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Projected potential for wind energy generation in South Africa under conditions of climate change

by

Lynette Herbst

Submitted in partial fulfilment of the requirements for the degree

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DECLARATION

I, Lynette Herbst, declare that the dissertation, which I hereby submit for the degree Master of Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

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Projected potential for wind energy generation in South Africa under conditions of climate change

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SUMMARY

The South African wind energy sector is developing rapidly with numerous wind energy facilities currently being commissioned. According to the Intergovernmental Panel on Climate Change (IPCC), some risks and opportunities for wind power generation as a result of climate change could be anticipated in future.

The objectives of this study were therefore to:

a. determine whether seasonal near-surface winds over South Africa, as generated by a Regional Climate Model (RCM) using boundary conditions supplied from coupled Global Circulation Models (GCMs), during a reference period of 1981 to 2005, are realistically represented;
b. establish whether differences exist between seasonal near-surface winds calculated for the reference period (1981-2005) versus a projected period of 2051 to 2075, incorporating two future Representative Concentration Pathways (RCP4.5 and RCP8.5);
c. determine the projected impact of climate change on wind power density.

Wind output from sophisticated atmospheric models (GCMs) provides valuable information on projected changes in wind patterns as a result of climate change. Through the CORDEX-Africa (COordinated Regional Downscaling EXperiment) project, the so-

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called RCA4 RCM has, by dynamically downscaling eight GCMs, produced a substantial collection of regional climate simulations. RCA4 RCM data were employed in this study to determine the impacts of climate change on South African winds and wind power resources.

Mean seasonal winds speeds were calculated for 1981 to 2005 for observed (ERA-Interim reanalysis) and RCA4 RCM output. The Root Mean Square Error (RMSE) between ERA-Interim and RCA4 RCM simulations was calculated. Wind speed frequencies were then simulated from ERA-Interim and RCA4 RCM data for each season and for different speed categories. RCA4 RCM data were also verified independently against weather station data. The RCA4 RCM was found to perform well, but a positive bias in the simulations of winds was detected.

Mean seasonal winds were calculated for the future period using RCA4 RCM output for the two pathways. Anomalies between RCA4 RCM output in the historical and future periods were then calculated and expressed as percentage changes in mean seasonal wind speeds. Wind speed frequencies of different categories were also simulated for the projected period under the two pathways. Anomalies between the historical and reference periods were also calculated for frequencies. Future projections indicate that parts of the country not typically considered as having substantial wind energy resources may become useful, such as north-eastern South Africa. As for the areas in which wind farms are currently being developed, mean wind speeds are projected to decrease by only 2% in two of the seasons, and to increase in the other two.

RCA4 RCM data were corrected for biases. Corrected mean wind speeds were then used as input to the calculation of wind power density in the projected period. Wind power density is projected to remain fairly similar in the future period as the historical period, as wind speeds have been projected to change by a maximum of 9%, which is a very small change when considered in terms of wind power density calculations.

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LIST OF ACRONYMS

agl:	above ground level
AOGCM:	Atmosphere Ocean General Circulation Model
AR5:	Fifth Assessment Report
CCC CGCMI:	Canadian Climate Centre Combined General Circulation Model
CFS-R:	Climate Forecast System Reanalysis
CMIP:	Coupled Model Intercomparison Project
CORDEX:	Coordinated Regional Downscaling Experiment
CWEA:	Canadian Wind Energy Atlas
DJF:	December-January-February
DoE:	Department of Energy
ECMWF:	European Centre for Medium-range Weather Forecasts
ENSO:	El Niño Southern Oscillation
GCAM:	Global Change Assessment Model
GCM:	General Circulation Model
GFDL:	Geophysical Fluid Dynamics Laboratory
GHG:	Greenhouse Gas
GIS:	Geographical Information System
GISS:	Goddard Institute for Space Studies
GrADS:	Grid Analysis and Display System
HadCMII:	Hadley Center's Combined Circulation Model
HadAM3H:	Hadley Center's Atmospheric Model
IPCC:	Intergovernmental Panel on Climate Change
IPSL:	Institut Pierre Simon Laplace
ITCZ:	Inter-Tropical Convergence Zone
JJA:	June-July-August
MAM:	March-April-May
MESSAGE:	Model for Energy Supply Strategy Alternatives and their General Environmental impact
MIROC:	Model for Interdisciplinary Research On Climate
MPI:	Max Planck Institute

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MRI: Meteorological Research Institute

NCAR: National Center for Atmospheric Research

NCEP: National Centers for Environmental Prediction

NNR: NCEP/NCAR Reanalysis

PRECIS: Providing Regional Climates for Impacts Studies

RCAO: Rossby Centre Coupled Atmosphere-Ocean

RCM: Regional Climate Model

RCP: Representative Concentration Pathways

REI4P: Renewable Energy Independent Power Producer Procurement Programme

RMSE: Root Mean Square Error

SAWS: South African Weather Service

SRES: Special Report on Emissions Scenarios

SON: September-October-November

VEMAP: Vegetation Ecosystem Modelling and Analysis Project

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CHAPTER 1

Introduction

1.1 BACKGROUND

It is known that energy received from the sun at the surface of the Earth is not homogeneously distributed. Equatorial areas absorb more energy per square meter in comparison to areas at the poles, a phenomenon that can be attributed to the shape of the Earth. This uneven distribution of solar energy absorption at Earth's surface leads to atmospheric temperature gradients when heat is emitted towards the atmosphere, which again leads to pressure gradients. In an effort to balance these pressure gradients, atmospheric particles start to move (from higher pressure areas to lower pressure areas), producing wind (Johnson and Erhardt, 2016). Winds are therefore, indirectly, a form of energy received from the sun, which could be utilized in our search for renewable energy generation (Jefferson, 2015).

Sophisticated atmospheric models are currently performing reasonably well in the simulation of wind fields, more so on larger scales (e.g. synoptic-scales) than on smaller scales (e.g. meso-scales). Wind output from these models could provide valuable information on wind prognoses, which include projected changes in wind patterns as a result of global warming. Such projections could provide information about the projected potential for energy generation under conditions of global warming (Johnson and Erhardt, 2016).

Some ground-breaking studies have already been conducted in projecting future wind pattern changes. Breslow and Sailor (2002) examined wind speed changes in the United States as simulated by the Canadian Climate Centre Combined General Circulation Model (CCC CGCMI) and the Hadley Center's Combined Circulation Model (HadCMII), both were General Circulation Models (GCM). Seasonally averaged mean wind speed data was extracted from Vegetation Ecosystem Modelling and Analysis Project (VEMAP) data. Historical datasets were constructed from model outputs of both GCMs for the period 1948 to 1978. In order to test the abilities of the two GCMs to replicate past climates, the data were evaluated against the VEMAP data for the same period. To ensure comparability with 30-year climatic norms as recognised in the climatology community and typical wind turbine lifespans, 25-year intervals were used in the assessments. Grid cell sizes of the three datasets differed (VEMAP data gridded at 0.5° by 0.5°; HadCMII cell sizes at 3.75° longitude by 2.5°

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latitude; CGCMI cell sizes at 3.75° by 3.75°). Discrepancies between cell sizes become problematic when GCM-predicted changes have to be applied to historical wind fields. The three datasets therefore have to be mapped to a consistent grid. An interpolation method of kriging (whereby interpolated values are modelled and weighted based on spatial covariance values) was applied to the GCM dataset to achieve consistency with the VEMAP grid. Another problem encountered was that the VEMAP and HadCMII datasets provide wind speeds at 10m, but CGCMI wind speeds could be extracted at 2m heights only. Using the logarithmic wind profile law, 2m wind speeds could be mapped to 10m heights. The deviation (in percentages) in wind speed changes for each of the GCMs' historical averages could then be calculated relative to the future climate. This process produced a gridded scaling factor that would then be applied to the historical data. There is more certainty in predicted changes in wind fields than in the absolute wind fields, hence the use of the gridded scaling factor. Wind speeds were projected to decrease by up to 3.2% in the 2050s and 4.5% in the 2100s.

In another study the Rossby Centre Coupled Atmosphere-Ocean (RCAO) Regional Climate Model (RCM) was employed by Pryor *et al.* (2005) to impart dynamically downscaled near-surface wind fields in northern Europe. Boundary conditions were derived from the ECHAM4/OPYC3 coupled atmospheric ocean GCM and the Hadley Centre's atmosphere-only GCM (HadAM3H). The name "ECHAM" is derived from the European Centre for Medium-range Weather Forecasting (ECMWF) atmospheric model that used a comprehensive parameterisation package developed in Hamburg. Three simulations were produced for each set of boundary conditions: a control run (1961-1990), an A2 carbon dioxide (CO_2) scenario run (2071-2100) and a B2 CO_2 scenario run (2071- 2100). "A2" and "B2"-scenarios refer to Intergovernmental Panel on Climate Change (IPCC) emissions "storylines" from the Special Report on Emissions Scenarios (SRES). A CO_2-emission increase of four times the 1990 emissions is projected in the A2-scenario; with a tripling in world population size. In the B2-scenario, CO_2-emissions are projected to increase by 2.5 times, and the world population is projected to double. The control run was compared to National Centre for Atmospheric Research/National Centres for Environmental Prediction (NCEP/NCAR Reanalysis - NNR) data to evaluate RCAO accuracy. The RCAO model produced four times daily output of the u- (west-to-east or zonal) and v- (south-to-north or meridonial) (Eichelberger *et al.,* 2008) components of 10m wind speeds. This data was used to calculate *inter alia* mean wind speeds, percentiles of wind distribution, Weibull

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parameters, extreme wind speeds and directional frequencies. Mean wind speeds were calculated for 30-year simulation periods. To compare RCAO simulations with NNR data, the mean absolute difference, Root Mean Square Error (RMSE) and correlation between the datasets were calculated. As in Breslow and Sailor (2002), grid structure (cell sizes) of the two models differed, and the data had to be aggregated to the NNR grid. Near-surface wind speeds for both of the projections indicated wind speeds higher than in the control period for the area studied.

Sailor *et al.* (2008) examined climate change impacts on wind power generation potential in the north-western United States. The authors selected four GCMs with output from the A1B (three-fold increase in CO_2-emissions, and a less than 50% population increase) and A2 IPCC scenarios to test. These models include ECHAM5/MPI-OM, GFDL-CM2.1, GISS-ER and the Japan Meteorological Agency's MRI-CGCM2.3.2. Data were statistically downscaled. Control period (1964-2000) data was compared with that of airport weather stations located within the study region. Observed daily average wind speeds were combined to calculate averaged monthly wind speeds for comparison with GCM output as well as downscaled data. GCM and downscaled data were compared to observed data using RMSE and index of agreement statistics. Agreement between downscaled outputs from different models was found to be far higher than that of the GCM outputs. Wind speed values are produced at 10m and had to be increased to 50m for wind power generation calculation using the power law profile for wind speeds. The 50m values were then compared to a default $5m.s^{-1}$ cut-in speed as in most commercial wind turbines. If values were below the cut-in speed, they were reduced to 0 to indicate that no power could be generated. The authors developed a method for mapping daily-resolution downscaled data to the hourly level. Hourly power density under the projections of climate change could then be calculated and summed to create monthly and annual totals. Decreased summertime wind speeds (5-10%) were detected for the area under climate change projections, resulting in a 40% reduction in summertime generation potential.

In other research, a fourteen member ensemble of GCM output was evaluated by Eichelberger *et al.* (2008). The simulations were based on the A2 and B1 emissions scenarios. The data was obtained from the World Climate Research Programme's Coupled Model Intercomparison Project (CMIP3) multi-model dataset. The baseline period in this study with which mean wind speed values were calculated was 1991 to 2000 and the future period was 2046 to 2055. Baseline results were compared to future period results for each

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GCM respectively. They noted that stronger surface wind speeds are predicted for the boreal regions of the northern hemisphere, as well as tropical and subtropical regions of Africa and Central and South America, and decreasing wind speed values could be expected for parts of Asia and Australia.

Pereira de Lucena *et al.* (2010) used output from HadCM3 GCM data, dynamically downscaled to regional climate output using the Providing Regional Climates for Impacts Studies (PRECIS) model to investigate changes in wind speed and power generation potential in Brazil. Projections were made under the A2 and B2 emissions scenarios. A 1961 to 1990 "baseline" simulation was created as a reference for future (2071-2100) period projections. Model output at 10m height was converted to 50m using the logarithmic rule. They presented variations between the baseline and climate model outputs, as well as an application of those variation results to estimated current wind speeds (as presented in the Brazilian Wind Power Potential Map). The wind power generation potential was estimated using a Geographical Information System (GIS). In the GIS, wind speed information was georeferenced with other variables such as cut-off speed of turbines and the presence of water bodies to locate "occurrences" i.e. grid cells (50km × 50km = 2500km^2) in which turbines can function. Wind power density was then assumed as 2MW.km^{-2}. Power installed for the area (assuming that only 20% of the gross wind power generation potential is exploitable) was then calculated as follows: 2MW.km^{-2} × 2500km^2 × 0.2 × number of occurrences. Furthermore, electricity generated could also be calculated by assuming predetermined (in the Brazilian Wind Power Potential Map) capacity factors at particular wind speeds. Increased wind speeds were found in both projections, particularly in the north-eastern part of the country.

Pašičko *et al.* (2012) analysed results from ECHAM5/MPI-OM GCM, dynamically downscaled by the NCAR developed RegCM RCM forced with the A2 emissions scenario for Croatia. The baseline period was 1961 to 1990, and two future periods were assessed: 2011 to 2040 and 2041 to 2070. Wind speed changes of up to 35% were projected to increase in the summer between 2011 and 2040. In the 2041 to 2070 period, increases between 35% and 60% could be expected for the coastal region, with only 5% for the inland areas.

The HadAM3H GCM supplied boundary conditions for the PRECIS model used by in Yao *et al.* (2012) in their study of the possible effect of climate change on wind power generation in Ontario, Canada. They projected wind speeds for 2071 to 2100 using 1961 to 1990 as reference period, under the A2 and B2 scenarios. They employed observed climate data from

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twelve weather stations and the Canadian Wind Energy Atlas (CWEA) to provide assessments of the PRECIS output. The purpose of using the CWEA as well, was to provide an independent assessment of the PRECIS output. The CWEA downscaled dataset was produced with NNR data and the Mesoscale Compressible Community model. Their results projected decreases of up to 5% in wind speed in southern Ontario. They went on to calculate power density and power production and pointed out the difference in the use of these two indicators, the latter being more accurate since it incorporated wind turbine features, but having the weakness of using specific turbine characteristics, thus limiting its comparability and representativeness.

In a more recent study, Pereira *et al.* (2013) used observed data from 1960 to 2007 from weather stations to detect trends in wind speed in Brazil. Using a quality-control data screening process, station data could be selected based on the continuity of the data as time series. Thereafter, a Kendall trend test was employed to search for trends at the 95% confidence level. Output data from the HadCM3 GCM was downscaled by the Eta mesoscale model and used in the study. The A1B scenario was assumed for this study. To validate Eta-HadCM3 model output, ground weather station data of 1960 to 1990 were employed. The data also served as baseline data. Future projections for 2010 to 2040, 2040 to 2070 and 2070 to 2100 were produced and compared with the baseline data. An average increase of 15-30% in wind power generation potential was found, particularly in the north-eastern regions of the country.

1.2 MOTIVATION FOR THE RESEARCH

The South African Department of Energy (DoE) has procured and is investing a great amount of resources into the research and development, installation and grid integration of wind energy. Between 1996 and 2012 wind generating capacity has encountered a 27% annual growth rate globally (Timilsina *et al.*, 2013), and the market is expected to grow by a further 6-10% annually after 2014 (GWEC, 2014). Countries around the globe are motivating their support of the deployment of wind power generation plants using a variety of arguments that differ in degrees of importance in each country. These include:

- Climate change mitigation policies (UNFCCC, 2014);
- Ageing electricity generation facilities (EurActiv, 2012);
- A need to diversify current electricity sources and its management (Li, 2005);

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- The increased availability, cost effectiveness, and learning rate of the technology (Kahouli-Brahmi, 2008);
- Job creation (Wei *et al*., 2010);
- Foreign business opportunities (Ellis *et al*., 2007);
- Less severe environmental impact compared to other energy resources and based on Life Cycle Assessments (Gagnon *et al*., 2002; Kennedy, 2005);
- Feed-in tariffs, whereby long-term contracts are offered to renewable energy producers, guaranteeing grid-access and electricity purchases from these producers (Meyer-Renschhausen, 2013); and
- Scientific research (Migoya *et al*., 2007).

