land cover types. Roughness maps were constructed from this information using satellite imagery (Google Earth); coastlines, lakes and rivers were derived from the SRTM Water Body Data set.

2.5 Other resources

In addition to the present report, the following information, data and files are available:

- Station and site description report (Mortensen *et al*., 2012)
- Photographs from the site inspection trip (Mortensen *et al*., 2012)
- WAsP-compatible elevation and roughness maps for each station
- WAsP Climate Analyst projects for each station
- WAsP workspaces for each station

The report *Planning and Development of Wind Farms: Wind Resource Assessment and Siting* (Mortensen, 2013) provides general background information, guidelines and best practices for the WAsP microscale modelling.

2.6 Estimating site air density

An estimate of the site air density must be made at any wind turbine or wind farm site in order to calculate a realistic wind power density and annual energy production (AEP). Air density can be calculated from measurements of atmospheric pressure and ambient air temperature at the site:

$$\rho = \frac{B \times 100}{R \times (T + 273.15)} \tag{1}$$

where ρ is air density (kg m^{-3}), B is atmospheric pressure (hPa), R is the gas constant for dry air (287.05 J kg^{-1} K^{-1}) and T is air temperature (°C).

Measurements of atmospheric pressure and air temperature have been made every 10 minutes for three (or two) years at masts WM01-WM10, see Table 3.

Table 3. Summary of air-density-related observations at the 10 meteorological stations: mean air temperature (T), mean atmospheric pressure (B), elevation of barometer above mean sea level (z_{baro}), measured mean air density (ρ_m), estimated mean air density (ρ_W).

Mast	***T*** [°C]	***B*** [hPa]	z_{baro} [m]	ρ_m [kg m^{-3}]	ρ_W [kg m^{-3}]	ρ_W/ρ_m
WM01	16.7	997.5	157.3	1.1990	1.195	0.997
WM02	16.4	922.2	829.8	1.1097	1.107	0.997
WM03	16.9	987.6	247.3	1.1861	1.182	0.997
WM04	16.9	1013.2	27.7	1.2170	1.213	0.997
WM05	14.9	983.4	293.1	1.1892	1.184	0.995
WM06	11.8	843.3	1586.0	1.0310	1.028	0.997
WM07	15.2	898.4	1052.0	1.0855	1.082	0.997
WM08	17.0	1004.1	115.5	1.2054	1.200	0.996
WM09*	12.7	821.7	1811.2	1.0014	0.999	0.997
WM10*	15.3	908.7	930.5	1.0973	1.097	1.000

* Results are given for the three-year period 2010-10-01 to 2013-09-30; except for stations WM04, WM09 and WM10; see Table 1.

At sites where measurements of atmospheric pressure have not been carried out, the *Air Density Calculator* tool of WAsP may be used to estimate the air density from the site elevation and the annual average air temperature at the site. Such estimates for the 10 WASA meteorological stations are given in the ρ_W-column (W for WAsP) in Table 3.

A comparison of measured (ρ_m) and WAsP-derived (ρ_W) mean air densities for the 10 WASA sites and eight sites in NE China (Mortensen *et al.*, 2010) is shown in Figure 3. The equation for a linear fit to the data points reads

$$\rho_W = \rho_m \times 1.009 - 0.013 \tag{2}$$

Given an estimate of the air density calculated by the WAsP tool, we can therefore estimate the true ('measured') air density as:

$$\rho_m = \rho_W \times 0.991 + 0.013 \qquad (3)$$

Even without this adjustment, the WAsP-derived values are close to those observed.

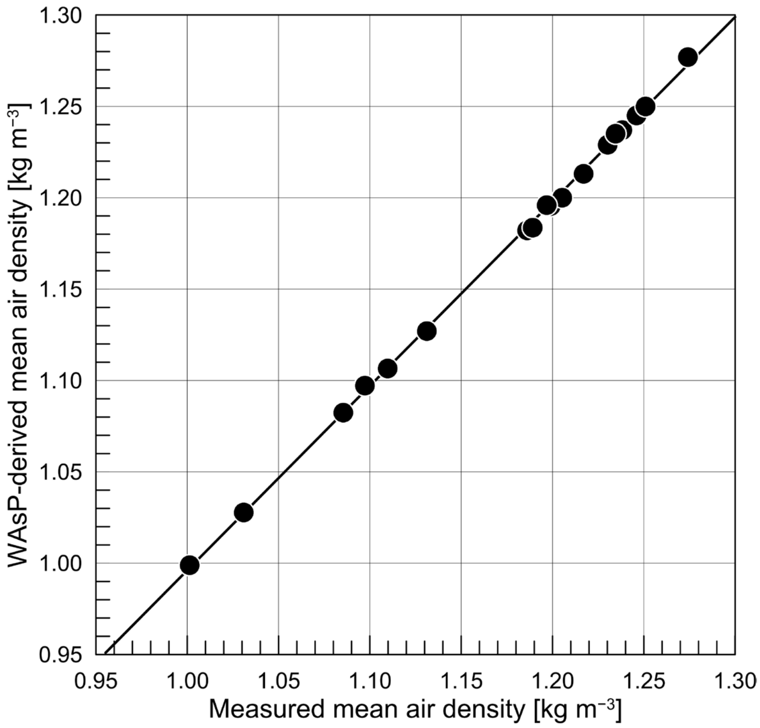


Figure 3. Measured and estimated mean air densities for 10 meteorological stations in South Africa and eight stations in NE China (Mortensen et al., 2010).

2.7 Uncertainties in the wind atlas analysis

The uncertainty factors investigated and addressed in the present wind atlas analysis are described below. In general, we have tried to minimise or even eliminate the uncertainty factors involved.

1. **Cup anemometer calibration**. The anemometer type employed is the P2546A cup anemometer, see www.windsensor.dk for specifications. Anemometers have been individually calibrated according to the MEASNET Cup Anemometer Calibration Procedure. The design of the masts and the mounting of anemometers and wind vanes follow international standards (IEC-61400-12) and best engineering practices as closely as possible.

2. **Cup anemometer heights**. The actual heights above ground level of most cup anemometers were determined with precision laser distance meters. The height of the top (reference) anemometer on each mast was determined from the design of the mounting arrangement and the mast dimensions. The uncertainties associated with the exact height of anemometers above ground level are therefore assumed to be negligible.

3. **Wind direction offset**. The wind vane alignment and wind direction calibration have been checked carefully using a handheld GPS and a sighting compass (Mortensen *et al*., 2012). During this procedure, the magnetic declination was also determined and compared to estimates derived from 1:50,000 topographical maps published by the Chief Directorate: Surveys and Mapping, and to estimates provided

from the NOAA web site calculator. The standard deviation of the wind vane alignment procedure at the ten masts is on the order of one degree, so the uncertainty associated with the wind direction measurements is assumed to be negligible.

4. **Wind atlas heights**. The calculation heights for generalised wind data sets (wind atlas heights) have been adapted to the measurement heights on the masts. The heights chosen here are 10, 20, 40, 62 and 100 meters above ground level. The uncertainties associated with vertical interpolation in the wind atlas data sets are therefore assumed to be negligible. The 100-m level is used for verification of the mesoscale modelling. These settings should be changed for microscale modelling at heights larger than 100 metres.

5. **Position of mast**. The exact positions of the masts were determined several times using hand-help GPS receivers. The accuracy of the positions is therefore likely to be on the order of 5-10 meters. Given the nature of the met. station sites, this uncertainty is not likely to introduce any significant uncertainty in the wind speed and power predictions.

6. **Air density**. As described elsewhere, air density can be calculated from temperature and atmospheric pressure measurements at the met. station sites. However, the performance tables for a wind turbine generator are given for discrete values of air density and WAsP will not interpolate between these. Therefore, the power density and power production may be slightly off if a certain wind turbine generator is used in WAsP and post-correction is not applied. This has no bearing on the wind speed predictions and the wind atlas results.

7. **Elevation map source and detail**. Elevation maps are derived from SRTM 2.1 data, and height contours have been constructed using intervals of 5, 10 and 20 meters, depending on the distance to the mast site. Based on experience from many other sites around the world, and given the topographical nature of the WASA met. station sites, these maps are assumed to be adequate for WAsP modelling. In Phase II of the WASA project, this assumption will be tested thoroughly.

8. **Background roughness length z_0**. Simple roughness maps are derived from SWBD data (water bodies) and the roughness lengths for land surfaces are determined from Google Earth imagery and based on site visits. In Phase II of the WASA project, more detailed land cover maps from a variety of sources will be tested.

9. **Heat flux offset value**. Given the elevation and roughness length maps described above, the WAsP offset heat flux value for over-land conditions has been adjusted at most sites in order to model the measured wind speed profile as accurately as possible. This heat flux may not be entirely realistic, but is used to tweak the shape of the wind profile. In Phase II of the WASA project, a more detailed investigation of the influence of the heat flux values will be carried out.

The current topographical and wind-climatological input data to the flow modelling are shown for each met. station in Section 3. Likewise, the non-default modelling parameters are given and the wind profile modelling results are shown. The mean absolute percentage errors, comparing measured and modelled mean wind speeds, are very low for all the met. station sites; mostly less than 1 per cent.

3 Observed and generalised wind climates

In this chapter, the topographical and climatological data for the meteorological stations used in the study are presented briefly in tables and graphs. For each station, the tables give the calculated regionally representative wind climatology – the generalised wind climate – obtained from the station data by applying the Wind Atlas analysis, together with a summary of the raw data – the observed wind climate – and the measuring conditions. Each station summary is printed on a pair of facing pages containing

- station name, coordinates and elevation map
- observed wind climate at 62 metres above ground level
- observed and WAsP-modelled wind speed profiles
- calculated regionally representative Weibull parameters
- calculated generalised mean wind speeds and power densities

The presentation of the data is explained in more detail in the following sections. Note, that data and results are valid at the time of writing only and will likely change when the analyses are updated with more wind data, improved topographical inputs, etc.

3.1 The station description

The station description comprises the geographical location and a station elevation map. The ruggedness index (RIX) for the meteorological mast site is given in the map caption.

Geographical coordinates

The longitude and latitude of each station are given in decimal degrees referred to the World Geodetic System 1984 (WGS84) horizontal datum.

Elevation

The elevation of the station is given in metres above mean sea level (m a.s.l.) referred to the WGS84 Earth Gravitational Model (EGM96) vertical datum.

Grid coordinates

The Cartesian grid coordinates consist of the Universal Transverse Mercator (UTM) Easting (E) and Northing (N) in integer metres. The number of the UTM zone is also given. The horizontal datum is World Geodetic System 1984 (WGS84).

Station topographical map

The topographical map shows the terrain height contours in a 20×20-km^2 area around the meteorological station – with the station approximately in the middle of the map. The height contour interval is 10 or 20 metres. The contour lines used in the orographic flow model may be more detailed (say, 5-m contours close to the station). Some areas of different land cover (roughness length) may be indicated as well; in particular land, sea, lake and river areas.

3.2 Observed wind climate

The observed wind climate comprises the distributions of the wind measurements at 62 m a.g.l. (nominal height) in the form of a wind rose and a histogram. The observed and modelled mean wind speed profiles at the mast are also shown.

The data period used for WM01-WM08 is the 2-year from October 2010 to September 2012. For WM09 the period is 1 year only and consists of September 2010 to July 2011 plus August 2012. For WM10 the period is 1-year only, from October 2010 to September 2011.

Wind rose and histogram

The wind rose shows the distribution of wind directions in the processed time-series. Wind directions are divided into twelve 30°-sectors; the angular axis is given in degrees from 0° to 360° clockwise, the units on the radius axis is per cent. A calm threshold of 0.5 ms^{-1} has been applied in the analysis.

The histogram shows the total distribution of observed wind speeds (bar graph) in the processed time-series. A Weibull distribution function has been fitted to the data and is shown with a grey dashed line. Also shown (with a blue dashed line) is the emergent distribution, i.e. the distribution that emerges by adding together the 12 sector-wise Weibull distributions. The units on the x-axis is [ms^{-1}], on the y-axis [% per ms^{-1}].

Wind speed profiles

This graph shows the measured and Weibull-derived mean wind speeds at the nominal heights 10, 20, 40, 60 and 62 metres above ground level (a.g.l.); these values are shown using black and blue dots, respectively. The data points are plotted using the actual height above ground level of each anemometer. Note, that the x-axis (wind speed) may be different from station to station, but always has a range of 5 ms^{-1}.

WAsP-modelled wind profiles are shown with full lines, using the 62-m level as the predictor level. The modelled wind profile using default WAsP model parameter values is shown in blue; a strictly neutral profile is shown in green for reference. At some sites, an adapted wind profile is shown in red, the adaptation value(s) are given in the caption.

The adaption consists of changing the mean heat flux value over land in the WAsP project configuration. The main purpose of this has been to illustrate this option and to minimise the difference between measured and modelled wind profiles. The adapted heat flux value may not be entirely realistic and the shape of the modelled wind profiles may also be changed by changing the roughness length of the terrain surface. The roughness maps and heat flux values proposed here may therefore change in future analyses.

3.3 Generalised wind climate

The Wind Atlas table give the estimated (calculated) omni-directional Weibull A- and k-parameters, the mean wind speed and the mean wind power density for each of 5 heights and 5 roughness length classes. Wind speed and power density were calculated using the Weibull parameters of the Wind Atlas tables. The Weibull A-parameters and the mean wind speeds are given in [ms^{-1}]; the mean power density in [Wm^{-2}].

Note that the five roughness classes correspond to uniform surfaces with a roughness length of 0 (0.0002) m, 0.03 m, 0.10 m, 0.40 m and 1.50 m, respectively. Compared to the European Wind Atlas (Troen and Petersen, 1989), an extra class with z_0 = 1.50 m is used here, because of the possible occurrence of forest at some sites in South Africa.

Below the wind atlas table are listed any non-default parameters values used in the calculation of the wind atlas; i.e. the site-specific air density and adapted atlas heights.

3.4 Station statistics and climatologies

The station statistics and climatologies given below were compiled and modelled in October 2012, using data collected in the period October 2010 to September 2012. The wind atlas data were calculated using the available information at the time of writing and the results may change in subsequent analyses and editions.

The 10 stations included in the report are listed in Table 4 below and their locations are shown on the sketch map in Chapter 1. This map further shows the elevations of South Africa, derived from the Shuttle Radar Topography Mission data set SRTM30, which contains spot heights of node points in grids with 30 arc-second resolutions (926 metres or less). More summaries of the wind measurements are given in the Appendix.

Table 4. Mast coordinates and elevations. The datum used is WGS 84; elevations are determined by the WAsP flow model from SRTM3 maps with 5-m height contours.

Mast ID	**Longitude**	**Latitude**	**Elevation**	**Easting**	**Northing**	**UTM**
	[°E]	[°S]	[m a.s.l.]	[m]	[m]	zone
WM 01	16.664410	28.601882	152	662743.2	6834989.4	33
WM 02	19.360747	31.524939	824	344361.1	6511054.9	34
WM 03	18.419916	31.730507	242	255549.9	6486539.1	34
WM 04	18.109217	32.846328	22	229440.3	6362045.0	34
WM 05	19.692446	34.611915	288	380119.2	6169215.6	34
WM 06	20.691243	32.556798	1581	471013.8	6397802.7	34
WM 07	22.556670	32.966723	1047	645479.5	6351326.6	34
WM 08	24.514360	34.109965	110	270725.8	6222861.2	35
WM 09	25.028380	31.252540	1806	312257.8	6540733.5	35
WM 10	28.135950	32.090650	925	607193.9	6448951.8	35

3.5 Alexander Bay (WM01)

WM01	16.66441°E	28.60188°S	152 m	E 662743 m	N 6834989 m	UTM 33

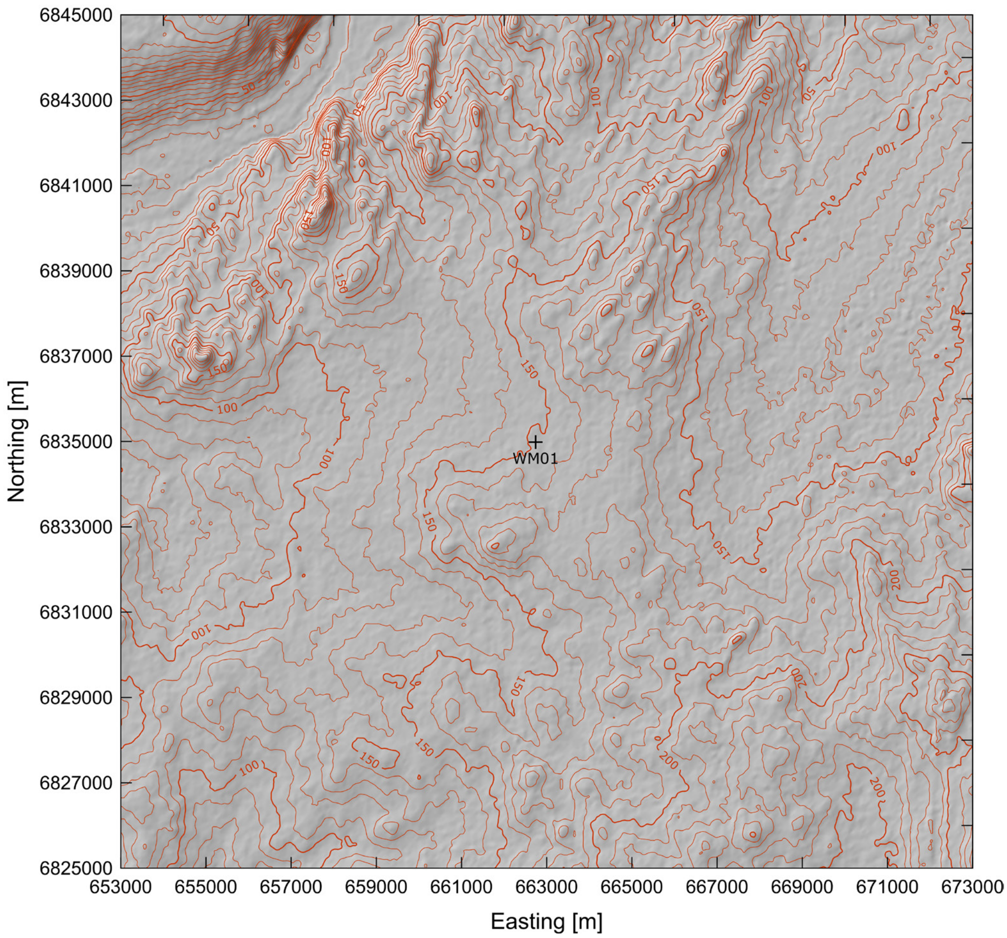


Figure 4. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0%.

3.5.1 Observed wind climate

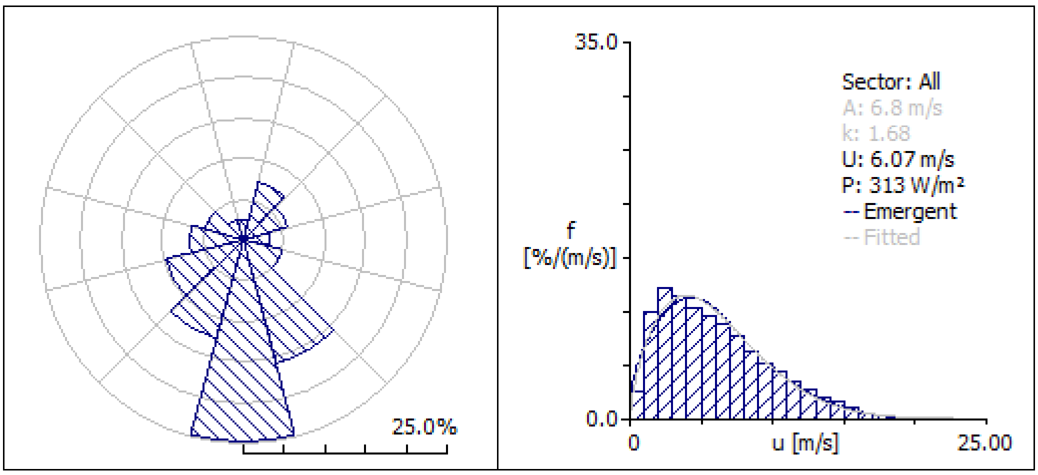


Figure 5. Wind rose and wind speed distribution for WM01 Alexander Bay at 62 m a.g.l. The data shown represent a 3-year period from October 2010 to September 2013.

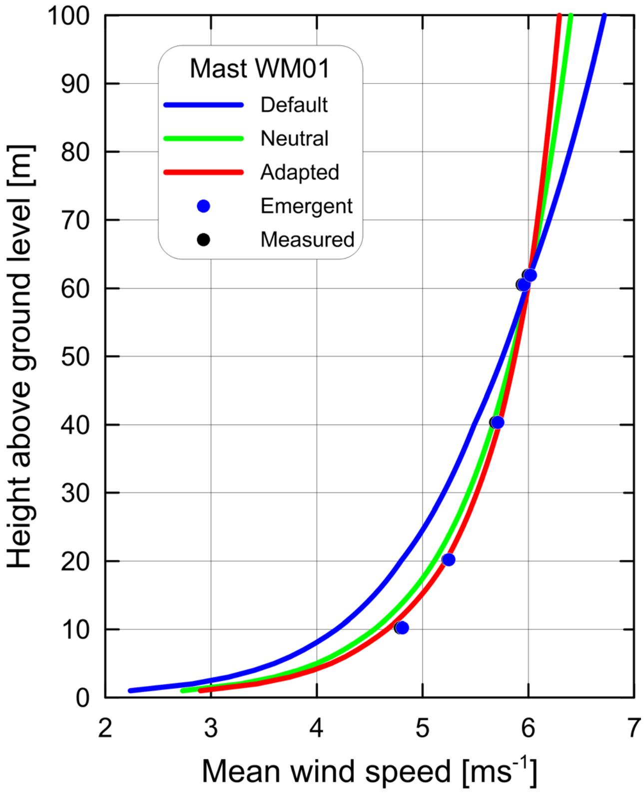


Figure 6. Measured and WAsP-modelled wind profiles for Alexander Bay. The adapted wind profile corresponds to a mean heat flux over land of 50 Wm^{-2} (default −40 Wm^{-2}).

3.5.2 Generalised wind climate

Table 5. Generalised wind climate for Alexander Bay. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.199 (1.21 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	6.6	4.7	4.1	3.2	2.1
	Weibull *k*	1.53	1.43	1.42	1.41	1.42
	Mean speed [ms^{-1}]	5.90	4.28	3.71	2.91	1.94
	Power density [Wm^{-2}]	329	139	92	45	13
20.0 m	Weibull *A* [ms^{-1}]	7.0	5.4	4.8	4.0	3.0
	Weibull *k*	1.55	1.48	1.46	1.45	1.46
	Mean speed [ms^{-1}]	6.32	4.88	4.35	3.58	2.69
	Power density [Wm^{-2}]	394	196	140	80	33
40.0 m	Weibull *A* [ms^{-1}]	7.5	6.2	5.6	4.8	3.9
	Weibull *k*	1.59	1.57	1.55	1.53	1.53
	Mean speed [ms^{-1}]	6.76	5.59	5.06	4.33	3.48
	Power density [Wm^{-2}]	467	268	203	130	67
62.0 m	Weibull *A* [ms^{-1}]	7.9	6.9	6.2	5.4	4.5
	Weibull *k*	1.59	1.68	1.64	1.61	1.60
	Mean speed [ms^{-1}]	7.08	6.12	5.59	4.86	4.02
	Power density [Wm^{-2}]	535	323	253	171	98
100.0 m	Weibull *A* [ms^{-1}]	8.3	7.7	7.0	6.2	5.2
	Weibull *k*	1.58	1.72	1.72	1.72	1.71
	Mean speed [ms^{-1}]	7.46	6.83	6.27	5.51	4.68
	Power density [Wm^{-2}]	636	434	335	230	141

3.6 Calvinia (WM02)

WM02	19.36075°E	31.52494°S	824 m	E 344361 m	N 6511055 m	UTM 34

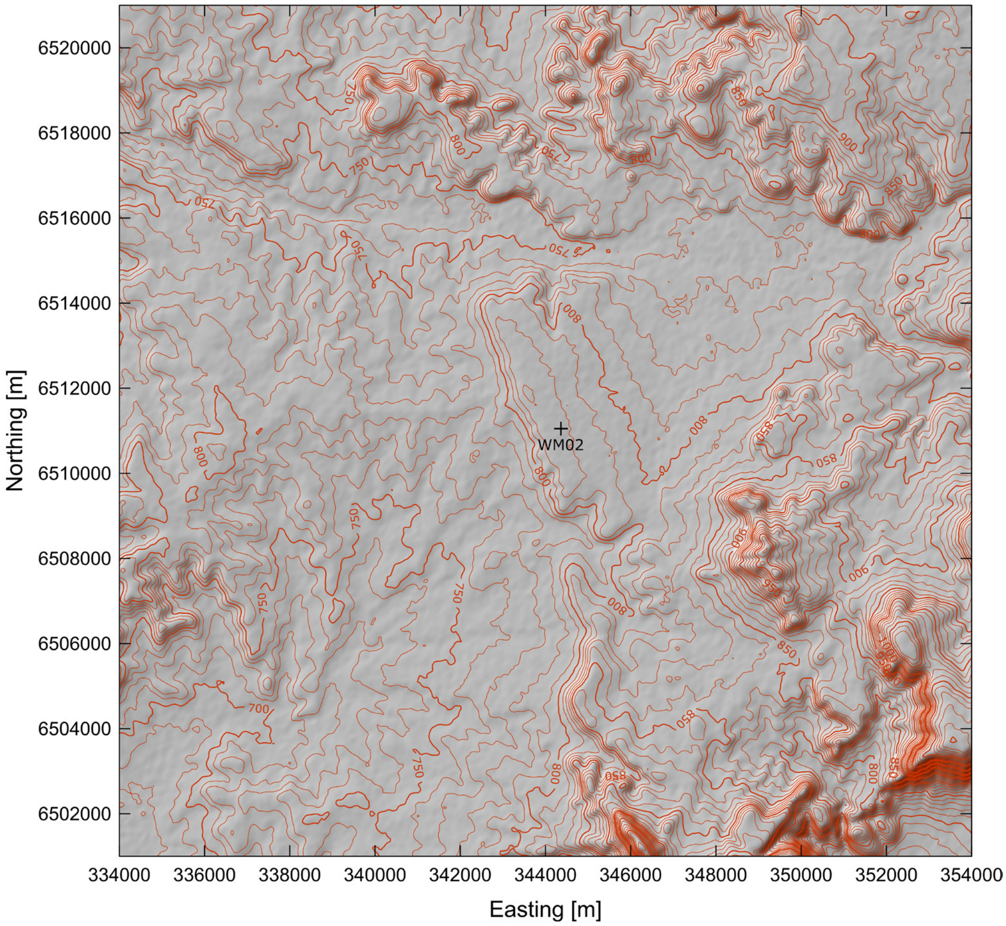
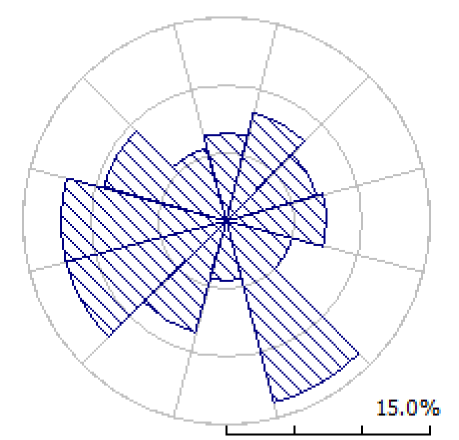


Figure 7. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0.0%.

