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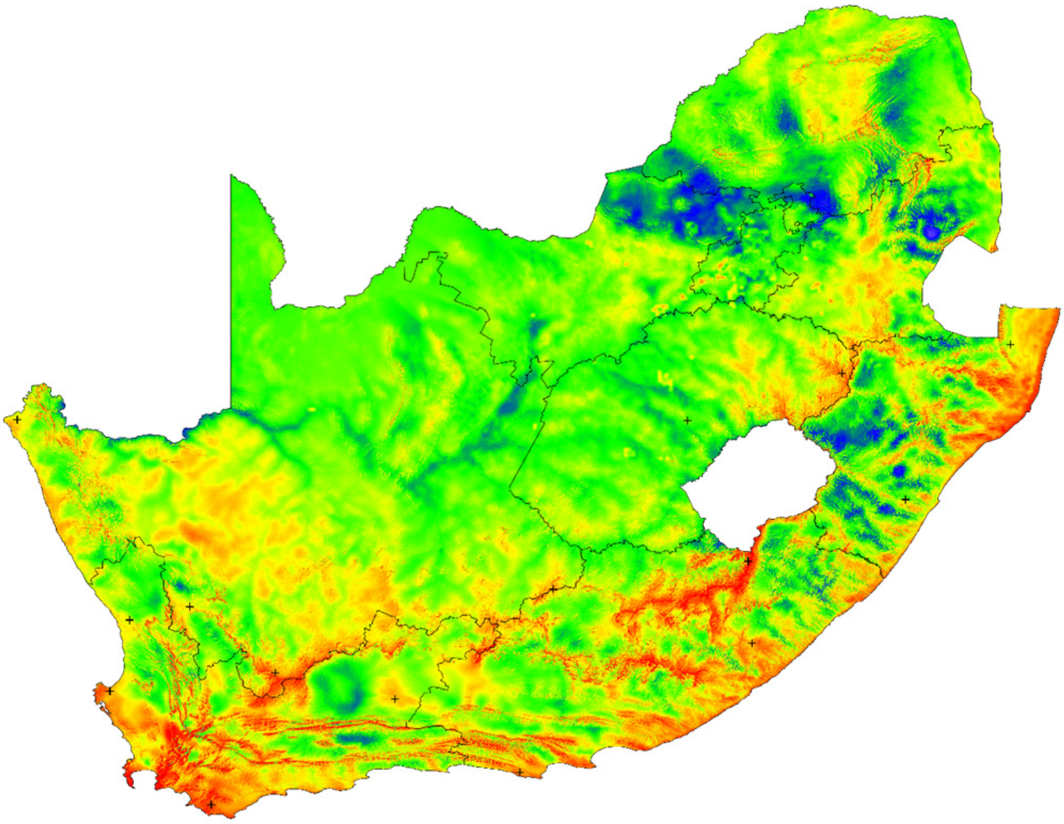

High-Resolution Wind Resource Map for South Africa 2018

Niels G Mortensen, Andrea N Hahmann, Jens Carsten Hansen, Duncan N Heathfield

DTU Wind Energy E-0179

December 2018

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By
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Contents

1. Introduction

The objective of this work package has been to develop a "*Large-Scale High-Resolution Wind Resource map for all of South Africa, based on a new 3-km Validated Numerical Wind Atlas".* This has been taken to mean that the results are generated as follows:

1. Maps are research-based, taking into account the latest knowledge; if at all possible
2. Maps are based on the full wind atlas methodology used in WASA Phases 1 and 2
3. Maps are high resolution, 250 m, and given for three heights, 50, 100 and 150 m
4. Maps cover all of South African land mass, and are divided into provinces
5. Databases of main results for all of South Africa are GIS compatible
6. Databases of additional results are comprehensive, i.e. contain Weibull *A*- and *k*-parameters and frequencies of occurrence for 12 sectors and three heights at all nodes.
7. Database of 3-km wind atlas files cover all of South Africa

The work reported here, and the results obtained, are necessarily of an interim nature. This is a feature and hallmark of the WASA project and approach; that the methods used are developed constantly and that the result therefore may improve over time as updated models, procedures and data become available. Improved maps and data will therefore be presented in the WASA projects Phase 3.

Improvements to the present mapping compared to the 2014- and 2017-editions are mainly related to an even and systematic national coverage, new mesoscale modelling results at 3-km resolution, an updated downscaling procedure and improved microscale modelling. The microscale modelling is now done using WAsP 12 versions of the microscale models.

The topographical inputs to the WAsP microscale modelling consist of SRTM elevation data (as used in previous modelling), and a new land cover data set referred to as ESACCI 2015. This data set was used for both the mesoscale and microscale modelling; initially we have used a translation table between land cover and roughness length that is also used for the Global Wind Atlas.

Investigations of land cover and roughness data sets will continue in Phase 3, where more land cover data sets and translation tables will be analysed and compared. Likewise, the variation of atmospheric stability over South Africa will be investigated, in order to obtain the best possible detailed wind resource maps at the end of WASA Phase 3. It is therefore anticipated that future versions of the wind atlas data sets and detailed wind resource maps will improve e.g. because of the improved land cover and stability information.

The *Large-Scale High-Resolution Wind Resource map for all of South Africa, based on a new 3-km Validated Numerical Wind Atlas* is validated by comparing modelled results to the observed wind climates at the 10 WASA 1 masts and the 5 WASA 2 masts.

The present report, together with the accompanying maps and data sets in GIS-compatible formats, constitute the final outputs of *WP34.01c Report with ArcGIS ASC files*, and are updates and extensions to previous components *WP24.02 Microscale resource maps for WASA 2 domain (part of All SA)* and *WP24.03 Resource maps for WASA1 domain updated*.

2. High-Resolution Wind Resource Maps

Here, we present the deliverables according to the Terms of Reference of the WASA project.

2.1 Wind resource maps

The deliverables consist of a validated numerical wind atlas and detailed wind resource maps for WASA 1 domain, WASA 2 domain and the rest of South Africa. The numerical wind atlas – or generalised wind climate data sets – have been generated by the Weather Research and Forecasting (WRF) model and the DTU downscaling procedure. In this section we show only one representation of the numerical wind atlas, the mean geostrophic wind; i.e. the wind at some level above the ground where the influence of the surface (both roughness and terrain) are no longer felt. The data sets are described further in the remainder of the report.

Detailed wind resource maps and data have been generated with the *WAsP Resource Mapping* system (aka Frogfoot), see below. For each modelling domain and province, results are given in grid format with a cell size of 250×250 metres and for three heights of 50, 100 and 150 m above ground level (a.g.l.). The detailed wind resource and topographical maps depict:

- Annual mean wind speed *U* in [ms^{-1}]
- Annual mean power density *P* in [Wm^{-2}]
- Annual mean air density *ρ* in [kgm^{-3}]
- Elevation above sea level *z* in [m]
- Ruggedness index RIX [n/a]

The WASA maps are based on a new 3.33-km validated numerical wind atlas, see Figure 1. This map represents the wind potential from which the detailed wind resource maps in Figure 2 and Figure 3 were derived, see Appendix B. In addition to wind resource maps, maps and data showing air density, elevation and terrain ruggedness have also been produced, Appendix C.

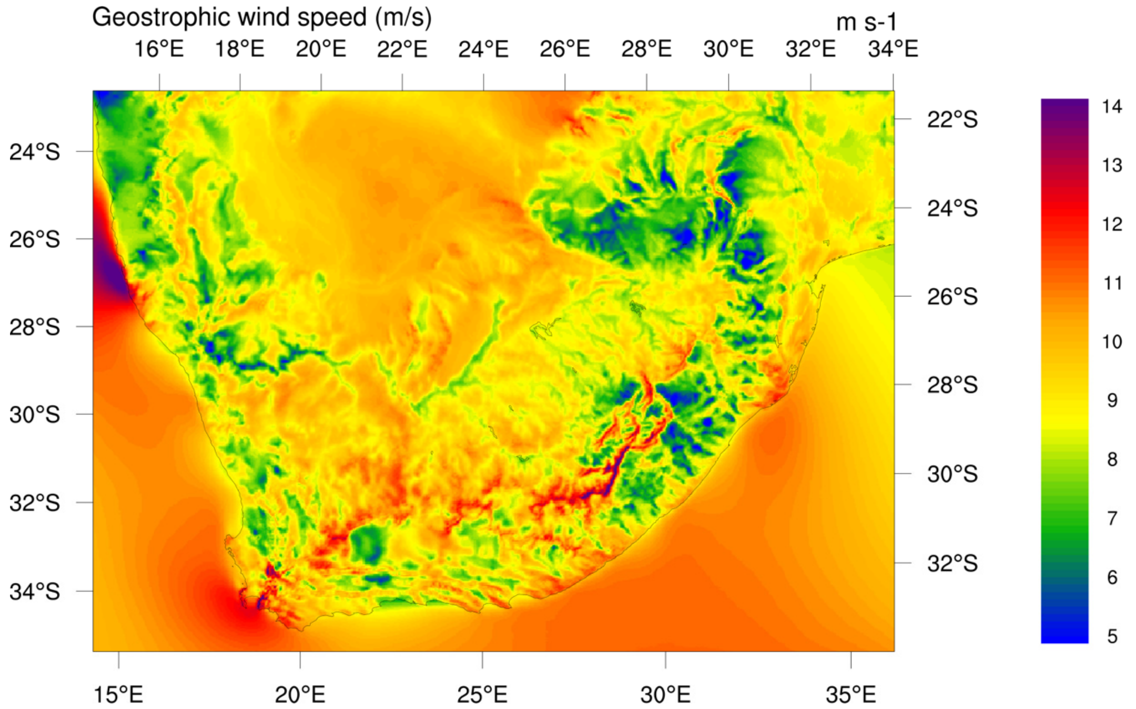

Figure 1. Numerical wind atlas map: Mean geostrophic wind speed [ms^{-1}] derived from the 100 m above ground level for the period 2010-2017 (3.33 km × 3.33 km).

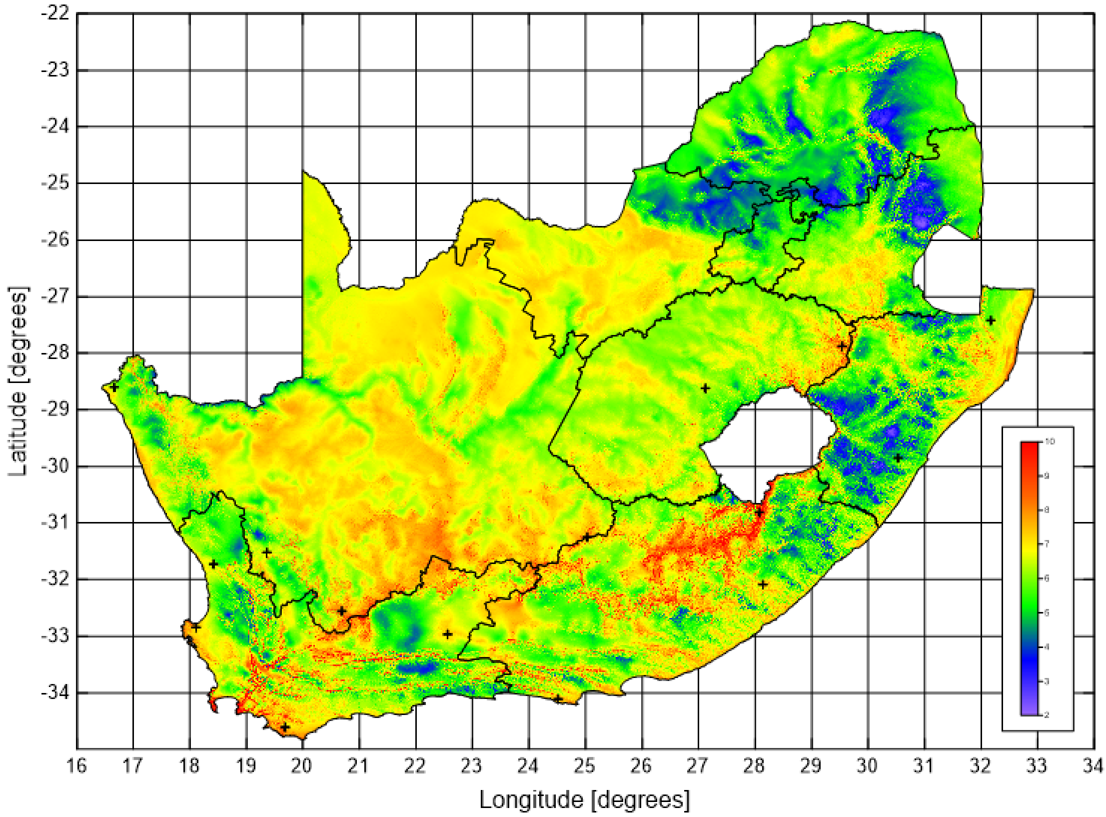

Figure 2. Detailed wind resource map: Mean wind speed at 100 m above ground level for South Africa.

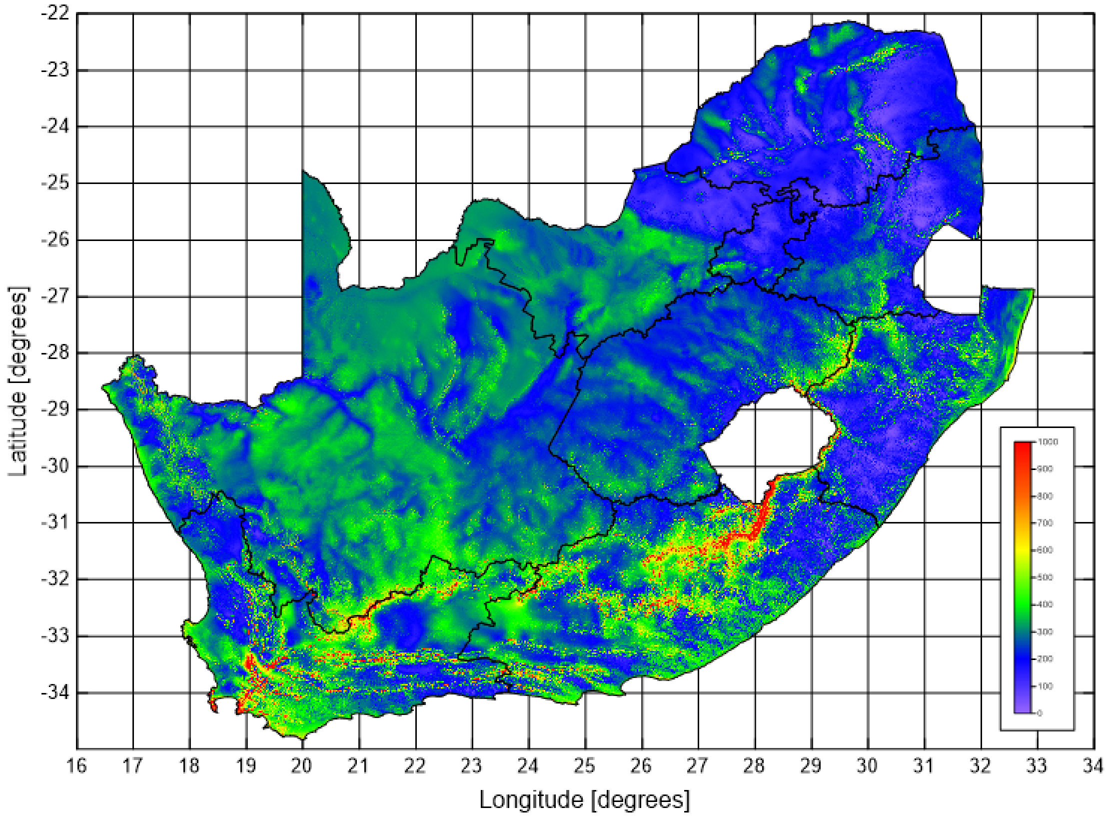

Figure 3. Detailed wind resource map: Mean power density at 100 m above ground level for South Africa.