In South Africa approximately 25 wind energy facilities are either under construction, in commercial operation, or in the financing stages of deployment. The majority of wind energy projects in South Africa have been commissioned by the Renewable Energy Independent Power Producer Procurement Programme (REI4P) (DoE, 2012). Eskom, South Africa's major electricity supply utility, currently manages two wind energy farms, i.e. the Sere 100MW and the Klipheuwel 3MW wind farms. Independent Power Producers (IPPs) wind farms that are under construction include the Kouga (Kouga Wind Farm, 2014) and Gouda (Kroes, 2012) facilities. Completed constructions include the Noblesfontein, Jeffrey's Bay (Jeffrey's Bay Wind Farm, 2012a; News24, 2014), Van Stadens (Engineering News, 2014b), Cookhouse, and Hopefield (Engineering News, 2014a) wind farms. In addition, projects that are still in their initial phases include the Nojoli (NERSA, 2014e), Gibson Bay, Longyuan Mulilo De Aar Maanhaarberg, Longyuan Mulilo De Aar 2 North, Khobab, Noupoort Mainstream Wind and Loeriesfontein 2 (Barradas, 2014) wind farms, all of whose locations are shown in Figure 1.

In Table A1 (see Appendix) various South African wind energy facilities are listed, including contracted capacities of the farms, turbine manufacturers, turbine specifications and information on the REI4P process where applicable. Turbine towers are all 80m or taller and rotor diameters are on average ~104m (excluding the two experimental wind farms, Klipheuwel and Darling).

To warrant long-term investment, and therefore the success of the wind energy industry, stakeholders need to account for possible changes to the mechanisms that play a role in this sector. The functioning of wind farms depends on specific local climatic conditions, making

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them vulnerable to climate change. The quantification of wind energy's susceptibility to global warming (and therefore climate change) is critical to assess the adaptation capacity to possible, but uncertain, effects on wind energy production (Pereira de Lucena *et al.*, 2009).

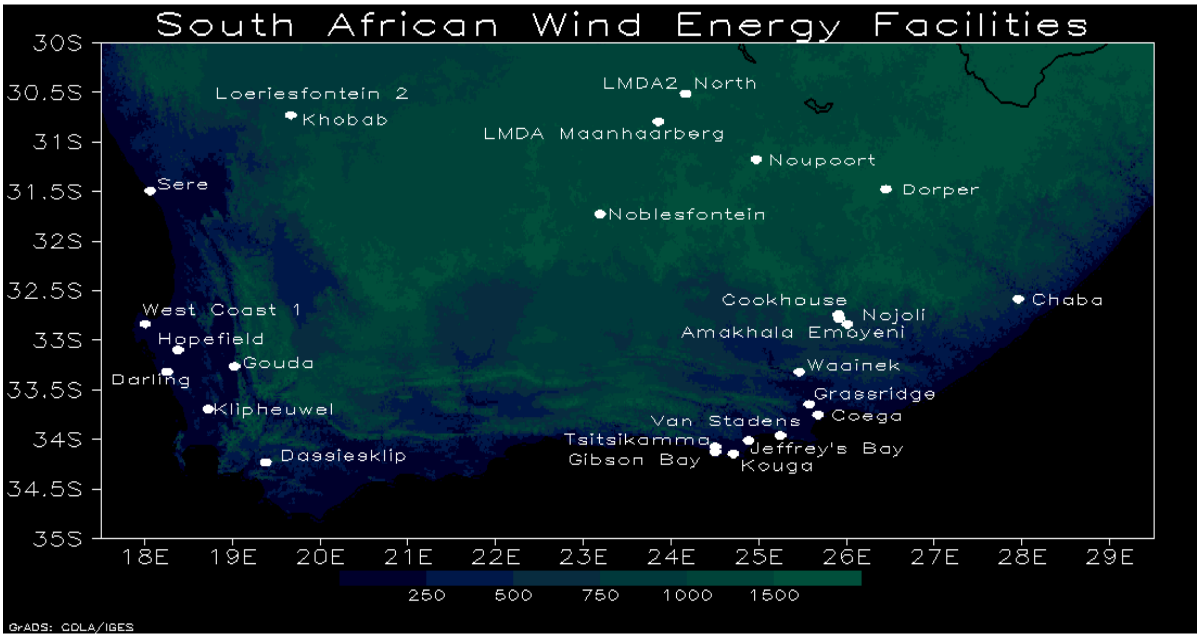

Figure 1: The locations of current and planned South African wind energy generation plants (LMDA=Longyuan Mulilo De Aar) (2015).

Comprehensive studies on the impact of climate change on wind power generation could improve confidence in wind as a profitable alternative energy resource in the long term (Pereira *et al.*, 2013). However, such studies are rare for the southern African region. In addition, research on fine resolution wind fields in the Southern Hemisphere is often limited by a lack of data (Trenberth, 1981). However, a number of studies had been conducted globally in the last two decades on the impact of climate change on the energy sector (Seljom *et al.*, 2011; Schaeffer *et al.*, 2012; Dowling, 2013; Chandramowli and Felder, 2014), renewable energy in general (Pereira de Lucena *et al.*, 2009; Pasicko *et al.*, 2012; Wachsmuth *et al.*, 2013), wind energy (Breslow and Sailor, 2002; Pryor *et al.*, 2005; Eichelberger *et al.*, 2008; Sailor *et al.*, 2008; Cradden, 2009; Pereira de Lucena *et al.*, 2010; Pryor and Barthelmie, 2010; Rasmussen *et al.*, 2011; Pereira *et al.*, 2013), and, wind climates in southern Africa (Hänsler, 2011; Fant and Schlosser, 2013; Herbst and Lalk, 2014).

1.3 RESEARCH PROBLEM

According to climate projections summarised in the Fifth Assessment Report (AR5) of the IPCC, some risks and opportunities for wind power generation could be expected in future,

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meaning that the distribution, timing and magnitude of wind resources might change over the projected 20-30 year lifetime of a wind turbine (Rasmussen *et al*., 2011).

However, Russo *et al*. (2013) noted that few significant wind speed changes might be expected in the near future in the African region. This, and similar assessments of climate change impacts on wind behaviour in South Africa, have mostly been performed using GCMs, which have spatially coarser resolutions than RCMs. Also, wind speed and direction on regional scales are more variable than large-scale circulation, as they are influenced by land surface features such as topography. Model simulated winds are found to be susceptible to large errors (Pasicko *et al*., 2012) if few models and emission scenarios are used, which emphasise the importance of considering multi-model ensemble comparisons (Rasmussen *et al*., 2011).

As yet, no research has been conducted on the projected potential for wind energy generation as a result of projected changes in wind fields and no finer resolution than that of the GCMs used in the AR5. Since South Africa is investing significantly in various renewable energy generation initiatives, which includes wind energy generation, a study on the possible impact of climate change on future wind patterns is regarded as essential.

1.4 RESEARCH QUESTIONS

- What changes in seasonal near-surface[1] winds may be expected in the long-term in southern Africa?
- How might these changes impact wind power generation potential?

1.5 AIM AND OBJECTIVES

The overarching aim of this study is to explore the variability in seasonal near-surface winds in South Africa and to project possible future changes in these winds.

The objectives of the study are therefore to:

a. determine whether seasonal near-surface winds over South Africa, as generated by a regional model using boundary conditions supplied from coupled GCMs during the reference period of 1981-2005, are realistically reproduced;

[1] "Near-surface" refers to a height between 1.5m to 10m (Christensen *et al*., 2014), but is assumed here to be 10m.

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b. establish whether differences exist between seasonal near-surface winds calculated for the historical period versus a projected period (2051-2075) incorporating each of two future CO_2 Representative Concentration Pathways (RCP4.5 and RCP8.5) (see Chapter 2, §2.3.1 on page 19 and Figure 3 on page 20 for a detailed description and visualisation of the Pathways);
c. determine the most likely impact of projected climate change on wind power density in South Africa.

Results serve not only as an addition to the current understanding of the impact of increasing Greenhouse Gas (GHG) concentrations on wind patterns, but also on the potential consequence for wind power generation in the wind energy industry in the South African region.

1.6 GENERAL RESEARCH APPROACH

In order to achieve the objectives mentioned in section 1.5:

a. Seasonal daily mean winds speeds were obtained for the historical 25-year period 1981 to 2005 using observed data and model output in order to calculate their differences. Wind direction differences were also calculated for this period. The RMSE between observed and model results were calculated to find the error in seasonal daily mean wind speeds ($m.s^{-1}$) between the two datasets. Daily wind speed frequencies per season were obtained for occurrences when wind blows at speeds:
   i. below a predetermined cut-in speed;
   ii. above cut-in and below cut-out speeds; and
   iii. above a predetermined cut-out speed for both of the datasets (observed and model historical period).
b. Seasonal daily mean winds and directions were calculated for the future period using projected model output for the RCP4.5 and RCP8.5 pathways. Frequencies were calculated in the same manner as in (a), but using projected model output for the RCP4.5 and RCP8.5 pathways. Anomalies between model output in the historical period and the future period were then calculated and expressed as:
   i. percentage differences in terms of seasonal daily mean wind speeds over the entire region;

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ii. differences between daily wind speed frequencies per season; and

iii. diversions from predominant wind direction in the historical period.

c. Wind power density was calculated using model output of wind speeds in the projected period as input to a common formula for wind power density estimation.

1.7 LIMITATIONS AND STRENGTHS OF CLIMATE MODELS

Estimates of wind climate projections are less robust than that of temperature climate projections, of which the agreement among multiple models is often fairly high (Pryor *et al*., 2010). Model output could therefore only be seen as general trends, rather than absolute projections, hence the inclusion of anomalies in this study. Agreement among global climate models is still fairly low (NIPCC, 2011). All known climate processes and feedbacks (chemical and biological) are not yet included in climate models, and some not have been recognized yet. These computer models are perhaps robust, but their initial assumptions and final results vary greatly on both temporal and spatial scales (Weart, 2010). For instance, fine scale phenomena such as clouds aren't consistently captured by models. Downscaling low resolution models to higher resolutions could introduce boundary conditions that could corrupt the modelling area (NIPCC, 2013). There are numerous different possible responses to carbon dioxide (CO_2) doubling in the atmosphere, and the magnitude thereof indicates inherent errors which remain to be corrected.

Sophisticated climate models nevertheless help improve our understanding of current, past and potential future climate. They're abilities to successfully simulate various processes are in increasing agreement with phenomena that are crucial in projecting future changes in climate (CCSP, 2008). Taking averages across multiple models provide superior results to individual models, thus making the multi-model approach the most reliable (CCSP, 2008). Furthermore, new satellite data is becoming available, as well as computationally intensive modelling techniques which will resolve fine-scale phenomena more realistically. (CCSP, 2008).

1.8 ORGANISATION OF THE REPORT

This study is divided into six chapters. Chapter 1 includes a review of the relevant literature on climate change impacts on wind energy around the globe. The rationale for conducting the study is then explained and linked to the South African wind energy context and the issue of

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climate change. Research questions are then stated, after which the study's aim and three objectives are introduced. A concise description of the methodology involved in achieving each of the three objectives is also provided.

In Chapter 2, the methods used in the achievement of each of the objectives are described in detail. Aspects of the data that were employed in the study are also given.

In the third chapter, the first objective of climate model validation is addressed. A description is given of how climate models function, as well as a summary of typical southern African climatological characteristics to provide context for the remainder of the chapter. The results of the first study component are then introduced. Projected mean wind speeds, a statistical evaluation, projected wind speed frequencies of various categories, and weather station data in relation to climate model performance are described and then summarised at the end of the chapter.

Chapter 4 addresses the second objective, namely determining the projected future changes in winds in South Africa. A summary is first provided of possible changes in southern African climates as conducted in another study. The results of projected wind speed changes, wind speed frequency changes, and wind direction changes are then introduced and subsequently discussed. As in Chapter 3, the findings are then summarised at the end of the chapter to reveal its application to the study aim.

In Chapter 5, the third objective of determining what the effect of climate change could be on wind power density is investigated. Bias corrected wind speed projections are introduced and followed by wind power density estimations in the projected period. Thereafter, the findings are discussed and summarised.

In Chapter 6, the study is concluded by summarising how each of the objectives had been achieved. As a final comment, recommendations are made as to how this study could be improved in future work.

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CHAPTER 2

Research methods

2.1 BACKGROUND

In order to address the research objectives, two CO_2 RCP pathways were considered in eight dynamically downscaled GCM simulations from the AR5 to determine the potential influence of global warming on South African winds, and therefore on wind power generation.

2.1.1 Data

The Rossby Centre, a climate modelling research unit at the Swedish Meteorological and Hydrological Institute, has produced a substantial collection of regional climate model simulations for the African region through dynamical downscaling of a subset of eight GCMs from the CMIP5 initiative. These downscaled model simulations were produced by the Rossby Centre's RCA4 RCM. This initiative forms part of the CORDEX-Africa (COordinated Regional Downscaling EXperiment) project. The forcing GCMs were the CanESM2, CNRM-CM5, EC-EARTH, MIROC5, HadGEM2-ES, MPI-ESM-LR, NorESM1-M, and GFDL-ESM2M coupled GCMs. The institutions and countries from which they originate are indicated in Table 1. CORDEX RCM data were provided at a 0.44° × 0.44° horizontal resolution for the historical period 1951 to 2005, and the projected period that extends from 2006 to 2100.

In order to identify model biases, historically simulated RCA4 RCM output had to be assessed, through comparison, with observational fields such as the ECMWF ERA-Interim reanalysis data, which is a global atmospheric reanalysis dataset available from 1979 to present. The grid resolution of ERA-Interim data is 0.75° × 0.75°. To examine changes in, for example daily wind speed distributions, 30-year assessment periods are preferred to comply with the World Meteorological Organization (WMO) definition for climate. Since ERA-Interim data is available from 1979 onwards, and the historical period for the RCA4 RCM output ends in 2005, a 25-year assessment period 1981 to 2005 was chosen for this study, which was then compared to a projection period 2051 to 2075.

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Table 1: Institutions and countries from where the RCA4 RCM forcing GCMs originated (SMHI, 2012)

Institute	Country	GCM
○ **Canadian Centre for Climate Modelling and Analysis (CCCma)**	Canada	CanESM2
○ **Centre National de Recherches Météorologiques and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CNRM-CERFACS)**	France	CNRM-CM5
○ **Irish Centre for High End Computing (ICHEC)**	Ireland	EC-EARTH
○ **Model for Interdisciplinary Research On Climate (MIROC)**	Japan	MIROC5
○ **Met Office Hadley Centre (MOHC)**	UK	HadGEM2-ES
○ **Max Planck Institut für Meteorologie (MPI-M)**	Germany	MPI-ESM-LR
○ **Norwegian Climate Centre (NCC)**	Norway	NorESM1-M
○ **National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory (NOAA-GFDL)**	USA	GFDL-ESM2M

2.2 CLIMATE MODEL VALIDATION

2.2.1 Mean seasonal wind speed

2.2.1.1 ERA-Interim reanalysis data

Model performance was evaluated by calculating differences between the RCA4 RCM output and ERA-Interim reanalysis data. For this purpose, daily (00:00UCT, 06:00UCT, 12:00UCT and 18:00UCT) historical near-surface (10m above ground level (agl)) u- and v-wind components have been obtained for the 25-year period 1981 to 2005, across the domain 18° to 42°S and 14° to 37° E, from the ERA-Interim reanalysis databank. For the comparison of RCA4 model output (0.44° × 0.44° resolution) to ERA-Interim reanalysis data (0.75° × 0.75° resolution), ERA-Interim reanalysis fields were interpolated (bilinear) to fit the RCA4 RCM fields. The ERA-Interim reanalysis domain size was also modified to correspond with the RCA4 RCM domain. The boundaries of this domain were 19.5° to 40.5°S and 15° to 35.25°E.

Wind speed (ws) was calculated from u- and v-components as follows:

$$ws = \sqrt{u^2 + v^2} \tag{1}$$

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Wind speeds at 00:00UCT, 06:00UCT, 12:00UCT and 18:00UCT were averaged to obtain daily means, which were compatible with RCA4 RCM data: RCA4 RCM data are provided as daily averages taken eight times a day, i.e. three-hourly (Christensen *et al*., 2014). The first 28 days of each month were then selected for further calculation. Residual days could not be used in the analysis, due to the fact that some model fields consist of 30-day months only, while others included leap years. A uniform month-day number for all 12 months of the year (in this case 28) was introduced for calculating cross-model ensemble averages. Seasonal wind speeds were then obtained after categorising daily data into four groups: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). From this, seasonal daily mean wind speeds for each season were calculated.