3.6.1 Observed wind climate



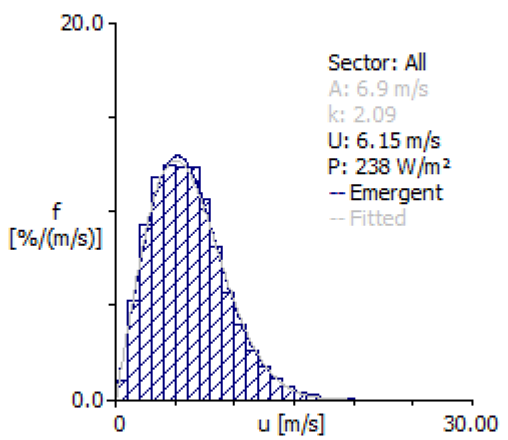


Figure 8. Wind rose and wind speed distribution for WM02 Calvinia at 62 m a.g.l. The data shown represent a 3-year period from October 2010 to September 2013.

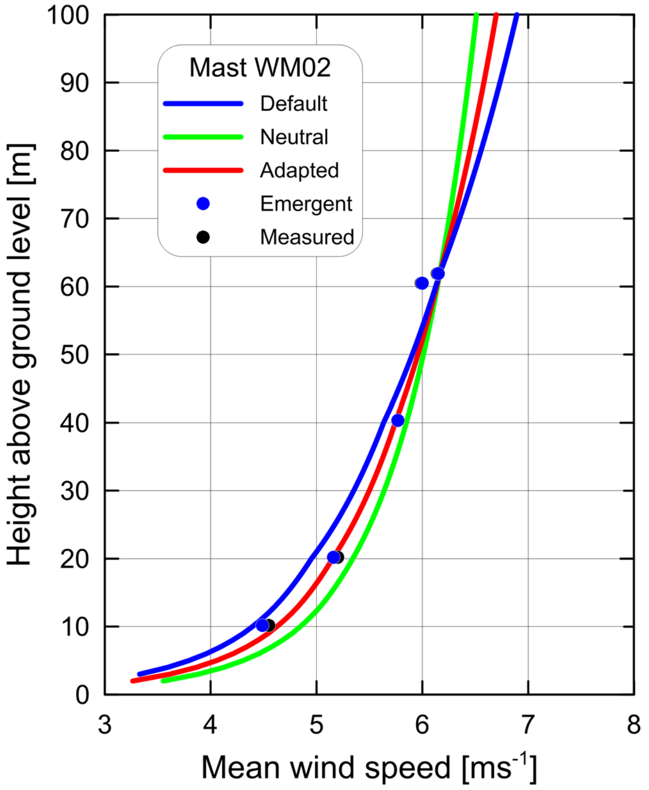


Figure 9. Measured and WAsP-modelled wind profiles for Calvinia. The adapted wind profile corresponds to a mean heat flux over land of −10 Wm^{-2} (default −40 Wm^{-2}).

3.6.2 Generalised wind climate

Table 6. Generalised wind climate for Calvinia. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.110 (1.12 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	6.4	4.6	4.0	3.1	2.1
	Weibull *k*	1.86	1.66	1.66	1.66	1.65
	Mean speed [ms^{-1}]	5.67	4.10	3.56	2.80	1.86
	Power density [Wm^{-2}]	211	91	60	29	9
20.0 m	Weibull *A* [ms^{-1}]	6.8	5.3	4.7	3.9	2.9
	Weibull *k*	1.90	1.74	1.73	1.72	1.71
	Mean speed [ms^{-1}]	6.07	4.69	4.18	3.46	2.58
	Power density [Wm^{-2}]	253	128	92	52	22
40.0 m	Weibull *A* [ms^{-1}]	7.3	6.1	5.5	4.7	3.8
	Weibull *k*	1.97	1.89	1.87	1.84	1.81
	Mean speed [ms^{-1}]	6.51	5.39	4.89	4.19	3.35
	Power density [Wm^{-2}]	301	177	134	86	45
62.0 m	Weibull *A* [ms^{-1}]	7.7	6.7	6.1	5.3	4.4
	Weibull *k*	1.95	2.06	2.01	1.97	1.91
	Mean speed [ms^{-1}]	6.83	5.94	5.42	4.72	3.89
	Power density [Wm^{-2}]	350	218	170	114	66
100.0 m	Weibull *A* [ms^{-1}]	8.2	7.5	6.9	6.1	5.1
	Weibull *k*	1.92	2.10	2.11	2.13	2.08
	Mean speed [ms^{-1}]	7.23	6.68	6.12	5.39	4.54
	Power density [Wm^{-2}]	423	305	233	158	96

3.7 Vredendal (WM03)

WM03	18.41992°E	31.73051°S	242 m	E 255550 m	N 6486539 m	UTM 34

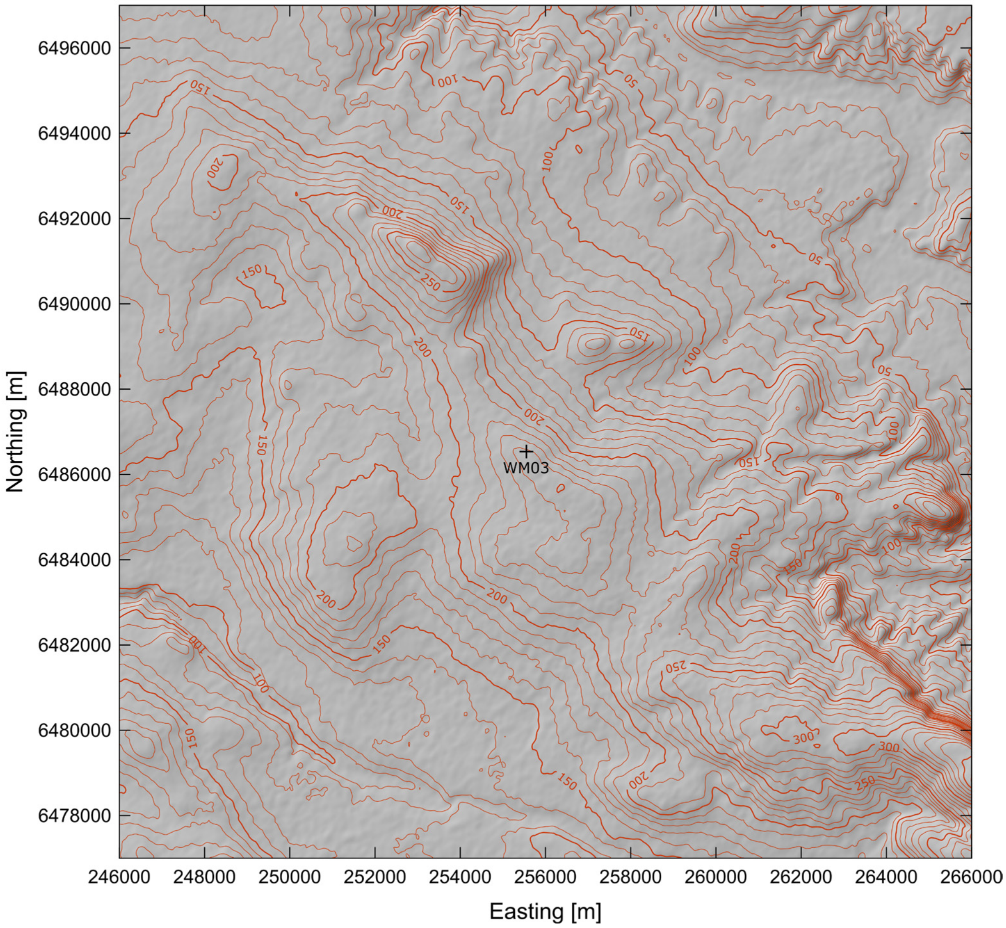


Figure 10. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0.0%.

3.7.1 Observed wind climate

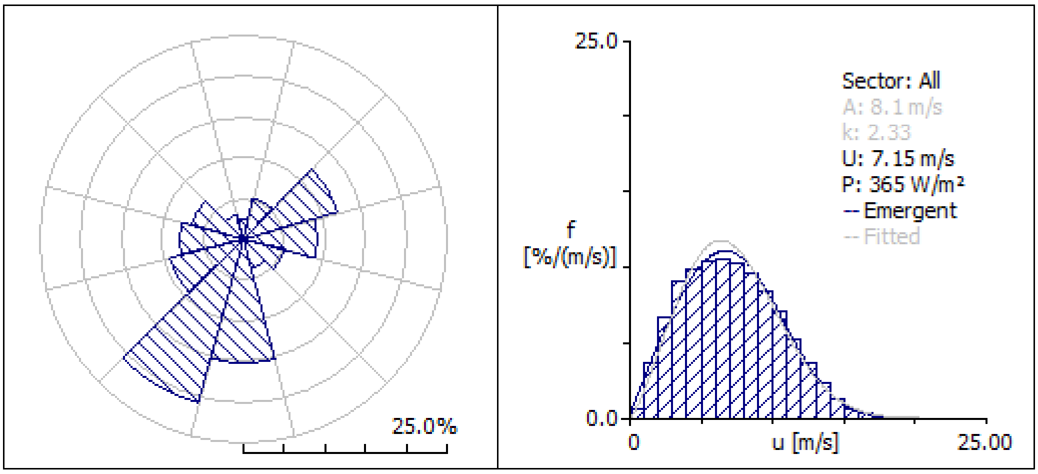


Figure 11. Wind rose and wind speed distribution for WM03 Vredendal at 62 m a.g.l. The data shown represent a 3-year period from October 2010 to September 2013.

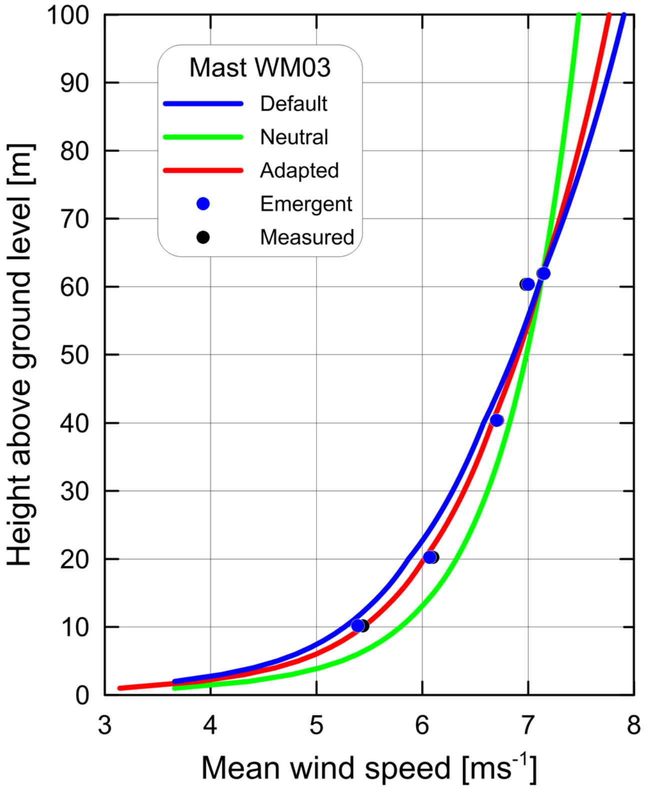


Figure 12. Measured and WAsP-modelled wind profiles for Vredendal. Adapted wind profile corresponds to a mean heat flux over land of −20 Wm^{-2} (default −40 Wm^{-2}).

3.7.2 Generalised wind climate

Table 7. Generalised wind climate for Vredendal. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.186 (1.18 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	7.1	5.1	4.4	3.5	2.3
	Weibull *k*	2.04	1.83	1.82	1.82	1.80
	Mean speed [ms^{-1}]	6.26	4.51	3.92	3.08	2.05
	Power density [Wm^{-2}]	271	114	75	36	11
20.0 m	Weibull *A* [ms^{-1}]	7.6	5.8	5.2	4.3	3.2
	Weibull *k*	2.08	1.91	1.90	1.89	1.87
	Mean speed [ms^{-1}]	6.70	5.17	4.60	3.81	2.84
	Power density [Wm^{-2}]	327	163	116	66	28
40.0 m	Weibull *A* [ms^{-1}]	8.1	6.7	6.1	5.2	4.2
	Weibull *k*	2.15	2.08	2.04	2.02	1.97
	Mean speed [ms^{-1}]	7.20	5.95	5.39	4.62	3.69
	Power density [Wm^{-2}]	391	228	173	110	57
62.0 m	Weibull *A* [ms^{-1}]	8.5	7.4	6.8	5.9	4.8
	Weibull *k*	2.13	2.26	2.20	2.15	2.08
	Mean speed [ms^{-1}]	7.55	6.55	5.98	5.20	4.28
	Power density [Wm^{-2}]	455	284	220	148	85
100.0 m	Weibull *A* [ms^{-1}]	9.0	8.3	7.6	6.7	5.6
	Weibull *k*	2.10	2.28	2.30	2.31	2.26
	Mean speed [ms^{-1}]	7.99	7.38	6.76	5.93	4.99
	Power density [Wm^{-2}]	550	401	306	206	126

3.8 Vredenburg (WM04)

WM04	18.10922°E	32.84633°S	22 m	E 229440 m	N 6362045 m	UTM 34

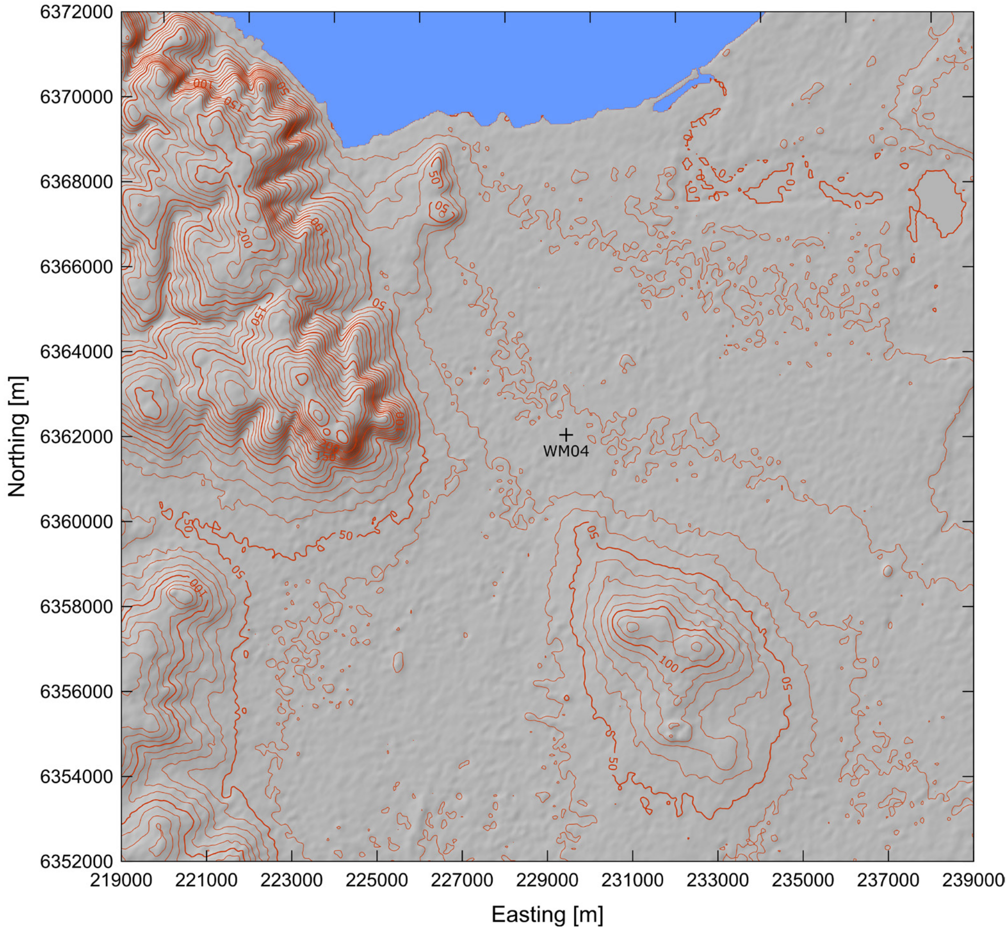


Figure 13. Elevation map from SRTM3 data, covering 20×20 km², with 10-m contours. The ruggedness index for the site is 0%.

3.8.1 Observed wind climate

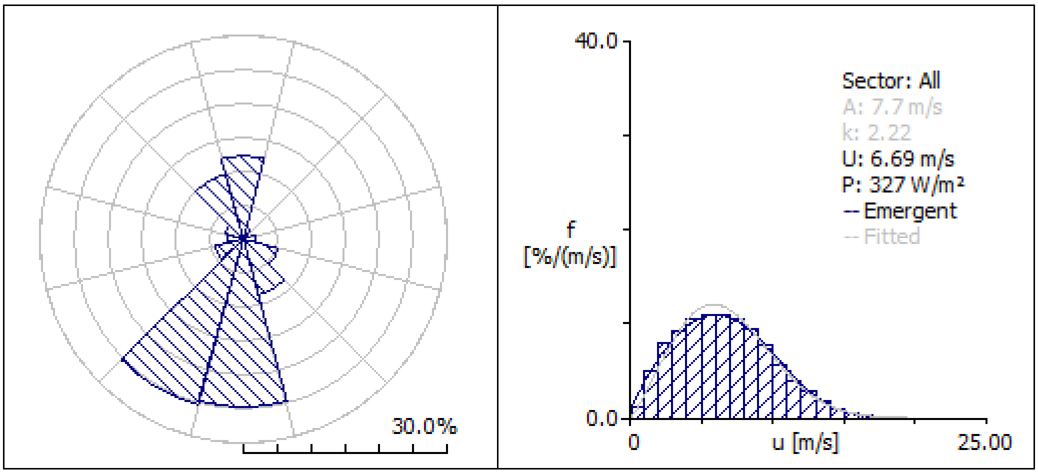


Figure 14. Wind rose and wind speed distribution for WM04 Vredenburg at 62 m a.g.l. The data shown represent a 3-year period from June 2010 to May 2013; the mast stopped operating in June 2013.

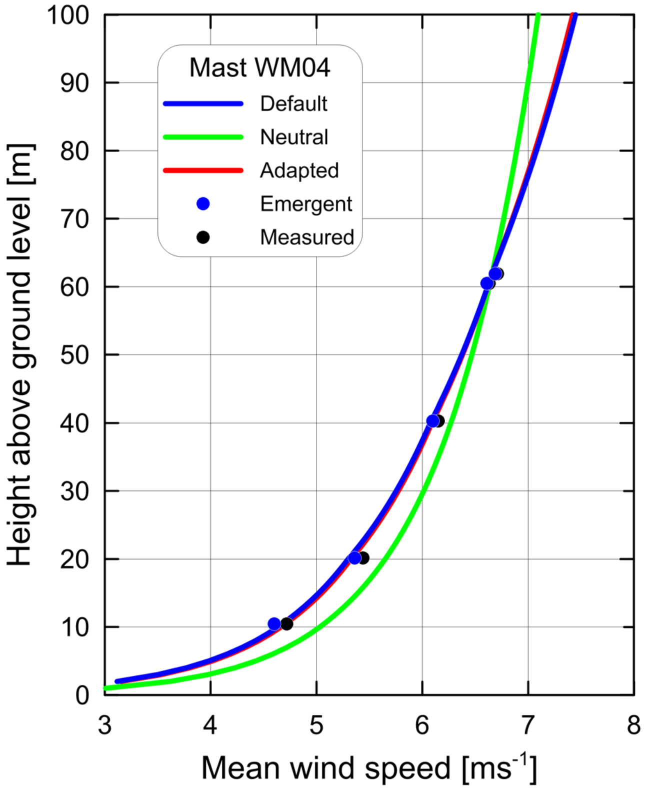


Figure 15. Measured and WAsP-modelled wind profiles for Vredenburg. Adapted wind profile corresponds to a mean heat flux over land of −35 Wm^{-2} (default −40 Wm^{-2}).

3.8.2 Generalised wind climate

Table 8. Generalised wind climate for Vredenburg. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.217 (1.21 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	7.2	5.2	4.5	3.5	2.3
	Weibull *k*	1.93	1.75	1.75	1.76	1.73
	Mean speed [ms^{-1}]	6.39	4.62	4.01	3.15	2.09
	Power density [Wm^{-2}]	312	131	86	42	12
20.0 m	Weibull *A* [ms^{-1}]	7.7	5.9	5.3	4.4	3.3
	Weibull *k*	1.96	1.83	1.82	1.82	1.78
	Mean speed [ms^{-1}]	6.84	5.28	4.70	3.89	2.89
	Power density [Wm^{-2}]	377	187	133	76	32
40.0 m	Weibull *A* [ms^{-1}]	8.3	6.8	6.2	5.3	4.2
	Weibull *k*	2.03	1.97	1.95	1.93	1.88
	Mean speed [ms^{-1}]	7.34	6.07	5.50	4.72	3.76
	Power density [Wm^{-2}]	450	261	197	126	66
62.0 m	Weibull *A* [ms^{-1}]	8.7	7.5	6.9	6.0	4.9
	Weibull *k*	2.02	2.13	2.09	2.05	1.97
	Mean speed [ms^{-1}]	7.69	6.68	6.10	5.31	4.36
	Power density [Wm^{-2}]	521	324	251	169	97
100.0 m	Weibull *A* [ms^{-1}]	9.2	8.5	7.8	6.8	5.7
	Weibull *k*	1.98	2.17	2.18	2.20	2.13
	Mean speed [ms^{-1}]	8.14	7.50	6.88	6.05	5.08
	Power density [Wm^{-2}]	628	453	347	234	143

3.9 Napier (WM05)

WM05	19.69245°E	34.61192°S	288 m	E 380119 m	N 6169216 m	UTM 34

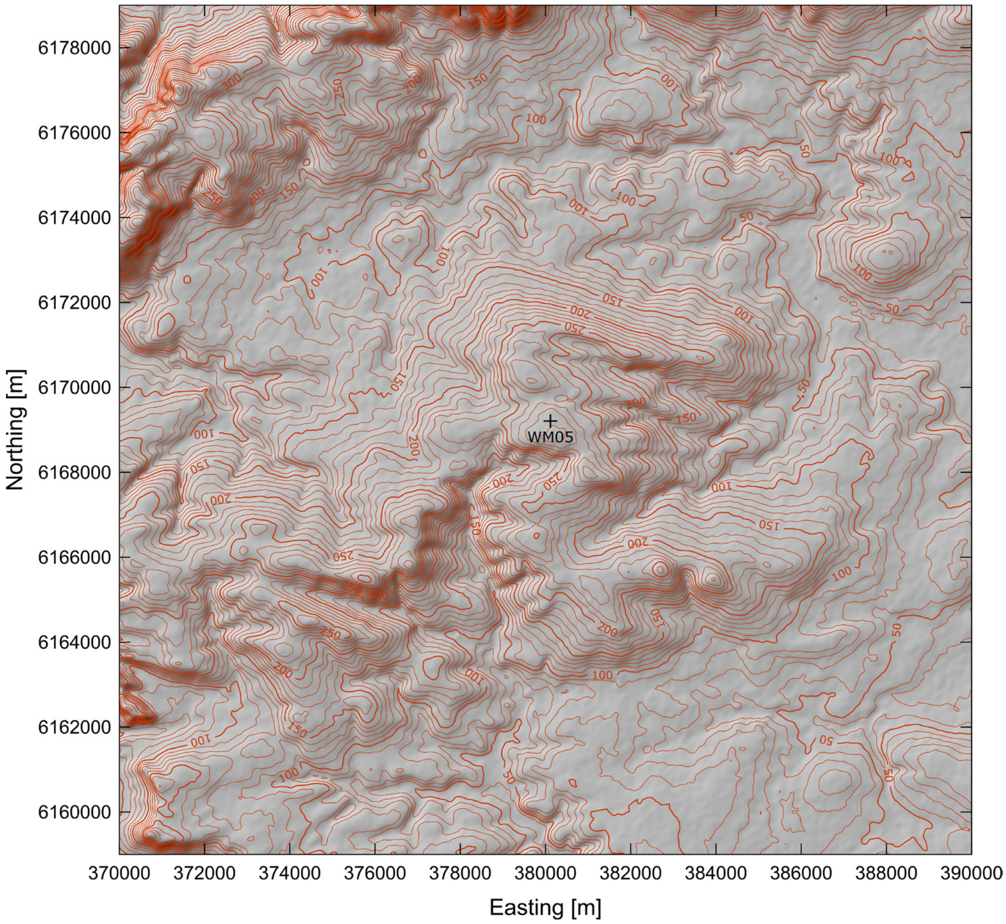


Figure 16. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0%.