2.2 Data formats and metadata

Data and metadata for the *wind resource maps* are delivered as (see Appendix B):

- ArcGIS ASC files
  - Nine ZIP archives for the nine provinces
- Adobe PDF documents
  - High-Resolution Wind Resource Map for South Africa 2018
- Google Earth KMZ files
  - One KMZ for mean wind speed
  - One KMZ for mean wind power density

Data and metadata for *numerical wind atlases* are delivered as:

- One ZIP archive of LIB file data for all of South Africa
  - lib_2010-2017_WASA2.nc (WASA 3-km data for SA)

2.3 Database of high-resolution maps and data

The database of wind resource maps contain 11 ASC-format grids of predicted wind climates and topographical characteristics for each province:

- Mean wind speed *U*: 10 min average in [ms^{-1}] @ 50, 100 and 150 m a.g.l.
- Mean power density *P*: 10 min average in [Wm^{-2}] @ 50, 100 and 150 m a.g.l.
- Mean air density ρ: 10-min average in [kgm^{-3}] @ 50, 100 and 150 m a.g.l.
- Elevation z: meters above sea level in [m]
- Ruggedness index RIX: using WAsP standard parameters

The database of high-resolution maps can be downloaded from files.dtu.dk, see Appendix C, or the WASA project download site.

The databases of generalised wind climates (wind atlas files) in WAsP LIB format (Mortensen *et al.*, 2014d) can also be downloaded from files.dtu.dk, see Appendix C, or the WASA project download site.

2.4 Database of high-resolution wind statistics

For each province, the following information is provided in ASCII TXT format files:

- Weibull A- and k-parameters for 12 sectors at each 250-m node and height
- Wind direction distribution (rose) for 12 sectors at each node and height

Wind climate and energy information is given for 50, 100 and 150 m above ground level. Climate information at each of the 250-m modelling grid points will make it possible to calculate, say, specific mean power density from 0-25 ms^{-1}, energy yield for any given wind turbine, capacity factor for any given wind turbine, etc.

Data will be stored in ASCII text files with the following format:

- JobID; *x*; *y*; *z*; SectorIndex; *A*; *k*; *f*;

where *x* is UTM Easting [m], *y* is UTM Northing [m], *z* is height above ground level [m], SectorIndex is a sector index from 1 to 12 clockwise starting from north, *A* is Weibull scale parameter [ms^{-1}], *k* is the Weibull scale parameter, and *f* is sector frequency. The TXT files are distributed in ZIP archives. The database of high-resolution wind statistics can be downloaded from the WASA project download site, see Appendix C.

3. Methodology

The same methodology that was used in the development of the WASA 1+2 Wind Atlas and Wind Resource maps and input into DEA SEA Phase 1+2 has been used for the development of the present *High-Resolution Wind Resource Map for South Africa 2018*, see Figure 4. This has been possible because the updated versions of the *DTU Generalization* procedure and the *WAsP Resource Mapping System* (aka *Frogfoot*) have been available and could produce the required results within the given time frame.

The DTU Generalisation procedure is required to link the mesoscale and microscale modelling, in order to downscale the large-scale wind climate to specific sites in South Africa. Importantly, the generalisation procedure works with the industry-standard WRF (Weather Research and Forecasting) model.

The Frogfoot modelling system is required to automate the microscale modelling (WAsP 12 application) for large areas at high speed. Frogfoot uses the microscale models in a batch-like operation mode, through distributed computing in a network. It features automatic selection of generalized wind climates (LIB files) and interpolation of generalized wind climates to specific sites; in order to provide a continuous wind resource map. Importantly, the Frogfoot system works with the industry-standard WAsP 12 software engine and models.

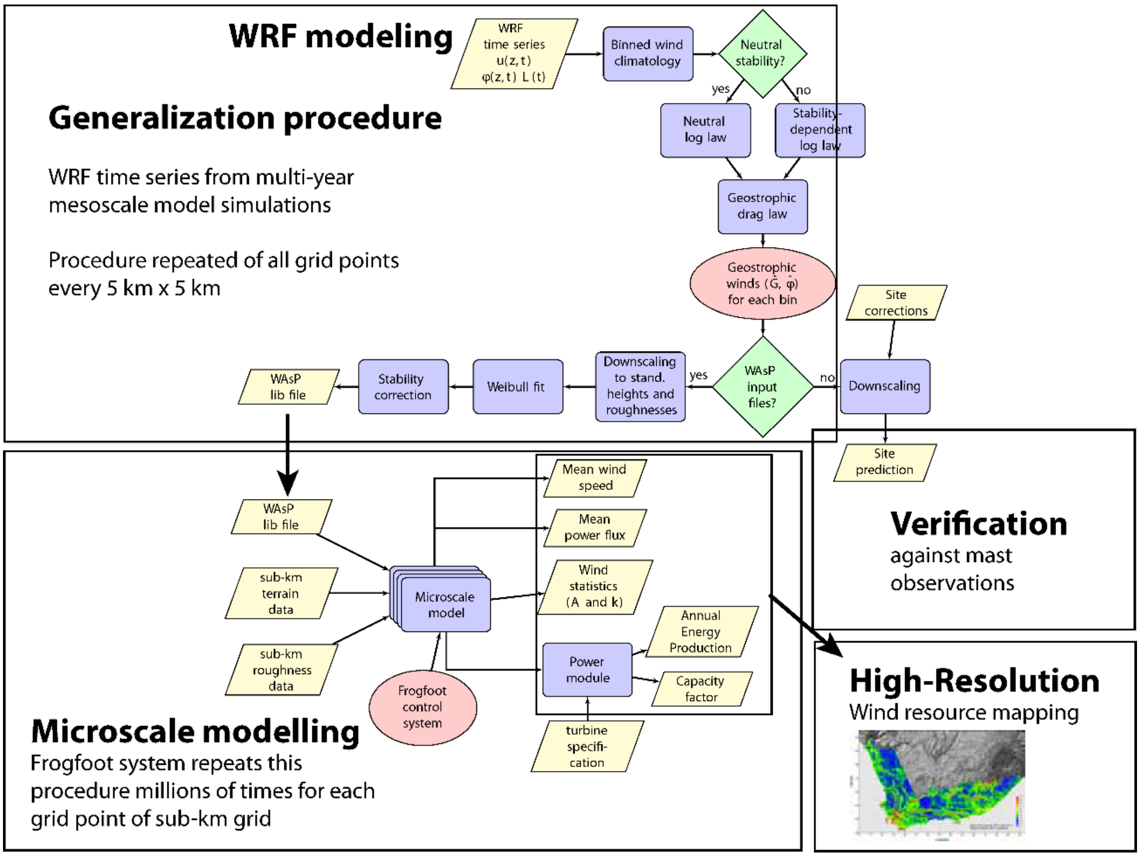

Figure 4. Schematic diagram showing the relationship and flow of data between the components of the Frogfoot system. Blue boxes represent core components of Frogfoot, red boxes represent ancillary components, purple boxes represent data that is input into the system, and the green box represents the result outputs. The mesoscale modelling was done with a resolution of 3.33 km and the microscale 250 m.

3.1 Mesoscale modelling – WRF and DTU generalization

The wind climatologies that form the basis of the wind atlas were created using the Weather, Research and Forecasting model (WRF; Skamarock et al. 2008). The WRF model is a mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. The WRF modelling system is in the public domain and is freely available for community use. It is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The WRF model is used worldwide for a variety of applications, from real-time weather forecasting, regional climate modelling, to simulating small-scale thunderstorms.

Although designed primarily for weather forecasting applications, ease of use and quality has brought the WRF model to be the model of choice for downscaling in wind energy applications, including the WASA1 wind atlas released in 2014 (Hahmann et al., 2015a).

A first mesoscale simulation for the High-Resolution Wind Resource Maps was carried out with WRF version 3.8.1 released 12 August 2016. After comparison with the results of the WASA1 simulation, it became clear that this simulation had a general overestimation (up to 4 ms^{-1} in some areas) of boundary layer winds over land. This was due to changes in the PBL scheme, which were not properly described in the model release. Therefore, a decision was made and the simulation was rerun using WRF version 3.6.1 model released on 14 August 2014, and the results presented here use the output from this simulation.

For the High-Resolution Wind Resource Maps, the WRF model was setup using the parameters described in Table 1 and follows the method described in Hahmann et al. (2015b). The simulations were integrated on a grid with horizontal spacing of 30 km × 30 km (outer domain, d01, with 140 × 160 grid points), 10 km × 10 km (first nested domain, d02, with 271 × 331 grid points) and 3.33 km × 3.33 km (second nest, d03, with 454 × 631 grid points). A map of the model set-up location, which was slightly rotated to better cover the region of interest over southern Africa, is displayed in Figure 5.

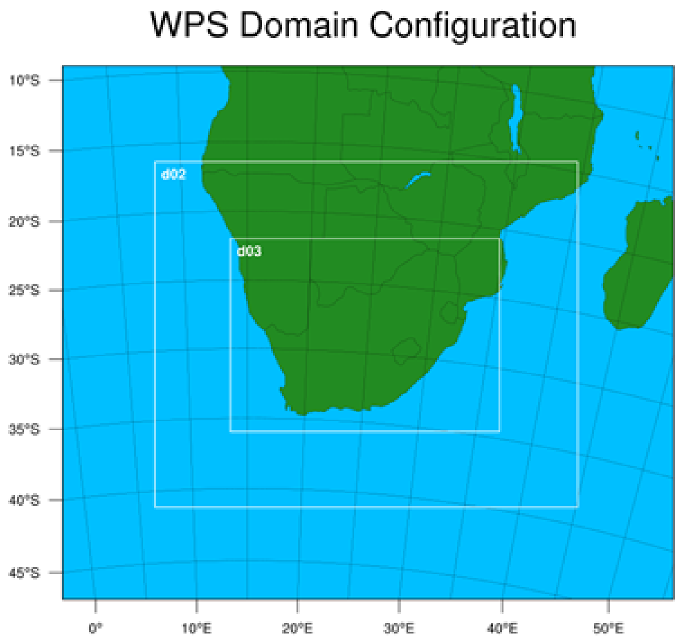

Figure 5. WRF domain configuration used to generate the mesoscale wind climatologies used in the High-Resolution Wind Resource Map.

The elevation of the terrain, land cover category and surface roughness length used in the inner domain of WRF (d03, ∆x=5 km) is shown in Figure 6.

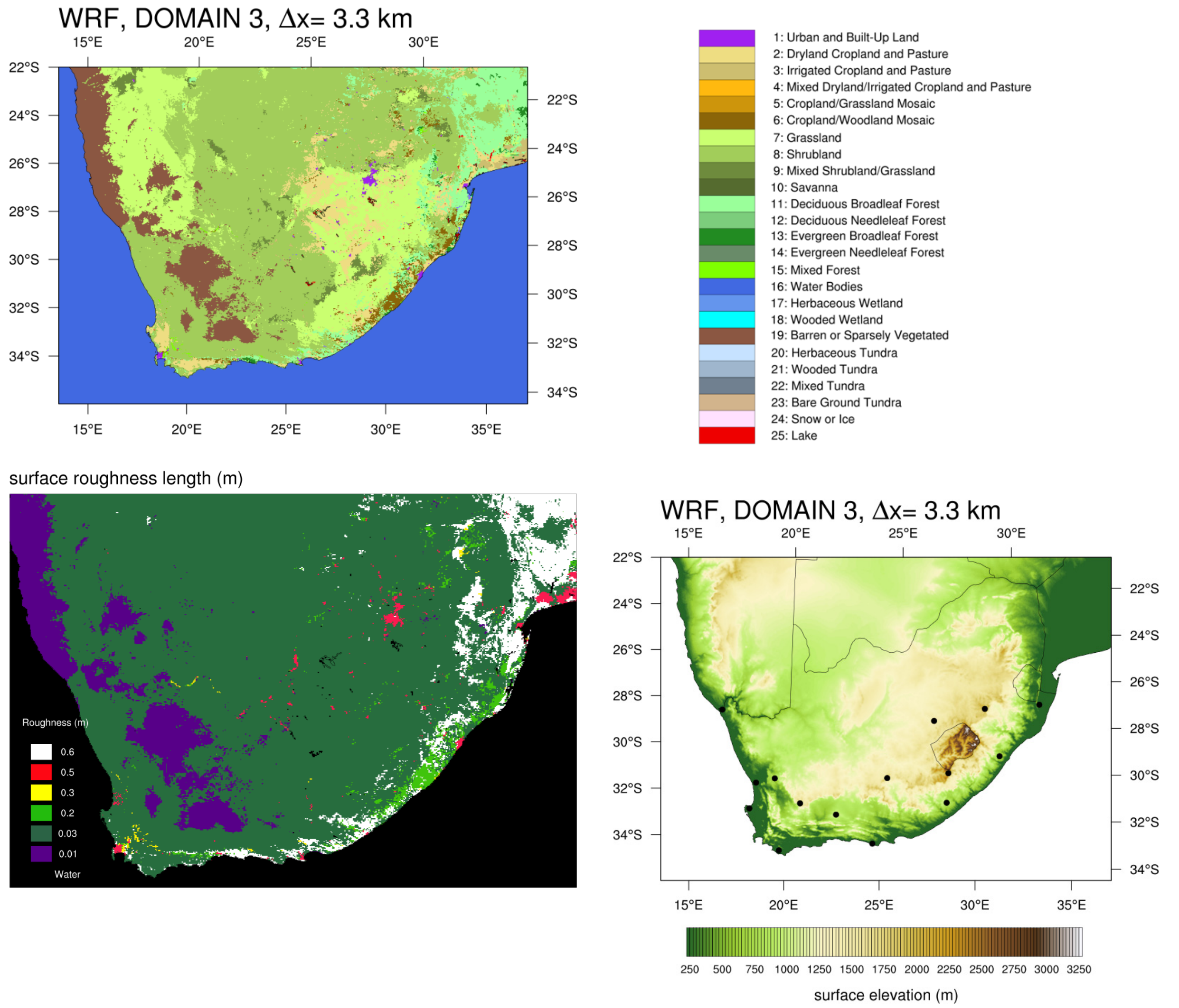

Figure 6. The d03 WRF land surface in land cover (top left), surface roughness length (m; bottom left) and surface elevation (m; bottom right).