2.2.1.2 Model data

Data from the eight GCMs that were dynamically downscaled using the RCA4 RCM were obtained. A domain extending from 22° to 35°S and 16.2° to 33°E was defined for the study. Daily historical near-surface wind speeds (10m agl) were extracted for each model for the 25 years extending from 1981 to 2005. For each of these eight model files, data were grouped into seasons (DJF, MAM, JJA and SON). Days 1 to 28 were then extracted, as explained previously, for each month per season and per model. Thereafter, ensemble means of the daily data were calculated from the eight RCA4 RCM simulations across the four seasons from where daily mean wind speeds for each of the seasons were calculated.

To project potential diversions from dominant wind directions, the u- and v-components at the 850hPa-level were extracted for each model for the 25 years extending from 1981 to 2005. The data were grouped seasonally, extracted from days 1 to 28, and ensemble means were calculated according to the same procedure used for the near-surface wind speed data. The u- and v-component data were then used as vectors in the Grid Analysis and Display System (GrADS) to calculate and display wind directions for the historical period of 1981 to 2005.

2.2.1.3 Statistical evaluation of model performance

In order to verify the model performance, the RMSE of seasonal daily mean wind speeds were calculated using the ERA-Interim and the ensemble RCA4 RCM data. The RMSE was calculated as follows (CTEC, 2015):

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$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_{obs,i} - x_{model,i})^2}{n}} \qquad (2)$$

where

$x_{obs,i}$ is the observed ERA-Interim values;

$x_{model,i}$ is the model values at a particular point i; and

n is the number of values.

2.2.2 Seasonal daily wind speed frequencies

Daily wind speed frequencies were obtained for each season to illustrate how often wind speeds appear to be appropriate for energy generation from wind turbines. Most of the turbines commissioned for South African wind energy facilities have cut-in speeds of 3m.s^{-1} and cut-out speeds of 25m.s^{-1}. The terms "cut-in" and "cut-out" are explained in Table 2.

Table 2: Cut-in speed and cut-out speed definitions and their respective values at 90m and 10m agl

Term	Definition	Source	At 90m	At 10m
Cut-in speed	*"The minimum wind speed at which a wind turbine becomes activated to [produce] useable power"* or *"the wind speed necessary for a wind-powered system to begin delivering electricity"*	Cleveland and Morris, 2006; Chambers and Kerr, 1996	3m.s^{-1}	~2m.s^{-1}
Cut-out speed	*"The wind speed at which a wind generator activates some kind of overspeed mechanism to either stop the unit's generation of power completely, or to control the rotational speed to produce constant power."*	Cleveland and Morris, 2006	25m.s^{-1}	~18m.s^{-1}

2.2.2.1 Wind shear

The majority of turbines contracted for South African wind farms have hub heights of 90m (the term "hub height" is illustrated in Figure 2).

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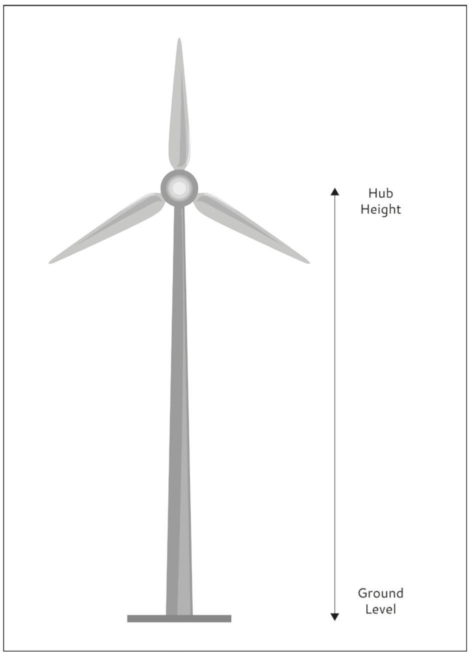

Figure 2: Generic onshore wind turbine and its hub height (Herbst, 2014).

In order to obtain appropriate wind speed limits for electricity generation (i.e., above cut-in speed and below cut-out speed) as defined at 90m agl for the associated ERA-Interim and RCA4 RCM wind fields that are given at 10m agl, these limits had to be extrapolated to be consistent with the heights at which ERA-Interim and RCA4 RCM data are provided. It is known that the vertical wind speed profile typically declines as the height agl declines. The wind speed at 90m, as well as the cut-in and cut-out speeds specified, will therefore be lower at 10m agl (if the atmosphere is assumed to be stable). The cut-in and cut-out speeds at 10m were calculated using the so-called "log law", often employed in the wind energy industry to extrapolate wind speeds from various heights:

$$v(z) = v_{ref} \frac{ln\frac{z}{z_0}}{ln\frac{z_{ref}}{z_0}} \quad (3)$$

where

$v(z)$	is wind speed at height z;
z	is the height;
v_{ref}	is the wind speed at a reference height z_{ref};
z_{ref}	is the reference height, taken here as 10m;
z_0	is the roughness length.

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Roughness length can be defined as the height (in metres) agl at which the wind speed is theoretically equal to zero (Ragheb, 2012). In the wind extrapolation, the reference height z_{ref}; was taken as 90m, the wind speed at that height was taken as either the cut-in (3m.s^{-1}) or cut-out (25m.s^{-1}) speed, and the required extrapolated height z was taken as 10m. The roughness length z_0 was taken as 0.05m, corresponding to "crops, tall grass prairie" (Gipe, 2004). In Table 2 the resulting cut-in and cut-out speeds at 10m agl are shown.

Three categories of wind frequencies were defined:

- Frequency of days when the wind blows below cut-in speed

  $0 < x \leq 2.1 \text{ m.s}^{-1}$;
- Frequency of days when the wind blows within the valid speed range

  $2.1 < x \leq 17.6 \text{ m.s}^{-1}$;
- Frequency of days when the wind blows above cut-out speed

  $> 17.6 \text{ m.s}^{-1}$.

Subsequently, the frequency of days with wind speeds of below 2.1m.s^{-1}, between 2.1m.s^{-1} and 17.6m.s^{-1}, and above 17.6m.s^{-1} was calculated from both ERA-Interim and RCA4 RCM ensemble data. This yielded three fields per season, each indicating the frequency category defined above, over 25 years. To obtain percentage frequencies, frequency fields were divided by 2100 (28 days per month × 3 months per season × 25 years), and then multiplied by 100.

It was found that there were no occurrences in the "above cut-out speed or 17.6m.s^{-1}" category from the ensemble mean modelled fields, which indicated a bias in the model data since this category is represented in the ERA-Interim data. The bias could be attributed to the fact that taking an ensemble mean from eight models' data output might smooth out outliers. To address this problem, the numerical values of the category limits (2.16m.s^{-1} and 17.6m.s^{-1}) had to be adjusted in the RCA4 RCM data in order to ensure that the model frequency spread could be compared to the ERA-Interim data. This was achieved by ranking the model and ERA-Interim time series, and then to find the RCA4 RCM equivalent to the 2.1m.s^{-1} and 17.6m.s^{-1} ERA-Interim values.

These corresponding model values were found to be:

- Frequency of days when the wind blows below cut-in speed

  $0 < x \leq 2.9 \text{ m.s}^{-1}$;

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- Frequency of days when the wind blows within the valid speed range
  $2.9 < x \leq 13.2 \text{ m.s}^{-1}$;
- Frequency of days when the wind blows above cut-out speed
  $> 13.2 \text{ m.s}^{-1}$.

Using the RCA4 RCM data, the percentage frequencies of days when the wind blows at speeds a) below the predetermined cut-in speed; b) above cut-in and below cut-out speeds (within a speed range appropriate for power production); and c) above a predetermined cut-out speed were calculated. This allowed for comparing ERA-Interim and RCA4 RCM frequency percentages for the reference period.

2.2.3 Model evaluation against observational data

As an independent verification of RCA4 performance, mean wind speeds from RCA4 RCM ensemble output were also evaluated against ground station data. For this purpose, data recorded at six South African Weather Service (SAWS) stations distributed across the country were obtained.

The stations were located at Malmesbury, Vredendal, Greytown, Upington, Nelspruit, and Mokopane. The data were provided as it was measured at 08:00UCT, 14:00UCT and 20:00UCT for varying periods starting in 1981 through to 2005. These three times daily observations were averaged to obtain single daily averages, which were then employed in calculating seasonal average wind speeds. Model values for comparison were selected from those grid boxes in model data within which the particular weather station's coordinates lie. These coordinates are shown in Table 3, as well as the period for which data were available. Note that two stations' data were considered for the Upington area, as the periods of availability of both differed.

2.3 PROJECTED WIND SPEED CHANGES

2.3.1 Climate change projections

In the IPCC's AR5, GHG emissions scenarios considered were expressed in terms of atmospheric heat based RCPs. Previously used IPCC SRES scenarios based on CO_2 concentrations were updated in the AR5 to heat based RCPs, due to new information on emerging technology, economies, land use, land cover change and environmental factors of almost a decade (Moss *et al*., 2010). The new AR5 GHG forcing for future projections used

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in this study consist of CO_2 RCPs related to 4.5W.m^{-2} and 8.5W.m^{-2} atmospheric heat increases by 2100 (henceforth RCP4.5 and RCP8.5, respectively), amongst other pathways. The use of the word 'representative' resembles the fact that each RCP signifies one of numerous possible scenarios leading to particular radiative forcing characteristics (Van Vuuren *et al.*, 2011). The word 'pathway' refers to the trajectory taken over a long time to achieve a given radiative forcing point in terms of long-term GHG concentration levels. Such time-evolving concentrations of radiatively active constituent pathways could be incorporated for driving global warming climate model simulations.

Table 3: South African Weather Service weather stations used for verification purposes

Station name	Coordinates	Period of data availability
Malmesbury	33.4720 S 18.7180 E	1986/02-2005/12
Vredendal	31.6730 S 18.4960 E	1981/01-2005/12
Greytown	29.0830 S 30.6030 E	1993/03-2005/12
Upington (1)	WK 28.4000 S 21.2670 E	1981/01-1992/04
Upington (2)	WO 28.4110 S 21.2640 E	1991/07-2005/12
Nelspruit	25.5030 S 30.9110 E	1993/07-2005/12
Mokopane	24.2050 S 29.0110 E	1995/09-2005/12

In more detail, RCP4.5 (RCP8.5) represents a radiative forcing of ~4.5W.m^{-2} at stabilisation after 2100 (>8.5W.m^{-2} in 2100) and a ~650 ppm CO_2-equivalent concentration at stabilisation after 2100 (>1370 ppm CO_2-equivalent in 2100). The RCP4.5 therefore represents a pathway that stabilises without overshoot, and RCP8.5 resembles a rising pathway. The RCP4.5 was developed by the Global Change Assessment Model (GCAM) as developed by the Pacific Northwest National Laboratory in the USA, while the RCP8.5 was developed by the Model for Energy Supply Strategy Alternatives and their General Environmental impact (MESSAGE) from the International Institute for Applied Systems Analysis in Austria (Moss *et al.*, 2010). These RCPs are two of four which were used in AR5. The relative radiative forcings (a) and CO_2 emissions (b) of the four RCPs for the 21st century, as well as their model sources are shown in Figure 3.

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2.3.2 Mean seasonal wind speed

Daily means of seasonal near-surface wind speed, as well as 850hPa-level u- and v-components in the projected period were calculated using RCA4 projections under conditions of both the RCP4.5 and RCP8.5 pathways. The data were extracted and grouped in the same manner as in the historical period, but in this case for a 25-year period extending from 2051 to 2075.

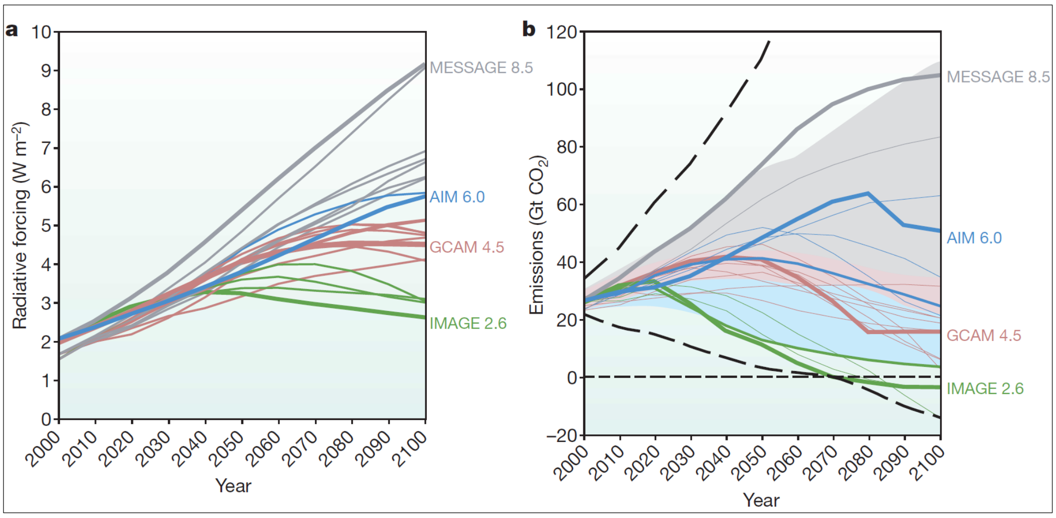

Figure 3: (a) Changes in radiative forcing over time. The four RCPs are shown by bold lines (thin lines show other candidate pathways). (b) CO_2 emissions from industry and energy use. The blue shaded area is related to mitigation scenarios, the grey area represents reference scenarios, and the red area shows the region where blue and grey regions overlap. The dashed curves represent the minimum and maximum amounts as found in post-SRES literature (Moss *et al.*, 2010).

2.3.3 Seasonal daily wind speed frequencies

Projected percentage frequencies were determined in the same manner (Section 2.2.2) as for the historical period, but for the years 2051 to 2075.

2.3.4 Anomalies

Anomalies between RCA4 RCM output in the reference period and RCA4 RCM output in the two projections were calculated and expressed as percentage differences. Anomalies were also calculated from the valid range of electricity generation as per the model data according to the categories specified in Section 2.2.2. Anomalies are shown in this case as differences in frequency percentages, as the simulations from which they were calculated were provided in percentages. Wind direction changes at the 850hPa-level were also calculated for the two RCPs by subtracting historical u/v components from projected u/v components, and then by using these anomalies to plot deviations from the wind direction in the reference period.

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2.4 PROJECTED WIND POWER DENSITY

2.4.1 Bias correction

Wind power density was calculated using RCA4 RCM output for the two projection pathways. The objective was not to indicate *changes* to wind power density, but to illustrate projected wind power density. Model biases necessitated bias corrections before the model data could be used in projected wind power density estimations. Raw daily projected model data were corrected using the bias correction methodology proposed by Hawkins *et al*. (2013) where biases in the mean and variability of the model output are "corrected" according to observational data:

$$v(t) = \overline{v_{obs}} + \frac{\sigma_{obs}}{\sigma_{his}}\left(v_{pro}(t) - \overline{v_{his}}\right) \quad (4)$$

where

$v(t)$ is the corrected wind speed;

$\overline{v_{obs}}$ is the average of the observations over the historical reference period;

σ_{obs} is the standard deviation of observations over the historical reference period;

σ_{his} is the standard deviation of model output over the historical reference period;

$v_{pro}(t)$ is the model projected values over a future period of the same length as the reference period;

$\overline{v_{his}}$ is the average of the raw model projected output.

2.4.2 Wind power density estimation

Wind power density was calculated as follows:

$$P/_A = \frac{1}{2}\rho v^3 \quad (5)$$

where

$P/_A$ is the wind power in Watts per m^2;

ρ is the air density in kg.m^{-3}, taken here as 1.225 kg.m^{-3};

v is the wind speed in m.s^{-1}.

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Using the bias corrected RCA4 RCM projections, wind power density was calculated for South Africa.

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CHAPTER 3

Climate model validation

3.1 BACKGROUND

3.1.1 Climate models

Climate forecasts and predictions are based on numerical computer models which consist of computer code of the atmospheric equations describing the conservation of momentum, mass and energy in the atmosphere. These models aim at simulating the earth's climate as realistically as possible. However, the complexity of the earth-climate system and its multiple constituents, as well as a component of internal chaos in the atmospheric system, make exact modelling difficult, but the understanding of feedback loops, sensitivity to changes in GHG and industrial growth rates are improving. With many advances over the past decades, GCMs are regularly used for the purpose of modelling the earth's climate system, as well as predicting and projecting climate (Dahan, 2010).