3.9.1 Observed wind climate

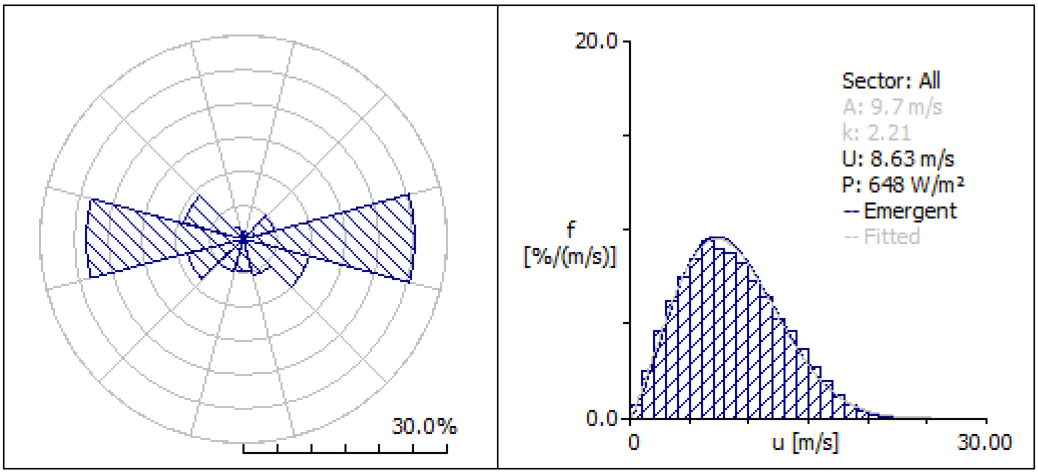


Figure 17. Wind rose and wind speed distribution for WM05 Napier at 62 m a.g.l. The data shown represent a 3-year period (98.6%) from October 2010 to September 2013.

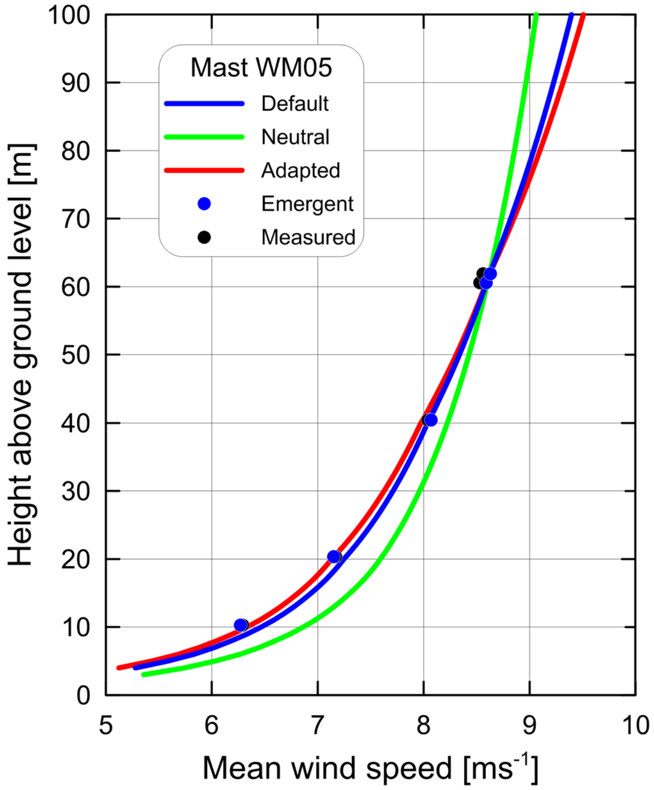


Figure 18. Measured and WAsP-modelled wind profiles for Napier. The adapted wind profile corresponds to a mean heat flux over land of −60 Wm^{-2} (default −40 Wm^{-2}).

3.9.2 Generalised wind climate

Table 9. Generalised wind climate for Napier. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.189 (1.18 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	9.0	6.5	5.6	4.4	2.9
	Weibull *k*	2.10	1.93	1.94	1.94	1.94
	Mean speed [ms^{-1}]	7.95	5.75	5.00	3.92	2.61
	Power density [Wm^{-2}]	539	222	146	70	21
20.0 m	Weibull *A* [ms^{-1}]	9.6	7.4	6.6	5.4	4.1
	Weibull *k*	2.13	1.99	2.00	1.99	1.99
	Mean speed [ms^{-1}]	8.50	6.53	5.83	4.82	3.59
	Power density [Wm^{-2}]	651	315	224	127	53
40.0 m	Weibull *A* [ms^{-1}]	10.3	8.4	7.6	6.5	5.2
	Weibull *k*	2.19	2.12	2.11	2.09	2.06
	Mean speed [ms^{-1}]	9.08	7.43	6.76	5.79	4.63
	Power density [Wm^{-2}]	777	437	331	210	109
62.0 m	Weibull *A* [ms^{-1}]	10.7	9.2	8.4	7.3	6.0
	Weibull *k*	2.19	2.26	2.22	2.19	2.15
	Mean speed [ms^{-1}]	9.49	8.10	7.42	6.47	5.34
	Power density [Wm^{-2}]	883	537	418	281	160
100.0 m	Weibull *A* [ms^{-1}]	11.3	10.1	9.3	8.2	7.0
	Weibull *k*	2.17	2.35	2.36	2.34	2.28
	Mean speed [ms^{-1}]	9.98	8.98	8.27	7.30	6.17
	Power density [Wm^{-2}]	1037	707	550	381	235

3.10 Sutherland (WM06)

WM06	20.69124°E	32.55680°S	1581 m	E 471014 m	N 6397803 m	UTM 34

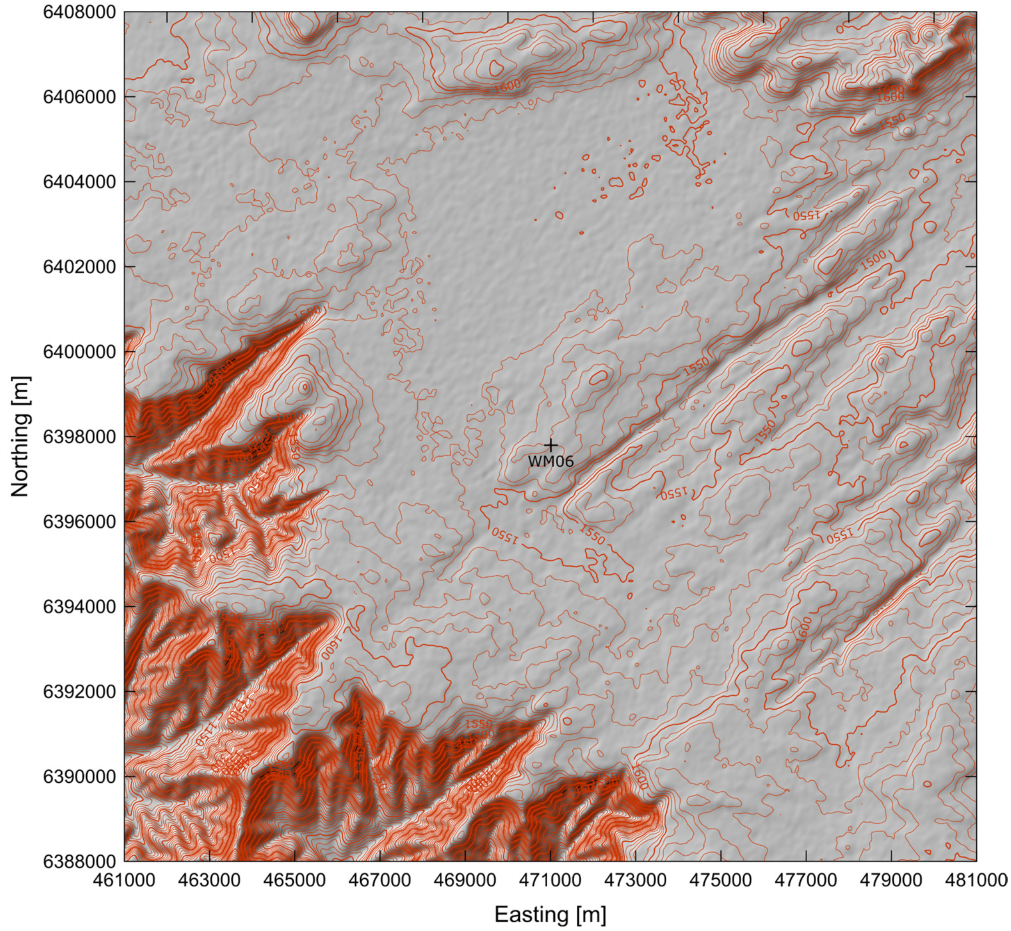


Figure 19. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0%.

3.10.1 Observed wind climate

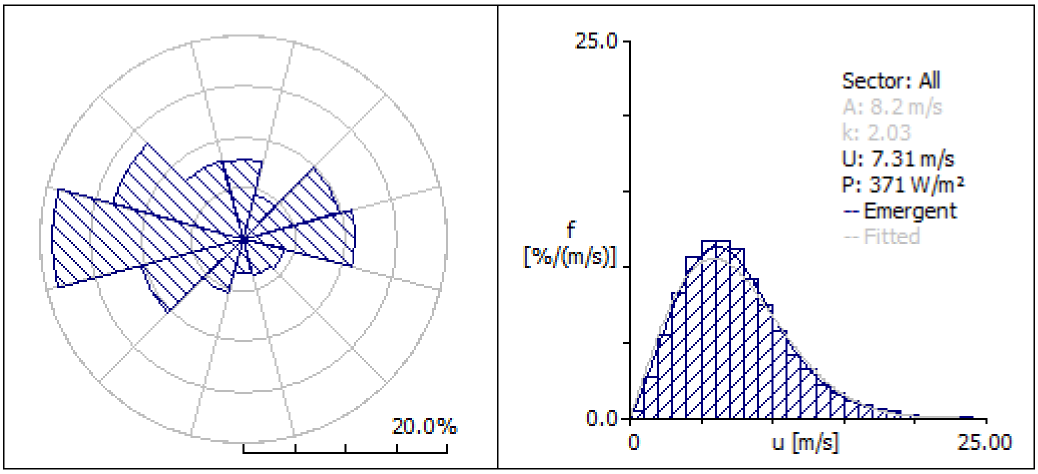


Figure 20. Wind rose and wind speed distribution for WM06 Sutherland at 62 m a.g.l. The data shown represent a 3-year period from October 2010 to September 2013.

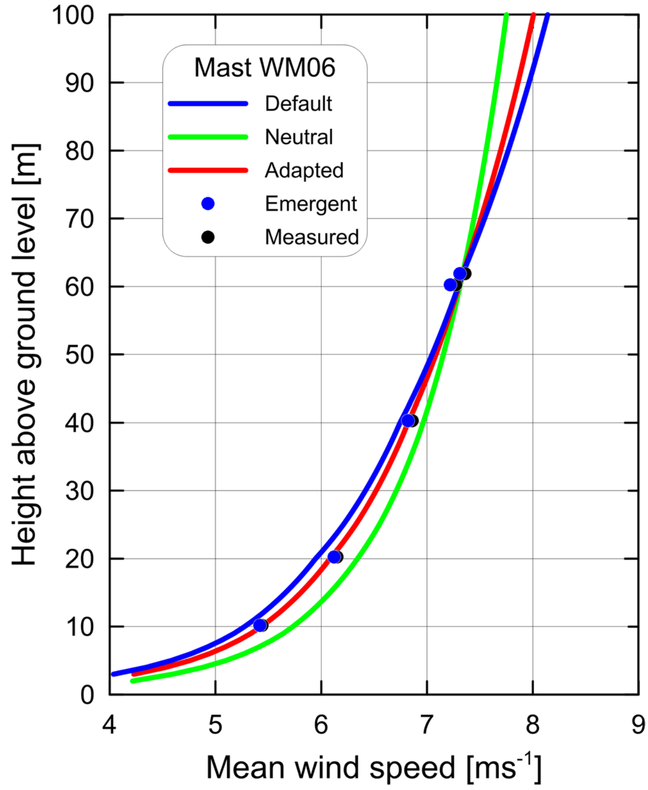


Figure 21. Measured and WAsP-modelled wind profiles for Sutherland. Adapted wind profile corresponds to a mean heat flux over land of −20 Wm^{-2} (default −40 Wm^{-2}).

3.10.2 Generalised wind climate

Table 10. Generalised wind climate for Sutherland. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.031 (1.03 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	7.7	5.5	4.8	3.8	2.5
	Weibull *k*	1.90	1.74	1.73	1.73	1.74
	Mean speed [ms^{-1}]	6.81	4.93	4.29	3.36	2.24
	Power density [Wm^{-2}]	328	138	91	44	13
20.0 m	Weibull *A* [ms^{-1}]	8.2	6.3	5.6	4.7	3.5
	Weibull *k*	1.93	1.80	1.79	1.78	1.79
	Mean speed [ms^{-1}]	7.28	5.63	5.01	4.14	3.09
	Power density [Wm^{-2}]	395	196	140	79	33
40.0 m	Weibull *A* [ms^{-1}]	8.8	7.3	6.6	5.6	4.5
	Weibull *k*	1.99	1.94	1.91	1.88	1.87
	Mean speed [ms^{-1}]	7.80	6.43	5.83	4.99	4.00
	Power density [Wm^{-2}]	470	271	205	130	67
62.0 m	Weibull *A* [ms^{-1}]	9.2	8.0	7.3	6.3	5.2
	Weibull *k*	1.99	2.08	2.04	1.99	1.96
	Mean speed [ms^{-1}]	8.17	7.05	6.44	5.59	4.62
	Power density [Wm^{-2}]	538	331	257	173	99
100.0 m	Weibull *A* [ms^{-1}]	9.7	8.9	8.1	7.2	6.1
	Weibull *k*	1.96	2.16	2.16	2.15	2.11
	Mean speed [ms^{-1}]	8.62	7.86	7.21	6.35	5.37
	Power density [Wm^{-2}]	641	444	343	235	145

3.11 Beaufort West (WM07)

WM07	22.55667°E	32.96672°S	1047 m	E 645480 m	N 6351327 m	UTM 34

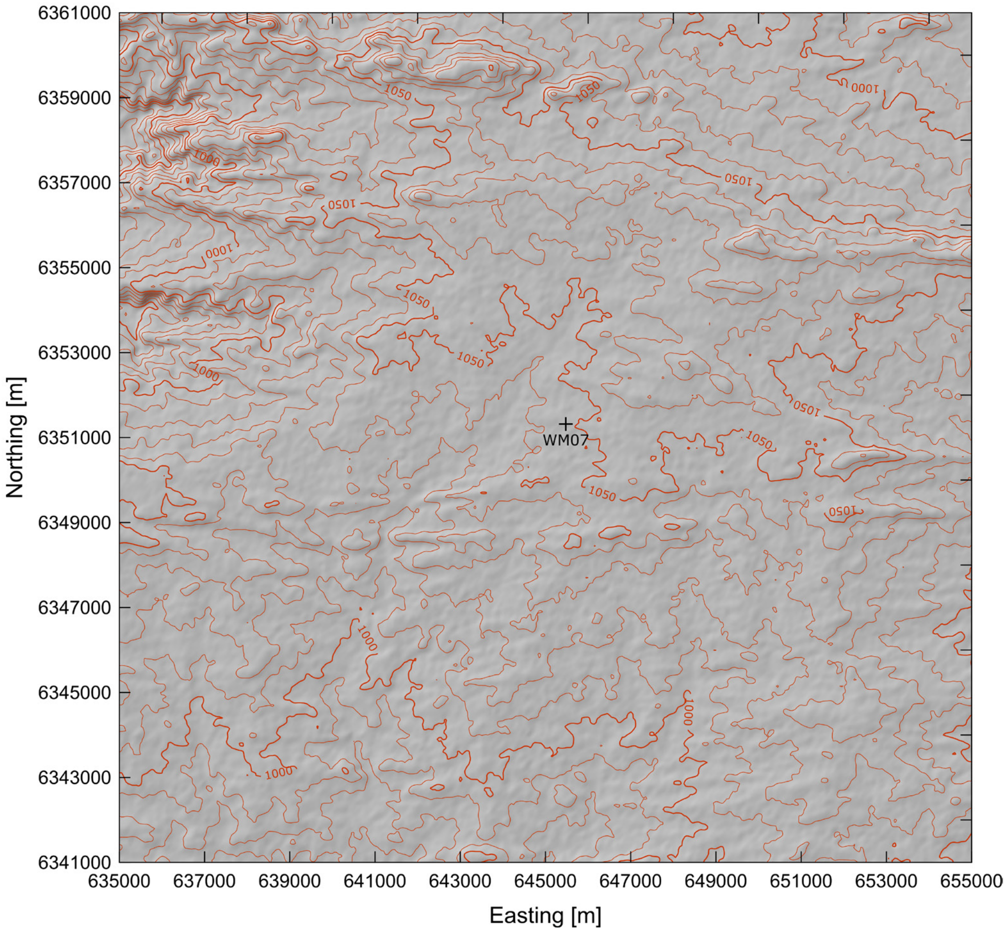


Figure 22. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0%.

3.11.1 Observed wind climate

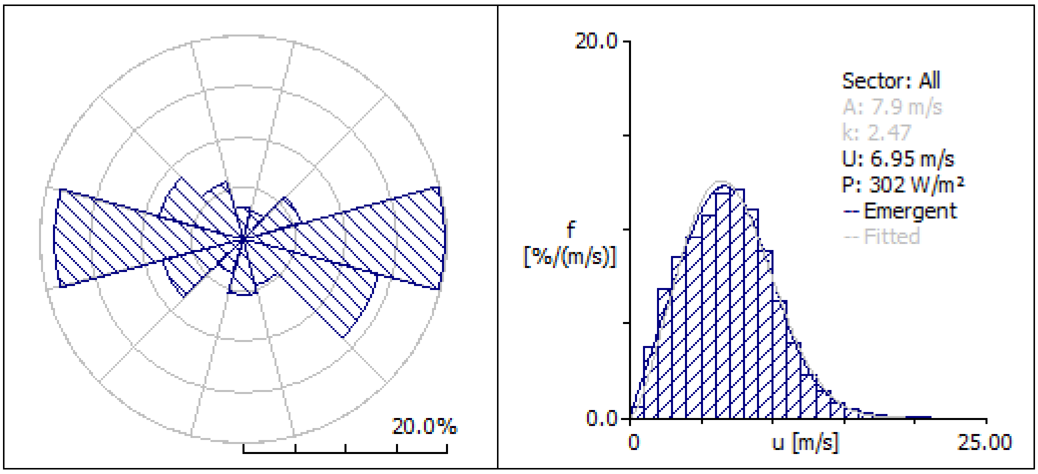


Figure 23. Wind rose and wind speed distribution for WM07 Beaufort West at 62 m a.g.l. The data shown represent a 3-year period from October 2010 to September 2013.

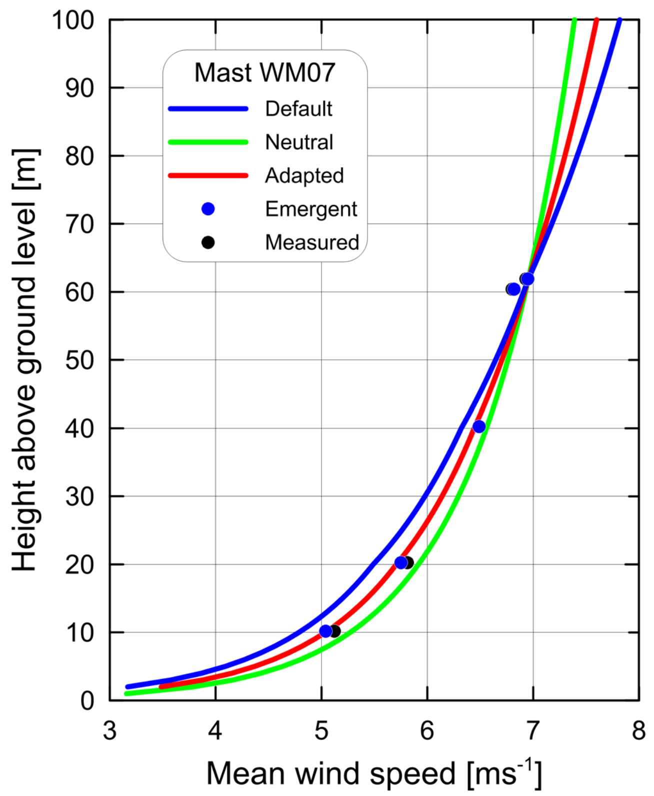


Figure 24. Measured and modelled wind profiles for Beaufort West. Adapted wind profile corresponds to a mean heat flux over land of −10 Wm^{-2} (default −40 Wm^{-2}).

3.11.2 Generalised wind climate

Table 11. Generalised wind climate for Beaufort West. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.085 (1.09 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	7.5	5.4	4.7	3.7	2.4
	Weibull *k*	2.12	1.86	1.88	1.87	1.87
	Mean speed [ms^{-1}]	6.65	4.78	4.17	3.27	2.17
	Power density [Wm^{-2}]	290	123	80	39	11
20.0 m	Weibull *A* [ms^{-1}]	8.0	6.2	5.5	4.6	3.4
	Weibull *k*	2.16	1.96	1.96	1.94	1.93
	Mean speed [ms^{-1}]	7.12	5.47	4.89	4.04	3.01
	Power density [Wm^{-2}]	349	174	124	70	29
40.0 m	Weibull *A* [ms^{-1}]	8.6	7.1	6.5	5.5	4.4
	Weibull *k*	2.24	2.13	2.12	2.08	2.04
	Mean speed [ms^{-1}]	7.64	6.28	5.71	4.89	3.90
	Power density [Wm^{-2}]	418	243	184	117	61
62.0 m	Weibull *A* [ms^{-1}]	9.0	7.8	7.1	6.2	5.1
	Weibull *k*	2.23	2.33	2.29	2.22	2.16
	Mean speed [ms^{-1}]	8.01	6.92	6.33	5.50	4.53
	Power density [Wm^{-2}]	484	301	234	157	90
100.0 m	Weibull *A* [ms^{-1}]	9.6	8.8	8.1	7.1	6.0
	Weibull *k*	2.19	2.37	2.41	2.41	2.36
	Mean speed [ms^{-1}]	8.47	7.78	7.14	6.27	5.28
	Power density [Wm^{-2}]	583	421	322	218	132

3.12 Humansdorp (WM08)

WM08	24.51436°E	34.10997°S	110 m	E 270726 m	N 6222861 m	UTM 35

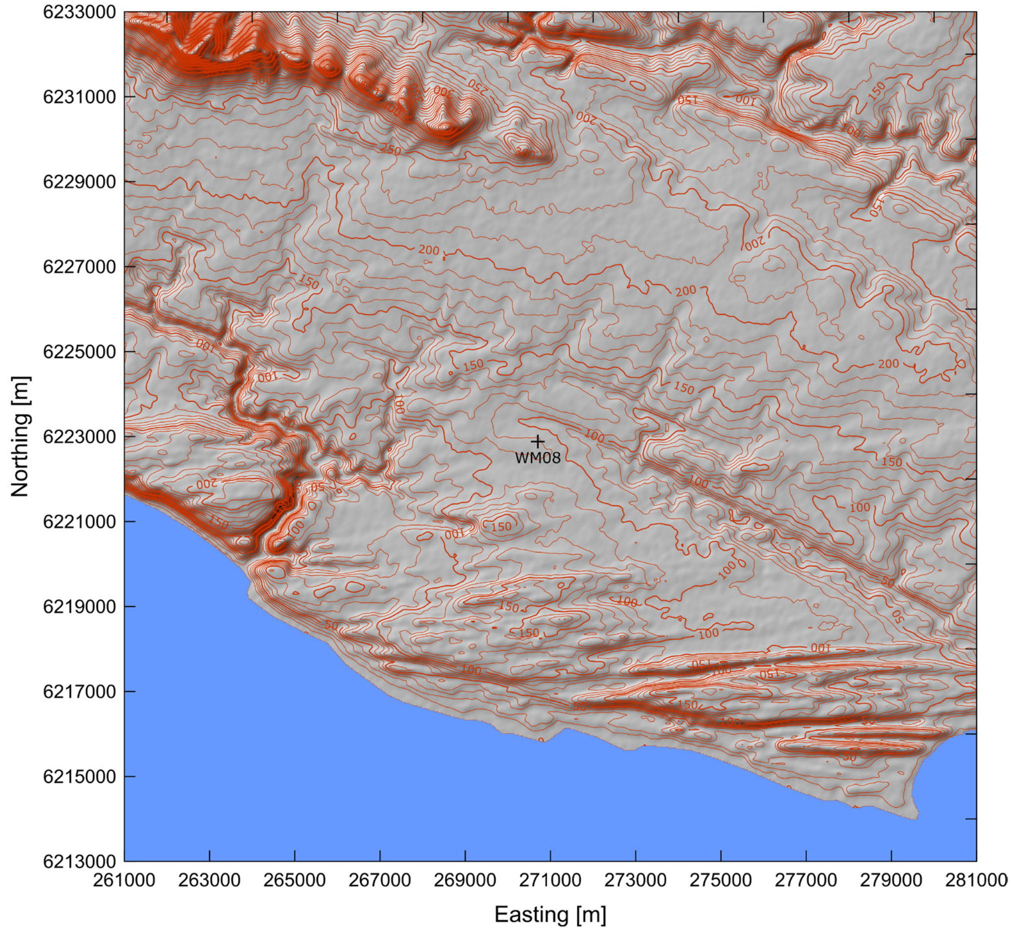


Figure 25. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 0%.