Table 1. Model setup parameters used in the WRF model simulations.

Model setup
• WRF (ARW) Version 3.8.1. • Lambert conformal projection. Reference latitude and longitude 30.0°S, 25.5°E, standard longitude 15.5°E. • Horizontal grid spacing: 30 km (d01), 10 km (d02) and 3.33 km (d03); • Grid size: 140×160 (d01), 271×331 (d02) and 454×631 (d03). • 61 vertical levels with model top at 50 hPa; 20 of these levels are placed within 1000 m of the surface; the first 9 levels are located approximately at: 6, 22, 40, 57, 73, 91,113, 140, 170 m. • Land-cover classification from European Space Agency (ESA) Climate Change Initiative land cover maps at 300 m spatial resolution, converted to USGS land categories. Dominant land cover category. • Period: 2010-01-01 to 2017-12-31, for running the downscaling (but a longer period was run 2010-01-01 to 2018-04-24). • Surface roughness lengths are modified as in Hahmann et al. (2015a).
Simulation setup
• Initial, boundary conditions, and fields for grid nudging come from the European Centre for Medium Range Forecast (ECMWF) ERA5 reanalysis (Dee et al., 2011) at 0.3°×0.3° grid spacing. • Runs are started (cold start) at 00:00 UTC every 10 days and are integrated for 11 days, the first 24 hours of each simulation are disregarded. • Sea surface temperature (SST) and sea-ice fractions come from the dataset produced at the UK Met O. • Model output: output frequency of 30 minutes for d03 (lowest 13 vertical levels, highest: ~340 m), hourly for d01 and d02. Organized in daily files. • Adaptive time step with maxi- mum allowed CFL of 0.84. One-way nested domains; 5 grid point nudging zone. • Grid nudging on d01 only and above level 15; nudging coefficient 0.0003 s^{-1} for wind, temperature and specific humidity. No nudging in the PBL.
Physical parameterizations
• Precipitation: WRF Single-Moment 5-class scheme (option 4), Kain-Fritsch cumulus parameterization (option 1) turned off on D3. • Radiation: RRTMG scheme for longwave (option 4); RRTMG shortwave for shortwave (option 4). • PBL and land surface: Nakanishi and Niino PBL scheme (Nakanishi and Niino (2006) (option 5), MYNN surface layer (option 5) surface-layer scheme, and Noah Land Surface Model (option 2). • Surface roughnesses are kept constant at their winter (lower) value. • Diffusion: Simple diffusion (option 1); 2D deformation (option 4); 6th order positive definite numerical diffusion (option 2); rates of 0.06, 0.08, and 0.1 for d01, d02, and d03, respectively; vertical damping. • Positive definite advection of moisture and scalars.

The wind atlas method is based on the generalization of the wind climatologies derived from the mesoscale modelling. The post-processing allows a proper validation to be carried out, in which wind climate estimates derived from mesoscale modelling and measurements can be compared. Without the post-processing step no validation is possible, because the surface description within the model does not agree with reality, and therefore model winds will not agree with measured winds, except perhaps in extremely simple terrain or over water far from coasts.

For the High-Resolution Wind Resource Maps the generalization method is that outlined in Hahmann et al. (2015) with a few small errors that have been corrected from previous versions of the generalization code. The parameters used are listed in Table 2. In the validation in Section 3.3, we evaluate the WRF-derived lib files for these new simulations.

Table 2. Parameters used in the generalization procedure.

Generalisation parameters	
Method: 4 (neutral)	ain_neut = False
levfreq = 100 m	nsec = 36
decayl = 10×10^4	Fixed at 0.0005

3.2 Microscale modelling – WAsP Resource Mapping System

The calculation system used for the High-Resolution Wind Resource Maps 2018 is called the *WAsP Resource Mapping System* (aka Frogfoot). It has been developed in association with the software development company World In A Box. The motivation for the development of Frogfoot was to allow high-resolution WAsP-like calculations of predicted wind climates to be made over large areas, using a large number of generalized wind climates. This need came about because of numerical wind atlases being carried out on nation-wide scale, which generated generalized wind climates on a grid with a spacing of, typically, 3-5 km.

The Frogfoot system employs the same flow modelling as WAsP (Mortensen *et al.*, 2014d). Unlike the present WAsP 12, the terrain descriptions can be input using raster maps, rather than vector maps. Also unlike the present WAsP desktop software, the starting point for describing the large-scale wind forcing is any number of geographically distributed generalized wind climate files (LIB files), whereas WAsP 12 can only use one input wind climate at a time. The following edited excerpt from science.globalwindatlas.info (Badger and Mortensen, *personal communication*) describes the Frogfoot system in some detail.

3.2.1 Frogfoot

Frogfoot is a system of programs and interlinked servers developed and set up to allow for very large geographical coverage of high-resolution wind resource maps, with inclusion of changing large-scale wind forcing and microscale flow effects. The core components of the Frogfoot system are:

- Terrain Service
- Climate Service
- Job Service
- Results Service
- WAsP Worker

Ancillary components are:

- Job Management Console
- Climate Data Manager
- Results Exporter

The core components are essential to carry out a Frogfoot calculation. The ancillary components are needed to set-up the configuration of a Frogfoot job, as well as import and export data into or out of the system.

The framework of Frogfoot can be understood by considering the elements required to carry out a WAsP calculation of a predicted wind climate at a single location. These elements are: the generalized wind climate data, roughness and orography data (in the form of maps) for the area around the location of interest, and flow models inside the WAsP software. The roughness and orography data are used by the flow models to determine flow effects at the location, and these flow effects are used to modify the generalized wind climate. These elements are also represented in the Frogfoot core components, see Figure 7. For Frogfoot though, instead of considering a single point, the Job service dispatches a very large number of points within an area of interest to be calculated.

For any particular application of Frogfoot, the Job Service is set up by the Job Management Console. Here the user specifies the map data to be used, selected from map data inside the Terrain Service. Here the user also specifies the generalized wind climate data to be used, selected from generalized wind climate data inside the Climate service. The generalized wind climate data consists of a number of geo-referenced WAsP generalized wind climate files. Within the Job Management Console the definition of the area to be calculated is specified, by a map containing a single closed contour outlining the boundary of the calculation area. The user also needs to set the grid spacing and origin of the calculation nodes.

The Job Management Console will split the job into a number of tiles which are 10×10 calculation nodes in size (i.e. 100 calculation nodes in all). A tile makes up a set of calculations that will be dealt with separately by distribution of the tile to a WAsP Worker. The WAsP Worker is a standalone installation of the WAsP flow models, without the user interface. In order for the WAsP Worker to calculate the predicted wind climate at the 100 nodes, tile maps of roughness and orography are prepared by the Terrain Service. The maps are given an extent sufficient for the tile by extending the map boundary with a 25 km buffer around the extent of the tile.

The calculation also needs generalized wind climate data. This is provided by the Climate Service in the form of 100 LIB files (one for each calculation node). For each calculation node a LIB file is calculated by the Climate Service based on an interpolation of the 3 nearest LIB files from the selected generalized wind climate dataset. The interpolation weighting of the LIB files is inversely proportional to distance. For each direction sector the wind speed distribution is calculated, based on the weighted combination of the Weibull distributions for the 3 nearest LIB files, then with this a new Weibull fit is performed to provide the Weibull parameters for the interpolated LIB file.

Figure 7 below shows how the different components are related to each other and the flow of data from one component to the next. The Job Service feeds tile data to the WAsP workers. The WAsP workers are installed on computers within the same local area network as the Frogfoot servers. Once the WAsP worker has finished the calculations for one tile, the tile results are sent to the Results Service. The Job Management Console allows users to get an overview of the current jobs running on the system, as well as jobs that have been completed or paused. Once the Frogfoot job has completed, the Result Exporter is used by the user to export output in the desired format for subsequent analysis or plotting.

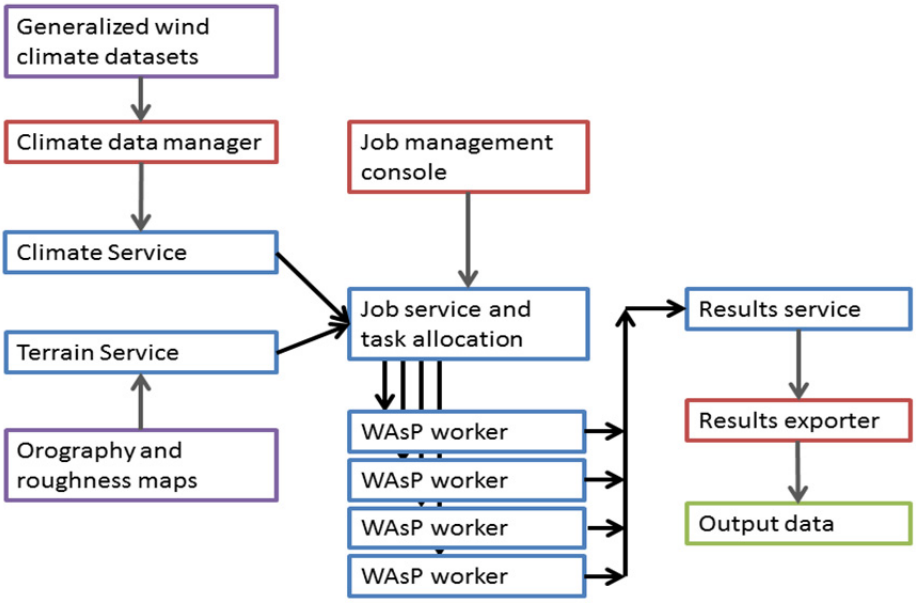

Figure 7. Schematic diagram showing the relationship and flow of data between the components of the Frogfoot system. Blue boxes represent core components of Frogfoot, red boxes represent ancillary components, purple boxes represent data input into the system, and the green box represents the result outputs.

The generalized wind climate data sets are described by Hahmann et al. (2018); the orography and roughness maps in the sections below.

3.2.2 Topographical inputs

The topographical inputs for the microscale flow modelling and data handling and display are: terrain elevation, land cover and provincial boundaries. These inputs are of the same types as were used in previous detailed wind resource maps (Mortensen et al., 2014c), but updated to present day status and quality. The inputs are described briefly below.

Elevation

Terrain elevation is given in raster format, as elevation grids with a horizontal resolution of 100 m between terrain spot heights given in metres above sea level, see Figure 8. The elevations were derived from Shuttle Radar Topography Mission data designated SRTM+, NASA version 3. The SRTM Plus data were downloaded from NASA's Land Processes Distributed Active Archive Center (LP DAAC) located at the USGS Earth Resources Observation and Science (EROS) Center.

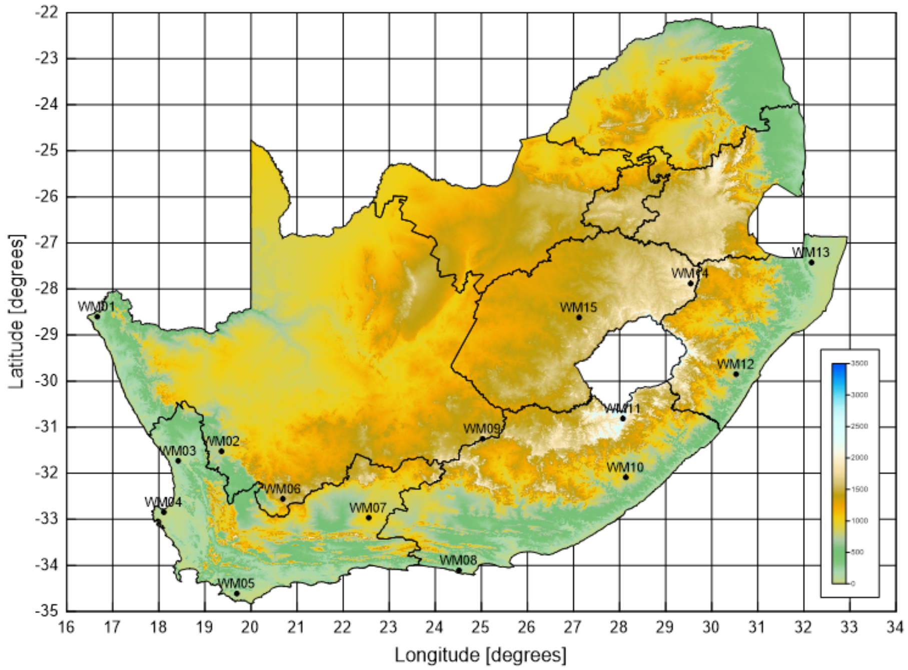

Figure 8. Elevation map of South Africa based on SRTM+ data.

SRTM Plus elevations are given in a regular grid of latitude and longitude, with a spacing of three arc-seconds. Since the flow modelling is done in a metric Cartesian coordinate system, UTM S WGS84, the raw data were transformed to either UTM 34S (NC, WC) or 35S (EC, FS, GT, LP, MP, NL, NW) and resampled to 100 m spacing using the *triangulation with linear interpolation* method in Surfer 12.

The SRTM Plus data set has been used for microscale flow modelling in all WASA activities so far and has been found to be adequate for this purpose (Mortensen et al., 2014b).

Land cover

Terrain land cover is also given in raster format, as land cover and roughness length grids with a horizontal resolution of 300 m, between terrain spot roughness lengths given in metres, see Figure 9. The land cover was derived from the ESA CCI 2015 data set, the source of which is the European Space Agency Climate Change Initiative and its Land Cover project. The data are copyright © ESA Climate Change Initiative – Land Cover project 2017; see the ESA CCI website.

ESA CCI land cover codes are given in a regular grid of latitude and longitude, with a spacing of ten arc-seconds. Since the flow modelling is done in a metric Cartesian coordinate system, UTM WGS84, the raw data were transformed to either UTM 34S (NC, WC) or 35S (EC, FS, GT, LP, MP, NL, NW) and resampled to 300 m spacing using the *nearest neighbour* method in Surfer 12.

The ESA CCI data set is also used for microscale flow modelling in the 2018-edition of the observation-based wind atlas for the WASA 1 and 2 domains. Its use relies on the transformation of CCI land cover codes to roughness lengths in metres. For the present study, the transformation table shown in Appendix A has been employed; in WASA 3 this transformation will be investigated further.