GCMs represent the atmosphere and ocean on grids with cell sizes varying from 1° to 4° latitude by longitude with 10 up to 200 vertical layers (Hardy, 2003). Natural phenomena impacting climate, including solar radiation gain and loss rates, humidity, ocean temperature, atmospheric gas concentrations (such as GHG concentrations), barometric pressure and salinity (which influences density) are incorporated in each grid cell. Models are set in motion by providing them with either initial or boundary forcing conditions. Changess in atmospheric variables like wind, temperature and precipitation are then calculated over time steps for each grid cell. The location and characteristics of the air and water as it mixes in reaction to changes in wind and density are recalculated at each time step (Randall *et al*., 2007).

Models usually integrate submodels of a number of systems such as the ocean, land surface, atmosphere and cryosphere. These submodels operate on different timescales because of different response times of climate systems from changes in these systems. For instance, the slow climate system (deep-ocean, perennial land-ice) responds over decades or centuries. The integration of models is referred to as 'coupling' (Hardy, 2003).

Two types of GHG GCM simulations exist. In equilibrium simulations, models are integrated for a few decades, starting off with present GHG concentrations, and later with GHG

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concentrations increased by a particular factor. In transient simulations, external forcing is incorporated over time. The latter type is more realistic, as it indicates a gradual increase of, for example, atmospheric CO_2 (Jones *et al*., 2011). The GCMs used in this study were run in transient mode.

To improve spatial detail from GCMs, RCMs were introduced. Atmosphere-Ocean GCMs (AOGCM) have resolutions too coarse to provide information of local and regional scale change, thus they are more appropriate for simulating global change. The development of RCMs was necessitated by the different magnitude or direction changes at finer scales as opposed to global scale changes. These finer scale changes are prompted by land cover, topography and surface hydrology (Randall *et al*., 2007).

3.1.2 Climatological characteristics of southern Africa

The sun provides energy to the air in the earth's atmosphere. Since the air in equatorial regions receives more energy than the air in polar regions, it is propagated, causing the phenomenon known as wind. Energy exchange between the polar and equatorial regions takes place by means of pressure systems and the wind systems resulting from them. Water circulation within oceans redistributes energy as well (Van Heerden and Hurry, 1998).

Although southern African weather patterns regularly change, it is influenced by a few basic, steady relationships between atmospheric pressure and wind originating from global atmospheric system interactions. The factors influencing pressure and wind systems over the region differ in summer and winter and will be summarised in this order.

In summer, the vertical noon sun is in the Southern Hemisphere, accumulating solar energy at around 15°S. At the Inter-Tropical Convergence Zone (ITCZ), southern tropical air converges with northern tropical air. The warm air from above this region moves polewards in the upper atmosphere, forming the Hadley circulation. During this poleward movement, the air radiates heat and becomes denser, causing it to sink downwards at around 35°S. Two important high pressure cells subsequently result on either side of the continental region: the South Atlantic High and the South Indian High. Counter clockwise rotated moisture-laden surface winds from the South Indian High enter and influence the eastern part of southern Africa. South-east trade winds also enter the country from the east, but influence the north-eastern part of the region. The South Atlantic High carries little moisture and invades the region from the south-west, but may occasionally migrate southwards, causing winds to have

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a longer sea track bringing more moisture to the region. South-east trade winds over the Atlantic Ocean blow north of the Atlantic High. As for the poleward side of the highs, surface winds move from the west, causing westerlies south of the continent. In summer, with an increase in land surface heat, a shallow low pressure system or trough usually forms over the Kalahari, influencing air movement from the east and bringing tropical moisture towards the eastern summer rainfall area.

In winter, solar energy accumulates at around 15°N as a result of the vertical noon sun being in the northern hemisphere. The ITCZ is now located north from its relative summer position. Consequently, high pressure cells move northwards, and may be linked across the continent causing subsidence and dry conditions. As a result of the northward movement of the highs, westerlies occur over the southern parts of South Africa with some rain from cold fronts. The region's climate is thus influenced by both mid-latitudinal and tropical weather systems.

Inter-annual climate variability is found to be significantly regulated by the El Niño Southern Oscillation (ENSO) (Jury, 2013), although influences from other ocean temperatures might also play a role. Trenberth (1981) notes that 500mb heights increase substantially over the subtropics and Antarctica. The upper air of South Africa is therefore dominated by subsidence from high pressure systems. In South Africa, long-term trends in summer rain bearing circulation generally have barotropic characteristics, although baroclinic influences are important during winter and the early summer months.

3.2 RESULTS

ERA-Interim reanalysis near-surface wind speeds ($m.s^{-1}$) are employed here as observations for the purpose of model performance evaluation. They are therefore assumed to provide a fairly reasonable indication of surface wind climates. They have been simulated for the historical period of 1981 to 2005. Wind climates are shown in the following figures as they occur in the DJF-, MAM-, JJA- and SON-seasons. These simulations are labelled as "[Season]: ERA" and are shown in Figures 4, 6, 8 and 10. The near-surface winds from RCA4 RCM ensemble data have been simulated for the same period, and are shown in Figures 5, 7, 9 and 11, labelled as "[Season]: Ensemble". Thereafter, the RMSE values are visually depicted in Figures 12-15 to show a quantification of the difference in wind speed projections by the RCA4 RCM versus observed (ERA-Interim reanalysis) data.

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Daily wind speed frequencies per season are then shown in the next section in Figures 16, 18, 20, and 22 for ERA-Interim data, and in Figures 17, 19, 21 and 23 for RCA4 RCM data. The percentage of days, in the 25-year historical period (1981-2005), that winds blow within a speed range that is appropriate for wind power generation, is shown in these figures. The observational projections are labelled "[Season]: ERA valid range", and the RCA4 RCM projections are labelled "[Season]: Ensemble valid range".

Figures were included to display how often winds blow below the speed range appropriate for wind power generation (as percentages), that is, below turbine cut-in speed. The figures derived from ERA-Interim output are labelled as "[Season]: ERA <=cut-in speed" (Figures 24, 26, 28 and 30), and those derived from RCA4 RCM data are labelled "[Season]: Ensemble <=cut-in speed" (Figures 25, 27, 29 and 31).

Winds blowing at above cut-out speed were then simulated for ERA-Interim and RCA4 RCM data. ERA-Interim figures are labelled "[Season]: ERA >cut-out speed" (Figures 32, 34, 36, and 38) and figures showing RCA4 RCM simulations are labelled "[Season]: Ensemble >cut-out speed" (Figures 33, 35, 37, and 39).

3.2.1 Mean seasonal wind speed

For the DJF-season, the winds in the north-western quarter of the country are captured well, showing wind speeds in the region of $4m.s^{-1}$ to $5m.s^{-1}$ in both ERA-Interim (Figure 4) and RCA4 RCM ensemble (Figure 5) runs. However, wind speeds are somewhat overestimated over the eastern escarpment by the RCA4 RCM. The ERA-Interim simulation shows that near-surface winds occur at around $1.5m.s^{-1}$ to $3.5m.s^{-1}$, whereas the model ensemble simulations project winds in this area to vary from $3m.s^{-1}$ to $5m.s^{-1}$. Winds are projected at around $3m.s^{-1}$ to $5m.s^{-1}$ in the ERA-Interim run, but the RCA4 RCM projection ranges from $4.5m.s^{-1}$ to $6m.s^{-1}$ in the south-east of the country. In summary, the RCA4 RCM ensemble projects near-surface wind speeds at around $1.5m.s^{-1}$ higher than observed data, except in the north-western quarter of the country.

In the MAM-season, the lower wind speeds occurring from central South Africa to the Highveld are well captured by the RCA4 RCM, with only a $1m.s^{-1}$ difference between ERA-Interim (Figure 6) and RCA4 RCM (Figure 7) output, the latter projecting the higher mean wind speed. An overestimation of wind speeds by the RCA4 RCM ensemble is observed along a west-east strip stretching from the Cape Town region to Lesotho. According to the

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ERA-Interim simulation, wind speeds range from 2.5m.s^{-1} to 4m.s^{-1}, and RCA4 RCM ensemble data projects wind speeds to range from 3.5m.s^{-1} to 5.5m.s^{-1}. Wind speed projection ranges are overestimated by model ensemble data by no more than 1.5m.s^{-1} greater than ERA-Interim data in this season.

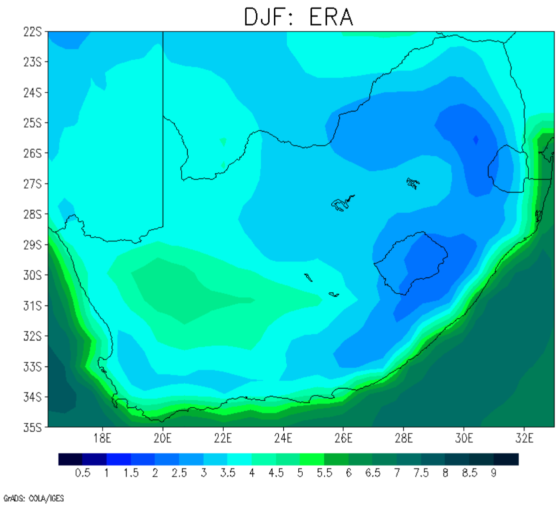

Figure 4: DJF mean seasonal wind speed (m.s^{-1}) from ERA-Interim data (1981-2005).

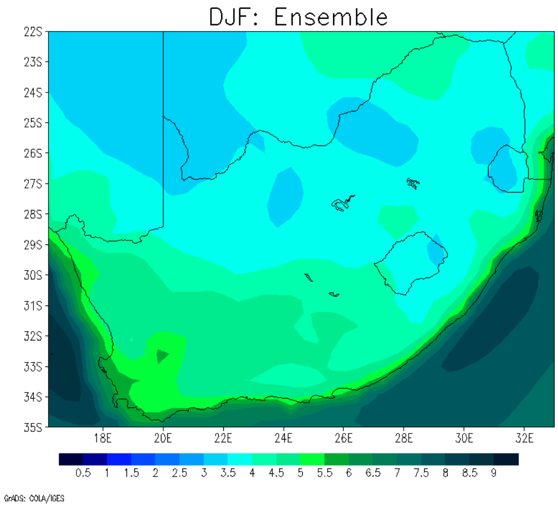

Figure 5: DJF mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

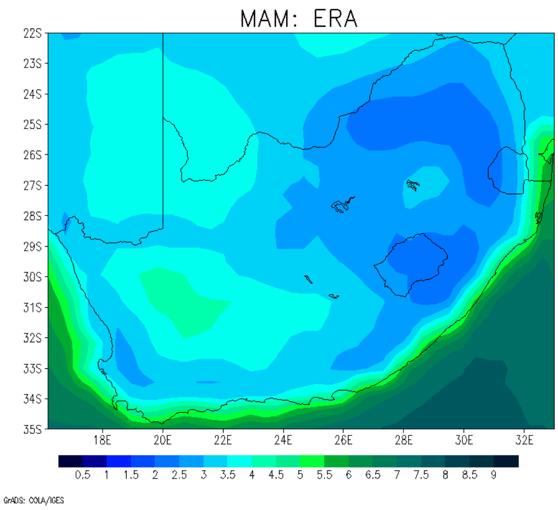

Figure 6: MAM mean seasonal wind speed (m.s^{-1}) from ERA-Interim data (1981-2005).

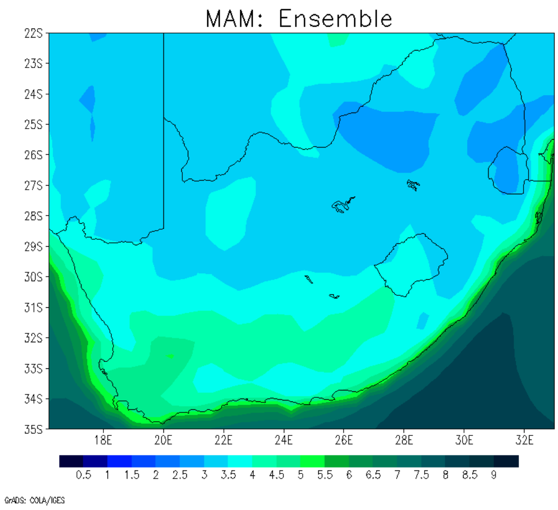

Figure 7: MAM mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

Near-surface wind speeds in the JJA-season are projected at no less than 2.5m.s^{-1} in the north-eastern quarter of the country in the RCA4 RCM ensemble run (Figure 9) – 0.5m.s^{-1} higher than the ERA-Interim run (Figure 8). The west-east strip RCA4 RCM ensemble overestimation observed from Cape Town to Lesotho in the MAM-season (Figure 7) is also present in the JJA-season: the ERA-Interim run shows that these winds range from 3m.s^{-1} to 5m.s^{-1}, while the RCA4 RCM ensemble run shows it could range from 3.5m.s^{-1} to 6m.s^{-1}.

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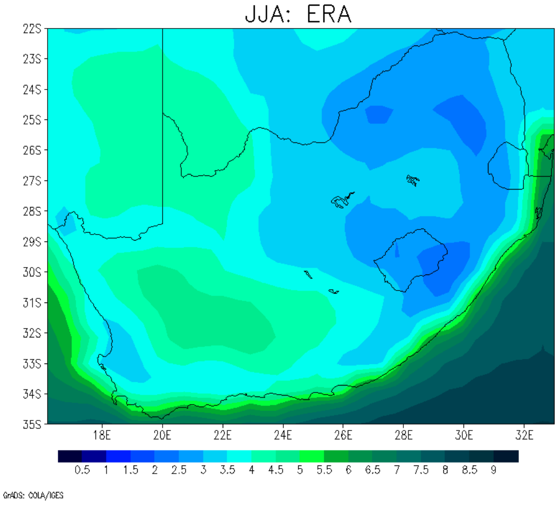

Figure 8: JJA mean seasonal wind speed (m.s^{-1}) from ERA-Interim data (1981-2005).

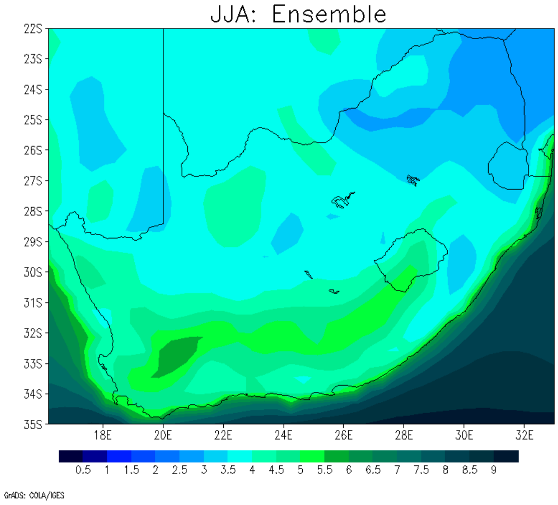

Figure 9: JJA mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

In the SON-season lower wind speeds in the south-eastern tip of the country are once more not well captured by the RCA4 RCM, nor is it represented along the eastern escarpment stretch (Figure 11). The simulation from the ERA-Interim data (Figure 10) suggests that winds range from 2m.s^{-1} to 5m.s^{-1}, but they range from 3.5m.s^{-1} to 6m.s^{-1} in RCA4 RCM ensemble run. On the other hand, winds over the central part of the country are well captured, as they occur at about 3.5m.s^{-1} to 4.5m.s^{-1} in both ERA-Interim and model ensemble runs.

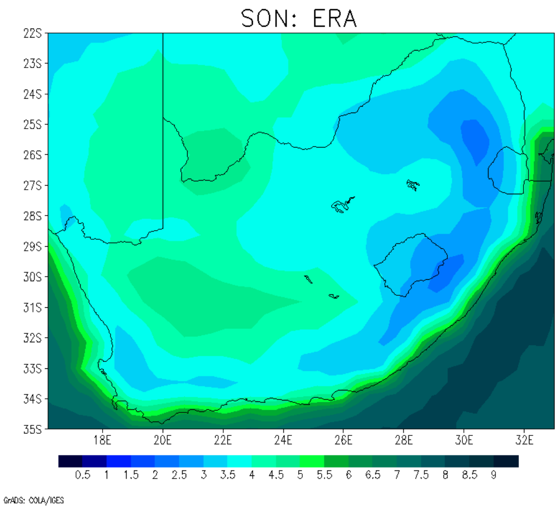

Figure 10: SON mean seasonal wind speed (m.s^{-1}) from ERA-Interim data (1981-2005).