3.12.1 Observed wind climate

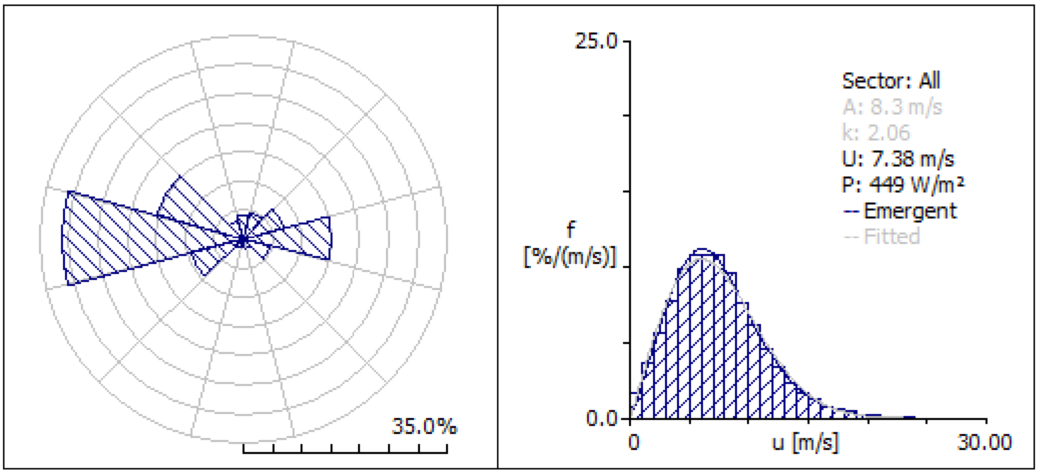


Figure 26. Wind rose and wind speed distribution for WM08 Humansdorp at 62 m a.g.l. The data shown represent a 2-year period from October 2010 to September 2012.

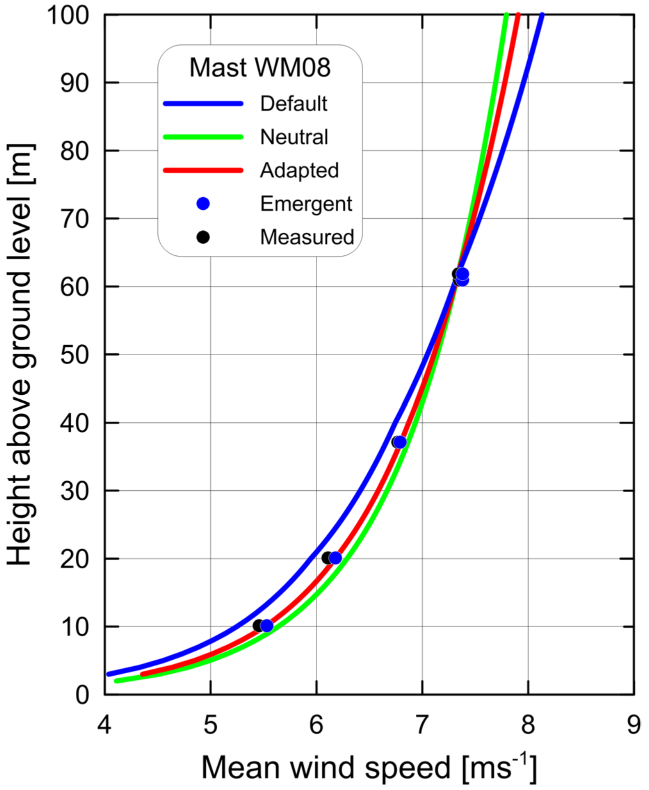


Figure 27. Measured and WAsP-modelled wind profiles for Humansdorp. Adapted wind profile corresponds to a mean heat flux over land of −10 Wm^{-2} (default −40 Wm^{-2}).

3.12.2 Generalised wind climate

Table 12. Generalised wind climate for Humansdorp. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.205 (1.21 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	7.8	5.6	4.9	3.8	2.6
	Weibull *k*	1.90	1.74	1.73	1.74	1.73
	Mean speed [ms^{-1}]	6.94	5.02	4.36	3.43	2.28
	Power density [Wm^{-2}]	407	171	112	54	16
20.0 m	Weibull *A* [ms^{-1}]	8.4	6.4	5.7	4.7	3.5
	Weibull *k*	1.94	1.81	1.79	1.79	1.78
	Mean speed [ms^{-1}]	7.43	5.73	5.10	4.22	3.14
	Power density [Wm^{-2}]	490	242	173	98	41
40.0 m	Weibull *A* [ms^{-1}]	9.0	7.4	6.7	5.7	4.6
	Weibull *k*	1.99	1.94	1.92	1.90	1.87
	Mean speed [ms^{-1}]	7.95	6.55	5.94	5.10	4.07
	Power density [Wm^{-2}]	583	335	253	162	84
62.0 m	Weibull *A* [ms^{-1}]	9.4	8.1	7.4	6.4	5.3
	Weibull *k*	2.00	2.09	2.04	2.01	1.96
	Mean speed [ms^{-1}]	8.32	7.18	6.56	5.71	4.70
	Power density [Wm^{-2}]	667	409	319	215	123
100.0 m	Weibull *A* [ms^{-1}]	9.9	9.0	8.3	7.3	6.2
	Weibull *k*	1.97	2.17	2.17	2.16	2.10
	Mean speed [ms^{-1}]	8.78	8.01	7.36	6.48	5.46
	Power density [Wm^{-2}]	792	550	426	292	180

3.13 Noupoort (WM09)

WM09	25.02838°E	31.25254°S	1806 m	E 312258 m	N 6540734 m	UTM 35

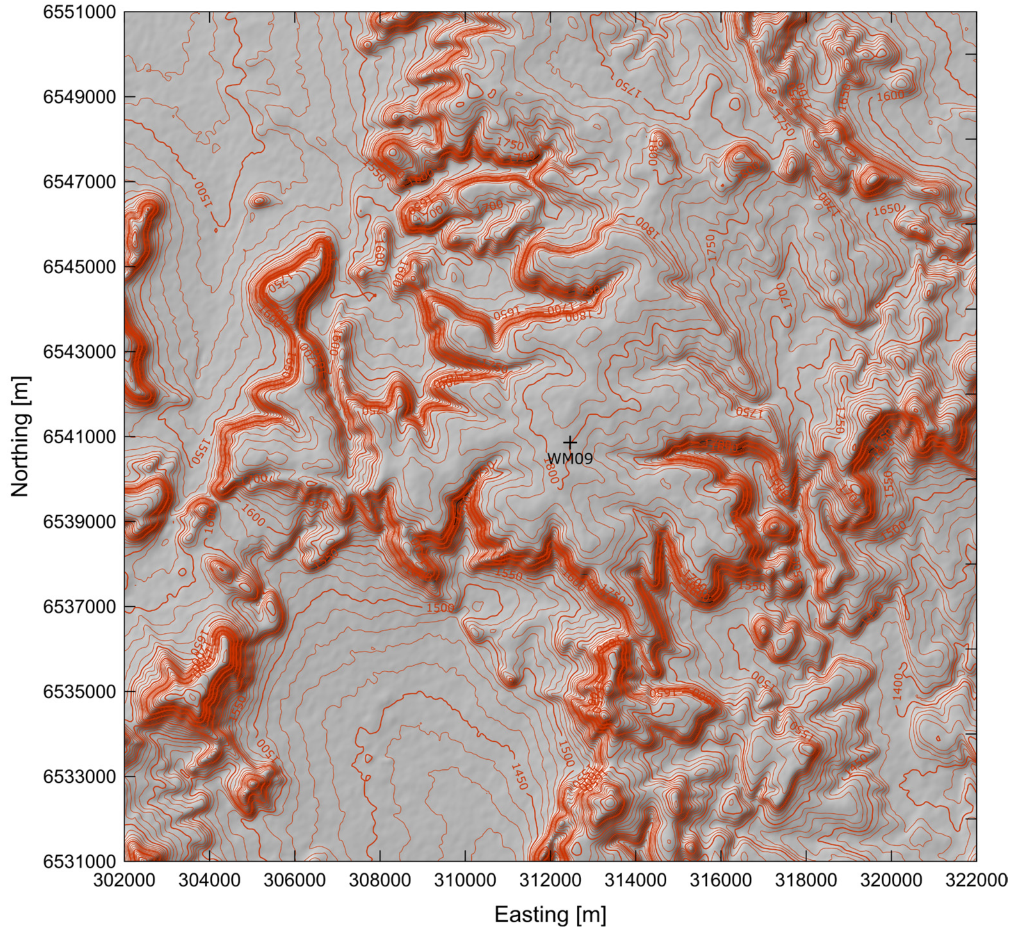


Figure 28. Elevation map from SRTM3 data, covering 20×20 km^2, with 10-m contours. The ruggedness index for the site is 4.0%.

3.13.1 Observed wind climate

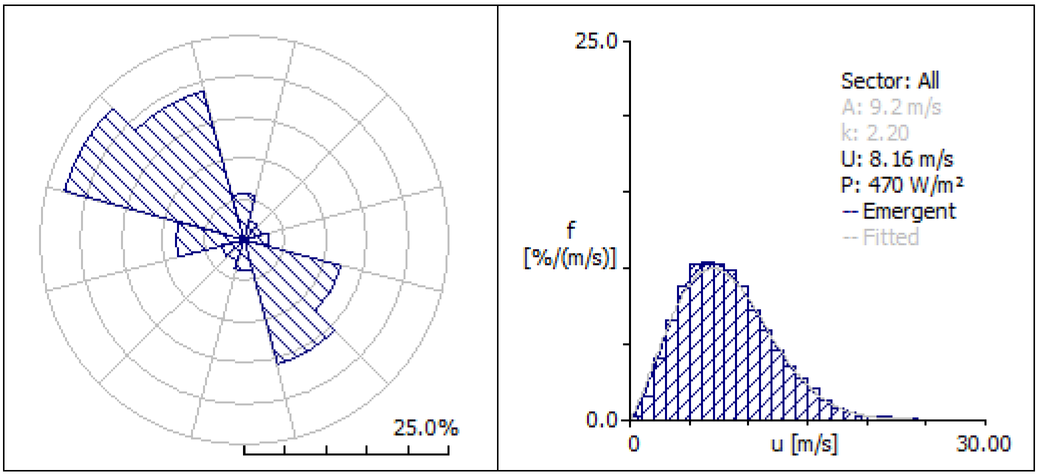


Figure 29. Wind rose and wind speed distribution for WM09 Noupoort at 62 m a.g.l. The data shown represent a 2-y period, consisting of data from October 2010 to September 2013 – less the calendar year 2011.

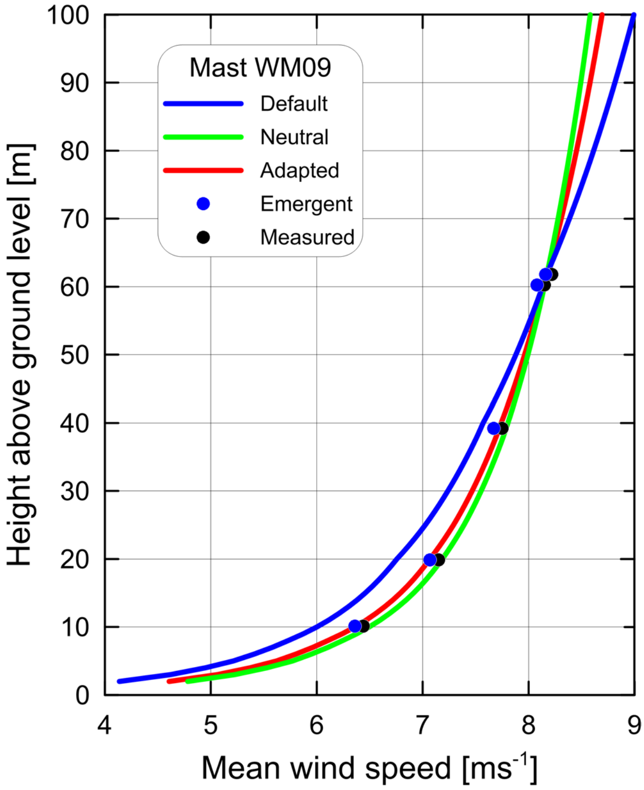


Figure 30. Measured and WAsP-modelled wind profiles for Noupoort. The adapted wind profile corresponds to a mean heat flux over land of −10 Wm^{-2} (default −40 Wm^{-2}).

3.13.2 Generalised wind climate

Table 13. Generalised wind climate for Noupoort. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.001 (1.00 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	8.2	5.9	5.1	4.0	2.7
	Weibull *k*	2.04	1.88	1.88	1.88	1.88
	Mean speed [ms^{-1}]	7.26	5.26	4.57	3.59	2.39
	Power density [Wm^{-2}]	357	148	97	47	14
20.0 m	Weibull *A* [ms^{-1}]	8.8	6.8	6.0	5.0	3.7
	Weibull *k*	2.07	1.95	1.94	1.94	1.94
	Mean speed [ms^{-1}]	7.76	5.99	5.34	4.42	3.30
	Power density [Wm^{-2}]	431	210	150	85	35
40.0 m	Weibull *A* [ms^{-1}]	9.4	7.7	7.0	6.0	4.8
	Weibull *k*	2.13	2.08	2.06	2.04	2.02
	Mean speed [ms^{-1}]	8.31	6.84	6.21	5.33	4.26
	Power density [Wm^{-2}]	515	294	222	142	73
62.0 m	Weibull *A* [ms^{-1}]	9.8	8.4	7.7	6.7	5.6
	Weibull *k*	2.13	2.22	2.18	2.15	2.11
	Mean speed [ms^{-1}]	8.69	7.48	6.84	5.97	4.92
	Power density [Wm^{-2}]	589	362	282	190	108
100.0 m	Weibull *A* [ms^{-1}]	10.3	9.4	8.6	7.6	6.4
	Weibull *k*	2.11	2.31	2.31	2.31	2.25
	Mean speed [ms^{-1}]	9.16	8.33	7.65	6.76	5.71
	Power density [Wm^{-2}]	696	485	376	259	159

3.14 Butterworth (WM10)

WM10	28.13595°E	32.09065°S	925 m	E 607194 m	N 6448952 m	UTM 35

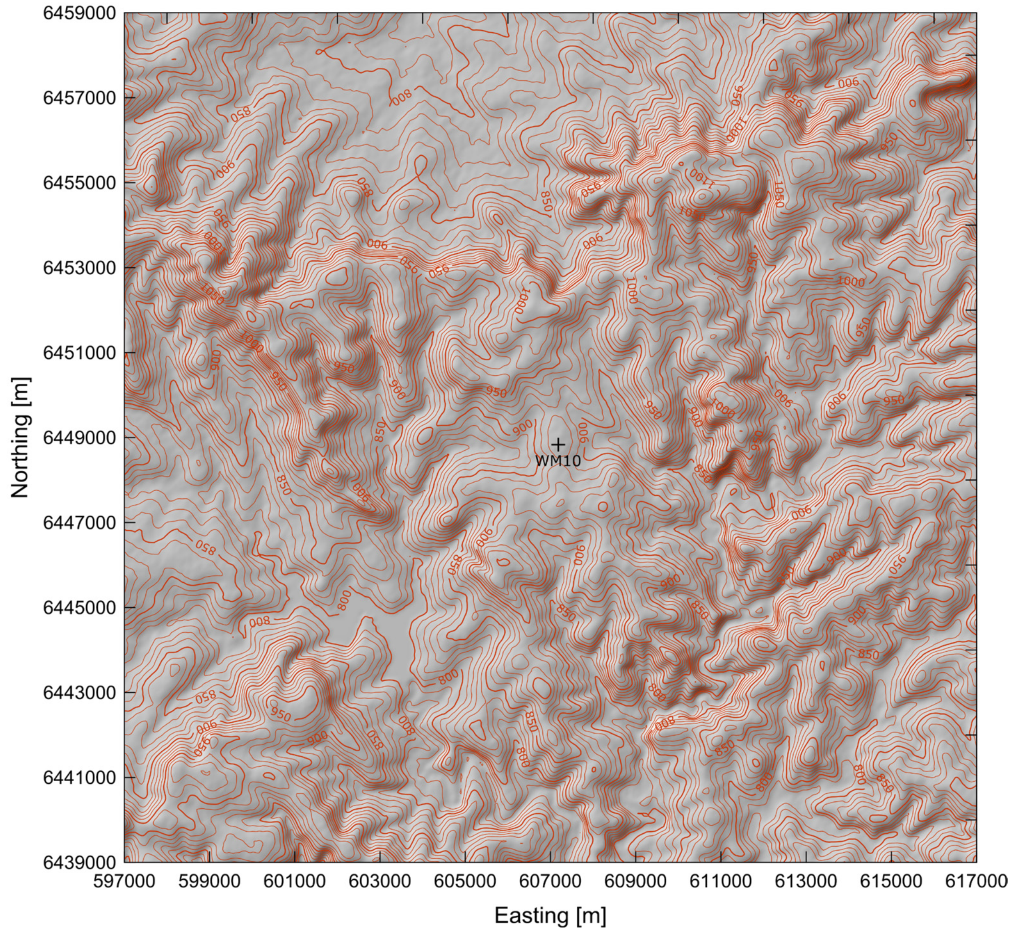


Figure 31. Elevation map from SRTM3 data, covering 20×20 km^2, with 20-m contours. The ruggedness index for the site is 0%.

3.14.1 Observed wind climate

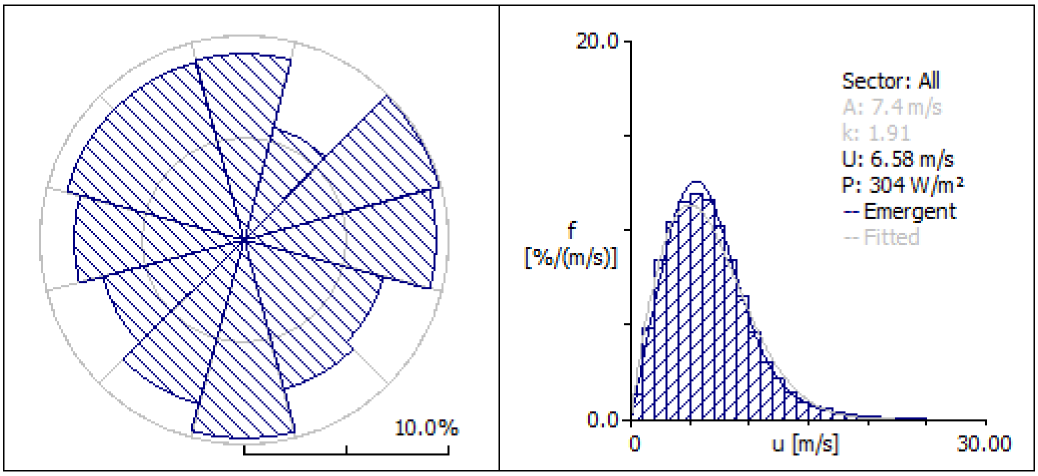


Figure 32. Wind rose and wind speed distribution for WM10 Butterworth at 62 m a.g.l. The data shown represent a 2-y period; from March 2011 to February 2012 and October 2012 to September 2013.

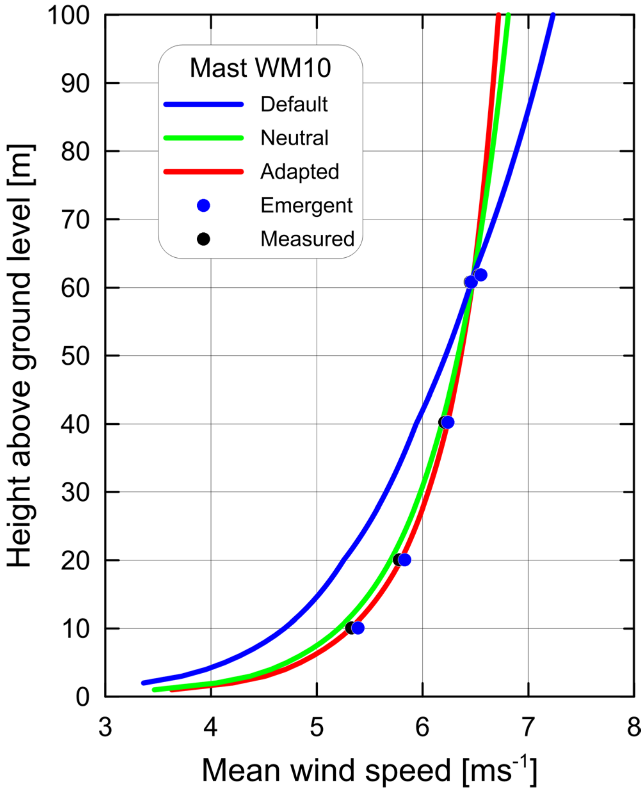


Figure 33. Measured and WAsP-modelled wind profiles for Butterworth. Adapted wind profile corresponds to a mean heat flux over land of +20 Wm^{-2} (default −40 Wm^{-2}).

3.14.2 Generalised wind climate

Table 14. Generalised wind climate for Butterworth. Non-default parameters are: Reference heights and air density [kg m^{-3}]: 1.110 (1.09 in WAsP project).

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m	1.50 m
10.0 m	Weibull *A* [ms^{-1}]	6.9	4.9	4.3	3.4	2.2
	Weibull *k*	1.78	1.60	1.60	1.61	1.61
	Mean speed [ms^{-1}]	6.12	4.42	3.84	3.02	2.01
	Power density [Wm^{-2}]	270	117	77	37	11
20.0 m	Weibull *A* [ms^{-1}]	7.4	5.7	5.0	4.2	3.1
	Weibull *k*	1.81	1.67	1.66	1.66	1.66
	Mean speed [ms^{-1}]	6.55	5.05	4.50	3.73	2.78
	Power density [Wm^{-2}]	324	164	117	67	28
40.0 m	Weibull *A* [ms^{-1}]	7.9	6.5	5.9	5.1	4.1
	Weibull *k*	1.87	1.81	1.78	1.77	1.75
	Mean speed [ms^{-1}]	7.01	5.79	5.25	4.51	3.61
	Power density [Wm^{-2}]	385	225	170	109	57
62.0 m	Weibull *A* [ms^{-1}]	8.3	7.2	6.5	5.7	4.7
	Weibull *k*	1.87	1.97	1.92	1.88	1.84
	Mean speed [ms^{-1}]	7.35	6.36	5.81	5.06	4.17
	Power density [Wm^{-2}]	442	272	213	144	83
100.0 m	Weibull *A* [ms^{-1}]	8.7	8.0	7.4	6.5	5.5
	Weibull *k*	1.85	2.04	2.03	2.04	1.99
	Mean speed [ms^{-1}]	7.76	7.12	6.53	5.76	4.86
	Power density [Wm^{-2}]	528	369	285	195	120

3.15 Summary of generalised wind climates

This section summarises the main characteristics of the *generalised wind climates* from the 10 stations, see Table 15. In order to compare wind atlas data sets to similar data sets elsewhere, the power densities in this section were calculated using standard air density.

Table 15. Summary of the generalised wind climates at 100 m a.g.l. over roughness class 1 (roughness length z_0 = 0.03 m) at the met. stations: Data-collecting period, Weibull A- and k-parameters, mean wind speed (U), and power density at standard conditions (E_0).

Mast ID	**Period**	***A*** [ms^{-1}]	***k***	***U*** [ms^{-1}]	***E*₀** [Wm^{-2}]
WM01	3 y	7.3	1.67	6.48	392
WM02	3 y	7.4	2.06	6.55	320
WM03	3 y	8.2	2.24	7.25	400
WM04	3 y	8.4	2.16	7.47	454
WM05	3 y	10.3	2.38	9.11	757
WM06	3 y	8.7	2.12	7.73	511
WM07	3 y	8.5	2.30	7.56	445
WM08	2 y	8.7	2.11	7.72	511
WM09	2 y	9.1	2.24	8.05	549
WM10	2 y	7.9	1.96	7.05	418

Figure 34 shows corresponding values of mean wind speed and standard power density for meteorological stations in South Africa, Denmark, Portugal and NE China.

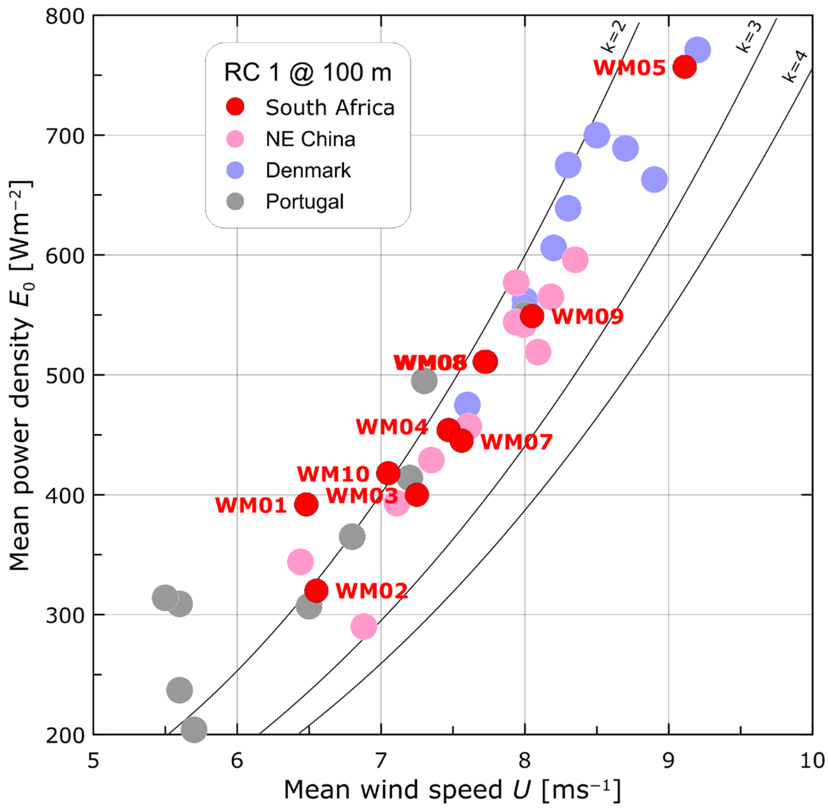


Figure 34. Summary of the generalised wind climates at 100 m a.g.l. over roughness class 1 (roughness length z_0 = 0.03 m) at the meteorological stations. Power densities are calculated and displayed using standard air density.