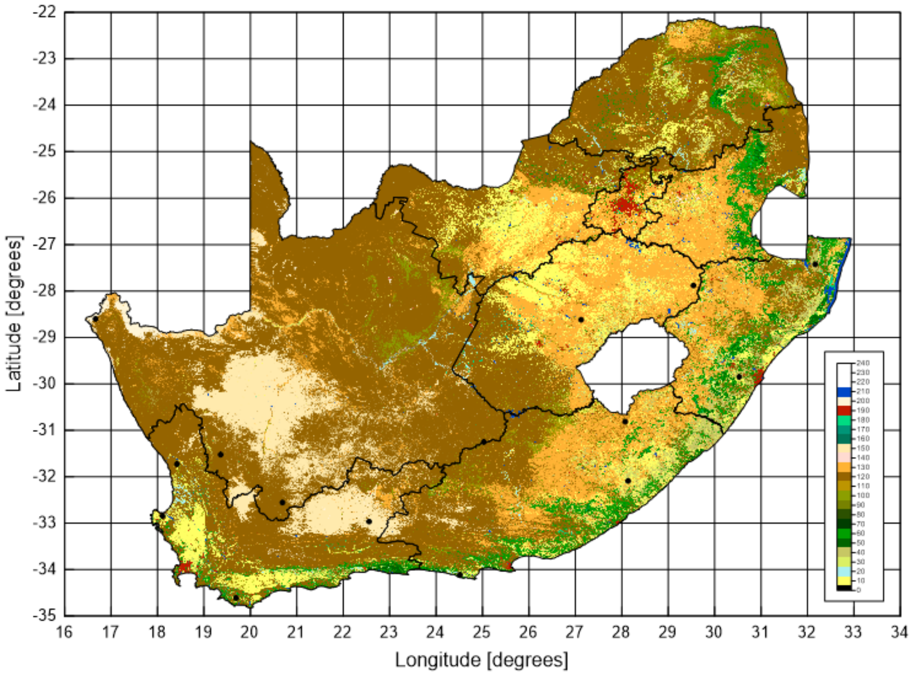

Figure 9. Land cover map of South Africa.

Boundaries

The microscale modelling and organisation of the data and results have been done for each of the nine provinces of South Africa: Eastern Cape (EC), Free State (FS), Gauteng (GT), Limpopo (LP), Mpumalanga (MP), Northern Cape (NC), KwaZulu-Natal (NL), North West (NW), and Western Cape (WC); see Figure 10.

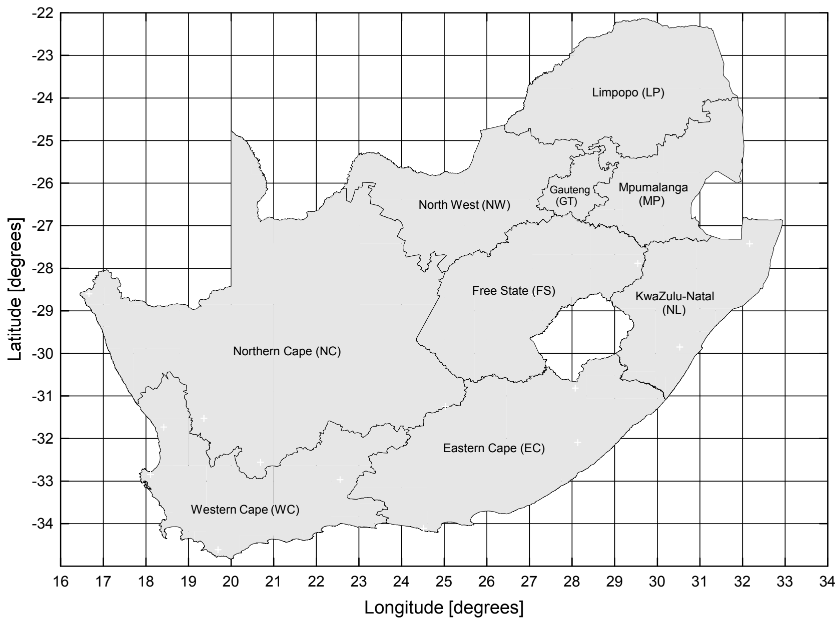

Figure 10. Provinces and boundaries of South Africa.

Present boundaries of the nine provinces have been obtained in September 2017 from the Municipal Demarcation Board (MDB); South Africa's municipal demarcation authority. The two-letter code used for each province is derived from the ISO 3166-2 standard.

3.2.3 Comparison to previous calculations

WASA domains 1 and 2 have already been mapped in 2013, 2014 and 2017; the differences between these detailed resource maps are given below:

Resource mapping in 2013

- Old FF engine
  - Vector map inputs
  - No air density calculations
- Wind climatologies
  - KAMM 5-km LIB files
  - comparison at 10 masts
- Elevation descriptions
  - 20-m SA 1:50,000 elevations
- Roughness length descriptions
  - GLCC roughness vector map
  - 1-km raster to vector by DTU
  - DTU translation table to roughness length values.

Resource mapping in 2014

- New FF engine
  - Raster map inputs
  - Site-specific air density model
- Wind climatologies
  - WRF 3-km LIB files
  - comparison at 10 masts
- Elevation descriptions
  - 100-m SRTM+ elevation grid
- Roughness length descriptions
  - 300-m GlobCover 2009 grid
  - DTU translation table from GC land cover to roughness length.

The 2017 detailed interim wind resource maps were modelled as given above for 2014, but with the latest WAsP 11 (FF) engine, updated WRF 3- and 5-km LIB files, and comparisons at all 15 WASA 1 and 2 masts. In addition, the detailed maps now covered all of South Africa.

The present (2018) detailed wind resource maps were modelled as given above, but with the latest WAsP 12 (FF) engine, a new model for air density variation over South Africa, completely new WRF 3.33-km LIB files, with comparisons at all 15 WASA 1 and 2 masts. The land cover input for the microscale modelling is now the ESA CCI 2015 data set, with a translation table developed at DTU. Again, the maps cover all of South Africa, but now in a systematic and uniform way.

3.2.4 Setting up the national calculation

For practical purposes, the calculation of South Africa was done province by province for the nine provinces. For Northern Cape (NC) and Western Cape (WC) provinces, the Universal Transverse Mercator (UTM) projection (zone 34S) has been used, with the World Geodetic System (WGS) 1984 datum. The coordinate system is thus referred to as UTM 34S WGS84.

For Eastern Cape (EC), Free State (FS), Gauteng (GT), Limpopo (LP), Mpumalanga (MP), KwaZulu-Natal (NL), and North West (NW) provinces, zone 35 of the same system has been used. This coordinate system is thus referred to as UTM 35S WGS84.

Like previously, the WAsP engine in Frogfoot has been employed in its default configuration. Note, that this configuration may not be optimal for all sites in different parts of South Africa. The topographical input data to the Frogfoot modelling are described above.

3.3 Validation

Validation of the modelling is done by comparing mean wind climates observed at the 10 WASA1 masts and 5 WASA2 masts with modelled mean wind climates at the same sites and heights. In Table 3, we compare the wind resource at these 15 sites; where the annual mean wind speed is taken to represent the 'wind resource'. The validation of the modelling is carried out for different full-year periods at the various masts, but the same period is used for the mesoscale modelling.

Table 3. Validation of the modelling at the WASA1 and WASA2 mast sites.

Station	Observed wind speed h = 62 m	Predicted wind speed h = 62 m	Difference	Difference
	[ms^{-1}]	[ms^{-1}]	[ms^{-1}]	[%]
WM01	6.04	5.20	−0.84	−14%
WM02	6.17	6.13	−0.04	−1%
WM03	7.14	6.32	−0.82	−11%
WM04	6.66	6.32	−0.34	−5%
WM05	8.45	7.88	−0.57	−7%
WM06	7.34	7.21	−0.13	−2%
WM07	7.07	6.49	−0.58	−8%
WM08	7.27	6.98	−0.29	−4%
WM09	7.82	7.75	−0.07	−1%
WM10	6.66	6.43	−0.23	−3%
Mean (01-10)			−0.39	−6%
WM11	7.51	8.25	0.74	+10%
WM12	5.07	4.89	−0.18	−4%
WM13	5.1	5.08	−0.02	0%
WM14	7.36	7.68	0.32	+4%
WM15	6.09	6.16	0.07	+1%
Mean (11-15)			+0.19	+2%
Mean (01-15)			−0.20	−3%

For the WASA1 domain, the average difference between modelled and measured winds at the 10 WASA1 mast sites is −6%. For the WASA2 domain, the average difference between modelled and measured winds at the 5 mast sites is +2.0%.

Overall, the average wind speed difference is −0.20 ms^{-1}; corresponding to an average percentage error of about −3%. However, these results may improve significantly when the analyses of land cover, roughness length and atmospheric conditions have been finalised. Figure 11 shows the same comparisons in a scatter plot format.

Figure 12 shows comparisons of observed and predicted mean wind speeds using the GlobCover 2009 land cover data set. This was used previously for mapping the wind resources of South Africa in 2017.

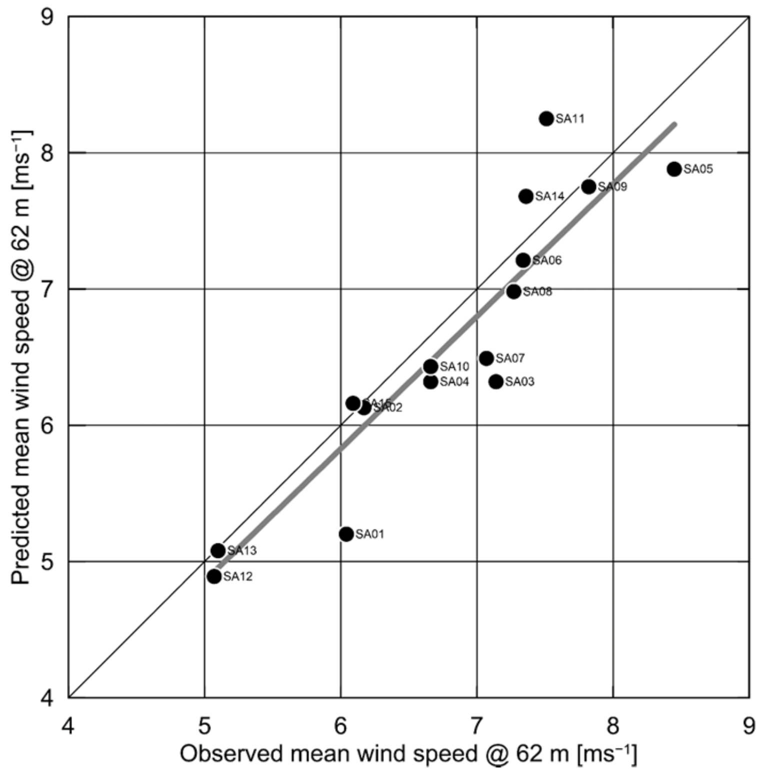

Figure 11. Observed and predicted annual mean wind speeds at the 15 WASA 1 and 2 sites; 62 m above ground level. The predictions were made using ESACCI 2015 land cover data.

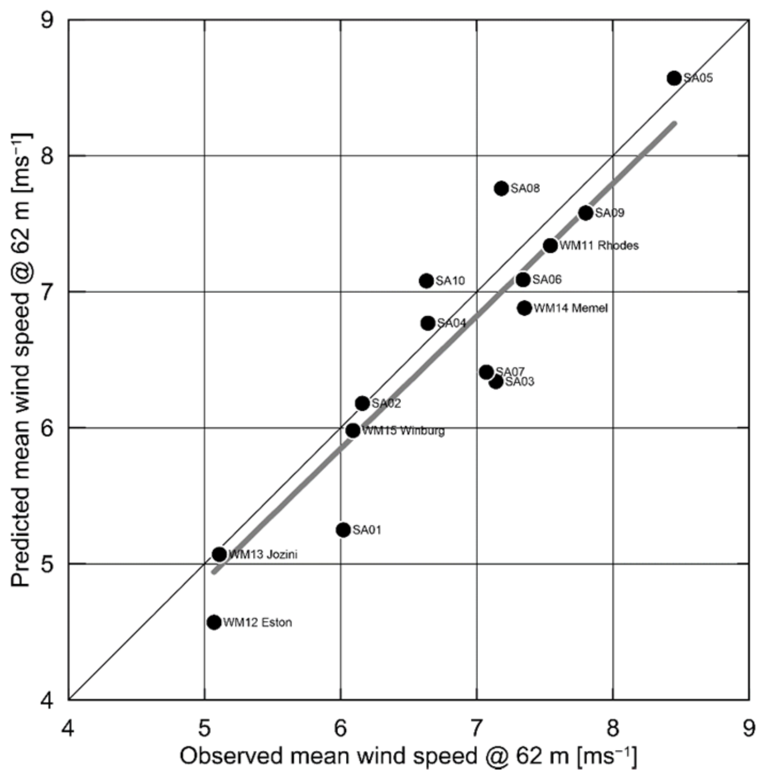

Figure 12. Observed and predicted annual mean wind speeds at the 15 WASA 1 and 2 sites; 62 m above ground level. The predictions were made using GlobCover 2009 land cover data.

4. Summary and conclusions

The present report, together with the accompanying maps and data sets in GIS-compatible formats, constitute the final outputs of *WP34.01c Report with ArcGIS ASC files*, and are updates and extensions to previous components *WP24.02 Microscale resource maps for WASA 2 domain (part of All SA)* and *WP24.03 Resource maps for WASA1 domain updated*. The entire land area of South Africa has been modelled with a system of mesoscale and microscale models, in order to obtain a realistic and updated estimate of South Africa's wind resources.

The modelling procedures have been improved since the WASA 1 domain was modelled in 2014; in particular the DTU Generalisation procedure and WAsP Resource Mapping System. In addition, the modelling is now based on the full 8-year temporal coverage in comparison to earlier shorter modelling periods. The topographical input data – 100-m elevation grids and 300-m land cover (roughness length) grids – are updated compared to the WASA 1 modelling, and cover the entire country using the most contemporary data.

The results of the modelling have been vastly extended and improved compared to WASA 1 and 2. Detailed wind resource maps in GIS-compatible format now exist for all of South Africa, not only for 100 m a.g.l., but also for 50 and 150 m a.g.l. In addition to these data sets, comprehensive results are provided for all 250-m modelling nodes at three modelling heights: Weibull *A*- and *k*-parameters and the frequencies of occurrence (wind rose) for 12 sectors. These data sets make it possible to calculate additional statistics for all of South Africa; e.g. specific mean power density from 0-25 ms^{-1}, energy yield for any given wind turbine, capacity factors, etc.

Finally, the wind-climatological inputs to the microscale modelling are also provided, in the form of WAsP LIB files for every 3.33-km mesoscale modelling node. These generalised wind climates make it possible to perform detailed calculations anywhere in South Africa, e.g. for wind farm project planning and design of measurement campaigns. However, it must be stressed that the results obtained here do not replace the detailed measurements required for planning and development of actual wind farms; they just add to the quality that can be obtained.

It should be borne in mind that the validation of the modelling does not have the same quality in all parts of South Africa. In the WASA 1 domain, the validation is based on long time-series of high-quality wind data, in an area of South Africa that is well described and analysed; whereas the measurements are of much shorter duration in the WASA 2 domain. For the rest of South Africa, no validation data were available at the time of writing and the terrain and weather have not been studied in the same detail.

The metadata documents given in Appendix B provide further information on the data sets: the purpose, methodology, limitations and some additional information available at the WASA download web site.