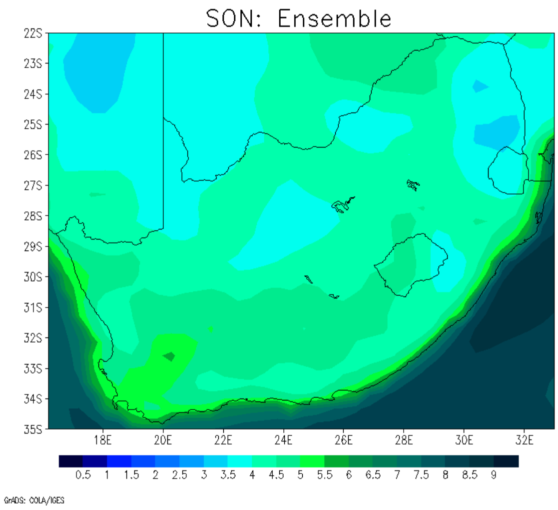

Figure 11: SON mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

The RMSE of seasonal mean daily near-surface wind speeds (m.s^{-1}) are shown in Figures 12 to 15. The high RMSE values on the south-eastern tip of the country in Figures, 12, 13, 14 and 15 demonstrate overestimations identified in previous paragraphs in all seasons. In general, the model performs best over central South Africa. The highest RMSE-values of

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2.8m.s^{-1} occur in the JJA-season in the Cape Town region and Lesotho (Figure 14). In general, the MAM-season has the largest area with the lowest RMSE, mostly between 0.8m.s^{-1} and 1.6m.s^{-1} (Figure 13).

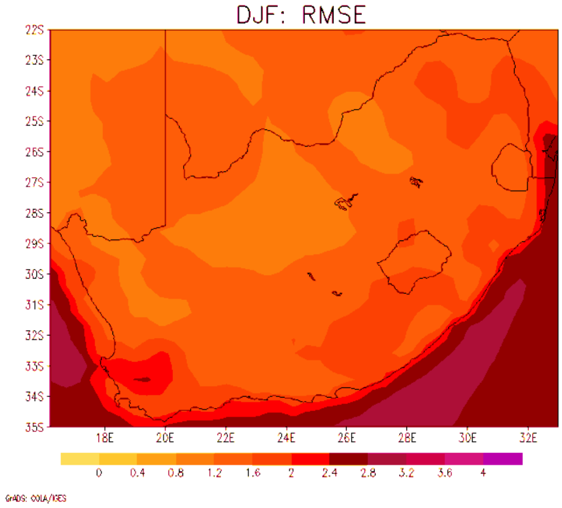

Figure 12: Root Mean Square Error (RMSE) for the DJF wind speeds (m.s^{-1}) (1981-2005).

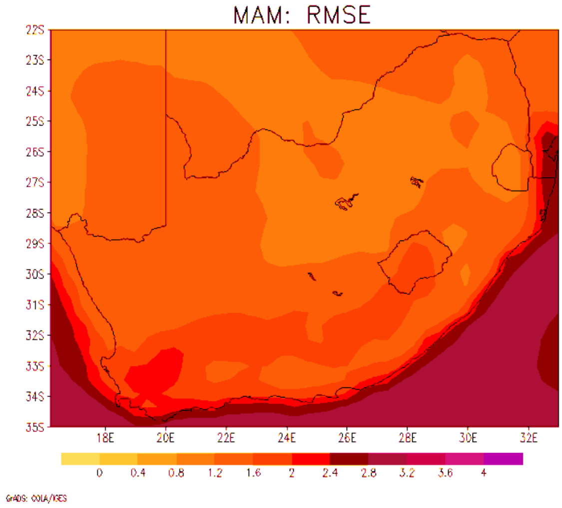

Figure 13: Root Mean Square Error (RMSE) for the MAM wind speeds (m.s^{-1}) (1981-2005).

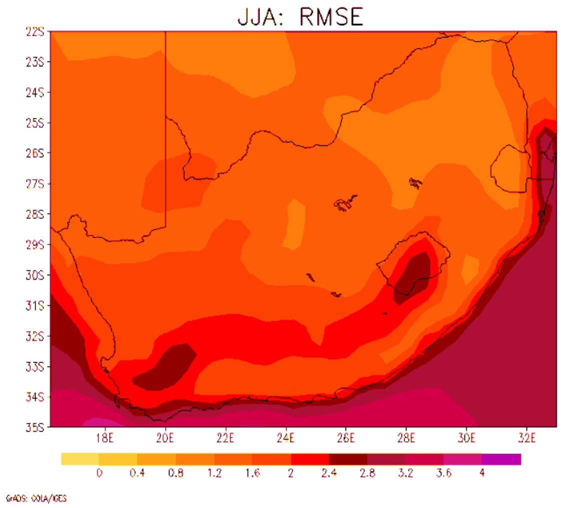

Figure 14: Root Mean Square Error (RMSE) for the JJA wind speeds (m.s^{-1}) (1981-2005).

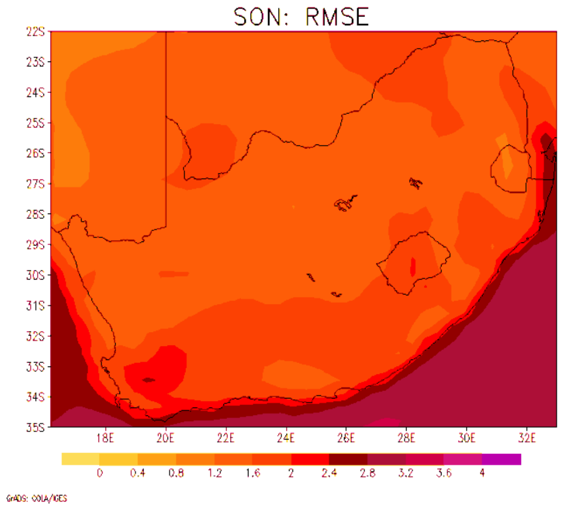

Figure 15: Root Mean Square Error (RMSE) for the SON wind speeds (m.s^{-1}) (1981-2005).

3.2.2 Seasonal daily wind speed frequencies

In terms of wind speeds occurring within a range acceptable for electricity generation, the results from the RMSEs become more apparent in Figures 16 to 23 – in particular the overestimation perceived in the southern half of South Africa in Figures 12-15.

The RCA4 RCM results show that for the DJF-season, wind speeds within valid range occur close to 100% across the entire country (Figure 17). According to the ERA-Interim output,

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however, wind speeds within the valid range do not occur as often in the north-eastern part of the country (Figure 16).

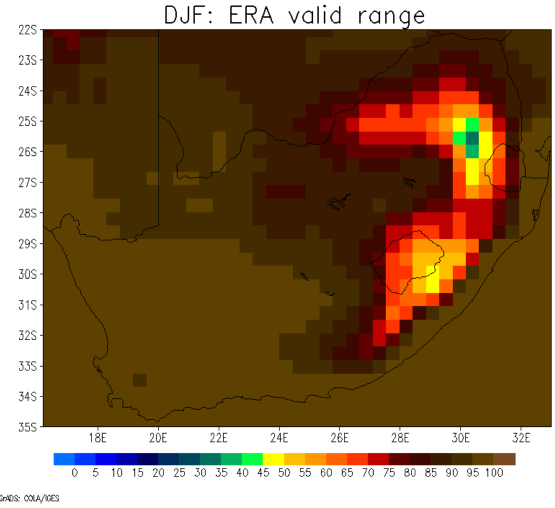

Figure 16: Frequency of days (%) when the wind blows within the valid speed range in DJF (ERA-Interim data) (1981-2005).

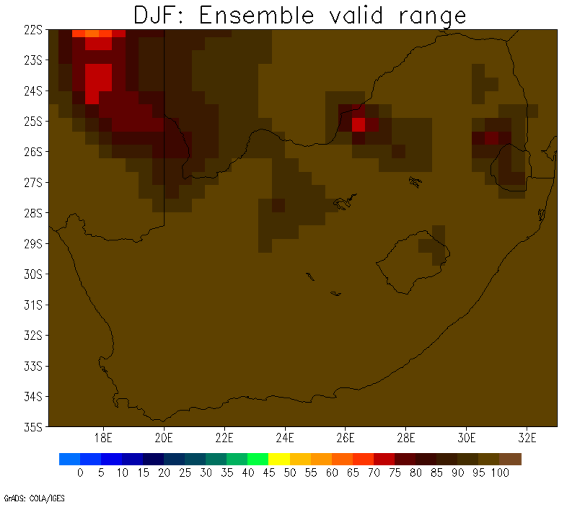

Figure 17: Frequency of days (%) when the wind blows within the valid speed range in DJF (RCA4 RCM ensemble data) (1981-2005).

In the MAM-season, winds blow in the valid wind speed range from 35% to 75% of the time according to the ERA-Interim run in the region of the Limpopo and North-West Provinces, extending further along the southeast as shown in Figure 18. The RCA4 RCM output (Figure 19), however, projects that winds blow within the valid range more frequently in the entire southern half of the country than does the ERA-Interim output. These results correspond with those of the RCA4 RCM mean wind speed projections shown in Figure 7. Because the RCA4 RCM generally estimates wind speeds at higher magnitudes than the ERA-Interim data (Figure 6), it could have been expected that winds more often blow within a higher speed range. Thus overestimations of wind speeds by the RCA4 RCM in the southern half of South Africa are evident in Figure 19 compared to the ERA-Interim data in Figure 18.

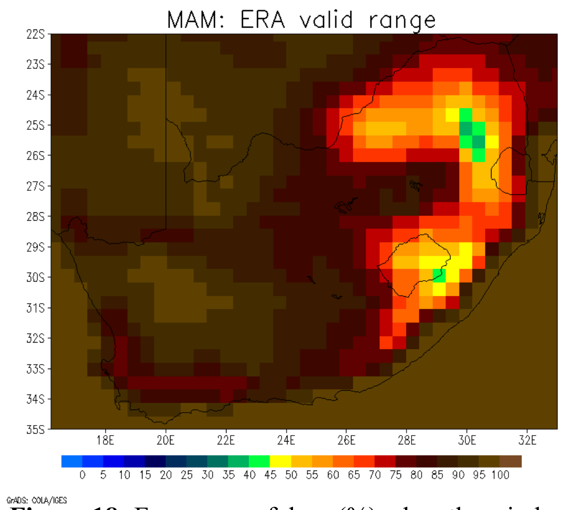

Figure 18: Frequency of days (%) when the wind blows within the valid speed range in MAM (ERA-Interim data) (1981-2005).

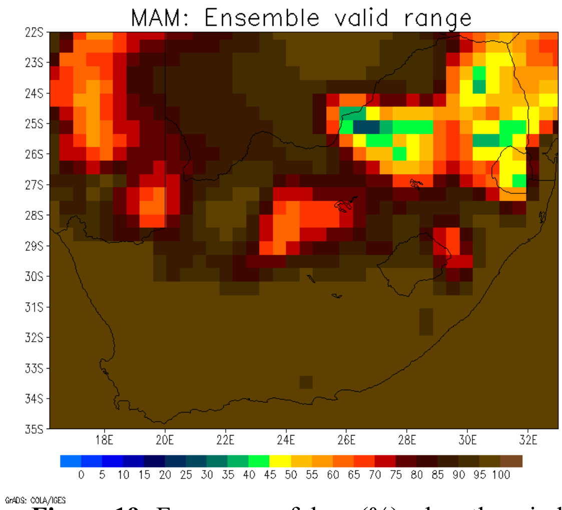

Figure 19: Frequency of days (%) when the wind blows within the valid speed range in MAM (RCA4 RCM ensemble data) (1981-2005).

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The valid range estimation in the JJA-season is similar for ERA-Interim output (Figure 20) and RCA4 RCM output (Figure 21) in its estimation of fewer occurrences of wind speed within valid range in the Limpopo Province, albeit of slightly different magnitudes. Fewer occurrences (as little as 75% of the days in the 25-year period analysed) of winds within the valid speed range are simulated in the ERA-Interim run in the Western Cape Province (Figure 20), whereas the RCA4 RCM output suggests that winds blow within the valid range 100% of the time in the Western Cape Province (Figure 21).

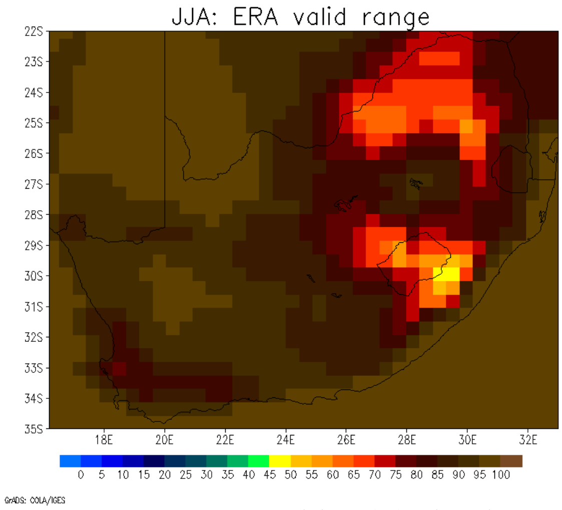

Figure 20: Frequency of days (%) when the wind blows within the valid speed range in JJA (ERA-Interim data) (1981-2005).

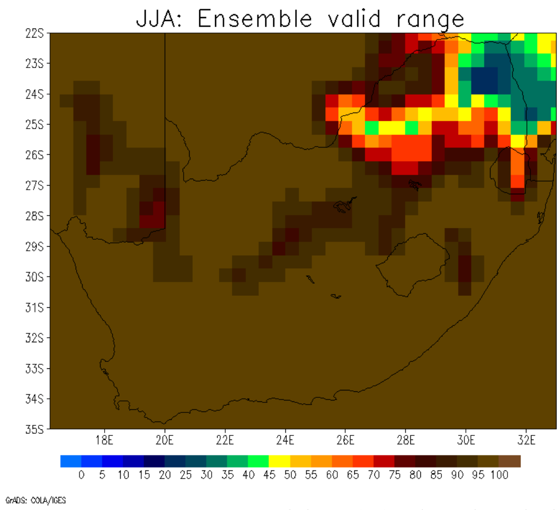

Figure 21: Frequency of days (%) when the wind blows within the valid speed range in JJA (RCA4 RCM ensemble data) (1981-2005).

As for SON, ERA-Interim results (Figure 22) project that winds speeds in the valid range could occur 60% of the time in the eastern half of the country. From the RCA4 RCM output (Figure 23), however, wind speeds are projected to remain within a valid speed range 100% of the time in the whole country, except for a tiny portion right above Swaziland.

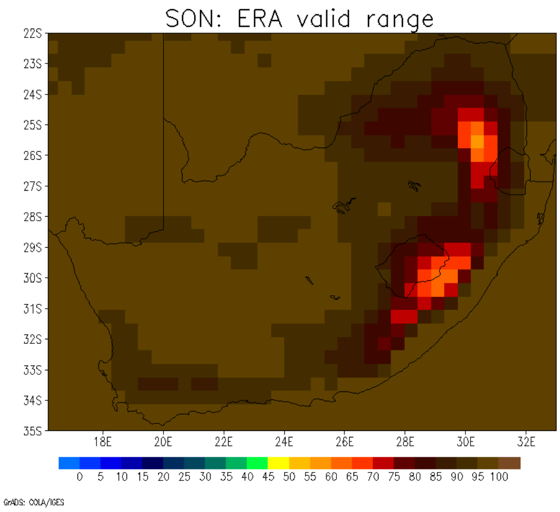

Figure 22: Frequency of days (%) when the wind blows within the valid speed range in SON (ERA-Interim data) (1981-2005).

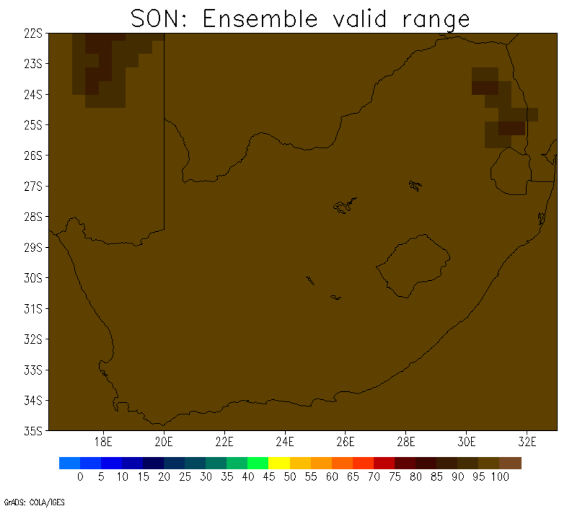

Figure 23: Frequency of days (%) when the wind blows within the valid speed range in SON (RCA4 RCM ensemble data) (1981-2005).