4 Concluding remarks

With this report, the first observational wind atlas for the WASA domain in South Africa has been established, based on data and analyses from 10 meteorological masts in Western, Northern and Eastern Cape provinces. The main results of the wind atlas analysis are reported in Chapter 3, but much more data and information are available in the Climate Analyst projects and WAsP workspaces that accompany this report. Based on this work, it will be straightforward to update the observational wind atlas if and when more data becomes available. It should be borne in mind that the present atlas is based on three years only and that long-term data from near-by meteorological stations are not included here.

The generalised wind climates determined in the wind atlas analysis can be used for verification of the mesoscale modelling close to the met. station sites; this verification is described on the WASA web pages and reports.

The observed wind climates established during the wind atlas analysis can also be used for verification of the microscale modelling, in particular how well the vertical wind profile can be modelled from 0-62 metres above the terrain. The main results of this comparison are shown in Chapter 3.

The general impression is that WAsP works well in South Africa – where the sites are within its operational envelope. However, unlike many sites in other countries that have been analysed using WAsP, the default heat flux modelling parameters seem to need some adaption in order for the model to be able to predict the wind profiles well. This can be seen from the wind speed profile graphs in Chapter 3, where the measured profile often lies between the WAsP default profile (slightly stable) and the strictly neutral wind speed profile. This is further illustrated in Table 16, which shows the results of the wind profile modelling derived with three different heat flux settings.

Table 16. Summary of some terrain characteristics related to wind speed profile analyses at the meteorological stations: Terrain type, general roughness length, average onshore heat flux setting in WAsP analysis (default is -40 Wm^{-2}), and mean absolute percentage error in the profile analysis (MAPE) for three different heat flux settings.

Mast ID	Terrain type	Roughness [m]	Heat flux [Wm^{-2}]	Neutral [%]	Default [%]	Adapted [%]
WM 01	coastal	0.03	+50	2.4	6.4	1.8
WM 02	inland	0.03	−10	3.3	2.2	1.0
WM 03	coastal	0.03	−20	3.4	1.9	0.6
WM 04	coastal	0.03	−35	4.5	0.7	0.7
WM 05	coastal	0.07	−60	4.4	1.2	0.6
WM 06	inland	0.03	−20	3.0	1.8	0.3
WM 07	inland	0.03	−10	2.1	3.1	0.4
WM 08	coastal	0.03	−10	1.4	2.8	0.3
WM 09	inland	0.03	−10	1.3	3.0	0.2
WM 10	inland	0.01	+20	1.6	5.8	0.6

The three right-most columns in the table show the mean absolute percentage errors between measured mean wind speeds and predicted wind speeds. The 60-m level on the masts is not included, because flow distortion from air traffic lights etc. may influence these measurements significantly. The *neutral* values were obtained with heat fluxes of 0

Wm^{-2}, the *default* values with an onshore heat flux of −40 Wm^{-2} and the *adapted* values with the heat flux listed in the column 'Heat flux'. The wind profiles at masts 4 and 5 are predicted quite well with the default settings, whereas masts to the west, north and east require heat flux values closer to neutral conditions – or even unstable conditions.

The wind profile analysis therefore suggests that modelling of the vertical wind profile can be improved significantly by adjusting the heat flux settings in WAsP. It has not been possible so far to develop an objective way of selecting the proper heat flux values for any given site in the WASA domain, but it is demonstrated that this parameter can be used to tweak the modelled wind profile to better fit the wind profile observed. Evidently, this requires accurate and reliable wind profile measurements at the site.

The adapted heat flux values cited above are not realistic since they are used here to simply tweak the modelled wind profiles so they fit better the measured profiles. More work will be done in WASA Phase II to explore this pattern; the mesoscale modelling may be able to confirm this.

Based on the work reported here, it is strongly recommended to follow the general *WAsP Best Practices* closely when applying WAsP and similar models in South Africa; the current version of these is given in Appendix B. Since the modelling of the vertical wind profile seems to be particularly challenging, the deployment of tall meteorological masts (comparable to the hub height of the wind turbine) is strongly recommended. It is also strongly recommended to design and instrument such masts according to international standards and best practices, and to independently inspect the installations when they are in operation (Mortensen *et al*., 2012).

The first verified numerical wind atlas, which is being developed as part of Phase I of the WASA project, makes it possible to design a measurement programme based on a preliminary WAsP analysis. Given the generalised wind climates from this atlas, elevation maps based on SRTM data and roughness maps based on interpretation of Google Earth imagery, one can readily explore the best sites for installation of meteorological mast(s) at a given wind farm site and determine the best layout of the mast instrumentation, e.g. the orientation of the instrument booms etc.

The present observation-based wind atlas report will be updated when three full years of wind data become available. Likewise, it will be improved when further analysis of other elevation and land cover data sets have been analysed and verified.

5 Acknowledgements

The Wind Atlas for South Africa project is an initiative of the Government of South Africa – Department of Minerals and Energy (now Department of Energy) – and the project is co-funded by:

- UNDP-GEF through the South African Wind Energy Programme (SAWEP)
- Royal Danish Embassy

The South African National Energy Development Institute (SANEDI) is the Executing Agency, coordinating and contracting contributions from the implementing partners: Council for Scientific and Industrial Research (CSIR), University of Cape Town (UCT), South African Weather Service (SAWS) and DTU Wind Energy (formerly Risø DTU).

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6.1 Additional resources

SANEDI's Wind Atlas for South Africa site, www.wasaproject.info, contains general information about the Wind Atlas for South Africa project (WASA).

The WASA data are displayed online at the CSIR Online site, www.wasa.csir.co.za. Weather Research and Forecasting model (WRF) wind forecasts are available from veaonline.risoe.dk/wasa**.**

The main WASA download site, wasadata.csir.co.za/wasa1/WASAData, contains all the 10-min data collected at the 10 meteorological masts. The site further contains a 'Wind Atlas download section' where the First Numerical Wind Atlas, the Observational Wind Atlas, several case studies, reports and guidelines, map data and map tools, and some software tools are available. Download is free of charge, but requires registration.

A Additional observed wind statistics

Wind-climatological fingerprints

With two or three years of wind data, we can calculate and show the wind-climatological fingerprints (Troen and Petersen, 1989) for the 10 meteorological stations, see Figure 35, Figure 36 and Figure 37.

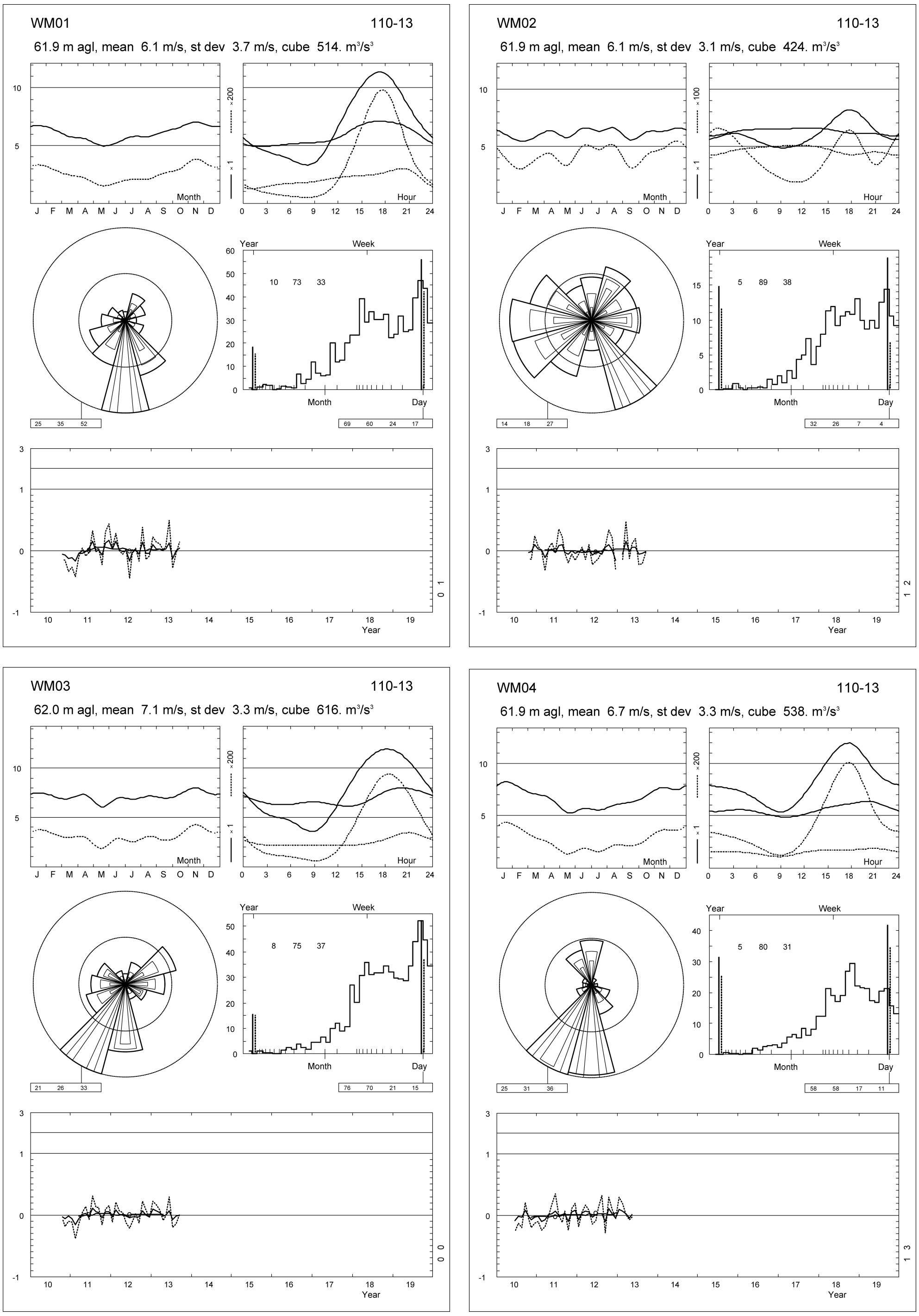

Figure 35. Wind-climatological fingerprint for WM01 Alexander Bay, WM02 Calvinia, WM03 Vredendal and WM04 Vredenburg at 62 m a.g.l. The graphs shown represent a 3-year period from October 2010 to September 2013.

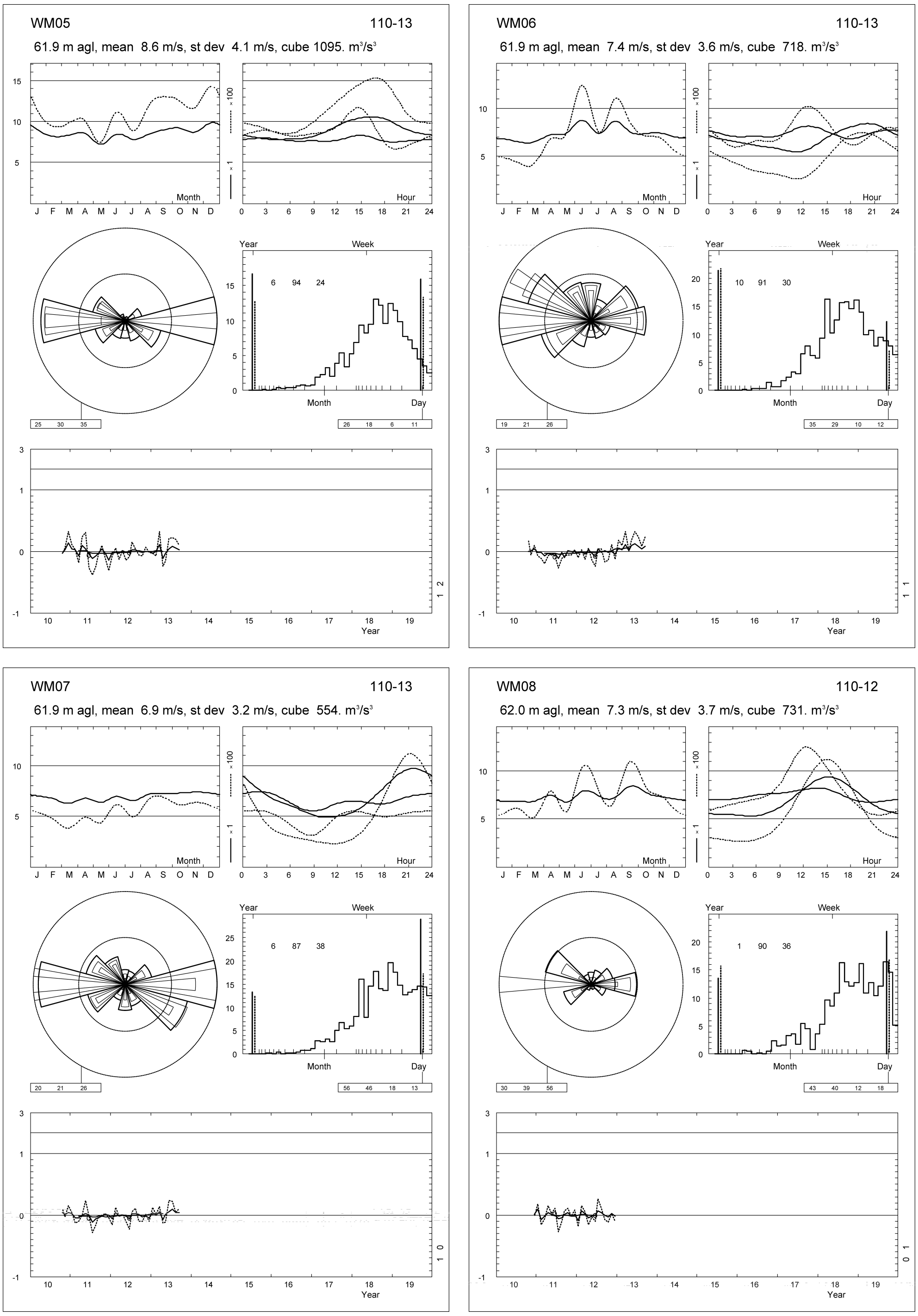

Figure 36. Wind-climatological fingerprint for WM05 Napier, WM06 Sutherland, WM07 Beaufort West and WM08 Humansdorp at 62 m a.g.l. The graphs shown represent a 3-year period from October 2010 to September 2013.

The detailed contents of the wind-climatological fingerprint are explained in the European Wind Atlas (Troen and Petersen, 1989).

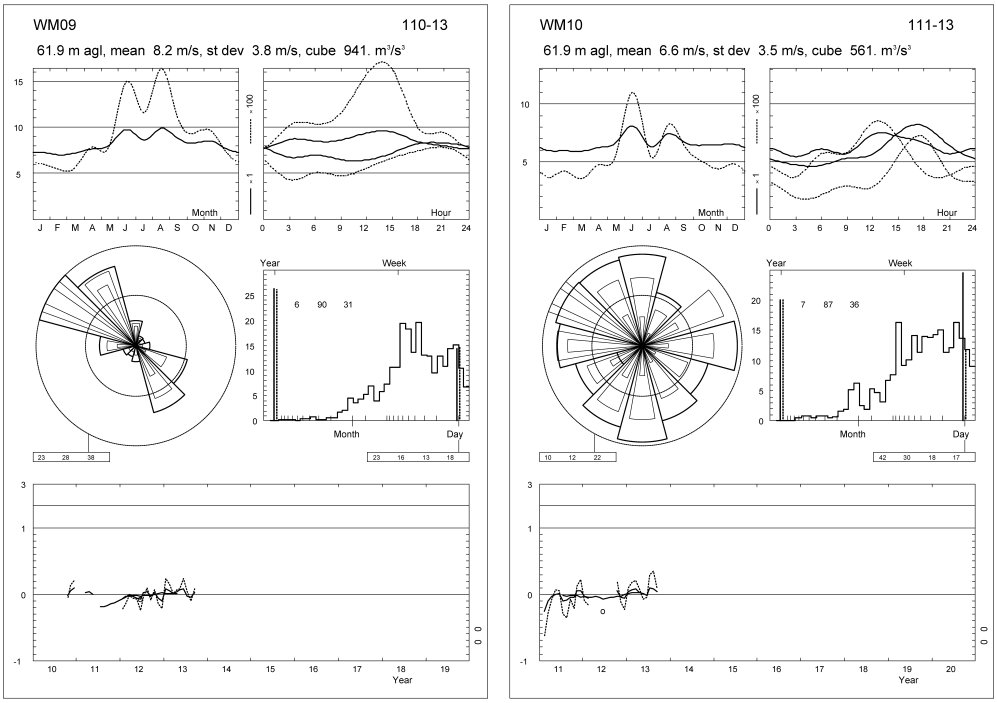

Figure 37. Wind-climatological fingerprint for WM09 Noupoort and WM10 Butterworth at 62 m a.g.l. The graphs shown represent 2-year periods only.

Summary of observed wind conditions

Table 17 provides a summary of the observed 62-m wind conditions at the stations. Data from WM08, WM09 and WM10 are given for two-year periods only.

Table 17. Summary of observed wind conditions 62 m above ground level at the meteorological stations: data recovery rate (R), Weibull A- and k-parameters, Weibull-derived mean wind speed (U), turbulence intensity (TI_{15}) at 15 ms^{-1}, 50-y wind speed (U_{50}), uncertainty of 50-y wind speed (σ_U), and α-parameter of Gumbel distribution.

Mast	*R* [%]	*A* [ms^{-1}]	*k*	*U* [ms^{-1}]	TI_{15} [%]	U_{50} [ms^{-1}]	σ_U [ms^{-1}]	*α* [%]
WM01	100.0	6.8	1.68	6.07	8.0	25.2	3.0	1.21
WM02	93.4	6.9	2.09	6.15	9.0	29.7	4.9	1.98
WM03	100.0	8.1	2.33	7.15	7.4	27.4	3.6	1.44
WM04	100.0	7.7	2.22	6.69	8.8	23.6	2.2	0.90
WM05	98.6	9.7	2.21	8.63	8.7	27.8	1.4	0.55
WM06	99.9	8.2	2.03	7.31	9.2	25.4	0.7	0.29
WM07	100.0	7.9	2.47	6.95	10.0	24.2	1.0	0.38
WM08	100.0	8.3	2.06	7.38	10.8	30.1	4.1	1.26
WM09	99.7	9.2	2.20	8.16	9.4	28.4	2.2	0.66
WM10	98.8	7.4	1.91	6.58	8.5	35.3	8.8	2.70

Hourly, monthly and yearly wind statistics

Mean wind speeds by hour of day and month of year, as well as monthly mean wind speeds for the years 2010 to 2014 are given in the tables below, see Table 18 to Table 37.

Table 18. Hourly and monthly mean wind speeds at WM01 Alexander Bay for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	5.6	5.4	5.0	4.9	4.3	4.8	5.2	4.7	5.5	5.2	6.0	5.1	5.1
1	5.3	5.0	4.3	4.5	4.2	4.9	5.1	4.8	4.9	4.9	5.4	4.6	4.8
2	5.0	4.3	4.1	4.2	4.0	4.9	4.9	4.7	4.7	4.9	5.0	4.5	4.6
3	4.5	3.9	3.9	4.1	4.0	4.9	4.9	5.0	4.7	4.7	4.8	4.4	4.5
4	4.2	3.8	3.5	4.1	4.0	4.9	5.0	5.0	4.5	4.5	4.6	4.3	4.4
5	4.2	3.6	3.6	3.8	4.0	5.0	5.0	5.2	4.2	4.4	4.3	4.3	4.3
6	3.8	3.5	3.7	4.0	4.4	5.0	5.1	5.1	4.2	4.4	4.1	4.3	4.3
7	3.6	3.5	3.4	4.1	4.6	5.3	5.3	5.1	4.1	4.2	3.7	4.0	4.2
8	3.3	3.1	3.1	4.4	4.5	5.3	5.3	5.5	4.0	3.9	3.7	3.7	4.2
9	3.5	3.4	3.1	3.9	4.3	5.0	5.3	5.1	3.7	4.2	4.0	4.0	4.1
10	3.9	3.6	3.3	3.8	4.0	4.4	4.5	5.0	3.9	4.4	4.3	4.5	4.1
11	5.1	4.3	3.7	4.3	4.3	4.6	4.7	5.3	4.4	5.0	5.2	5.6	4.7
12	6.6	6.1	4.9	4.7	4.6	4.5	5.7	5.4	5.3	6.3	7.0	7.4	5.7
13	8.0	7.9	6.7	5.7	5.2	4.9	5.8	5.8	6.7	8.0	8.4	8.9	6.8
14	9.2	9.1	8.0	6.8	5.5	5.5	6.5	6.6	7.6	8.9	10.0	10.0	7.8
15	10.2	10.2	9.1	7.7	6.2	5.8	6.8	7.3	8.7	10.1	10.9	10.5	8.6
16	10.8	10.7	9.8	8.4	6.7	6.6	7.3	7.6	9.3	10.6	11.6	10.7	9.2
17	11.2	10.8	9.9	8.8	7.1	6.7	7.4	7.8	9.8	10.7	11.7	10.6	9.4
18	11.2	10.7	9.7	8.5	7.0	6.2	7.1	7.6	9.7	10.3	11.4	10.2	9.1
19	10.5	10.1	9.1	8.0	6.3	6.1	7.2	6.9	9.3	9.5	10.8	9.7	8.6
20	9.6	9.0	8.4	7.4	5.9	5.6	7.1	6.4	8.5	8.5	9.5	8.6	7.9
21	8.3	8.1	7.1	6.7	5.3	5.2	6.5	5.9	7.9	7.6	8.6	7.7	7.1
22	7.3	7.0	6.3	5.8	4.7	5.0	5.7	5.5	7.2	7.1	7.6	6.6	6.3
23	6.4	5.9	5.2	4.9	4.5	4.9	5.3	5.2	6.3	6.1	6.5	5.8	5.6
	6.7	6.4	5.8	5.6	5.0	5.2	5.8	5.8	6.2	6.6	7.1	6.7	6.1

Table 19. Monthly and yearly mean wind speeds at WM01. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	5.2	5.6	6.0	6.2	6.5	5.8	–
2011	5.9	5.2	5.5	5.6	4.9	5.5	6.7	5.7	6.3	6.1	7.9	7.8	6.1
2012	6.9	7.3	5.9	5.5	5.0	4.4	5.6	5.9	5.9	7.5	6.7	6.3	6.1
2013	7.3	6.5	6.0	5.7	5.1	5.9	5.0	5.7	6.5	6.7	6.8	6.5	6.1
2014	6.9	6.9	6.1	–	–	–	–	–	–	–	–	–	–
	5.9	5.2	5.5	5.6	4.9	5.5	6.7	5.7	6.3	6.1	7.9	7.8	6.1

Table 20. Hourly and monthly mean wind speeds at WM02 Calvinia for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	5.6	4.7	5.9	6.2	5.3	6.2	5.9	5.7	4.8	5.8	5.7	6.6	5.7
1	5.6	5.0	5.9	6.0	5.5	6.5	6.1	5.9	4.9	5.9	5.9	6.7	5.8
2	6.0	5.1	5.6	6.3	5.6	6.4	6.3	6.0	4.7	5.8	6.2	6.7	5.9
3	6.1	5.1	5.8	6.4	5.4	6.3	6.3	6.4	4.6	5.5	5.8	6.4	5.8
4	5.8	5.4	5.7	6.3	5.6	6.4	6.3	6.0	5.0	5.7	5.8	6.7	5.9
5	5.5	5.3	5.5	6.7	5.7	6.2	6.3	6.4	5.0	5.7	5.5	6.6	5.9
6	5.5	4.6	5.3	6.5	5.6	6.6	6.5	6.5	5.0	5.7	5.5	5.8	5.8
7	4.9	4.6	5.3	6.7	5.9	6.6	6.4	6.5	5.3	5.2	5.2	5.4	5.7
8	4.7	4.0	5.3	6.5	5.7	6.6	6.5	6.6	5.3	5.4	5.2	5.5	5.7
9	4.9	4.0	5.0	6.1	5.5	6.5	6.5	6.2	5.1	5.6	5.3	5.3	5.5
10	5.0	4.2	4.9	6.0	5.6	6.6	6.1	6.5	5.3	5.6	5.7	5.2	5.6
11	5.1	4.4	5.0	6.2	5.9	6.8	6.3	7.2	5.6	5.6	5.8	5.5	5.8
12	5.3	4.6	5.2	6.1	6.1	6.8	6.6	7.6	5.8	5.9	5.9	5.6	6.0
13	5.6	4.9	5.5	6.2	6.2	7.1	6.6	7.7	5.9	6.1	6.1	6.1	6.2
14	6.2	5.5	5.6	6.2	6.3	6.9	6.6	7.7	6.0	6.5	6.7	6.4	6.4
15	6.9	6.1	6.2	6.0	6.2	6.8	6.5	7.8	6.2	6.7	7.0	7.0	6.6
16	7.3	6.7	6.5	6.2	6.3	6.9	6.2	7.5	6.5	7.2	7.4	7.2	6.8
17	7.5	7.4	6.9	6.5	6.3	6.7	6.4	7.2	6.4	7.5	7.7	7.9	7.0
18	8.2	8.0	6.9	6.7	6.1	6.8	6.1	6.9	6.6	7.9	8.1	8.1	7.1
19	8.4	7.8	7.0	7.2	6.1	6.9	6.5	6.5	6.6	8.0	8.2	8.5	7.2
20	7.7	7.1	6.5	6.7	5.6	6.5	6.3	6.1	6.3	7.5	7.6	8.1	6.8
21	6.4	5.7	6.1	6.3	5.0	6.4	6.1	6.0	5.8	6.8	7.0	7.2	6.2
22	5.8	5.0	5.9	6.3	5.1	6.5	5.8	5.8	5.4	6.6	6.1	6.9	5.9
23	5.8	4.9	5.7	6.1	5.1	6.2	6.0	5.6	5.1	5.7	5.9	6.6	5.7
	6.1	5.4	5.8	6.4	5.7	6.6	6.3	6.6	5.6	6.2	6.3	6.6	6.1