The work reported here will continue in Phase 3 of the WASA project, in the years 2019-20. During the work, it has become apparent how important e.g. the land cover descriptions and atmospheric stability are for the modelling. These are two topics that will be studied further, in order to obtain the best possible updated wind resource maps at the end of WASA Phase 3.

Acknowledgements

WASA team for provision of wind-climatological and topographical data. WAsP development teams at DTU Wind Energy and World in a Box Oy for Frogfoot development and application. SRTM Plus data were downloaded from NASA's Land Processes Distributed Active Archive Center (LP DAAC) located at the USGS Earth Resources Observation and Science (EROS) Center. ESA CCI data are copyright © ESA Climate Change Initiative – Land Cover project 2017. Province boundaries in South Africa were provided by the Municipal Demarcation Board (MDB).

The Wind Atlas for South Africa (WASA) project is an initiative of the South African Government, Department of Energy (DoE), and the project is co-funded by GEF through South African Wind Energy Programme (SAWEP) and the Royal Danish Embassy with UNDP support. The WASA Project Steering Committee has members from DoE (chair), DEA, DST, UNDP, Royal Danish Embassy, and SANEDI.

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A ESACCI main land cover codes and labels

The table below shows the main ESACCI land cover codes and labels (UCL-Geomatics, 2017). The roughness lengths z_0 assigned to the different classes are shown too.

Value	Label	Colour	Roughness [m]
0	No Data		n/a
10	Cropland, rain-fed		0.10
20	Cropland, irrigated or post-flooding		0.05
30	Mosaic cropland (>50%) Natural vegetation (tree, shrub, herbaceous cover) (<50%)		0.20
40	Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) Cropland (<50%)		0.30
50	Tree cover, broadleaved, evergreen, closed to open (>15%)		1.50
60	Tree cover, broadleaved, deciduous, closed to open (>15%)		1.00
70	Tree cover, needle-leaved, evergreen, closed to open (>15%)		1.50
80	Tree cover, needle-leaved, deciduous, closed to open (>15%)		1.20
90	Tree cover, mixed leaf type (broadleaved and needle-leaved)		1.50
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)		0.20
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)		0.10
120	Shrubland		0.10
130	Grassland		0.03
140	Lichens and mosses		0.01
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)		0.05
160	Tree cover, flooded, fresh or brackish water		0.80
170	Tree cover, flooded, saline water		0.60
180	Shrub or herbaceous cover, flooded, fresh/saline/brackish water		0.10
190	Urban areas		1.00
200	Bare areas		0.005
210	Water bodies		0
220	Permanent snow and ice		0.003

B Metadata for “High-Resolution Wind Resource Map for South Africa 2018”

The next 15 pages contain the original metadata document for all of South Africa.

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DTU Wind Energy

High-Resolution Wind Resource Map for South Africa 2018
December 2018

METADATA	
Data set name	High-Resolution Wind Resource Map for South Africa 2018
Data set coverage	Land area of South Africa
Data set date	Compiled and published in December 2018
Data set creator	DTU Wind Energy and World in a Box Oy
Data set publisher	DTU Wind Energy and Council for Scientific and Industrial Research
Contact persons	Niels G. Mortensen (DTU) or Ursula von Saint Ange (CSIR)
Contact details	nimo@dtu.dk (DTU) or UvstAnge@csir.co.za (CSIR)
Data type	Raster data sets with a grid cell size of 250 m
Data format	ArcGIS ASC
File name(s)	ZA_<province>_<resolution>_<parameter>_<version ID>.asc
Data origin	Microscale WAsP modelling in each grid point; no interpolation
Data storage	Wind Atlas for South Africa download site or DTU Data

DATA PARAMETERS	
Mean wind speed	Annual mean wind speed U [ms^{-1}] @ 50, 100 and 150 m a.g.l.
Mean power density	Annual mean power density P [Wm^{-2}] @ 50, 100 and 150 m a.g.l.
Mean air density	Annual mean air density ρ [kgm^{-3}] @ 50, 100 and 150 m a.g.l.
Terrain elevation	Elevation of modelling site in [m] above mean sea level
Ruggedness index RIX	Site RIX value [n/a] calculated by WAsP (standard parameters)

COORDINATE SYSTEM	
Projection	Universal Transverse Mercator (UTM)
Zone number	34S (NC, WC) and 35S (EC, FS, GT, LP, MP, NL, NW)
Datum	World Geodetic System 1984 (WGS 84)

TECHNOLOGY	
Modelling software	WAsP Resource Mapping System with WAsP engine (version 12)
Wind-climatological input	3.3-km NWA, WRF-based, code name L18_C18_F1.0_D1.0(8y)
Elevation input	100-m elevation grid derived from SRTM+ (NASA version 3)
Land cover input	300-m land cover grid derived from ESACCI 2015 (version 2.0.7)
Air density input	0.5-degree CFSR global reanalysis data 2011-2018 (version 2)

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DESCRIPTION

Purpose

These data sets were created as part of the Wind Atlas for South Africa project (WASA). The wind resource maps were originally designed for inclusion in GIS-based strategic environmental assessments (SEA) for the entire land mass of South Africa. The maps cover the 9 provinces of South Africa, corresponding to an area of about 1,221,000 km^2. The wind resource maps are preliminary in nature, even though they are based on high-quality data and contemporary models; maps are subject to change without notice if and when more accurate and reliable data, models and procedures become available.

Methodology

Reference is made to the information and documentation available from www.wasa.csir.co.za. A more detailed description of the data sets available are given at the end of this document. Validation is reported elsewhere.

Limitations

The data set is limited by the operational envelopes of the wind atlas methodology and the WAsP models. The accuracy depends on a) the accuracy of the VNWA, which has been validated against the data from 15 WASA measurement masts, b) the WAsP 12 microscale modelling and c) the input topographical data.

In complex terrain (RIX > 5%), the wind resources may be significantly over-estimated by the WAsP microscale modelling. Above and close to built-up areas like cities, towns and villages, the results are less reliable. Close to and above forested areas, the results are also less reliable and should be interpreted and used accordingly.

The data set was designed specifically for planning purposes and should be used with utmost care for design, development and detailed assessments of actual wind farms; where local, on-site measurements are strongly recommended.

Available documentation

The wind atlas methodology is described in the European Wind Atlas (1989); the application of WAsP in the software documentation, see www.wasp.dk. The Validated Numerical Wind Atlas (VNWA) for South Africa is a product of the Wind Atlas for South Africa project (WASA) and is described on the WASA download pages.

Acknowledgements

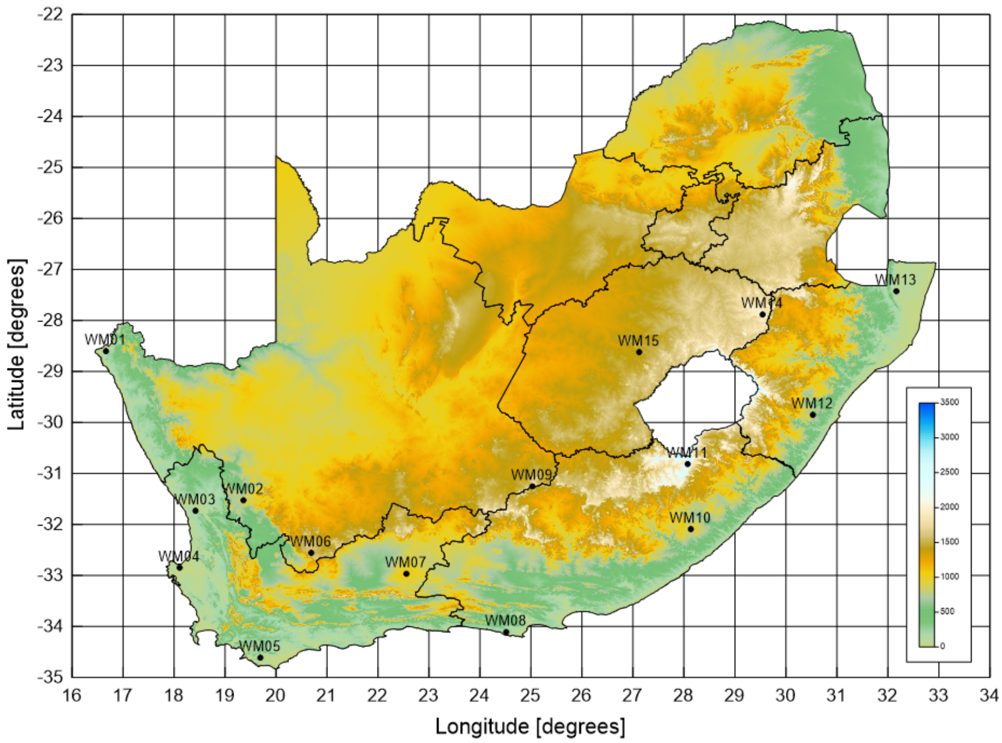
WASA team for provision of wind-climatological and topographical data. WAsP development teams at DTU Wind Energy and at World in a Box Oy for WAsP Resource Mapping System (Frogfoot) development and application. SRTM Plus data were downloaded from NASA's Land Processes Distributed Active Archive Center (LP DAAC) located at the USGS Earth Resources Observation and Science (EROS) Center. ESACCI land cover data are copyright © ESA Climate Change Initiative – Land Cover project 2017. South African province boundaries by Municipal Demarcation Board (MDB).

DISCLAIMER

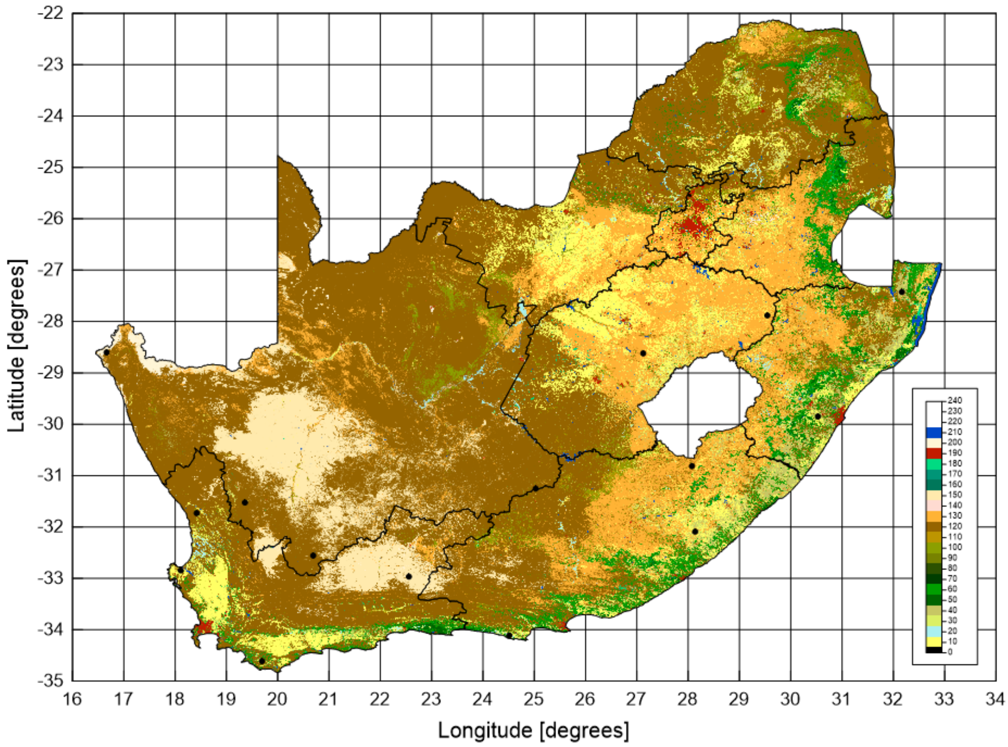
In no event will the Technical University of Denmark (DTU) or any person acting on behalf of DTU be liable for any damage, including any lost profits, lost savings, or other incidental or consequential damages arising out of the use or inability to use the information and data provided in this data set, even if DTU has been advised of the possibility of such damage, or for any claim by any other party.

The principles, rules, exclusions and limitations provided in the Disclaimer on the WASA download site apply to the data set described here as well, even though this data set may not be distributed via the web site. By using this data set, you agree that the exclusions and limitations of liability set out in this disclaimer are reasonable. If you do not think they are reasonable, you must not use this data set.

South Africa terrain elevation (SRTM+, NASA version 3)



South Africa land cover (ESACCI version 2.0.7, 2015)



Detailed wind resource maps

The data sets are organised according to each of the nine provinces of South Africa.

ISO	Province	Capital	Area	Fraction	UTM
EC	Eastern Cape	Bhisho (Bisho)	168,966 km^2	14%	35
FS	Free State	Bloemfontein	129,825 km^2	11%	35
GT	Gauteng	Johannesburg	18,178 km^2	1%	35
LP	Limpopo	Polokwane (Pietersburg)	125,754 km^2	10%	35
MP	Mpumalanga	Nelspruit	76,495 km^2	6%	35
NC	Northern Cape	Kimberley	372,889 km^2	31%	34
NL	KwaZulu-Natal	Pietermaritzburg	94,361 km^2	8%	35
NW	North West	Mahikeng (Mafikeng)	104,882 km^2	9%	35
WC	Western Cape	Cape Town	129,462 km^2	11%	34
ZA	Republic of South Africa	Pretoria, Cape Town, Bloemfontein	1,220,813 km^2	100%	

For each province, the following information is provided in metric ArcGIS ASC format grid files:

- Annual mean wind speed [ms^{-1}]
- Annual mean power density [Wm^{-2}]
- Annual mean air density [kgm^{-3}]
- Terrain surface elevation [m a.s.l.]
- Terrain ruggedness index, RIX

Wind information given for 50, 100 and 150 m above ground level and all data sets are given at 250 m horizontal resolution. The ASC files are distributed in ZIP archives.

Database of wind climates

For each province, the following information is provided in ASCII TXT format files:

- Weibull *A*- and *k*-parameters for 12 sectors at each node and height
- Wind direction distribution (rose) for 12 sectors at each node and height

Climate information at each of the 250-m modelling grid points makes it possible to calculate, say, specific mean power density from 0-25 ms^{-1}, energy yield for any given wind turbine, capacity factor for any given wind turbine, etc.