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According to Figure 24, ERA-Interim data projects that wind speeds occur below cut-in speed, up to 65% of the time in the eastern half of the country in the DJF-season. The RCA4 RCM run (Figure 25), projects that winds occur below cut-in speed, 0% to 5% of the time in the southern half of the country, with two small areas just north of Swaziland and around Gauteng experiencing winds below cut-in speed more frequently than the rest of the country (about 35% of the time).

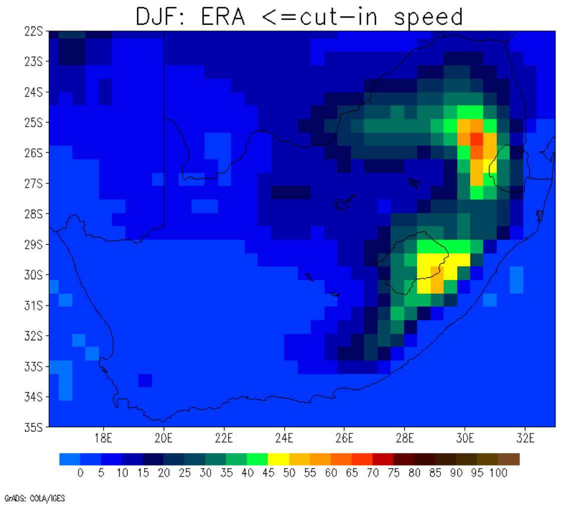

Figure 24: Frequency of days (%) when the wind blows below cut-in speed in DJF (ERA-Interim data).

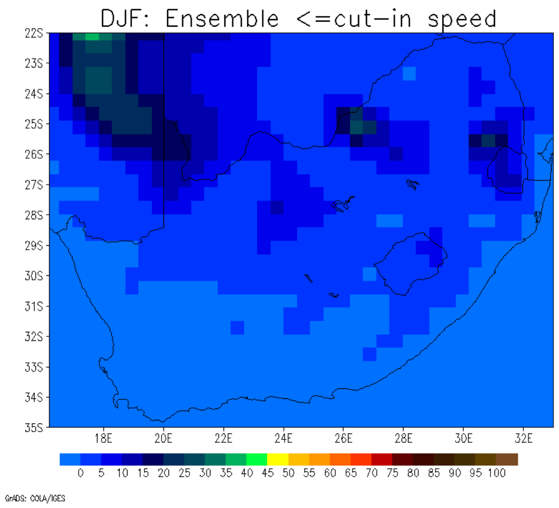

Figure 25: Frequency of days (%) when the wind blows below cut-in speed in DJF (RCA4 RCM ensemble data).

In the MAM-season, the ERA-Interim run (Figure 26) projects a similar pattern as in the DJF-season, where the eastern half of the country could experience winds below cut-in speed more frequently than the western half. The wind speed occurrences in north-eastern quarter of the country are also higher than the rest of the country in the RCA4 RCM simulation (Figure 27), indicating that the RCA4 RCM performs well in this area. However, considering the Western Cape Province, the RCA4 RCM simulation (Figure 27) shows that wind speeds are not below cut-in speed, while the ERA-Interim simulation (Figure 26) shows that it may occur up to 30% of the time in this province.

The ERA-Interim simulation shows that winds could blow below cut-in speed up to 55% of the time just east of Lesotho in the JJA-season (Figure 28). The RCA4 RCM simulation, however, only projects it to occur up to 20% of the time in this area (Figure 29). In contrast to this area, the RCA4 RCM simulation projects that winds could blow below cut-in speeds quite frequently in the Limpopo Province (up to 80% of the time) (Figure 29), while the

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ERA-Interim projection shows a maximum frequency of 45% of winds blowing below cut-in speed (Figure 28).

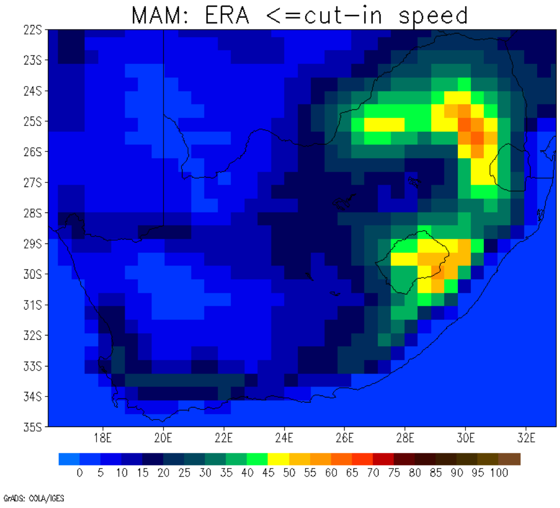

Figure 26: Frequency of days (%) when the wind blows below cut-in speed in MAM (ERA-Interim data) (1981-2005).

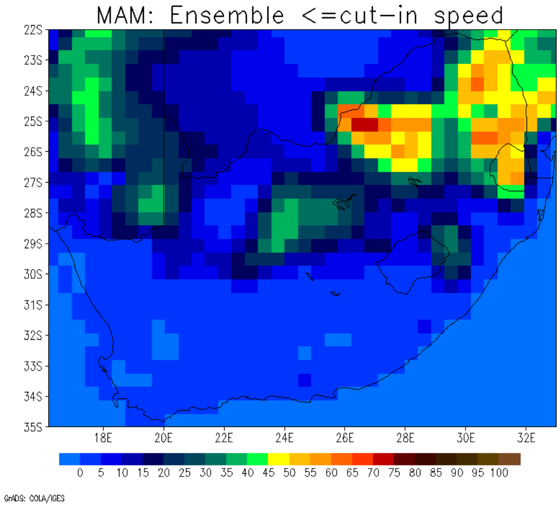

Figure 27: Frequency of days (%) when the wind blows below cut-in speed in MAM (RCA4 RCM ensemble data) (1981-2005).

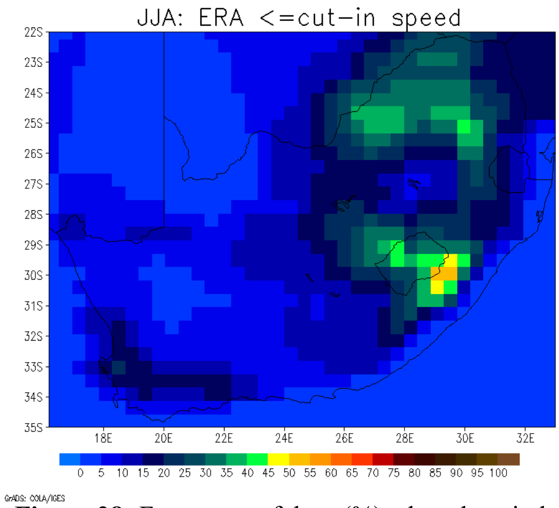

Figure 28: Frequency of days (%) when the wind blows below cut-in speed in JJA (ERA-Interim data) (1981-2005).

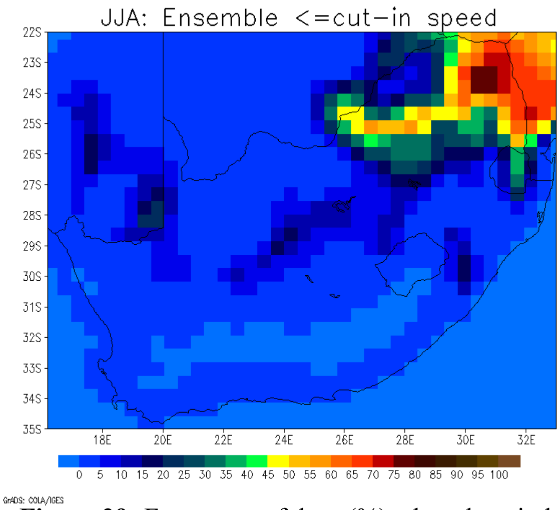

Figure 29: Frequency of days (%) when the wind blows below cut-in speed in JJA (RCA4 RCM ensemble data) (1981-2005).

For the SON-season, the ERA-Interim output shows that winds could blow below cut-in speed as frequently as 45% of the time in a north-south strip along the eastern boundary of the country (Figure 30). The RCA4 RCM simulation does not capture these low wind speeds in the same area, except for a small area north of Swaziland (Figure 31). The western half of the country, however, looks fairly similar in both ERA-Interim and RCA4 RCM simulations, projecting below cut-in speed winds to occur seldom, but there are differences in frequencies.

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The ERA-Interim data show below cut-in speed winds to occur up to 15% of the time, while RCA4 RCM data show it to occur only up to 5% of the time.

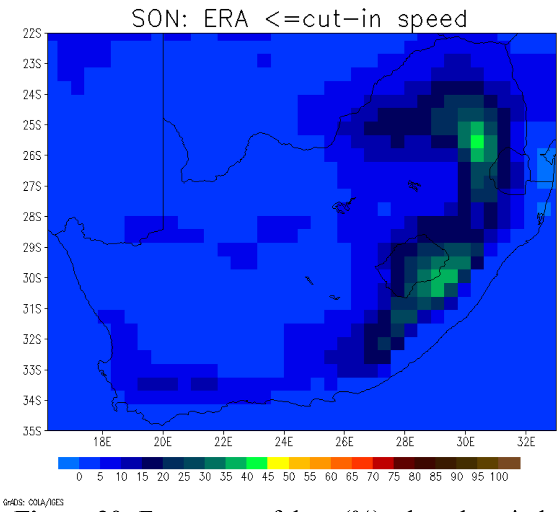

Figure 30: Frequency of days (%) when the wind blows below cut-in speed in SON (ERA-Interim data) (1981-2005).

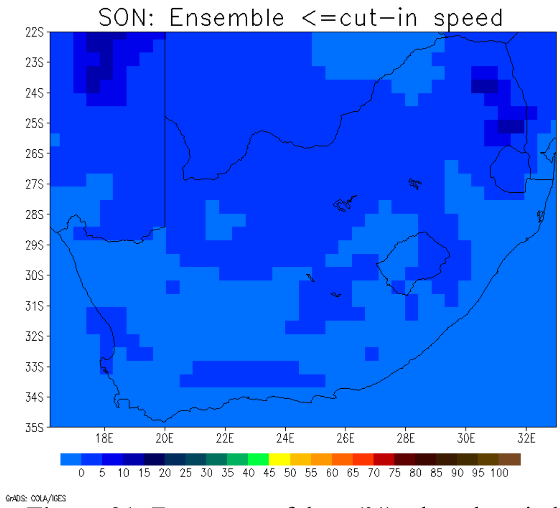

Figure 31: Frequency of days (%) when the wind blows below cut-in speed in SON (RCA4 RCM ensemble data) (1981-2005).

In the DJF-season, winds are projected to reach speeds above cut-out speed only up to 0.06% of the time in a marginal area south of the Eastern Cape Province over the Indian Ocean by the ERA-Interim data (Figure 32). As for the RCA4 RCM simulations, a small area, also showing a frequency of 0.06% of wind speeds occurring above cut-out speed, is shown directly to the east of the country, just south of the Mozambican coast (Figure 33).

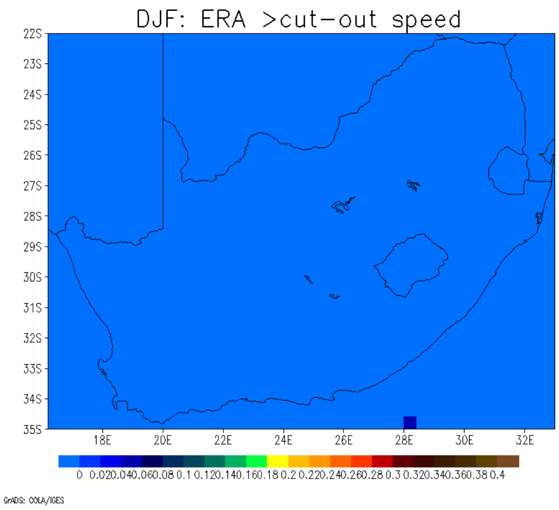

Figure 32: Frequency of days (%) when the wind blows above cut-out speed in DJF (ERA-Interim data) (1981-2005).

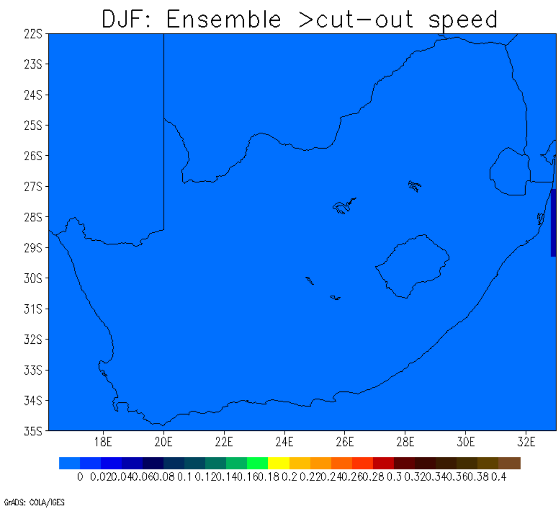

Figure 33: Frequency of days (%) when the wind blows above cut-out speed in DJF (RCA4 RCM ensemble data) (1981-2005).

For the MAM-season, winds are shown to blow at speeds above cut-out speed only up to 0.3% of the time over the ocean only, never over land according to the ERA-Interim

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simulation (Figure 34). According to the RCA4 RCM ensemble, winds never blow at speeds above cut-out speed in the entire domain assessed (Figure 35).

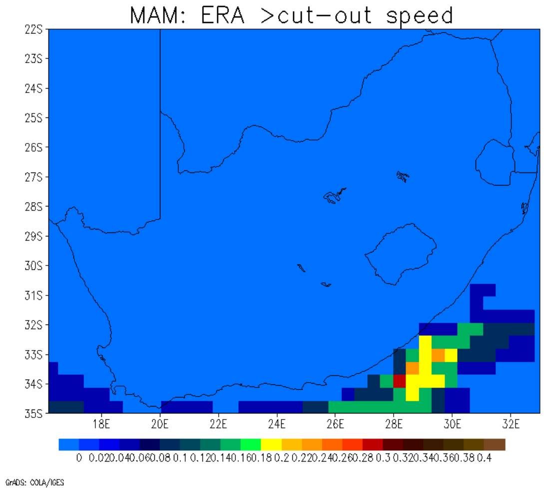

Figure 34: Frequency of days (%) when the wind blows above cut-out speed in MAM (ERA-Interim data) (1981-2005).

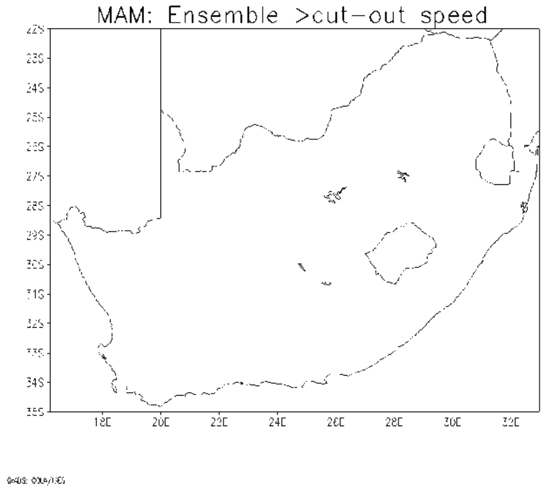

Figure 35: Frequency of days (%) when the wind blows above cut-out speed in MAM (RCA4 RCM ensemble data) (1981-2005).

In the JJA-season, ERA-Interim simulation (Figure 36) shows winds to blow at speeds above cut-out speed to occur only 0.3% of the time over the ocean, similar to the MAM-season (Figure 34). The RCA4 RCM simulation shows that winds may blow at speeds above cut-out speed up to 0.1% over a very small region over the ocean, but never on land (Figure 37).