Table 21. Monthly and yearly mean wind speeds at WM02. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	6.8	6.9	6.3	6.0	6.2	7.2	–
2011	6.2	5.5	5.1	6.4	5.9	6.4	6.8	7.2	5.4	5.8	6.3	6.3	6.1
2012	5.9	5.5	5.6	6.5	5.3	6.4	6.1	6.2	5.9	6.9	6.4	5.5	6.0
2013	–	5.1	6.7	6.2	6.1	7.0	6.0	6.3	5.4	6.2	6.6	6.9	6.3
2014	5.8	6.1	5.5	–	–	–	–	–	–	–	–	–	–
	6.0	5.6	5.7	6.4	5.7	6.6	6.4	6.7	5.7	6.2	6.4	6.7	6.2

Table 22. Hourly and monthly mean wind speeds at WM03 Vredendal for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.6	7.4	6.8	7.4	6.1	7.1	7.2	6.9	7.4	7.4	8.0	7.4	7.2
1	6.4	6.4	6.2	7.2	5.8	7.0	6.7	6.6	6.8	6.8	7.3	6.3	6.6
2	5.7	5.7	5.8	7.1	5.9	6.8	6.7	6.8	6.3	6.4	6.8	5.9	6.3
3	5.3	5.2	5.6	7.0	5.8	6.8	6.4	6.7	6.4	6.1	6.4	5.8	6.1
4	5.1	4.9	5.3	6.9	5.6	6.7	6.6	6.9	6.0	5.9	6.3	5.4	6.0
5	4.7	4.9	5.2	7.0	5.5	6.6	6.3	6.8	5.6	5.7	5.9	5.2	5.8
6	4.6	4.8	5.1	6.8	5.7	6.5	6.3	6.6	5.7	5.4	5.7	5.0	5.7
7	4.3	4.6	4.6	6.8	5.8	6.3	6.6	6.7	5.9	5.2	5.5	4.4	5.6
8	3.7	4.2	4.7	6.8	5.9	6.5	6.5	6.5	5.5	5.0	5.2	4.6	5.4
9	3.6	3.8	4.5	6.3	5.6	6.4	6.6	6.1	5.3	4.8	5.2	4.6	5.2
10	4.0	3.7	4.3	6.2	5.0	6.1	5.9	6.0	5.1	5.1	5.2	4.8	5.1
11	4.9	4.1	4.6	6.3	5.2	6.0	5.8	6.7	5.4	5.3	5.5	5.5	5.4
12	6.4	5.2	5.2	6.3	5.6	6.5	6.2	7.1	5.7	6.1	6.6	6.5	6.1
13	7.7	7.1	6.4	6.2	5.7	6.6	6.5	7.5	6.1	7.6	8.2	7.7	6.9
14	9.2	8.5	7.5	6.8	5.6	6.9	6.4	7.9	6.8	8.6	9.3	8.8	7.7
15	10.2	9.6	8.5	7.2	6.1	7.1	6.4	7.9	7.8	9.4	10.5	9.6	8.4
16	11.1	10.4	9.4	7.8	6.7	7.1	6.9	8.1	8.5	10.0	11.3	10.4	9.0
17	11.8	11.1	9.8	8.4	6.8	7.4	7.1	8.2	8.8	10.3	11.7	11.2	9.4
18	11.9	11.2	9.9	8.6	7.2	7.7	7.7	7.9	9.0	10.3	11.7	11.1	9.5
19	11.5	10.9	10.3	8.9	7.5	8.0	8.3	8.1	9.2	10.0	11.2	10.5	9.5
20	11.0	10.4	10.1	8.7	7.2	7.7	8.0	7.9	9.2	9.7	10.7	9.9	9.2
21	10.6	10.2	9.5	8.6	6.9	7.7	7.9	7.7	8.9	9.3	9.9	9.5	8.9
22	9.8	9.3	8.8	8.1	6.6	7.6	7.5	7.5	8.3	8.6	9.5	8.8	8.4
23	8.7	8.2	7.6	7.9	6.3	7.5	7.5	7.0	7.6	8.2	8.9	8.0	7.8
	7.5	7.2	6.9	7.3	6.1	6.9	6.8	7.2	7.0	7.4	8.0	7.4	7.1

Table 23. Monthly and yearly mean wind speeds at WM03. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	6.7	7.2	7.3	7.2	7.6	7.2	–
2011	7.1	6.0	6.5	7.4	6.2	6.8	7.6	7.6	7.2	7.0	8.5	7.8	7.1
2012	7.2	7.8	7.0	7.3	6.0	6.6	6.6	6.9	6.7	7.9	8.0	7.1	7.1
2013	8.2	7.6	7.2	7.2	6.1	7.4	6.4	7.0	7.0	7.6	7.7	7.7	7.3
2014	7.2	7.4	6.9	–	–	–	–	–	–	–	–	–	–
	7.4	7.2	6.9	7.3	6.1	6.9	6.8	7.2	7.0	7.4	8.0	7.5	7.2

Table 24. Hourly and monthly mean wind speeds at WM04 Vredenburg for the 3-year period from June 2010 to May 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.9	7.3	7.0	6.4	5.2	5.5	5.5	5.9	5.8	6.6	7.2	7.2	6.5
1	7.8	7.3	6.7	6.4	5.2	5.6	5.6	5.9	5.8	6.4	7.2	6.8	6.4
2	7.6	7.2	6.4	6.0	5.3	5.7	5.4	5.6	5.5	6.3	7.0	6.5	6.2
3	7.6	7.2	6.5	6.0	4.9	5.3	5.6	5.6	5.4	6.3	6.7	6.5	6.1
4	7.2	6.9	6.1	6.1	4.9	5.1	5.3	5.4	5.3	6.0	6.4	6.3	5.9
5	6.9	6.6	5.9	6.1	4.7	5.2	5.6	5.6	5.3	5.9	6.5	6.1	5.9
6	6.5	6.1	5.7	5.9	4.6	5.4	5.4	5.6	5.0	5.6	6.2	5.6	5.6
7	6.0	5.9	5.4	5.8	4.3	5.3	5.3	5.5	5.0	5.1	5.4	5.3	5.3
8	5.4	5.0	5.0	5.6	4.5	5.2	5.1	5.4	4.7	4.6	5.5	5.6	5.1
9	5.3	5.0	4.8	5.2	4.4	5.2	4.9	5.0	4.7	5.1	5.7	5.7	5.1
10	5.6	5.1	5.3	5.2	4.2	4.8	4.4	5.1	5.2	5.4	5.7	5.8	5.2
11	5.9	5.5	5.5	5.2	4.7	5.1	4.7	5.7	5.5	5.6	6.1	6.4	5.5
12	7.1	6.3	5.8	5.4	5.1	5.6	5.1	6.0	5.8	6.1	7.1	6.8	6.0
13	8.1	7.5	6.9	6.0	5.3	6.0	5.6	6.5	6.4	7.1	8.0	7.6	6.7
14	9.3	8.4	8.0	6.7	5.7	6.3	5.8	6.8	6.8	8.1	9.6	8.9	7.5
15	10.4	9.6	9.1	7.7	5.7	6.3	5.8	6.8	7.3	8.8	10.4	9.7	8.1
16	11.3	10.6	9.7	8.2	6.2	6.3	6.0	7.0	7.9	9.5	10.8	10.5	8.7
17	11.7	11.4	10.1	8.7	6.2	6.0	6.1	6.9	8.3	9.7	11.1	10.8	8.9
18	11.9	11.4	10.3	8.5	6.3	6.1	6.2	6.8	8.4	9.6	10.9	10.8	8.9
19	11.4	10.9	9.6	8.1	6.6	6.1	6.3	6.7	8.3	8.7	10.2	10.1	8.6
20	10.3	9.4	8.6	7.5	6.2	6.4	6.4	6.5	8.0	8.2	8.9	9.1	8.0
21	9.3	8.5	7.9	7.1	5.9	6.2	6.3	6.3	7.4	7.7	7.9	8.0	7.4
22	8.8	7.7	7.0	6.9	5.5	6.0	5.9	6.2	6.8	7.2	7.3	7.6	6.9
23	8.4	7.4	6.8	6.5	5.5	5.9	5.3	5.8	6.4	6.7	7.3	7.2	6.6
	8.2	7.7	7.1	6.5	5.3	5.7	5.6	6.0	6.3	6.9	7.7	7.5	6.7

Table 25. Monthly and yearly mean wind speeds at WM04. Only the 3-year period from June 2010 to May 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	5.2	5.4	5.8	6.8	6.8	7.2	7.3	6.4
2011	8.1	6.9	6.5	6.6	5.4	6.1	5.6	6.1	6.5	6.3	8.1	8.1	6.7
2012	7.6	7.9	7.5	6.9	5.1	5.7	5.7	6.2	5.7	7.7	7.9	7.2	6.8
2013	9.1	8.2	7.2	6.2	5.3	–	–	–	–	–	–	–	–
2014	–	–	–	–	–	–	–	–	–	–	–	–	–
	8.2	7.7	7.1	6.5	5.3	5.7	5.6	6.0	6.3	6.9	7.7	7.5	6.7

Table 26. Hourly and monthly mean wind speeds at WM05 Napier for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	8.3	7.6	7.9	7.9	7.0	8.4	7.8	8.3	8.7	8.4	7.8	9.0	8.1
1	8.2	7.6	7.8	7.9	7.2	8.4	7.8	7.9	8.7	8.2	7.8	8.8	8.0
2	7.9	7.5	7.6	8.1	7.0	8.7	7.9	7.6	8.6	8.1	7.7	9.0	8.0
3	7.9	7.6	7.6	8.3	7.3	8.5	8.0	7.7	8.7	8.3	8.0	9.1	8.1
4	8.1	7.5	7.6	8.3	7.5	8.5	7.8	7.5	8.6	8.6	8.1	9.0	8.1
5	8.1	7.6	7.5	8.3	7.6	8.5	7.7	8.0	8.6	8.4	8.0	9.0	8.1
6	7.9	7.8	7.5	8.4	7.7	8.6	7.7	8.2	8.7	8.6	8.0	9.0	8.2
7	7.7	7.3	7.7	8.3	7.6	8.7	7.6	8.2	8.4	8.3	7.7	8.8	8.0
8	7.8	7.0	7.5	8.4	7.1	8.1	7.7	8.4	8.1	8.3	8.0	9.2	8.0
9	8.2	7.3	7.9	8.0	6.8	8.1	7.6	8.2	8.1	8.8	8.1	9.4	8.0
10	8.6	7.6	8.1	8.4	6.7	8.0	7.3	8.3	9.0	9.1	8.5	9.8	8.3
11	9.0	7.8	8.5	8.5	7.2	8.2	7.5	8.6	9.1	9.4	8.8	10.2	8.6
12	9.5	8.4	8.7	8.7	7.3	8.6	7.7	9.0	9.4	9.7	9.0	10.3	8.9
13	9.9	8.9	8.8	8.9	7.3	8.9	8.3	9.2	9.5	10.1	9.5	10.8	9.2
14	10.0	9.2	9.5	9.2	7.6	8.7	8.4	9.6	10.0	10.7	10.0	11.3	9.5
15	10.5	9.7	9.6	9.6	7.7	9.0	8.3	9.3	10.2	10.8	10.4	11.5	9.7
16	10.6	9.7	10.0	9.5	7.6	8.9	8.1	9.5	10.2	11.0	10.6	11.7	9.8
17	10.6	9.7	10.0	9.6	7.3	8.5	7.9	9.3	10.1	10.8	10.6	11.5	9.7
18	10.3	9.5	9.7	9.2	7.4	8.7	7.6	8.8	9.5	10.5	10.1	11.1	9.4
19	9.9	8.9	9.0	8.6	7.2	8.5	7.8	8.5	9.1	9.7	9.3	10.5	8.9
20	9.2	8.4	8.5	8.2	6.8	8.2	7.8	8.2	9.0	9.1	8.8	9.9	8.5
21	8.9	7.9	8.3	8.1	6.9	8.1	7.7	8.2	8.5	8.8	8.2	9.4	8.3
22	8.4	7.8	8.1	7.9	6.8	7.9	7.8	7.9	8.4	8.6	8.0	9.3	8.1
23	8.6	7.8	7.8	8.1	6.7	8.0	7.8	8.3	8.7	8.6	8.1	9.1	8.1
	8.9	8.2	8.4	8.5	7.2	8.5	7.8	8.4	9.0	9.2	8.7	9.9	8.6

Table 27. Monthly and yearly mean wind speeds at WM05. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	7.9	7.2	8.9	8.5	9.0	9.0	11.2	–
2011	9.3	8.3	7.8	9.4	7.5	8.1	7.0	7.8	8.8	9.6	8.5	8.5	8.4
2012	8.8	8.0	8.1	8.6	7.1	8.3	8.1	8.7	9.0	9.0	8.7	9.9	8.5
2013	8.7	8.2	9.3	7.6	7.0	8.7	8.4	8.9	9.2	8.3	9.3	9.6	8.6
2014	7.3	8.4	7.4	–	–	–	–	–	–	–	–	–	–
	8.5	8.2	8.1	8.5	7.2	8.3	7.7	8.6	8.9	9.0	8.8	9.8	8.5

Table 28. Hourly and monthly mean wind speeds at WM06 Sutherland for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.1	6.2	6.4	7.1	7.7	9.0	7.6	8.4	7.8	7.0	7.1	7.0	7.4
1	6.9	5.9	6.5	7.2	7.6	8.8	7.4	8.6	7.9	7.3	6.8	7.0	7.3
2	6.7	6.0	6.6	7.3	7.5	8.9	7.3	8.5	7.5	7.3	7.0	6.8	7.3
3	6.6	6.0	6.4	7.4	7.6	9.1	7.1	8.3	7.5	7.5	6.9	6.9	7.3
4	6.1	6.1	6.2	7.5	7.7	8.9	7.1	7.9	7.3	7.2	7.0	6.8	7.1
5	6.2	6.0	6.3	7.3	7.5	8.9	7.0	8.3	7.3	7.1	6.7	6.5	7.1
6	6.1	5.8	6.2	7.0	7.3	8.5	7.1	8.4	7.1	7.2	6.6	6.4	7.0
7	5.4	5.6	5.9	7.4	7.4	8.4	7.2	8.4	7.2	6.7	6.2	6.0	6.8
8	5.3	5.1	5.4	7.1	7.2	8.6	7.3	8.4	6.8	6.1	6.2	5.9	6.6
9	5.7	5.6	5.4	6.8	6.8	8.3	7.1	8.0	7.0	6.7	6.2	5.8	6.6
10	5.6	5.5	6.0	7.3	7.2	8.1	7.3	8.5	7.5	6.7	6.5	5.9	6.8
11	5.6	5.8	5.9	7.4	7.7	8.7	7.6	9.2	7.6	7.0	6.8	5.9	7.1
12	5.5	6.1	6.2	7.3	7.8	9.0	8.1	9.5	7.7	7.0	7.2	6.4	7.3
13	5.9	6.4	6.6	7.5	7.8	9.0	8.0	9.6	7.6	7.2	7.6	6.7	7.5
14	6.7	6.7	6.7	7.6	8.0	8.9	7.8	9.5	7.8	7.8	7.8	7.0	7.7
15	6.9	7.0	7.0	7.5	7.8	8.8	7.6	9.3	7.9	8.3	8.3	7.5	7.8
16	7.4	7.5	7.1	7.3	7.6	8.7	7.6	9.1	8.1	8.1	8.4	7.7	7.9
17	7.6	7.6	7.5	7.2	7.2	8.4	7.1	8.7	8.0	8.1	8.9	7.9	7.8
18	8.0	8.0	7.6	7.2	6.8	8.6	6.8	8.5	7.8	8.3	8.9	8.2	7.9
19	8.6	8.0	7.5	7.6	7.1	8.6	6.7	8.3	7.6	8.3	8.9	8.4	8.0
20	8.9	7.8	6.9	7.2	7.1	8.9	7.2	8.4	7.4	8.0	8.4	8.2	7.9
21	8.3	7.1	6.6	7.0	7.1	8.8	7.5	8.5	7.3	7.4	7.7	7.4	7.6
22	7.8	6.5	6.4	7.1	7.2	8.9	7.4	8.6	7.4	7.2	7.3	7.1	7.4
23	7.4	6.3	6.3	7.2	7.1	9.1	7.6	8.8	7.4	7.0	7.3	7.1	7.4
	6.8	6.4	6.5	7.3	7.4	8.7	7.3	8.7	7.5	7.3	7.4	6.9	7.4

Table 29. Monthly and yearly mean wind speeds at WM06. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	–	–	–	7.3	7.4	7.2	–
2011	6.6	6.3	6.0	7.0	6.9	8.5	6.5	8.5	6.8	7.5	7.3	6.9	7.1
2012	6.6	6.4	6.2	7.5	7.1	7.9	7.6	8.5	7.6	7.3	7.3	6.7	7.2
2013	7.1	6.6	7.2	7.3	8.1	9.8	7.9	9.0	8.1	6.9	7.3	7.2	7.7
2014	6.4	6.4	6.8	–	–	–	–	–	–	–	–	–	–
	6.7	6.4	6.6	7.3	7.4	8.7	7.3	8.7	7.5	7.2	7.3	7.0	7.3

Table 30. Hourly and monthly mean wind speeds at WM07 Beaufort West for the 3-year period from October 2010 to September 2013.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	9.0	8.4	8.1	7.7	7.3	7.4	7.3	7.4	7.7	8.3	8.3	8.5	7.9
1	8.4	8.1	7.5	7.5	7.3	7.3	7.1	7.3	7.5	8.0	7.9	8.1	7.7
2	7.9	7.8	7.2	7.5	7.0	7.4	7.2	7.3	7.1	7.5	7.6	7.5	7.4
3	7.1	7.4	6.7	7.1	6.8	7.5	7.4	7.2	7.0	7.0	7.7	7.3	7.2
4	6.9	7.0	6.5	6.6	6.5	7.3	6.8	7.3	7.1	6.9	7.2	7.0	6.9
5	6.5	6.7	6.1	6.8	6.4	7.0	6.7	7.1	7.2	6.5	7.0	6.8	6.7
6	6.1	6.6	6.1	6.7	6.1	6.8	6.3	7.0	7.0	6.5	6.5	6.5	6.5
7	5.7	5.9	5.8	6.5	5.9	6.8	6.4	6.8	6.7	6.3	6.2	6.2	6.3
8	5.4	5.5	5.0	6.6	5.9	6.8	6.3	6.3	6.2	6.1	5.9	6.3	6.0
9	5.1	5.3	4.8	6.0	5.5	6.7	5.5	6.3	6.4	5.9	5.7	6.0	5.8
10	4.8	4.8	4.7	6.2	5.7	6.2	5.6	6.7	6.4	5.9	5.7	5.8	5.7
11	4.7	4.7	4.8	6.2	5.9	6.7	6.0	7.0	6.4	6.2	5.7	5.8	5.8
12	5.0	4.7	5.0	5.9	6.2	6.9	6.3	7.3	7.0	6.4	6.0	5.8	6.1
13	5.5	5.2	5.1	6.2	6.3	7.1	6.4	7.6	7.3	6.6	6.5	5.7	6.3
14	5.7	5.5	5.3	6.2	6.2	7.0	6.5	7.6	7.5	6.7	6.6	5.9	6.4
15	5.9	5.8	5.4	6.5	6.2	7.0	6.4	7.6	7.5	6.8	7.1	6.1	6.5
16	6.7	6.3	5.6	6.5	6.0	7.0	6.4	7.4	7.5	7.3	7.7	6.8	6.8
17	7.0	6.7	6.0	6.5	5.8	6.2	6.3	7.3	7.6	7.7	8.3	7.6	6.9
18	7.9	6.8	6.8	6.7	5.4	6.1	6.2	7.0	7.7	8.2	8.8	8.2	7.2
19	9.0	7.9	7.2	7.0	6.1	6.7	6.3	7.1	8.0	8.7	9.4	9.1	7.7
20	9.6	8.5	7.4	7.2	6.6	7.1	6.6	7.6	7.7	9.0	9.3	9.6	8.0
21	9.7	8.4	7.7	7.5	7.2	7.1	7.0	7.5	7.8	9.2	8.8	9.6	8.1
22	9.6	8.7	7.8	7.9	7.4	7.7	7.0	7.4	7.9	9.0	8.8	9.5	8.2
23	9.2	8.6	8.2	8.1	7.4	7.4	7.1	7.3	7.9	8.4	8.7	9.0	8.1
	7.0	6.7	6.3	6.8	6.4	7.0	6.5	7.2	7.3	7.3	7.4	7.3	6.9

Table 31. Monthly and yearly mean wind speeds at WM07. Only the 3-year period from October 2010 to September 2013 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	6.9	7.0	7.8	7.1	7.6	7.5	7.6	–
2011	7.2	6.4	6.0	6.8	6.5	7.0	5.8	6.7	6.9	7.2	7.4	7.3	6.8
2012	6.6	7.0	6.2	6.8	6.2	6.6	6.7	7.4	7.3	7.1	7.2	7.0	6.8
2013	7.3	6.7	6.6	6.3	6.4	7.3	7.1	7.5	7.5	7.2	7.5	7.2	7.1
2014	6.7	6.4	6.6	–	–	–	–	–	–	–	–	–	–
	6.9	6.7	6.4	6.8	6.4	7.0	6.7	7.3	7.2	7.3	7.4	7.3	7.0

Table 32. Hourly and monthly mean wind speeds at WM08 Humansdorp for the 2-year period from October 2010 to September 2012.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	5.6	5.9	5.9	6.9	6.4	7.5	7.0	7.0	7.7	6.6	6.0	6.0	6.5
1	5.9	5.8	5.8	6.6	6.6	7.7	6.9	7.2	8.1	6.6	6.3	6.0	6.6
2	5.7	6.2	5.8	6.6	6.3	7.9	7.1	7.2	8.2	6.4	6.2	6.1	6.6
3	5.5	5.8	6.0	6.5	6.6	7.9	7.1	6.8	8.2	6.7	6.4	6.4	6.6
4	5.5	5.6	5.8	6.6	6.7	7.5	7.1	6.7	8.3	6.2	6.5	6.4	6.6
5	5.4	5.3	5.9	6.5	6.3	8.2	7.3	6.8	8.3	6.5	6.3	6.3	6.6
6	5.3	5.3	5.8	6.7	6.4	8.2	7.5	6.8	8.0	6.3	6.4	5.9	6.6
7	5.2	5.7	5.5	6.9	6.5	7.9	7.5	6.8	8.1	6.2	5.9	6.1	6.5
8	5.5	6.0	5.7	6.7	6.7	7.9	7.6	6.8	8.2	6.7	6.8	7.2	6.8
9	6.2	6.6	6.2	6.8	6.6	7.7	7.7	6.6	8.5	7.6	7.6	7.8	7.2
10	6.8	7.5	6.6	7.2	6.8	7.5	7.8	7.4	8.8	8.1	8.3	8.1	7.6
11	7.6	7.9	7.5	7.6	7.2	8.4	7.9	7.4	9.0	8.8	9.0	8.2	8.0
12	8.1	8.3	8.1	8.2	7.5	8.5	8.1	7.7	9.3	9.1	9.5	8.5	8.4
13	8.6	8.6	8.4	8.5	7.7	8.7	8.3	7.8	9.2	9.5	9.5	8.8	8.6
14	9.1	8.8	9.0	8.7	7.7	8.6	8.2	8.3	9.6	9.4	9.4	8.9	8.8
15	9.4	8.6	8.9	8.6	7.5	8.5	8.1	8.0	9.4	9.5	9.2	8.7	8.7
16	9.1	8.5	8.8	8.7	7.4	8.3	8.0	8.1	9.3	9.3	9.2	9.2	8.6
17	9.0	8.2	8.4	8.5	6.9	7.8	7.5	7.6	8.7	8.9	8.7	8.8	8.3
18	8.3	7.9	8.0	7.8	6.6	7.5	7.1	7.0	8.3	8.3	8.2	8.5	7.8
19	7.4	7.1	7.3	7.9	6.6	7.5	6.7	6.9	8.0	7.8	7.1	7.8	7.3
20	6.9	6.8	6.7	7.9	6.4	7.6	6.6	7.0	7.9	7.7	7.1	7.3	7.2
21	6.4	6.2	6.6	7.7	6.1	7.2	6.8	7.1	7.6	7.5	6.5	6.6	6.9
22	6.1	6.2	6.1	7.4	6.5	7.5	7.0	6.7	7.8	7.1	6.2	6.4	6.8
23	5.9	6.0	6.1	7.3	6.3	7.6	6.9	6.7	7.6	6.8	6.2	6.3	6.6
	6.9	6.9	6.9	7.5	6.8	7.9	7.4	7.2	8.4	7.7	7.4	7.3	7.3