Wind climate and energy information is given for 50, 100 and 150 m above ground level. Data are stored in ASCII text files with the following format:

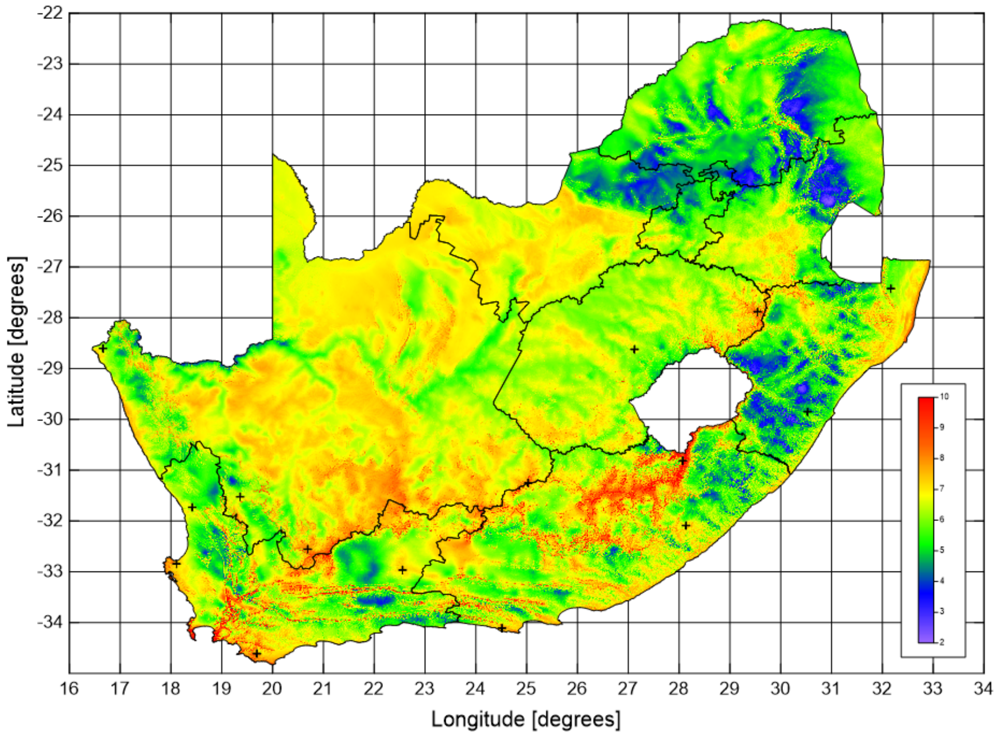
- *JobID; x; y; z; SectorIndex; A; k; f;*

where *x* is UTM Easting [m], *y* is UTM Northing [m], *z* is height above ground level [m], *SectorIndex* is a sector index from 1 to 12 clockwise starting from north, *A* is the Weibull scale parameter [ms^{-1}], *k* is the Weibull scale parameter, and *f* is sector frequency. The TXT files are distributed in ZIP archives.

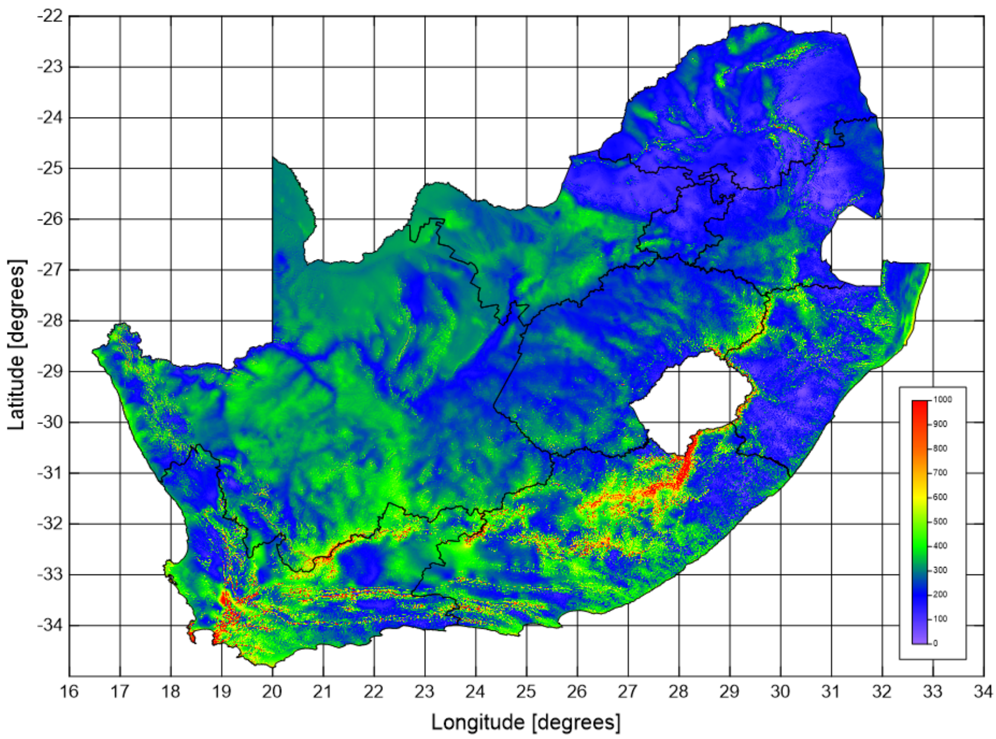
For South Africa, the following information is provided in geographical ArcGIS ASC format grid files:

- Terrain land cover classification code (ESACCI, 2015)
- Transformation table from land cover to terrain surface roughness in [m]

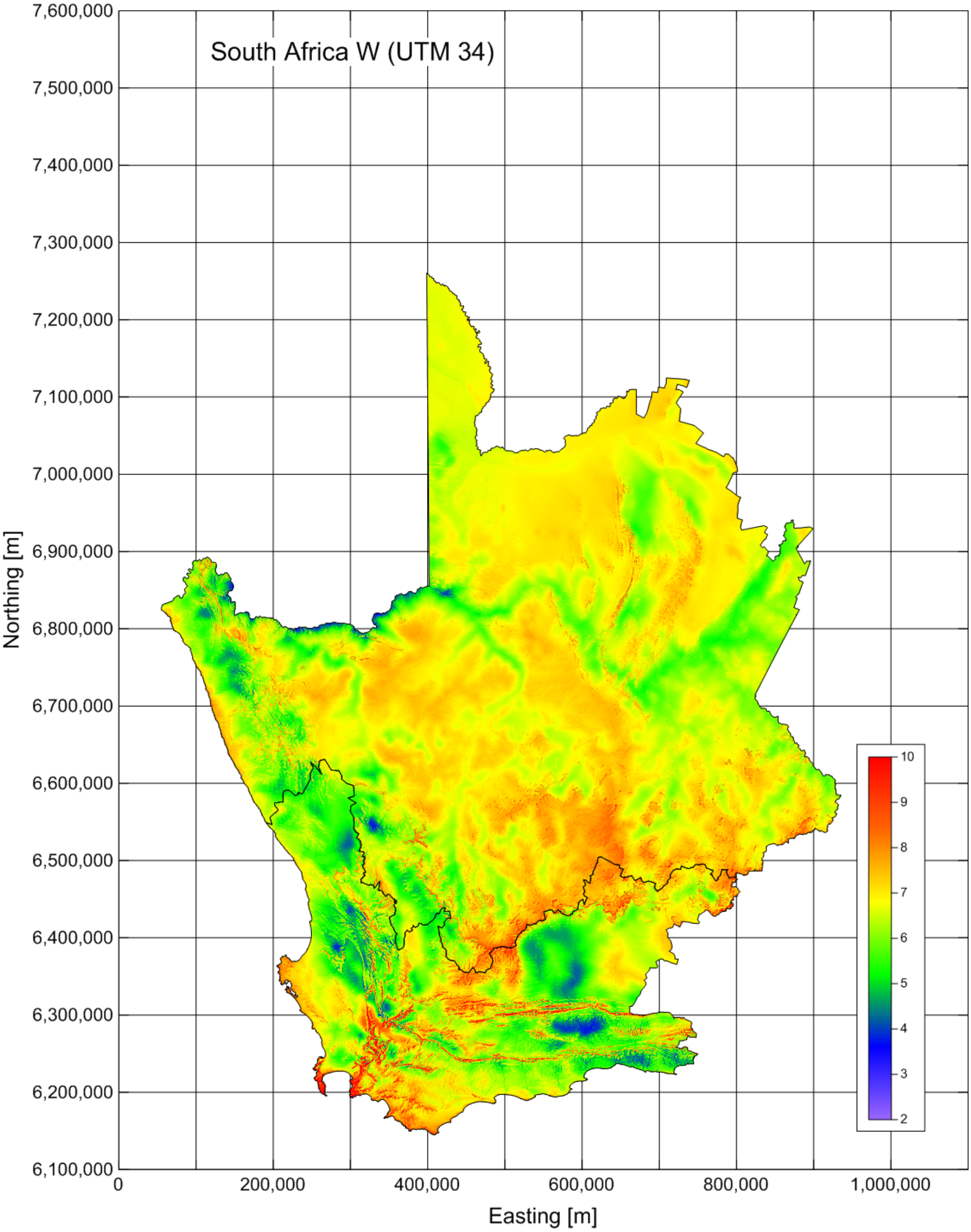
South Africa mean wind speed [ms^{-1}] @ 100 m a.g.l.



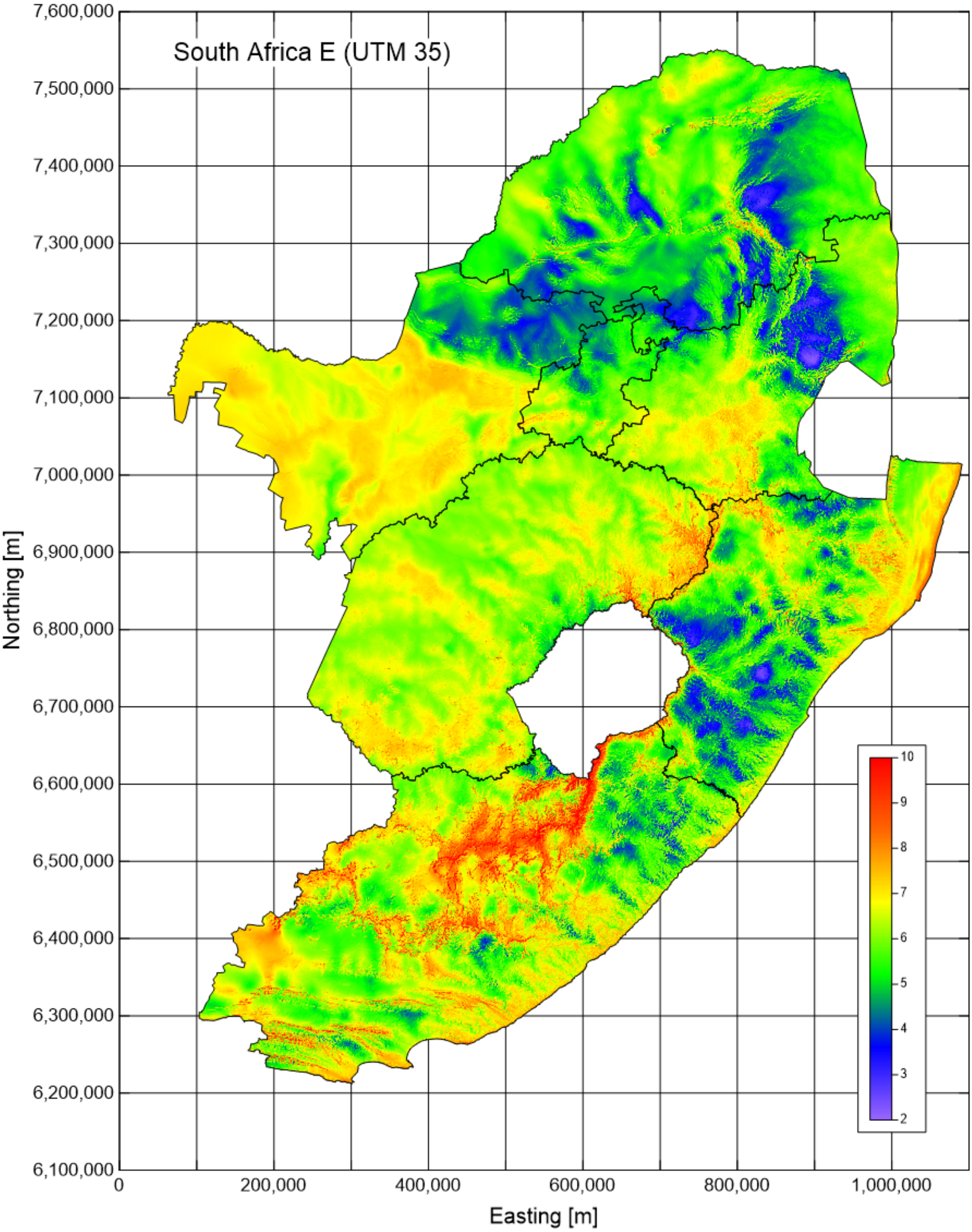
South Africa mean power density [Wm^{-2}] @ 100 m a.g.l.



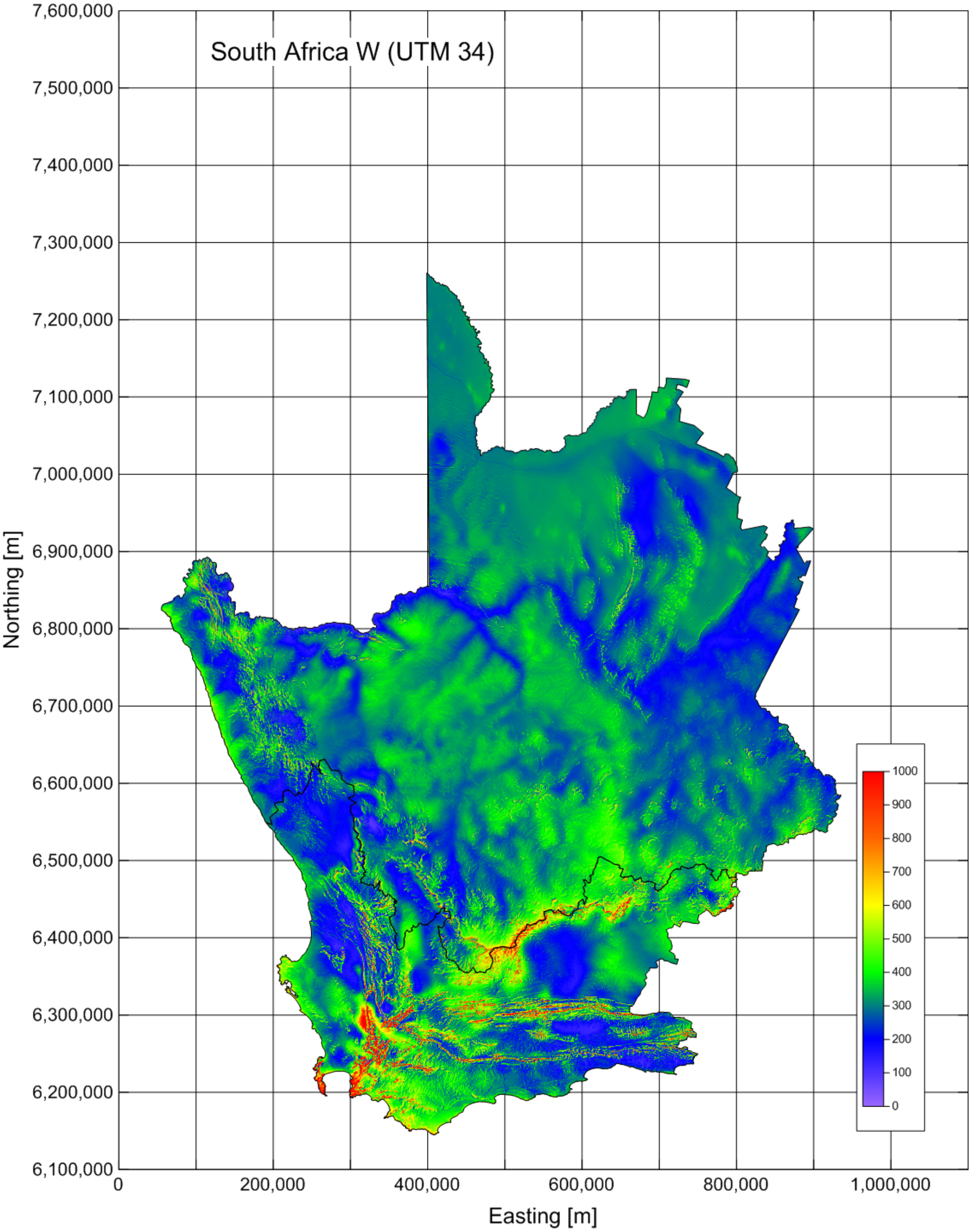
South Africa W mean wind speed at 100 m a.g.l.