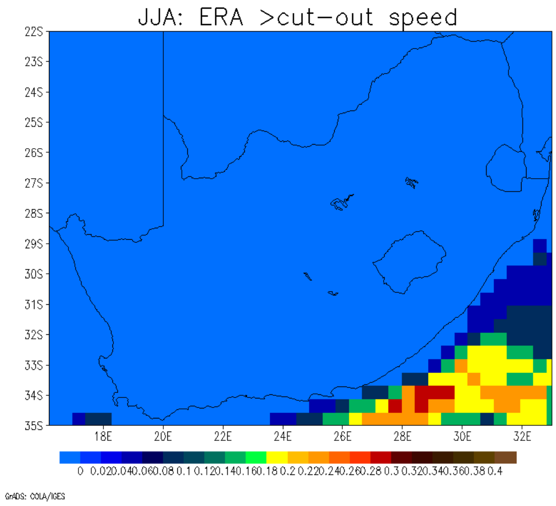

Figure 36: Frequency of days (%) when the wind blows above cut-out speed in JJA (ERA-Interim data) (1981-2005).

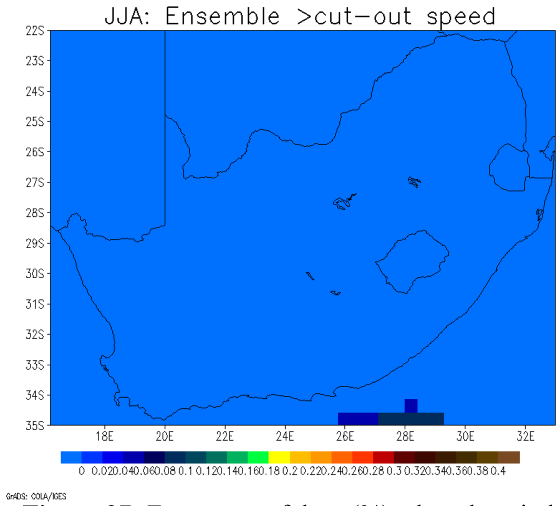

Figure 37: Frequency of days (%) when the wind blows above cut-out speed in JJA (RCA4 RCM ensemble data) (1981-2005).

Wind speeds could exceed cut-out speed up to 0.2% of the time over the ocean in the SON-season according to ERA-Interim data, but never on land (Figure 38). No occurrences of

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winds blowing at above cut-out speeds are shown for the RCA4 RCM ensemble in the entire domain studied (Figure 39).

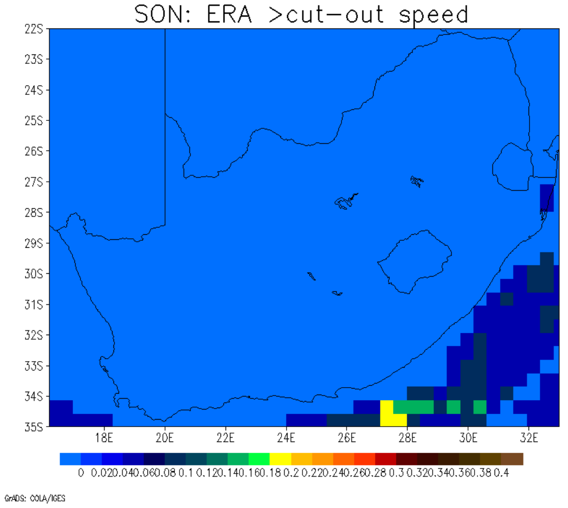

Figure 38: Frequency of days (%) when the wind blows above cut-out speed in SON (ERA-Interim data) (1981-2005).

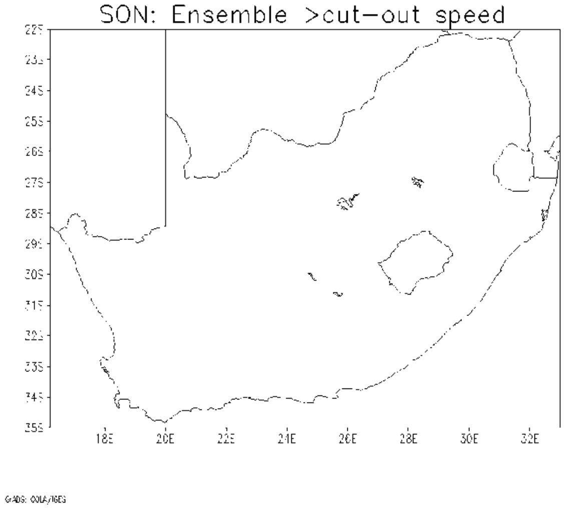

Figure 39: Frequency of days (%) when the wind blows above cut-out speed in SON (RCA4 RCM ensemble data) (1981-2005).

3.2.3 Model evaluation against observational data

Figure 40 shows mean daily wind speeds as simulated from RCA4 RCM data, plotted together with mean daily wind speeds calculated from ground station data recorded at six SAWS weather stations. Four separate values were plotted per location according to seasons. Wind speeds from RCA4 RCM ensemble data at all of the points plotted were higher than the observational data from the SAWS weather stations. Wind speeds vary on scales smaller than the grid resolution of model data of 0.44º × 0.44º (0.44º latitude translates roughly to between 45 and 40km; 0.44º longitude to 49km). Minor topographical variations, land cover and temperature variations can intensify or slow winds (Jarvis and Stuart, 2001). The model performs best at the Upington region and Mokopane regions (locations 13-16 and 21-24, respectively in Figure 40). The overestimation of winds demonstrated by the high RMSE-values in previous figures in the Western Cape region (Figures 12 to 15) are supported by the large differences in Malmesbury and Vredendal observations versus model output in Figure 40 (locations 1-4 and 5-8, respectively).

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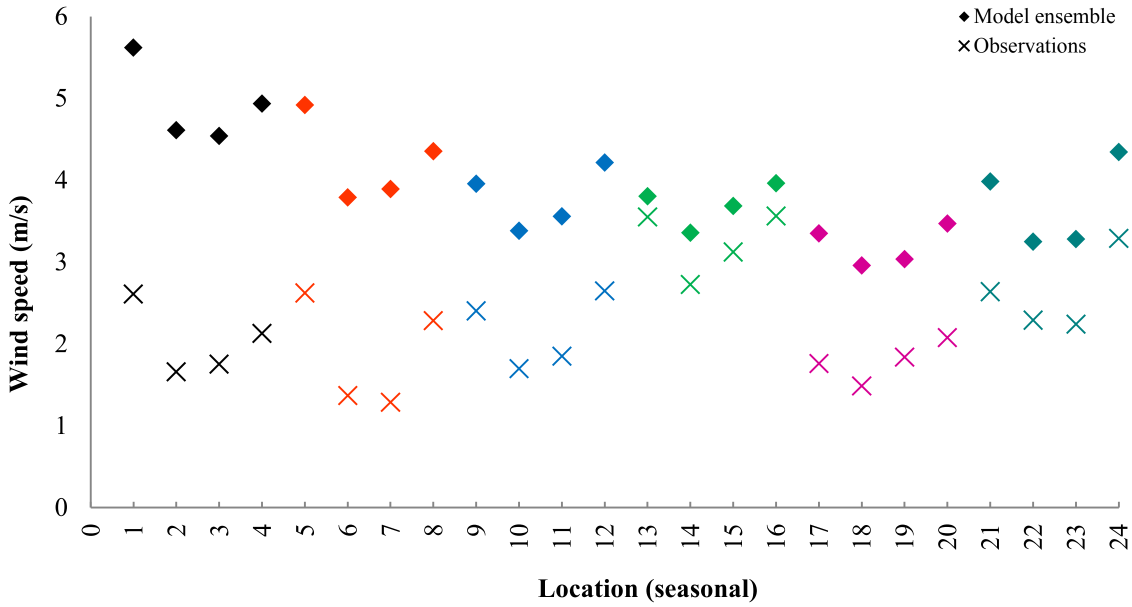

Figure 40: Comparison of wind speeds from SAWS station data with RCA4 RCM ensemble data. Location numbers 1 to 4 denote Malmesbury DJF, MAM, JJA, SON; location numbers 5 to 8 denote Vredendal DJF, MAM, JJA, SON etc. - in the same order as in Table 3.

3.3 VALUE OF FINDINGS

In terms of seasonal daily mean near-surface wind speed projections, the RCA4 RCM performed well in all seasons in the north-eastern quarter of the country, as well as over northern central South Africa. As for a southern strip stretching from around Cape Town to Lesotho, the RCA4 RCM projected a higher range of wind speeds than the observed ERA-Interim runs. The wind speed overestimates were no more than $1.5m.s^{-1}$. The RCA4 RCM ensemble data could therefore be employed in projecting potential changes in seasonal daily mean near-surface winds.

The RMSE-values for all seasons show that the RCA4 RCM performs differently than can be seen from only the projections themselves. RMSE-values are as high as $2.8m.s^{-1}$ in the DJF-, JJA-, and SON-seasons, and go up to $2.4m.s^{-1}$ in the MAM-season. Particularly concerning is the generally higher RMSE-values overlapping with areas that are currently being developed as wind power generation facilities from a latitude of about 30ºS (see Figure 1). This overestimation is to be kept in mind when interpreting the results from the second objective of the study, where winds in the future are projected by the RCA4 RCM. Fortunately, the highest RMSE-values are observed over relatively small areas of the country, as the RMSE-values in the majority of the country are in the range of $0.8m.s^{-1}$ to $2m.s^{-1}$. The importance of quantifying the differences between ERA-Interim data and RCA4 RCM output through, for

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instance, the calculation of the RMSE, is emphasised. Relying solely on projections does not provide the complete picture in terms of model performance.

The results of the frequencies of seasonal daily winds blowing at speeds within a range that is useful to wind energy generation shows that the RCA4 RCM generally projects this speed category to occur more often than the ERA-Interim simulations do. In the DJF- and SON-seasons, the RCA4 RCM projects valid speed range winds to occur more frequently in the east of the country than the ERA-Interim observational data shows it to occur. On the other hand, MAM- and JJA-season RCA4 RCM simulations show valid range wind speeds to occur less frequently in the northern half of the country than the ERA-Interim data.

The frequencies of winds blowing below cut-in speed show seasonal projections similar to the valid wind speed range category mentioned above. DJF- and SON-seasons are projected by the RCA4 RCM to have wind speeds below cut-in speed less often in the eastern part of the country than the ERA-Interim data. In the MAM-season, the northern half of the country is projected by the RCA4 RCM to have wind speeds below cut-in speeds more often than the ERA-Interim output. In the JJA-season, the RCA4 RCM only projects more frequent below-cut-in speed winds in the north-eastern quarter of the country (around Limpopo), without capturing the ERA-Interim data's simulation of more frequent below cut-in speed winds further south of the Limpopo area.

In Figures 32 to 39 it is shown that there were instances of no wind speeds occurring above cut-out speed on land for both ERA-Interim and RCA4 RCM ensemble data. Even though wind speeds were found to occur in this category (zero) over the ocean, oceanic wind data are of little use for this study. RCA4 RCM performance can therefore not be evaluated using this wind speed frequency category.

The results of high RMSE-values in the Cape Town region (Figures 12 to 15) were confirmed through the independent comparison of RCA4 RCM data to weather station data in Figure 40. The RCA4 RCM ensemble indeed simulated mean wind speeds at higher magnitudes than they have been recorded at all six ground stations, but were especially high at Malmesbury and Vredendal, both occurring in the area where the highest RMSE-values were found in all four seasons. The RCA4 RCM data were most comparable at the Upington and Mokopane stations.

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CHAPTER 4

Climate model projections

4.1 CLIMATIC CHANGES OBSERVED IN SOUTHERN AFRICA

Jury's (2013) analysis of sea-level pressure over southern Africa suggests that the sub-tropical highs are migrating poleward, and the increased sea-level pressure observed over the region from 1958 onwards in ECMWF reanalysis data are in contrast with a trough suggested by an Institut Pierre Simon Laplace (IPSL) GCM (1900-2100) simulation. His Climate Forecast System Reanalysis (CFS-R) (1979 onwards) and MIROC CGCM (1900-2100) runs suggest intensification of the South Atlantic High. Hadley observations (1900-2010) and IPSL simulations show intensification of the South Indian High. In his 20th century analysis, he found no trend in surface zonal winds, but future projections from CGCMs suggested intensified easterly flow along the south coast of South Africa. Such a trend is consistent with the poleward migration of the South Atlantic and South Indian Highs. In addition his results support findings of Hadley cell expansion (Hu and Fu, 2007).

4.2 RESULTS

To show potential changes in near-surface winds using RCA4 RCM ensemble projected data output for the projected period of 2057 to 2075, historical simulations were subtracted from their corresponding future projections for the RCP4.5 and RCP8.5 pathways for each of the four seasons. The differences that were subsequently obtained were then expressed as percentage changes relative to wind speeds in the historical period. These percentage changes are shown in Figures 41 to 48. They are labelled as "[Season]: r45 anomaly" for the RCP4.5 pathway, and as "[Season]: r85 anomaly" for the RCP8.5 pathway".

To show potential changes in the frequencies of winds occurring within speed ranges appropriate for wind power generation, historical RCA4 RCM projections were subtracted from their corresponding future projections of these frequencies for each season and shown in Figures 49 to 56. The figures showing differences are also displayed for both RCP4.5 and RCP8.5. They are labelled as "[Season]: r45 valid range anomaly" for the RCP4.5 pathway, and as "[Season]: r85 valid range anomaly" for the RCP8.5 pathway.

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Projected future changes in frequencies of wind speeds below the cut-in speed were also calculated for all seasons under the two RCPs and are shown in Figures 57 to 64. They are labelled as "[Season]: r45<=cut-in speed anomaly" for the RCP 4.5 pathway and as "[Season]: r85<=cut-in speed anomaly" for the RCP8.5 pathway.

Projected future changes in frequencies of winds blowing above cut-out speed were calculated. They are, however, not shown in this chapter as there were no occurrences of these winds in the projections. It was shown in the previous chapter that these winds never occur over land; therefore the calculation of potential changes in the frequency of occurrences of these winds could be omitted.

RCA4 RCM projected changes in mean wind directions are then given. Firstly, wind directions as simulated by the RCA4 RCM in the historical period are provided as wind vectors in Figures 65, 68, 71, and 74 and are labelled "[Season]: Ensemble". The projected changes in those directions are then given for the RCP4.5 pathway in Figures 66, 69, 72, and 75 and are labelled "[Season]: Anomaly RCP4.5". The projected wind direction changes are given in Figures 67, 70, 73, and 76 and are labelled "[Season]: Anomaly RCP8.5". The vector data are shown in these figures with mean wind speed change anomalies in the background, but the focus in this part of the study will be to analyse the potential diversions from dominant wind directions in each of the four seasons for the projected period extending from 2051 to 2075.

4.2.1 Mean seasonal wind speed

For the DJF-season, it is shown that in Figure 41 that wind speeds are expected to increase by up to 4% along the southern parts of the Western and Eastern Cape Provinces under RCP4.5 (Figure 41). For the RCP8.5 pathway, increases in wind speeds could reach 6% in this area (Figure 42). Decreases in wind speeds of up to 1.5% might be expected in the Highveld under the RCP4.5 pathway (Figure 41) and 2.5% under the RCP8.5 pathway (Figure 42).

In the MAM-season under the RCP4.5 pathway, wind speeds are projected to increase by up to 3.5% in the north-eastern quarter of the country, and could also increase by up to 3% in the Cape Town region (Figure 43). Projected increases in wind speeds are more apparent in the RCP8.5 pathway in these regions, where it could increase by up 5% in the Limpopo province and 4.5% in the Cape Town region (Figure 44). The central part of the country could expect a slight increase in wind speeds of about 1% to 3% under the RCP8.5 pathway as well (Figure

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44). Decreased wind speeds are projected under the RCP4.5 pathway in the Northern Cape and the Eastern Cape Provinces, but at only 1% (Figure 43). In the RCP8.5 pathway it is projected that the western half of the Northern Cape Province could expect decreased wind speeds of up to 2% and the Eastern Cape Province could expect wind speeds to increase by 2% along the coast, and decrease by 1% closer to the escarpment edge over the east of South Africa (Figure 44).