Table 33. Monthly and yearly mean wind speeds at WM08. Only the 2-year period from October 2010 to September 2012 has been used to generate the observed wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	–	–	7.8	7.3	7.7	7.6	–
2011	7.5	6.4	6.7	7.8	6.9	7.9	6.9	6.9	8.5	8.0	7.2	7.1	7.3
2012	6.2	7.3	7.0	7.1	6.6	7.9	7.9	7.5	8.4	7.5	7.4	6.9	7.3
2013	–	–	–	–	6.1	7.7	7.5	8.1	8.3	7.1	8.0	7.3	–
2014	6.6	6.7	6.7	–	–	–	–	–	–	–	–	–	–
	6.8	6.8	6.8	7.5	6.6	7.8	7.4	7a.5	8.2	7.5	7.6	7.3	7.3

Table 34. Hourly and monthly mean wind speeds at WM09 Noupoort for the 2-year period from 2010-10 to 2010-12 + 2012-01 to 2013-09.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	7.8	6.6	7.2	7.2	7.6	10.2	7.7	9.3	7.8	8.0	8.1	7.2	7.9
1	7.4	6.9	7.4	7.2	7.9	10.0	8.0	9.4	8.2	7.6	7.8	7.2	7.9
2	7.0	6.5	7.4	7.0	7.8	9.9	8.5	9.5	8.1	7.6	7.7	6.9	7.8
3	6.7	6.3	7.0	7.1	7.9	9.9	8.7	9.3	8.1	7.6	7.6	6.7	7.8
4	6.5	6.1	6.7	7.4	7.8	10.0	8.5	9.2	8.1	7.6	7.7	6.3	7.7
5	6.9	6.0	6.4	7.5	7.7	9.5	8.5	9.5	8.5	7.2	7.7	6.1	7.6
6	7.0	6.2	6.5	7.6	8.1	9.4	8.5	9.2	8.3	7.3	7.8	6.2	7.7
7	6.5	6.3	6.7	7.4	8.3	9.5	8.7	9.4	8.6	7.4	7.4	6.3	7.7
8	6.4	5.9	6.5	7.3	7.9	9.9	8.8	9.0	8.0	7.3	7.7	6.4	7.6
9	6.5	6.2	6.5	7.1	7.7	9.6	8.6	8.9	8.3	7.5	7.7	6.6	7.6
10	6.6	6.5	7.1	7.7	7.8	9.5	9.0	9.4	8.9	7.8	8.4	6.8	8.0
11	6.5	7.0	7.2	8.0	8.1	9.6	8.9	10.2	9.4	8.4	8.7	7.4	8.3
12	6.5	7.5	7.1	8.2	8.6	10.0	9.4	10.8	9.7	8.6	9.2	7.7	8.6
13	6.9	7.8	7.2	8.6	9.1	10.4	9.8	11.4	9.7	8.7	9.4	8.0	8.9
14	7.0	7.8	7.1	8.4	9.1	10.3	9.7	11.7	10.2	8.9	9.3	8.3	9.0
15	7.2	7.3	7.2	8.4	9.2	10.1	9.5	11.6	10.1	9.2	9.7	8.5	9.0
16	7.6	7.8	7.6	8.4	9.0	10.1	8.9	11.4	9.7	9.1	9.5	8.5	9.0
17	8.1	7.7	7.5	8.2	8.4	9.6	8.7	10.7	9.7	9.1	9.2	8.7	8.8
18	8.2	7.8	7.4	8.0	8.0	9.6	8.4	9.9	9.0	9.6	9.2	8.5	8.6
19	8.6	7.8	7.9	7.7	7.5	9.3	8.3	9.5	8.9	9.6	9.5	8.5	8.6
20	8.7	7.5	8.0	7.5	7.7	9.5	8.3	9.7	8.5	9.6	9.0	8.7	8.6
21	8.3	8.0	8.5	7.6	7.8	9.3	8.0	9.5	8.3	8.7	8.8	8.8	8.5
22	8.4	7.7	7.6	7.5	7.7	9.6	7.8	9.4	8.2	8.7	8.5	8.0	8.3
23	7.9	7.2	7.5	7.1	7.8	9.5	7.5	9.3	8.1	8.2	8.2	7.7	8.0
	7.3	7.0	7.2	7.7	8.1	9.8	8.6	9.9	8.8	8.3	8.5	7.5	8.2

Table 35. Monthly and yearly mean wind speeds at WM09. Only a 2-year period from 2010-10 to 2010-12 + 2012-01 to 2013-09 has been used to generate the wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	–	–	8.5	8.1	8.9	8.2	–
2011	6.9	6.1	6.6	7.2	8.4	9.0	5.9	–	–	–	–	–	–
2012	6.7	6.6	7.2	7.4	7.6	9.0	8.9	10.3	8.5	8.5	8.0	6.8	8.0
2013	7.9	7.4	7.3	7.9	8.6	10.5	8.4	9.5	9.0	7.9	8.2	7.2	8.3
2014	7.6	6.7	7.5	–	–	–	–	–	–	–	–	–	–
	7.3	6.7	7.1	7.5	8.2	9.5	7.8	9.9	8.7	8.2	8.4	7.4	7.9

Table 36. Hourly and monthly mean wind speeds at and WM10 Butterworth for the 2-year period from 2011-03 to 2012-02 + 2012-10 to 2013-09.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
0	5.2	5.5	5.2	5.8	6.0	7.9	6.1	7.2	5.8	5.7	5.5	6.6	6.1
1	5.3	5.6	5.3	5.8	6.3	7.8	5.6	7.0	6.0	5.6	5.7	6.2	6.0
2	5.1	5.6	5.1	5.9	6.1	7.8	5.5	7.4	5.9	5.3	5.7	6.0	6.0
3	4.7	5.2	5.3	5.7	6.0	8.2	5.4	7.0	6.1	5.3	5.3	5.7	5.8
4	4.9	4.7	4.7	5.7	6.5	7.9	5.8	6.8	6.1	5.2	5.6	5.8	5.8
5	4.7	5.0	5.0	5.6	6.4	7.6	6.1	6.6	5.4	5.4	5.8	5.6	5.8
6	4.7	4.7	4.7	5.7	6.4	7.4	6.1	6.6	5.5	5.0	5.4	5.2	5.6
7	4.7	4.7	5.1	5.8	6.5	7.7	6.4	6.9	6.0	5.3	5.5	5.1	5.8
8	5.0	4.7	5.1	5.8	6.7	8.0	5.9	6.5	6.4	5.8	5.9	5.2	5.9
9	5.3	5.0	5.6	6.1	6.6	8.2	5.7	7.5	6.5	6.0	6.2	5.5	6.2
10	5.5	5.2	5.8	6.1	6.8	8.7	6.2	7.7	7.1	5.8	6.4	5.8	6.4
11	5.4	5.3	5.6	7.0	7.4	9.3	6.9	7.8	7.2	6.3	6.6	5.6	6.7
12	5.7	5.7	5.6	7.0	7.8	9.3	7.4	8.3	7.2	6.4	6.5	6.0	6.9
13	6.1	5.8	6.2	7.2	7.8	9.1	7.4	8.2	7.4	6.9	6.8	6.4	7.1
14	6.8	6.2	6.5	7.2	7.6	9.4	7.3	8.2	7.7	7.5	7.6	7.0	7.4
15	7.5	6.8	6.8	7.4	7.3	9.1	7.2	8.3	8.3	8.2	8.2	7.6	7.7
16	7.7	7.8	7.5	7.3	7.2	8.1	6.8	8.1	8.5	8.6	8.6	8.4	7.9
17	8.0	7.9	7.9	7.1	6.9	7.8	6.8	8.3	8.6	8.1	8.5	8.1	7.8
18	8.1	7.9	7.3	6.9	6.7	7.4	6.6	8.1	8.3	8.1	7.8	8.3	7.6
19	7.3	7.5	7.4	6.6	6.4	7.7	6.6	7.9	7.6	7.7	7.3	7.7	7.3
20	7.1	7.1	6.3	6.1	6.2	7.3	6.0	6.8	6.3	7.2	6.7	7.2	6.7
21	6.4	6.8	5.9	5.4	6.2	7.2	5.7	6.5	5.6	6.6	6.1	7.1	6.3
22	6.3	6.2	5.9	5.2	6.2	7.2	5.6	6.7	5.5	6.1	5.7	6.8	6.1
23	5.9	5.7	5.8	5.4	6.4	7.7	5.7	7.0	5.7	5.9	5.5	6.7	6.1
	6.0	5.9	5.9	6.2	6.7	8.1	6.3	7.4	6.7	6.4	6.5	6.5	6.6

Table 37. Monthly and yearly mean wind speeds at WM10. Only the 2-year period from 2011-03 to 2012-02 + 2012-10 to 2013-09 has been used to generate the wind climate.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2010	–	–	–	–	–	–	–	8.3	7.5	7.2	7.1	6.6	–
2011	6.8	5.4	5.3	6.1	6.6	8.2	5.7	6.7	6.4	6.1	6.8	6.9	6.4
2012	5.8	5.6	–	–	–	–	7.8	8.0	7.2	6.7	6.1	6.1	–
2013	6.2	6.3	6.3	6.4	6.7	8.0	6.9	8.1	7.0	6.6	7.0	6.0	6.8
2014	6.3	5.8	5.5	–	–	–	–	–	–	–	–	–	–
	6.2	5.8	5.7	6.2	6.7	8.1	6.7	7.8	7.0	6.7	6.7	6.4	6.7

B Topographical data for flow modelling

Which elevation and land cover data sets to use for flow modelling in South Africa? This is a fundamental question for both the mesoscale and microscale modelling. Many different types of data exist and this appendix explores several data sets and contains some observations and recommendations regarding their characteristics and use for microscale modelling.

Elevation data sets

Several elevation data sets have been identified, investigated and compared:

- Stellenbosch University Digital Elevation Model (SUDEM 25 m).
    - Commercial data set; considered the reference data set here.
- National Geo-spatial Information 25-m DEM (NGI ORT files).
    - Note…
- Digital 20-m height contours from NGI 1:50,000 SA topographical maps.
    - This data set was used for the first detailed wind resource mapping.
- Shuttle Radar Topography Mission, SRTM version 2.1.
    - This data set used for microscale modelling of the 10 masts in this report.
- Shuttle Radar Topography Mission, SRTM+, version 3 (void filled).
    - Data set used for second (final) detailed wind resource mapping.
- Shuttle Radar Topography Mission, SRTM CGIAR CSI 4 (void filled)
    - Data set based on SRTM 2.1, but void filled. Not used in present project.
- ASTER Global Digital Elevation Map, GDEM V2
    - A high-resolution global data set; not used in present project

Methodology

The purpose of the present analysis is to show simple differences between the different data sets. The tools used are Surfer 12 for gridding and contouring and WAsP Projection Transformer 11 for coordinate conversions. The initial analyses consist of:

- Constructing 25-m elevation grids for all data sets for the same area(s)
- Subtracting SUDEM elevations from all [test data set] elevations
- Making WAsP vector contour maps for all data sets using Surfer 12
- Plotting maps and comparing results:
    - [test data set] vector map and SUDEM vector map
    - Difference between data sets as colour plots overlaid SUDEM vector map
    - Histograms of data set differences

Results

The results are shown below in two maps for each data set: The first (upper) map shows a 10-m height contour map prepared from the data set in question. The contours are based on a 25-m grid; re-gridded from the original data set using Surfer (kriging).

The second (lower) map shows a 10-m height contour map based on the SUDEM data set, overlaid with a colour map showing the elevation differences between the data set in question and the SUDEM data set (plotted as: $z_{test} - z_{SUDEM}$). Colour scale ranges from −20 to +20 metres.

Histograms of elevation data set differences follow after the maps.

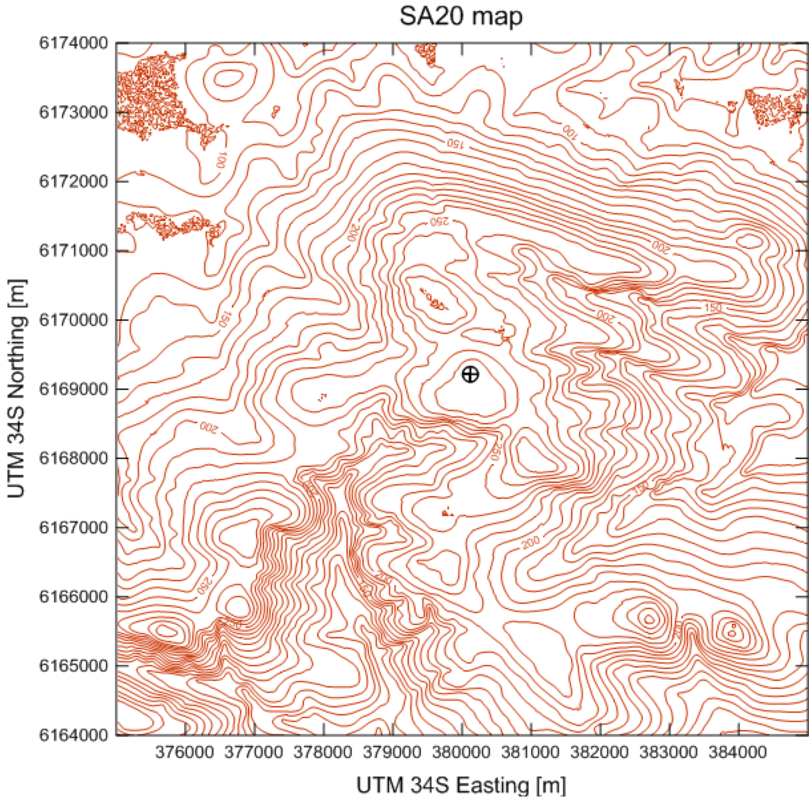

Figure 38. Height contour map of WM05 site based on digital 20-m height contours from 1:50,000 SA topographical maps.

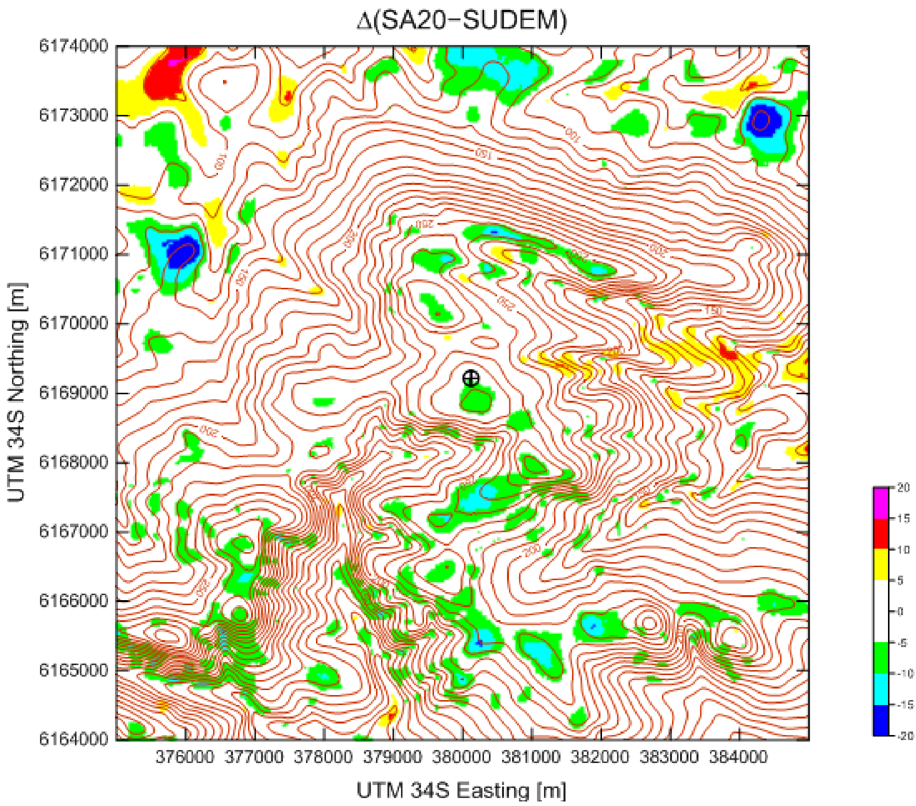

Figure 39. Elevation difference between map shown above and SUDEM reference map.

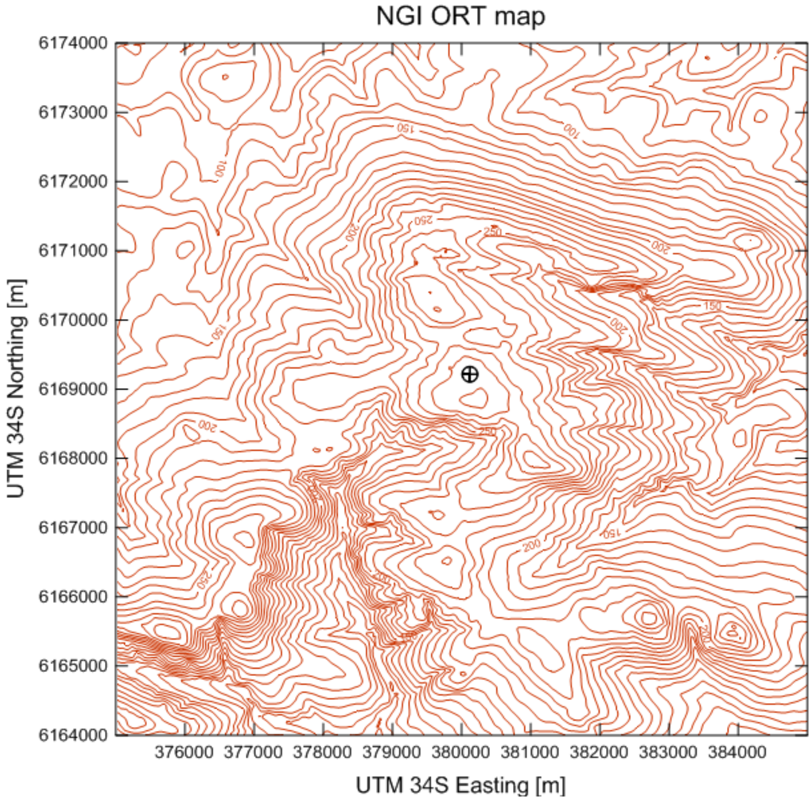

Figure 40. Height contour map of WM05 site based on the National Geo–spatial Information (NGI) ORT files.

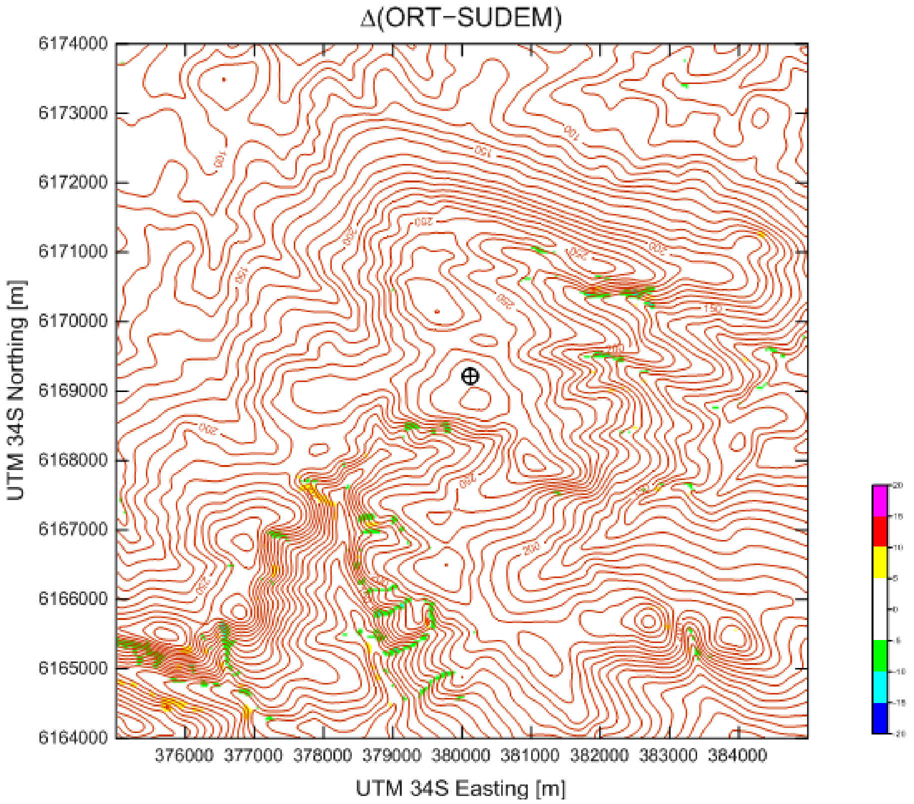

Figure 41. Elevation difference between map shown above and SUDEM reference map.

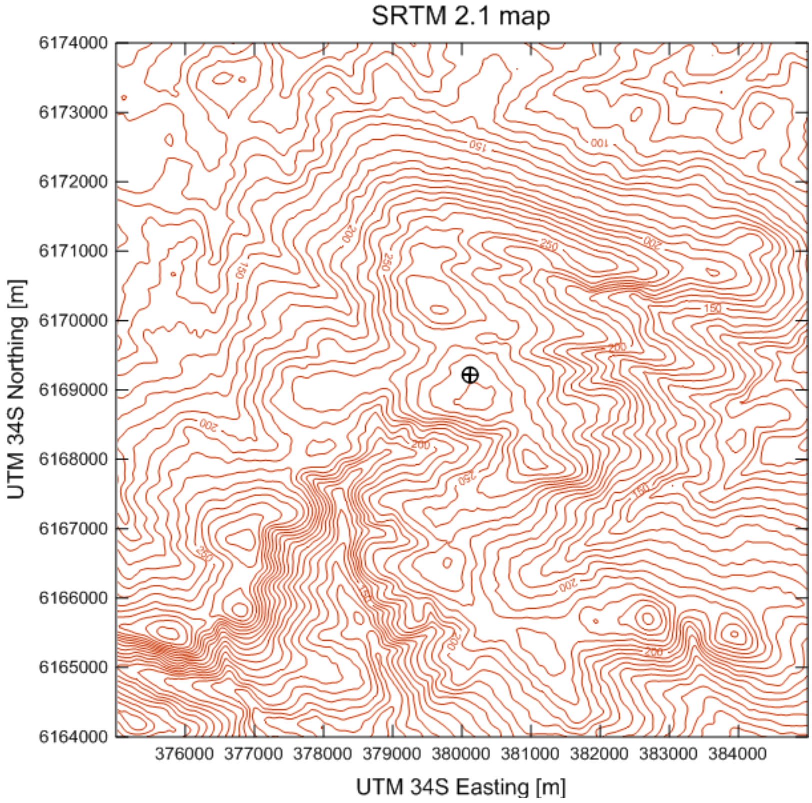

Figure 42. Height contour map of WM05 site based on SRTM data, version 2.1. The data files were downloaded from dds.cr.usgs.gov/srtm/version2_1.

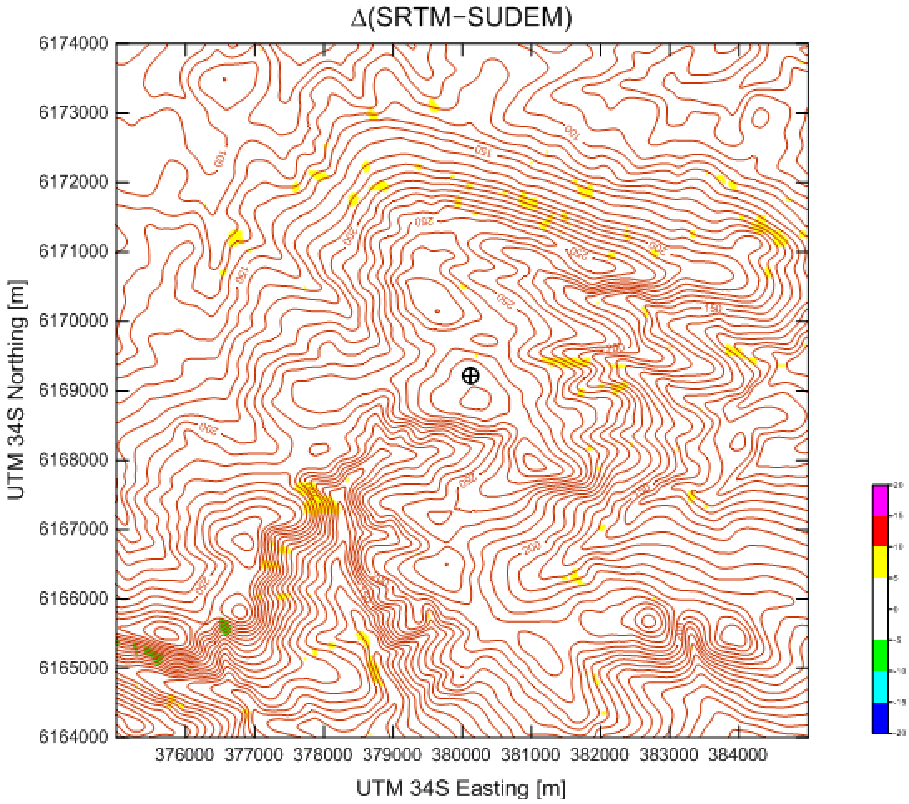

Figure 43. Elevation difference between map shown above and SUDEM reference map.