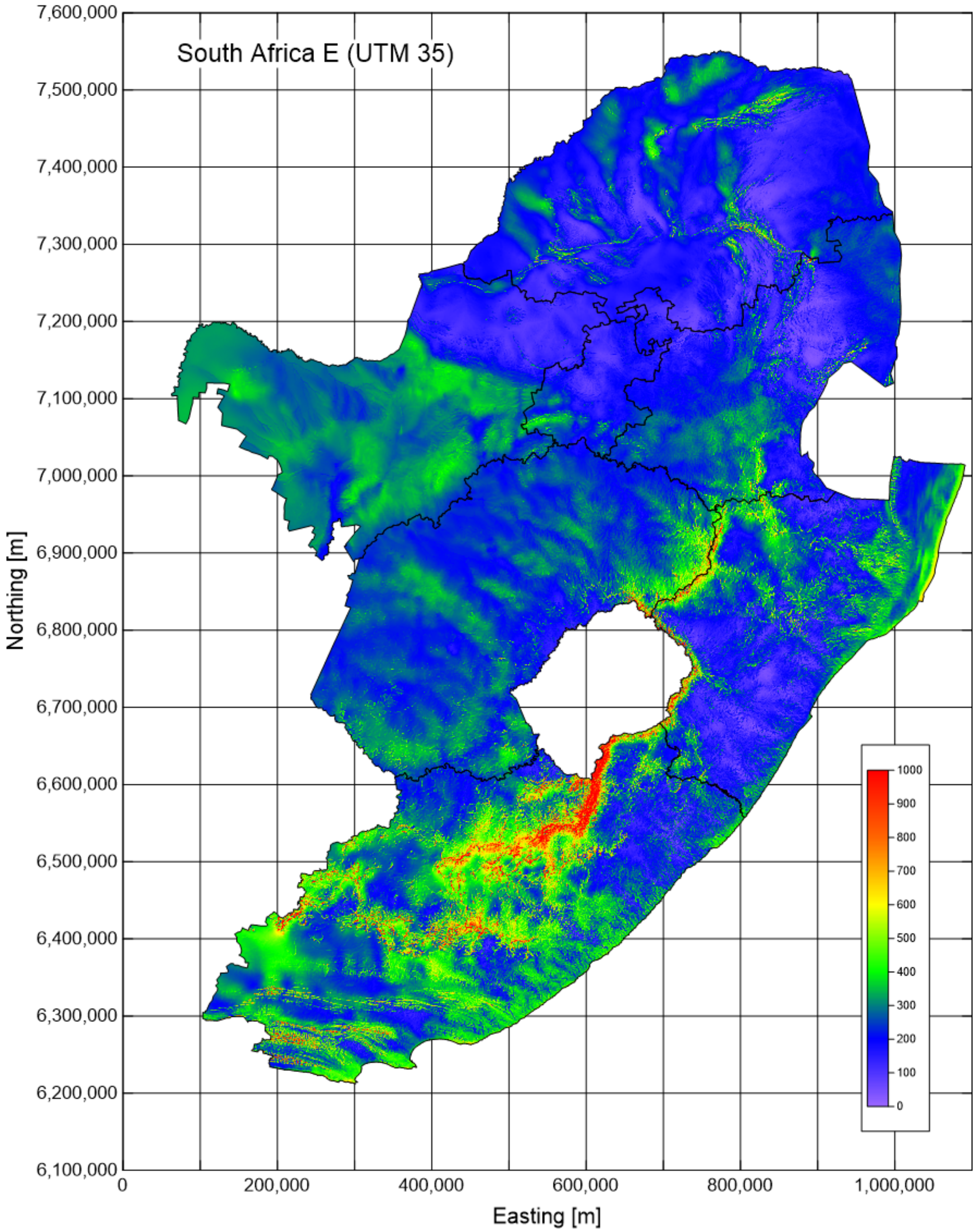
South Africa E mean wind speed at 100 m a.g.l.



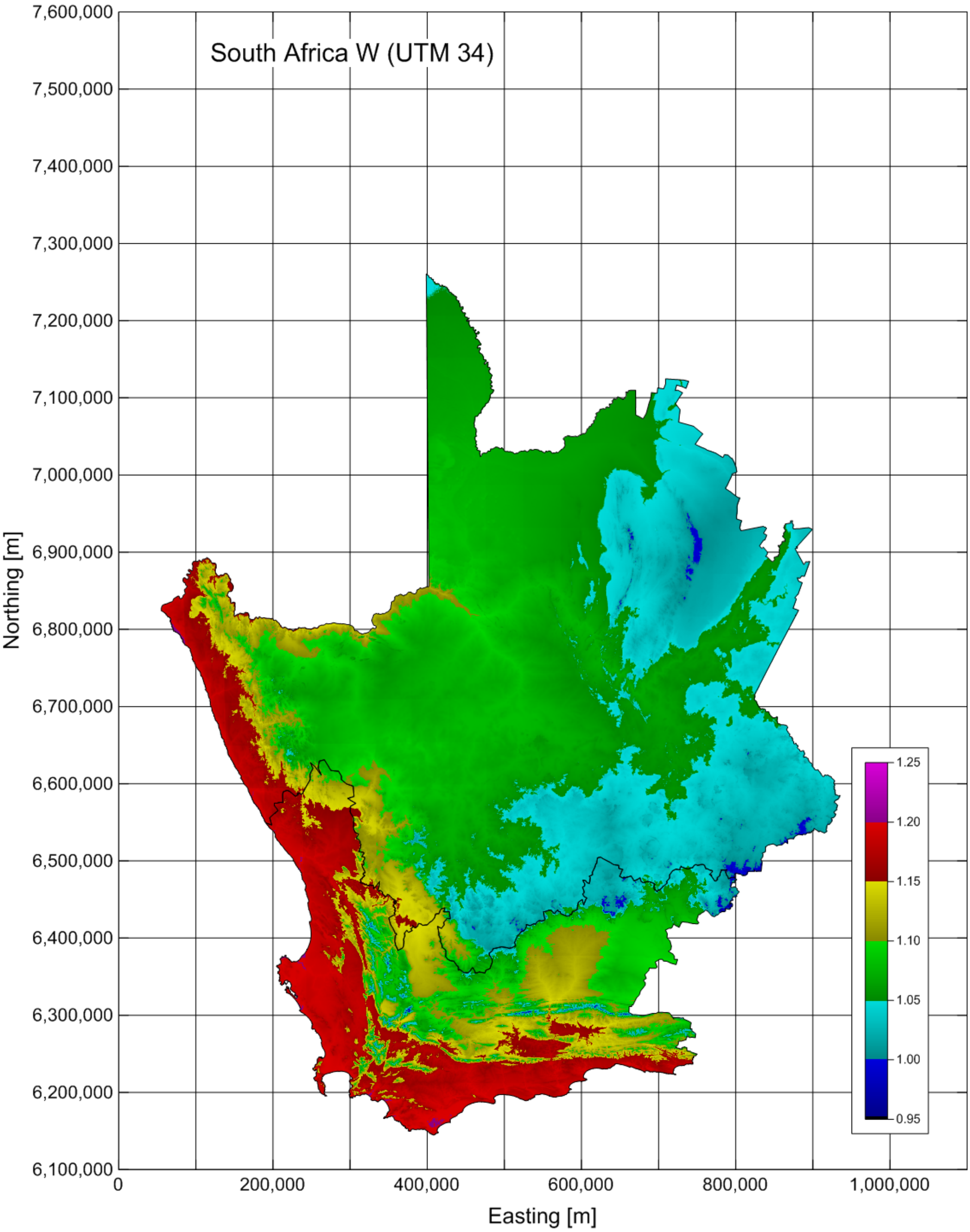
South Africa W mean power density at 100 m a.g.l.



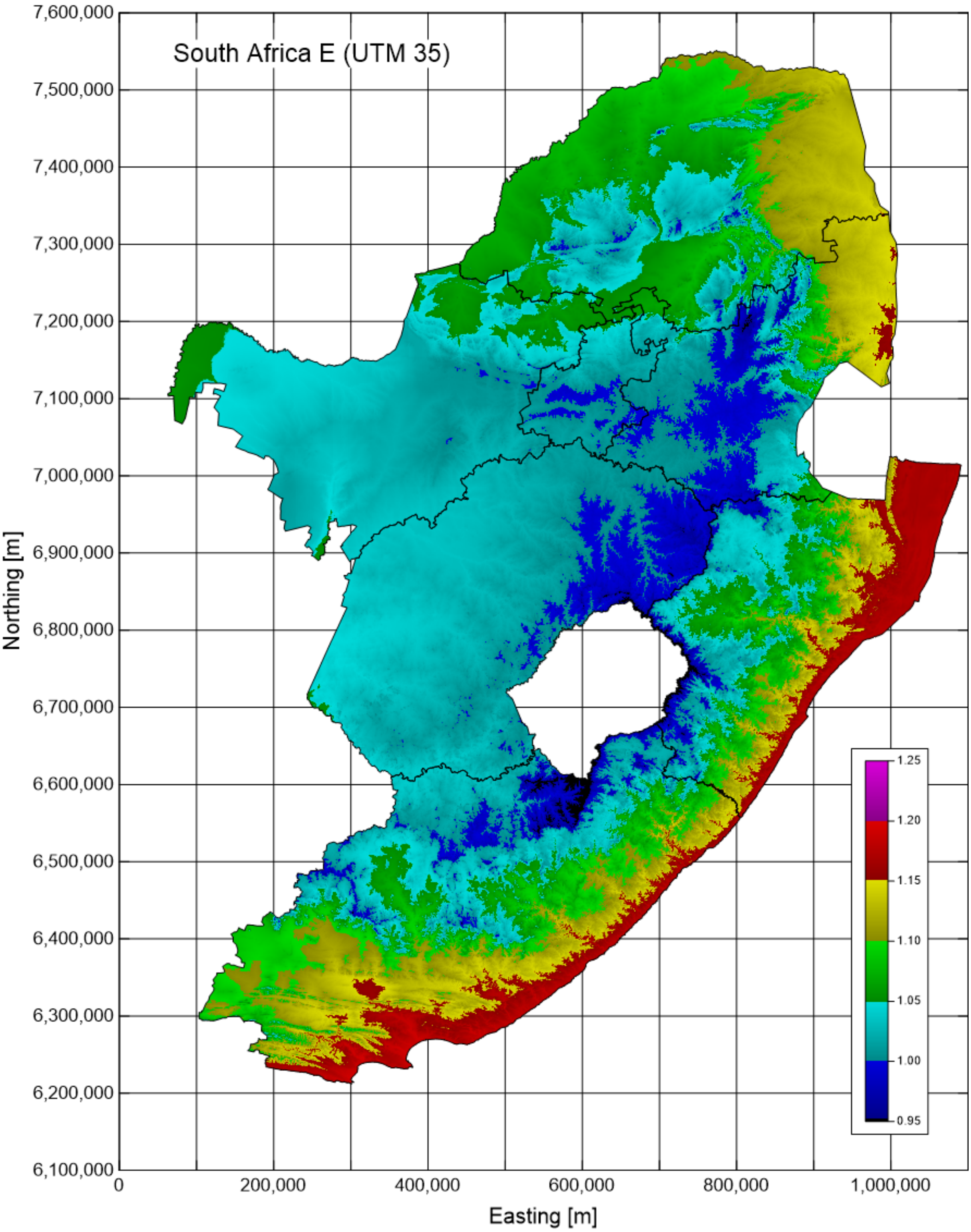
South Africa E mean power density at 100 m a.g.l.