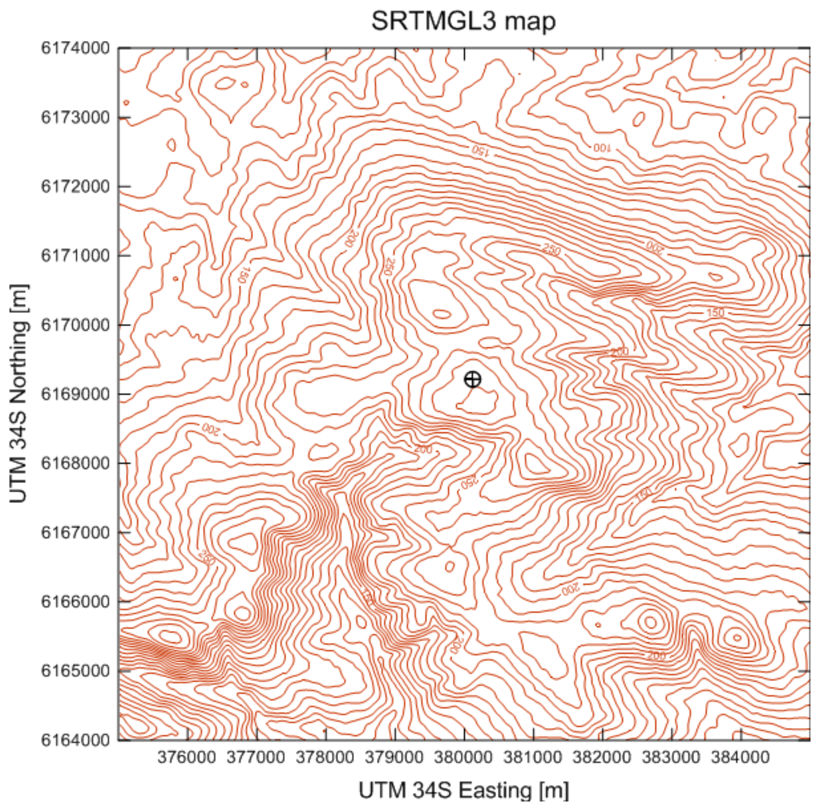

Figure 44. Height contour map of WM05 site based on SRTM data, version 3.0. The data files were downloaded from e4ftl01.cr.usgs.gov/SRTM/SRTMGL3.003/2000.02.11

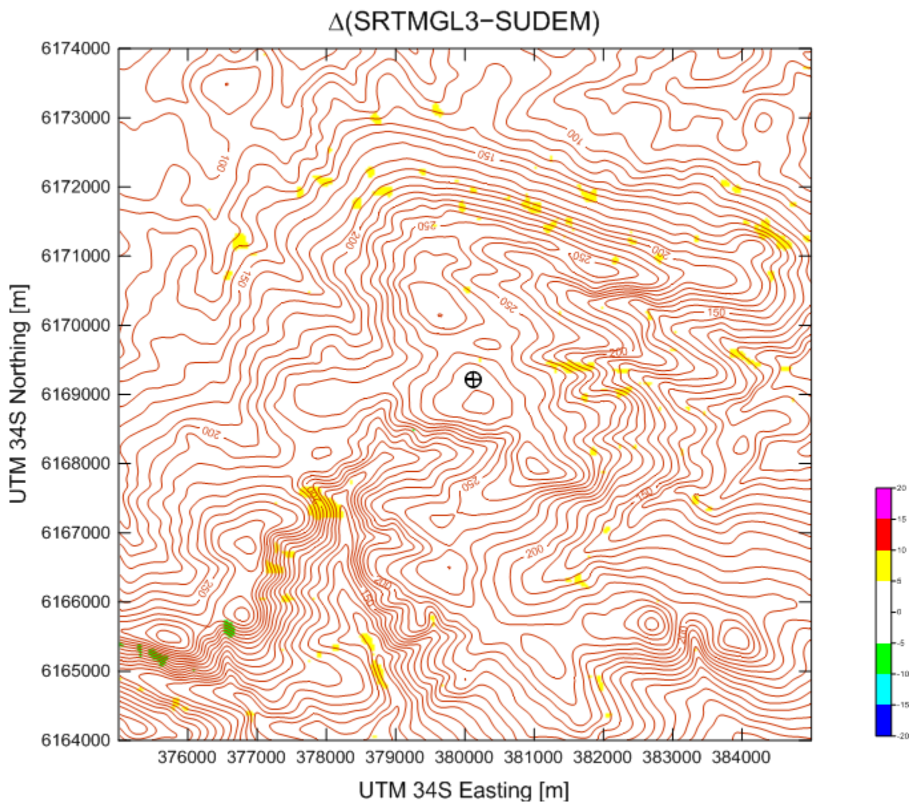

Figure 45. Elevation difference between map shown above and SUDEM reference map.

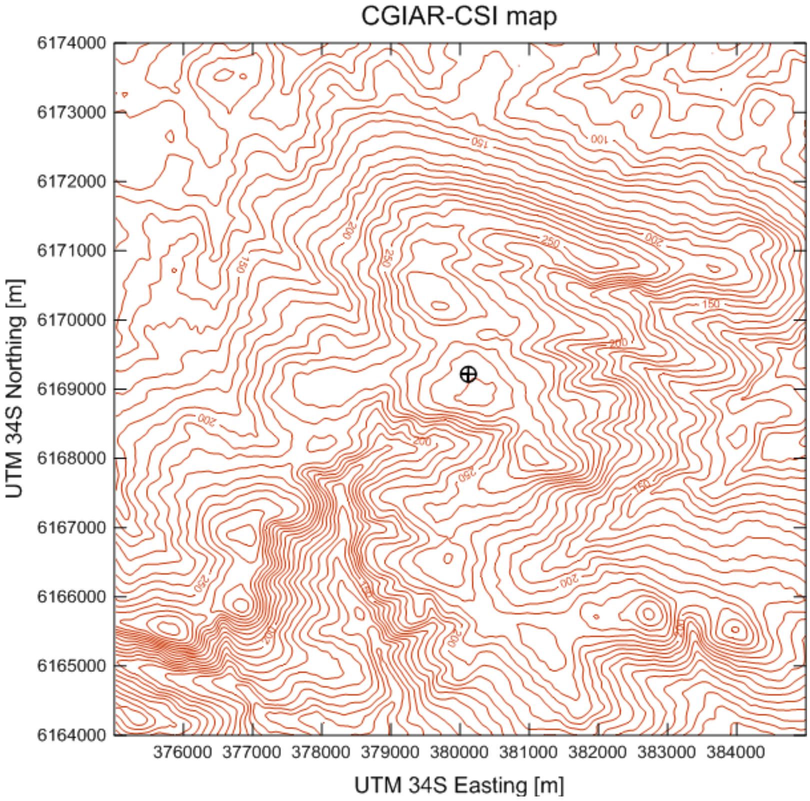

Figure 46. Height contour map of WM05 site based on SRTM data, CGIAR-CSI version. The data files were downloaded from srtm.csi.cgiar.org.

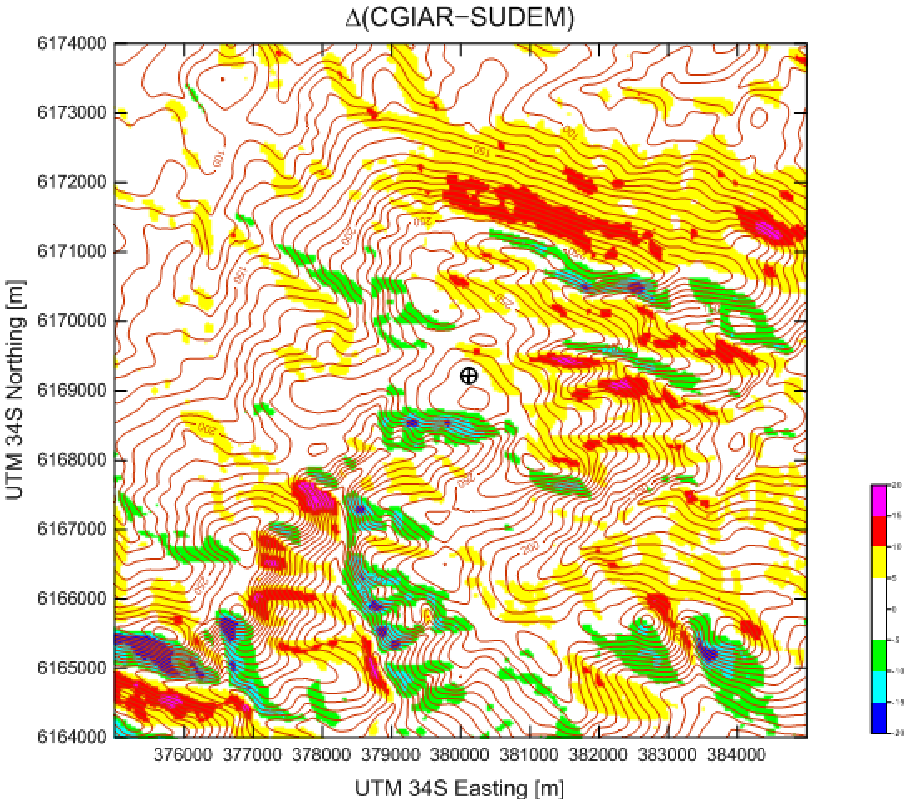

Figure 47. Elevation difference between map shown above and SUDEM reference map.

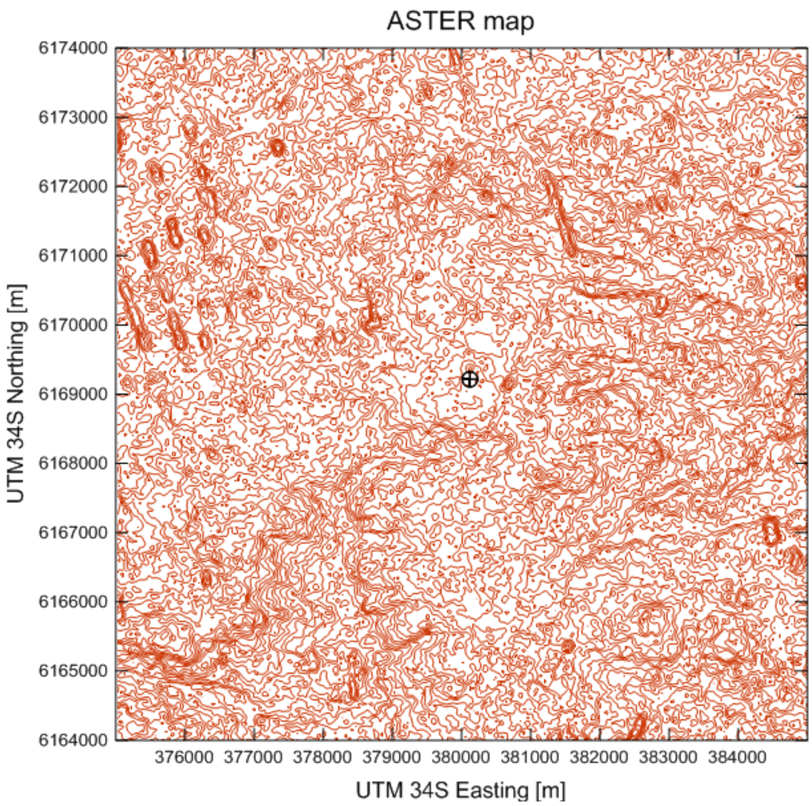

Figure 48. Height contour map of WM05 site based on SRTM data, CGIAR-CSI version. The data files can be downloaded from gdex.cr.usgs.gov/gdex.

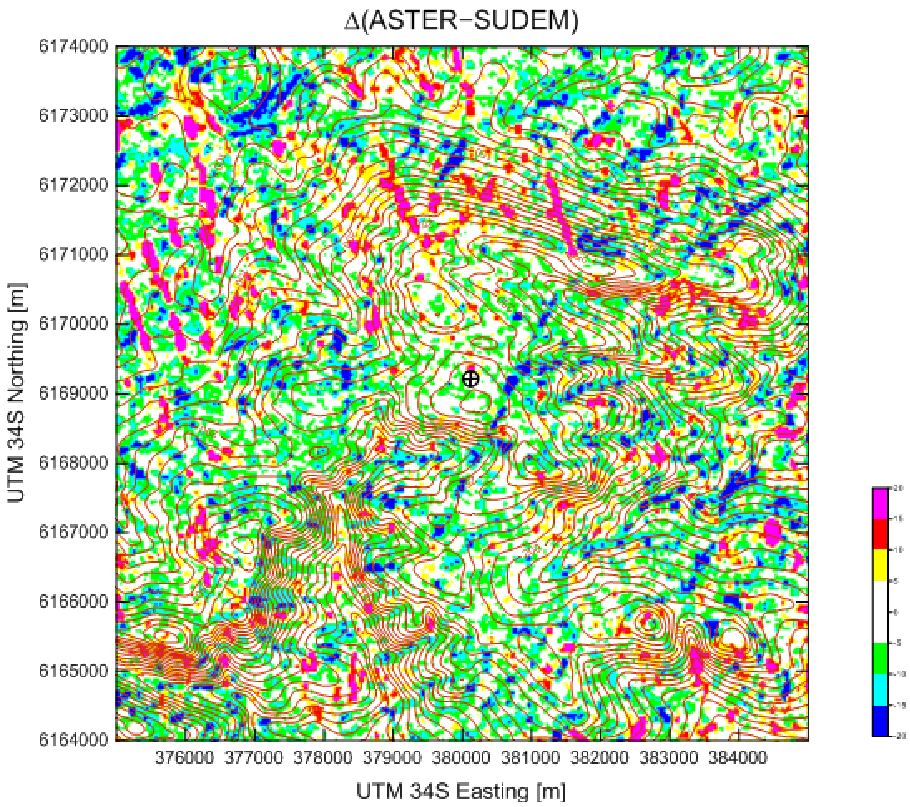

Figure 49. Elevation difference between map shown above and SUDEM reference map.

The statistics of the elevation differences shown above in Figure 38 to Figure 49 are given in histogram form below, see Figure 50.

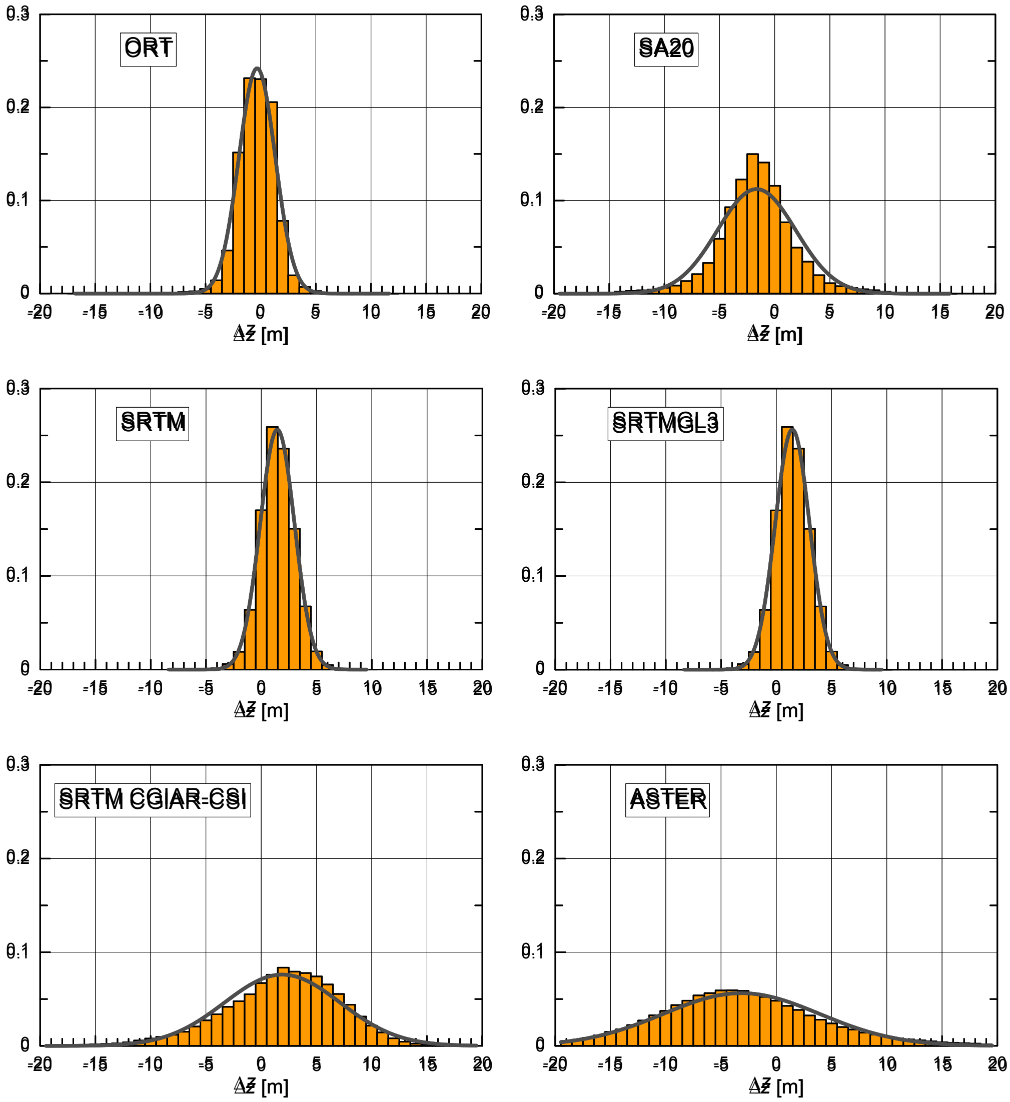

Figure 50. Distribution of elevation differences between different elevation data sets and the SUDEM reference data set.

A normal distribution has been fitted to the histograms in Figure 50; the mean value (bias) and standard deviation of the distributions are given in Table 17.

Table 38. Summary of elevation difference distributions shown in Figure 50. The data sets are arranged according to ascending numeric mean value and standard deviation.

Test data set	$\lvert\Delta z\rvert$ [m]	σ_Δ [m]
NGI ORT	−0.32	1.65
SRTM 2.1	+1.45	1.56
SRTM GL3	+1.45	1.56
SA20	−1.65	3.59
SRTM CGIAR-CSI	+1.89	5.31
ASTER	−2.86	8.55

In the comparisons above, we have used the SUDEM data set as the reference. The NGI ORT files (25-m DEM) seem very similar to the SUDEM data set and the average difference (bias) and spread are small. The NGI data set definitely seems adequate for flow modelling although some mismatch between different data tiles have been observed.

The two Space Shuttle Topography Mission data sets, SRTM 2.1 and SRTM+ or GL3, are designed to be identical except for the void filling in the GL3 data set. Both data sets have a slightly larger average difference to the SUDEM elevations than the NGI DEM, but this is not so important for the flow modelling. Here, the elevation differences are most important and the spread of these is actually smaller than for the NGI data set. Both SRTM data sets are used world-wide for microscale flow modelling and they seem adequate in South Africa as well.

The SRTM+ data set has been employed for the second detailed wind resource mapping of the WASA domain. Contrary to the first detailed mapping, where vector elevation maps were used, the second mapping have employed 100-m raster elevation data sets.

The 20-m digital height contours from South African standard 1:50,000 topographical maps were used for the first detailed wind resource mapping in the WASA domain (Mortensen *et al*., 2013). Based on the differences and results reported above, we expect slightly larger uncertainties in the modelling results using this data set.

The CGIAR-CSI data set is also a void-filled SRTM data set. We would therefore expect maps based on this data set to be quite similar to the ones described above. However, as can be seen from Table 17, the bias and especially the spread are significantly larger. The reason for this is not known at the time of writing and the data set should therefore be used with caution for flow modelling.

The ASTER (1-sec DEM) data set has the largest bias and spread of any of the data sets tested here. It is not clear from the present tests whether this is a general characteristic of the data set so it should be used with extreme caution for microscale flow modelling in South Africa.

Land cover data sets

Five land cover data sets have been identified for testing

- Satellite imagery, e.g. Google Earth or Virtual Earth
    - Traditional, manual way of obtaining land cover information
- 1:50,000 topographical maps for South Africa
    - Used in connection with satellite imagery for land cover classification
- USGS Global Land Cover Characteristics database (GLCC)
    - Used for the detailed WASA wind resource maps. Requires land-cover-to-roughness table. The same classification was used for the KAMM and WAsP modelling.
- National Land Cover 2000 (NLC 2000, dated) and 2009 (NLC 2009)
    - National land cover database. Requires land-cover-to-roughness table
- GlobCover Land Cover Map version 2.3
    - Global land cover database. Requires land-cover-to-roughness table

Several different types of land cover information have been used for the WASA analysis; both vector and raster roughness maps. It has not been possible to reach firm conclusions like those described for the elevation maps; partly because atmospheric stability seems to play a significant role too, and partly because a sample of ten sites is quite small. For the time being it is therefore recommended to use several levels of anemometry on each mast, in order to be able to verify the roughness and stability classifications for a site.

C WAsP best practices and checklist

This following list of requirements, best practices and recommendations for microscale modelling using the WAsP software is not exhaustive, but is meant to provide a brief summary of some important considerations regarding WAsP modelling.

More information is available in the WAsP help system and at www.wasp.dk.

Measurement programme

- ❑ Design measurement programme based on preliminary WAsP analysis
  - Use SRTM elevation and water body data + land cover from Google Earth
- ❑ Follow WAsP similarity principle as much as possible when siting the mast(s)
- ❑ Height of reference anemometer(s) similar to hub height (preferably > 2/3 h_{hub})
- ❑ Optimum boom direction is @ 90° (lattice) or @ 45° (tubular) to prevailing wind direction
- ❑ Deploy 2 or more masts for horizontal extrapolation analyses
- ❑ Deploy 2 or more masts if RIX and ΔRIX analyses are required
- ❑ Deploy 2 or more levels on masts for vertical wind profile analyses
- ❑ Deploy 2 or more levels on masts for redundancy in instrumentation
- ❑ Measure temperature (@ hub height) and pressure for air density calculations
- ❑ Are anemometers calibrated according to international/traceable standards?

Wind data analysis

- ❑ Collect required information, e.g. by filling out the WAsP Data Description Form
- ❑ All fields in Climate Analyst protocol editor should correspond to data spec's
- ❑ Plot and inspect time traces of all meteorological measurements
- ❑ Visual inspection of time-series – in particular reference wind speed and direction
- ❑ Visual inspection of polar scatter plot – any patterns or gaps?

Observed wind climate

- ❑ Use an integer number of whole years when calculating the OWC
- ❑ Check Weibull fit: is power density discrepancy < 1%?
- ❑ Check Weibull fit: is mean wind speed discrepancy < a few per cent?
- ❑ Check within context of long-term wind climate (MCP)

Elevation map(s)

- ❑ Size of map: should extend <u>at least</u> several (2-3) times the horizontal scale of significant terrain features from any site – meteorological mast, reference site, wind turbine site or resource grid point. This is typically 5-10 km.
- ❑ Coordinates and elevations must be in meters
- ❑ Set map projection and datum in the Map Editor
- ❑ Add spot heights within wind farm site; interpolate contours if necessary
- ❑ High-resolution contours around calculation sites (contour interval ≤ 10 m)
- ❑ Low-resolution contours away from calculation sites (contour interval ≥ 10 m)
- ❑ Non-rectangular maps are allowed (circular, elliptic, etc.)
- ❑ Check range of elevations in final map

Roughness/land cover map(s)

- ❑ Size: map should extend <u>at least</u> max(150×h, 10 km) from any site – meteorological mast, reference site, turbine site or resource grid point.
- ❑ Coordinates and roughness lengths must be in meters
- ❑ Set map projection and datum in the Map Editor

- ❑ Set roughness length of water surfaces to 0.0 m!
- ❑ Check range of roughness length values in final map
- ❑ Map date should correspond to modelling scenario (met. mast or wind farm)
- ❑ Check for dead ends and cross points – and edit map as needed
- ❑ Check consistency of roughness values – there must be no LFR-errors!

Sheltering obstacles

- ❑ Is site closer to obstacle than 50 obs. heights and height lower than about 3 obs. heights?
- ❑ If yes to both, treat as sheltering obstacle; if no, treat as *roughness element*

WAsP modelling – site visit

- ❑ Go on a site visit! Use e.g. the WAsP Site/Station Inspection Checklists
- ❑ Print and bring the WAsP forms for recording the necessary information
- ❑ Bring GPS and note projection and datum settings – change if required
- ❑ Determine coordinates of all masts, sites, landmarks and other characteristic points on site
- ❑ Bring sighting compass and determine boom directions and wind vane calibration
- ❑ Take photos of station and surroundings (12 × 30°-sector panorama)
- ❑ Download GPS data and photographs to PC as soon as possible (daily)

WAsP modelling – parameters

- ❑ Wind atlas structure: roughness classes should span and represent site conditions
- ❑ Wind atlas structure: standard heights should span and represent project conditions
- ❑ Adjust off- & on-shore mean- and RMS-heat fluxes values to site conditions (*caution!*)
- ❑ Ambient climate: Set air density to site-specific value (WAsP 10+ only)

WAsP modelling – analysis and application

- ❑ Get site-specific (density, noise, …) wind turbine generator data from manufacturer
- ❑ Within forest: effective height = nominal height minus displacement length
- ❑ Complex or steep terrain is when RIX > 0 for one or more sites (terrain angles > 17° or 30%)
- ❑ Make RIX and ΔRIX analyses if RIX > 0 for any calculation site

WAsP modelling – offshore

- ❑ Roughness length of sea (and other water) surfaces: set to 0.0 m in WAsP!
- ❑ Add combined elevation/roughness change line around wind farm site
- ❑ Change wake decay constant to offshore conditions

WAsP modelling – sensitivity analyses and uncertainties

- ❑ Identify and try to estimate the main uncertainties
- ❑ Sensitivity of results to background roughness value and other important parameters

DTU Wind Energy is a department of the Technical University of Denmark with a unique integration of research, education, innovation and public/private sector consulting in the field of wind energy. Our activities develop new opportunities and technology for the global and Danish exploitation of wind energy. Research focuses on key technical-scientific fields, which are central for the development, innovation and use of wind energy and provides the basis for advanced education at the education.

We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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