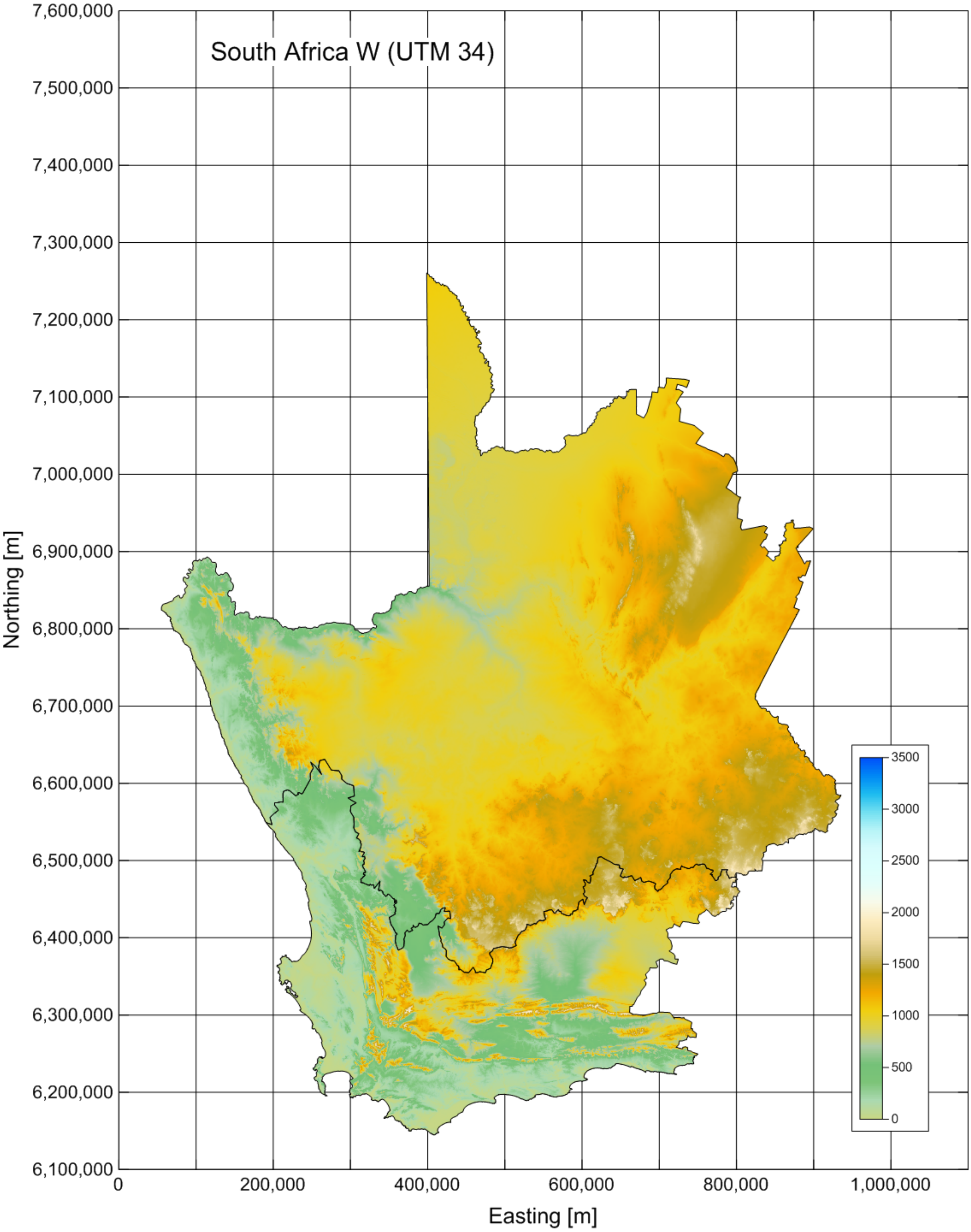
South Africa W air density



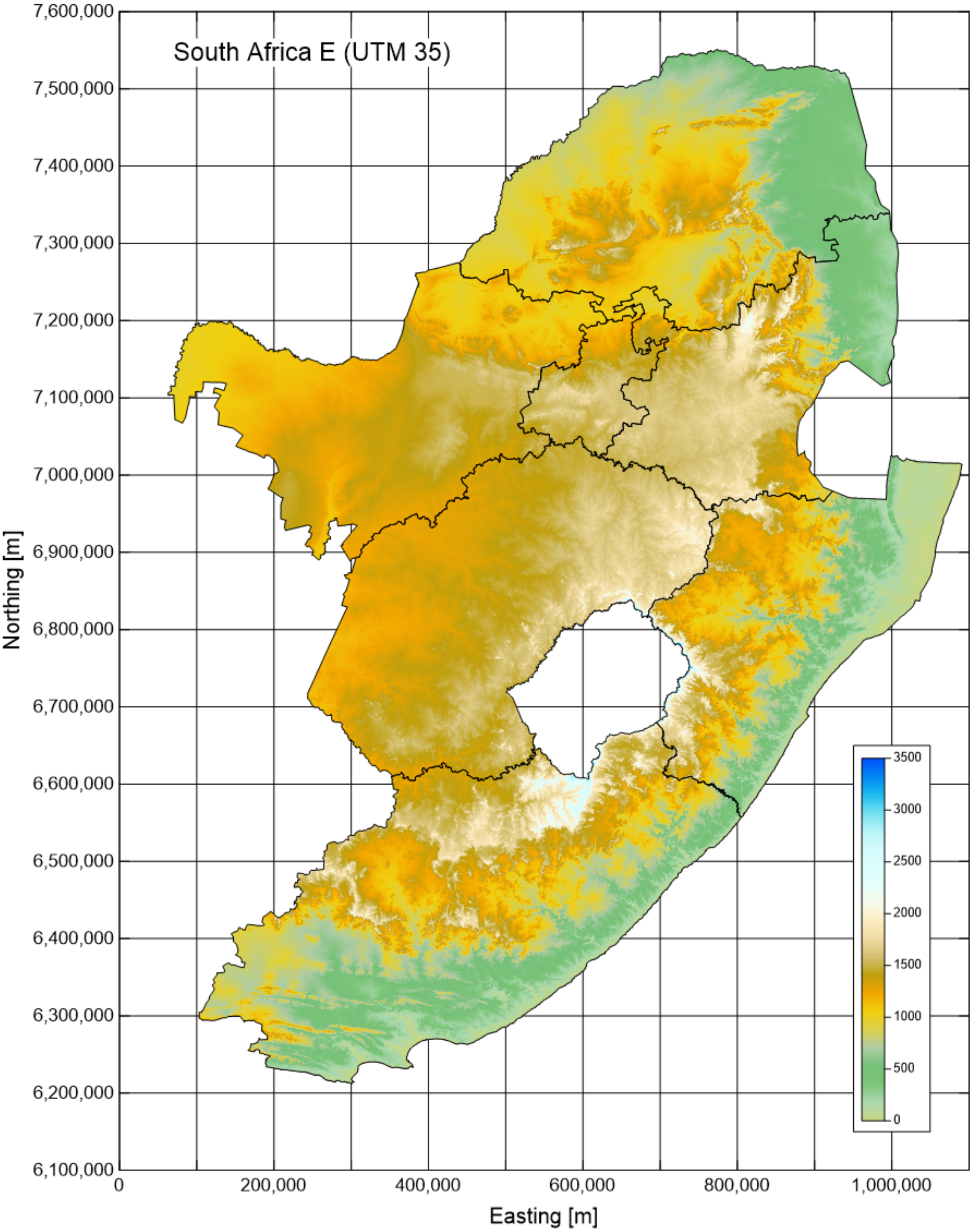
South Africa E air density



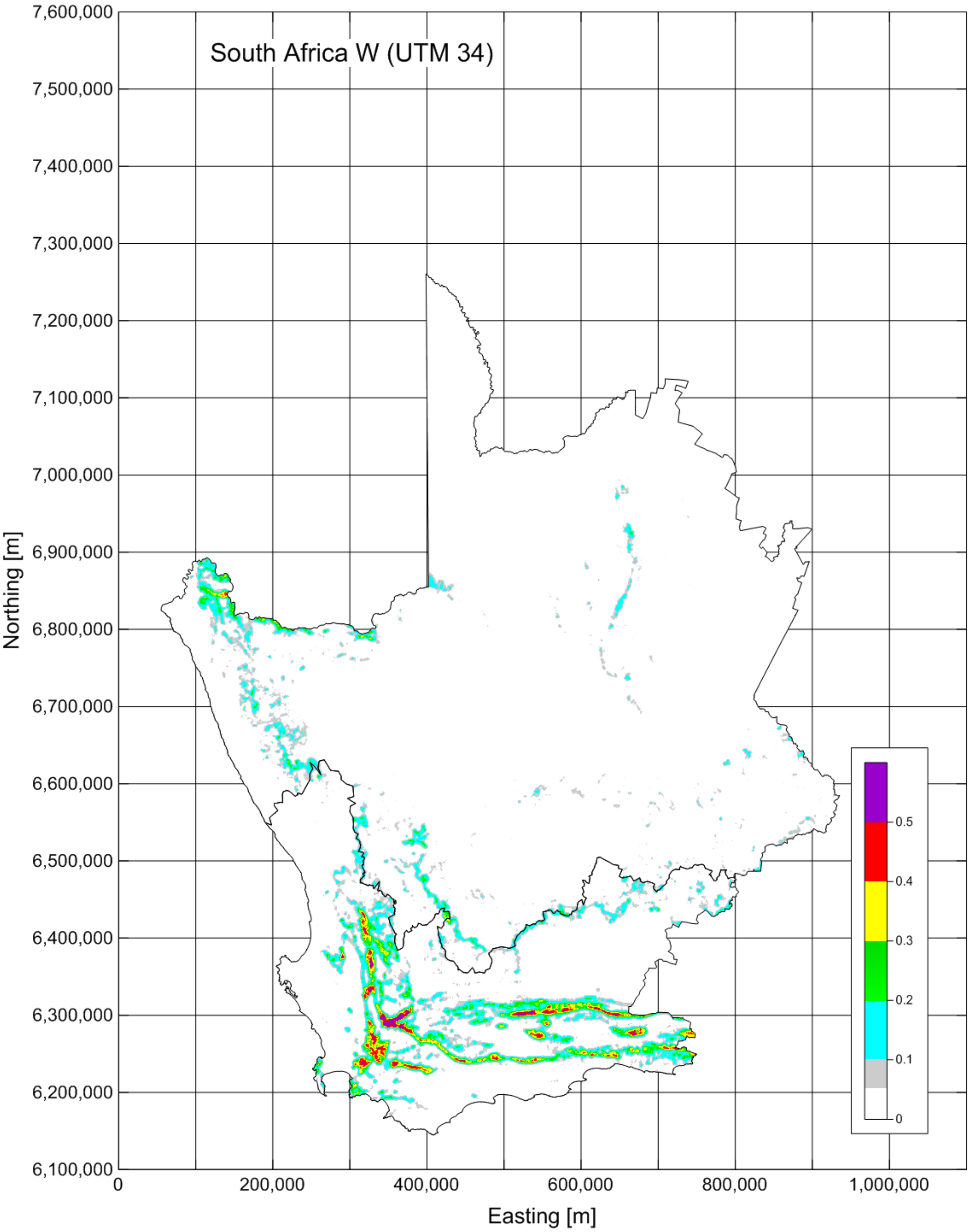
South Africa W elevation



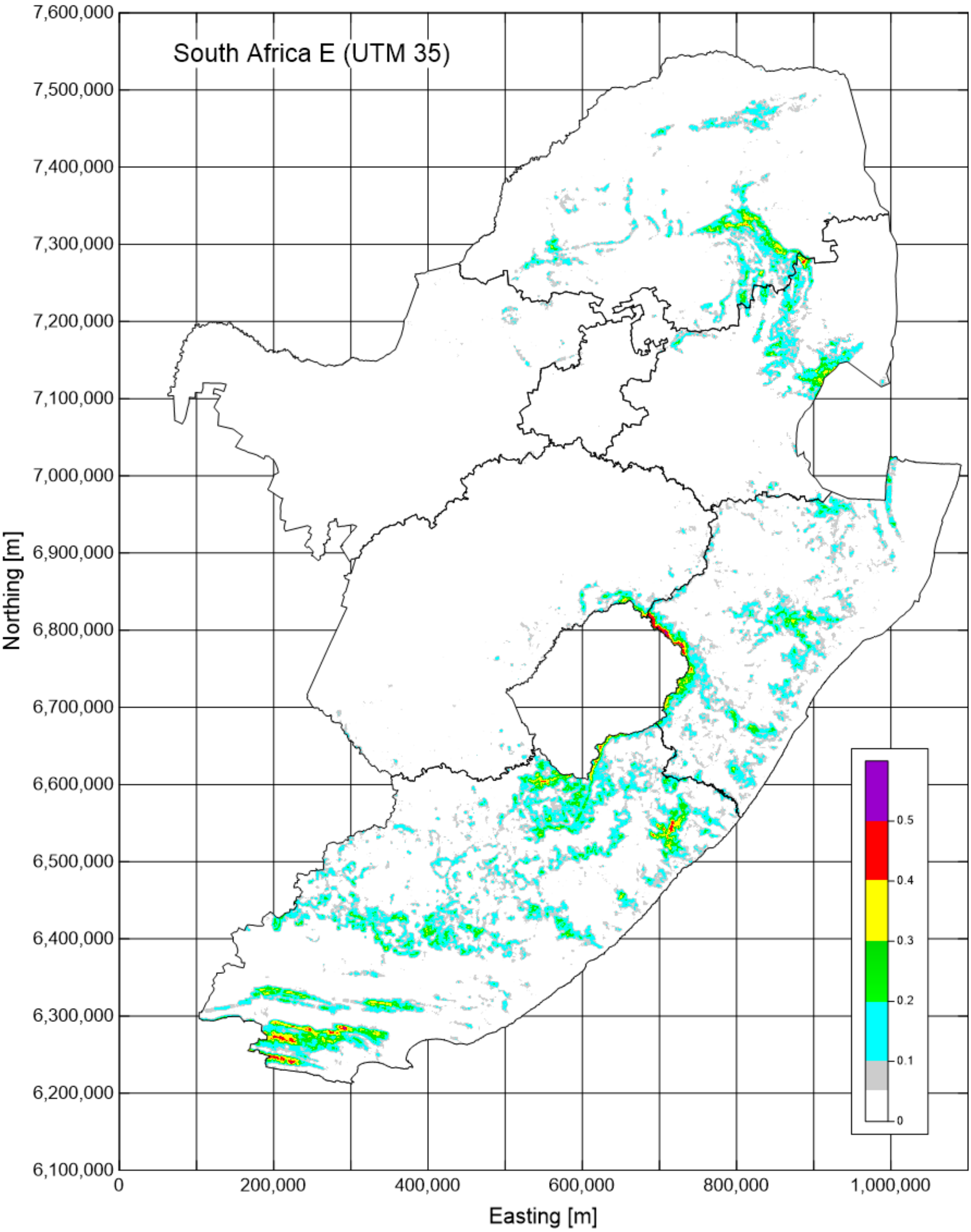
South Africa E elevation



South Africa W ruggedness index



South Africa E ruggedness index



C Files on files.dtu.dk

Files available the WASA download site are listed below. The format of files given in the metadata documents. The data set comes in five categories:

- Database of high-resolution maps and data
- Database of high-resolution wind statistics
- Database of generalised wind climate files
- Elevation grids for each province
- Land cover grid for each province

Database of high-resolution maps and data

The folder above contains one ZIP archive per province:

1. ZA_EC_250_All_20181214.zip
2. ZA_FS_250_All_20181214.zip
3. ZA_GT_250_All_20181214.zip
4. ZA_LP_250_All_20181214.zip
5. ZA_MP_250_All_20181214.zip
6. ZA_NC_250_All_20181214.zip
7. ZA_NL_250_All_20181214.zip
8. ZA_NW_250_All_20181214.zip
9. ZA_WC_250_All_20181214.zip

Metadata documents and graphics files for data sets:

1. High-Resolution Wind Resource Map for South Africa 2018.pdf
2. South Africa mean wind speed 100 m.kmz
3. South Africa mean power density 100 m.kmz

Database of high-resolution wind statistics

One ZIP archive per province:

1. ZA_EC_250_Akf_ClimateSectorwise_20181214.zip
2. ZA_FS_250_Akf_ClimateSectorwise_20181214.zip
3. ZA_GT_250_Akf_ClimateSectorwise_20181214.zip
4. ZA_LP_250_Akf_ClimateSectorwise_20181214.zip
5. ZA_MP_250_Akf_ClimateSectorwise_20181214.zip
6. ZA_NC_250_Akf_ClimateSectorwise_20181214.zip
7. ZA_NL_250_Akf_ClimateSectorwise_20181214.zip
8. ZA_NW_250_Akf_ClimateSectorwise_20181214.zip
9. ZA_WC_250_Akf_ClimateSectorwise_20181214.zip

Database of generalised wind climate files

One ZIP archive of LIB file data for all of South Africa:

- lib_2010-2017_WASA2.nc (WASA 3.33-km data for SA)

Coordinates of LIB files in CSV or DAT files:

- WASA_Libs_coords.csv
- WASA_Libs_coords.dat