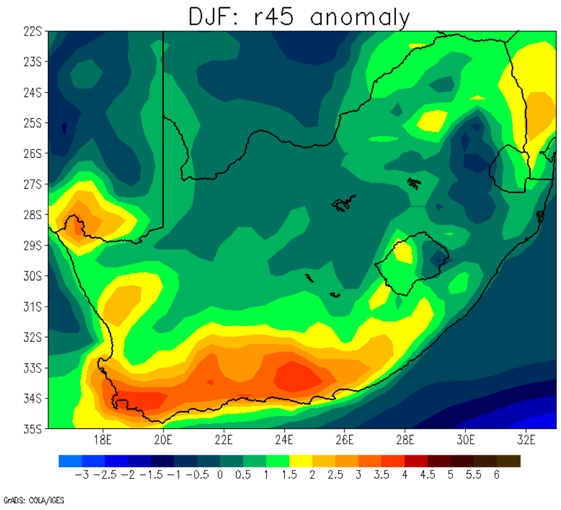

Figure 41: Projected anomaly in mean wind speed (%) for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

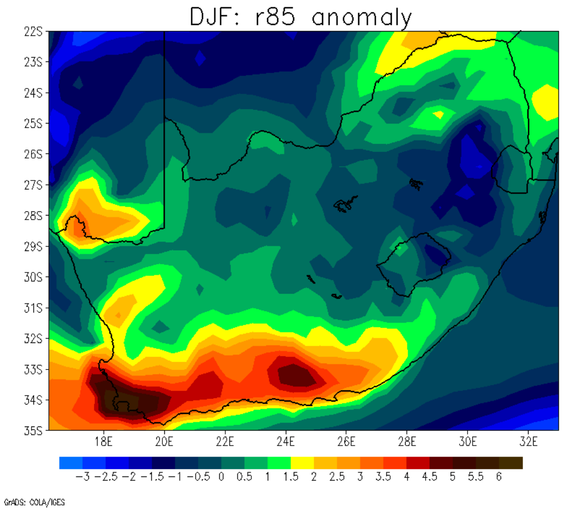

Figure 42: Projected anomaly in mean wind speed (%) for DJF (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

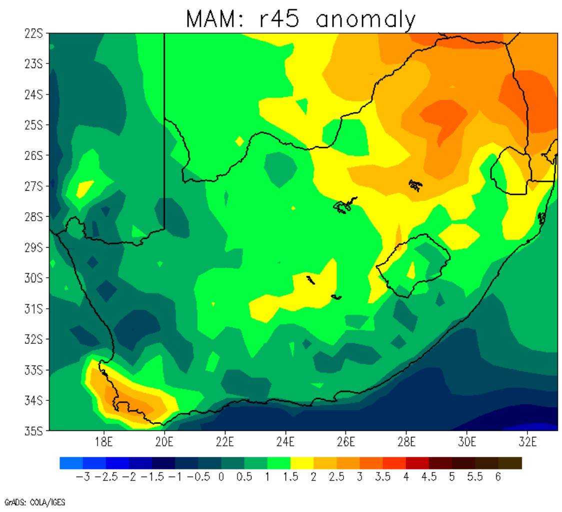

Figure 43: Projected anomaly in mean wind speed (%) for MAM (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

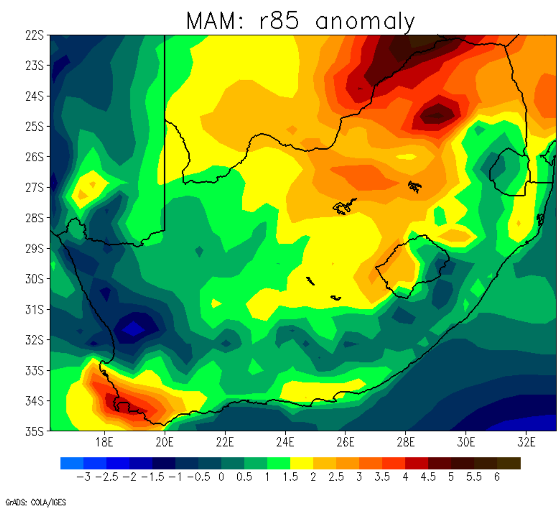

Figure 44: Projected anomaly in mean wind speed (%) for MAM (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

In the RCP4.5 pathway in the JJA-season, wind speeds are projected to increase for the majority of the country (Figure 45). Specifically the eastern half of the country could expect wind speeds to increase by up to 4.5%, but central South Africa and the Cape Town region could expect wind speeds to increase by up to 3%. Decreased wind speeds of up to 1% are

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projected in this same pathway over the coastal Eastern Cape Province and the West Coast. Under the RCP8.5 pathway, wind speeds are projected to increase by up to 6% in the far east of South Africa, and in the region of 1% to 3% in the interior (Figure 46). Wind speeds are projected to decease along the West Coast by up to 2%, and could decrease by 1.5% in the Eastern Cape Province.

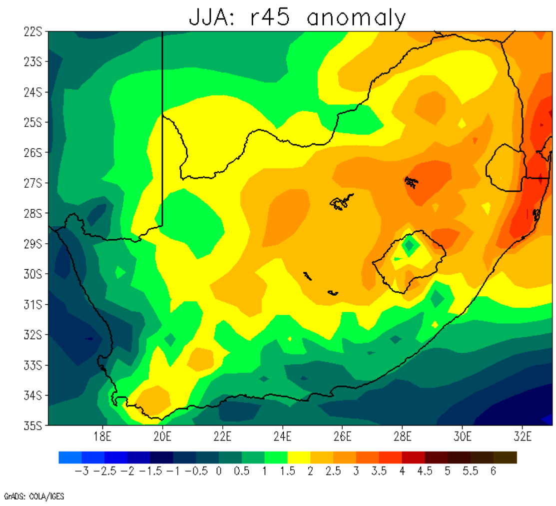

Figure 45: Projected anomaly in mean wind speed (%) for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

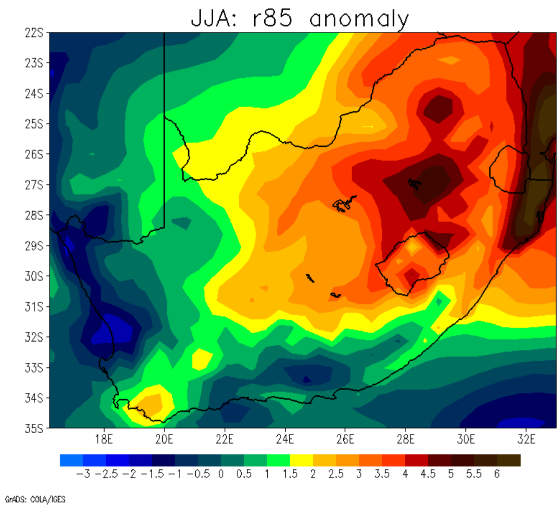

Figure 46: Projected anomaly in mean wind speed (%) for JJA (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

In the SON-season, wind speeds are projected to increase by 5% in the Limpopo Province, and lesser increases are projected along the South African coast starting at KwaZulu-Natal all the way to Cape Town under the RCP4.5 pathway (Figure 47). The region around and including the Northern Cape Province could expect wind speeds to increase by 0% up to 1.5%. Under the RCP8.5 pathway, the Limpopo Province could expect wind speeds to increase by up to 6% (Figure 48). The rest of the country could expect milder wind speed increase ranging from 0.5% in parts of the Northern Cape Province, to 4% in the Cape Town region and central South Africa. Thus wind speeds are not projected to decrease under either of the pathways for the SON-season.

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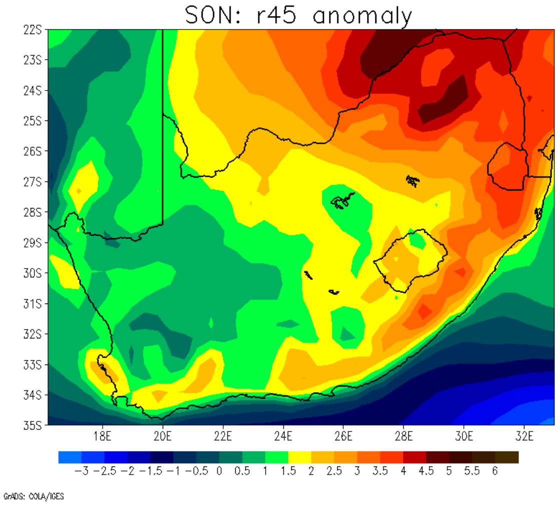

Figure 47: Projected anomaly in mean wind speed (%) for SON (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

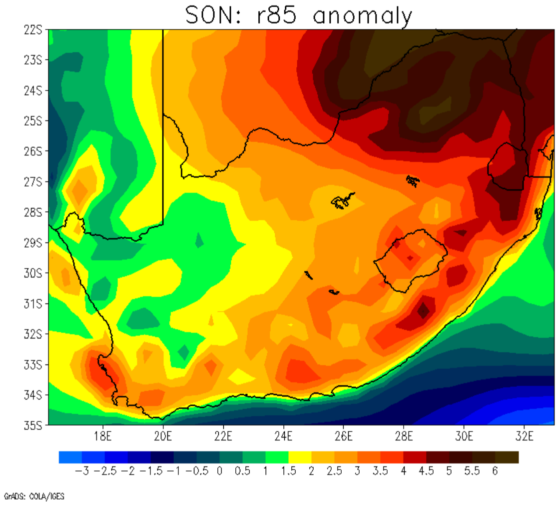

Figure 48: Projected anomaly in mean wind speed (%) for SON (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

4.2.2 Seasonal daily wind speed frequencies

During the DJF-season, decreases of 1% of wind speed frequencies of winds within valid range for wind power generation might occur in the Northern Cape, Western Cape, and parts of the Eastern Cape Provinces under both the RCP4.5 (Figure 49) and RCP 8.5 pathways (Figure 50). Up to 3% more days with winds blowing in the valid wind speed range are projected in the north of the country in the RCP4.5 pathway (Figure 49). Under the RCP8.5 pathway, however, these wind speeds are projected to occur by up to 3% less frequently in a small area west of Swaziland (Figure 50). In the majority of the country, the frequency of winds blowing within the appropriate speed range is projected to remain fairly unchanged.

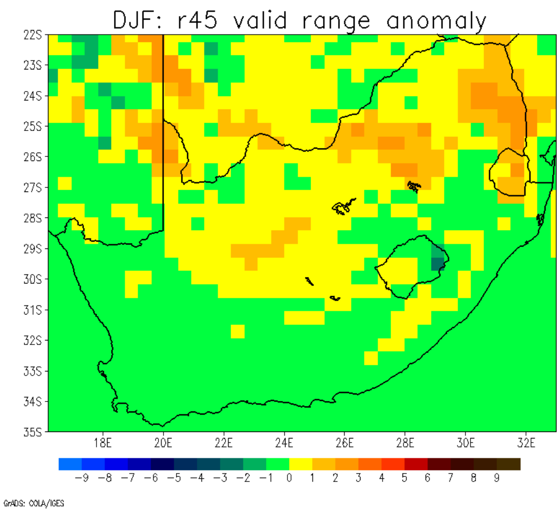

Figure 49: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

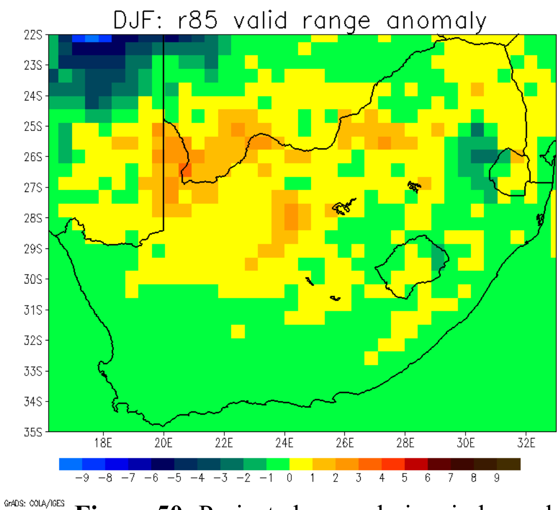

Figure 50: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for DJF (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

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During the MAM-season, wind speed frequencies of winds within the valid range are projected to increase by up to 9% in the north-eastern quarter of the country in the RCP4.5 (Figure 51) and RCP8.5 (Figure 52) pathways. In the remaining portion of the country, frequency changes are small, with increases and decreases seldom exceeding 1% in both RCPs.

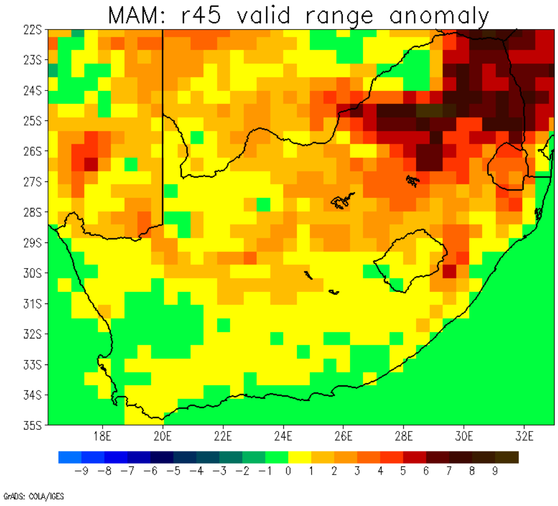

Figure 51: Projected anomaly in wind speed frequencies (%) in the valid speed range for MAM (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

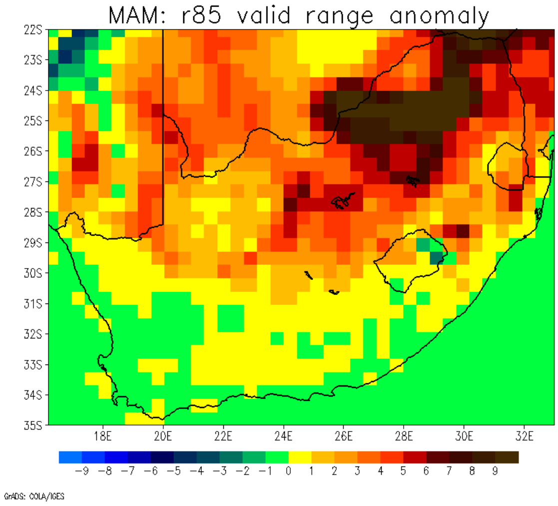

Figure 52: Projected anomaly in wind speed frequencies (%) in the valid speed range for MAM (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

In the JJA-season, valid speed range winds are projected to occur more often over the Limpopo Province by between 3% and 9% in the RCP4.5 pathway (Figure 53). The Western Cape and Eastern Cape Provinces could expect these winds to occur up to 1% less frequently in the RCP4.5 pathway. In the RCP8.5 pathway, a large region in north-eastern South Africa could expect 9% more valid speed range winds (Figure 54). These winds are projected to occur up to 3% more often in central South Africa, and to occur up to 1% less often in the Eastern Cape and parts of the Western Cape Province (Figure 54).

During the SON-season, changes in frequencies of winds within the valid range are small in both the RCP4.5 (Figure 55) and RCP8.5 (Figure 56) pathways, changes not exceeding 1% in either direction for the majority of the country. However, a small strip can be seen between Nelspruit and Musina (above Swaziland) where occurrences of these winds are projected to increase by up to 6% for both pathways.

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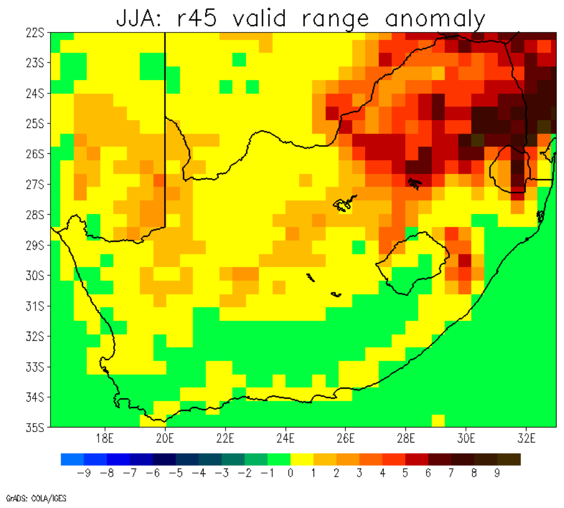

Figure 53: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

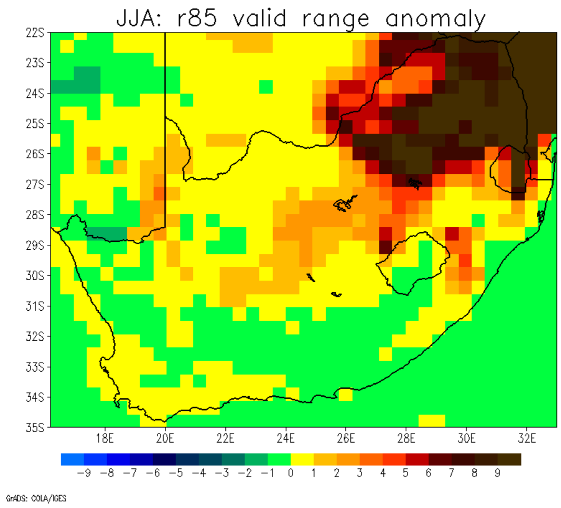

Figure 54: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for JJA (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

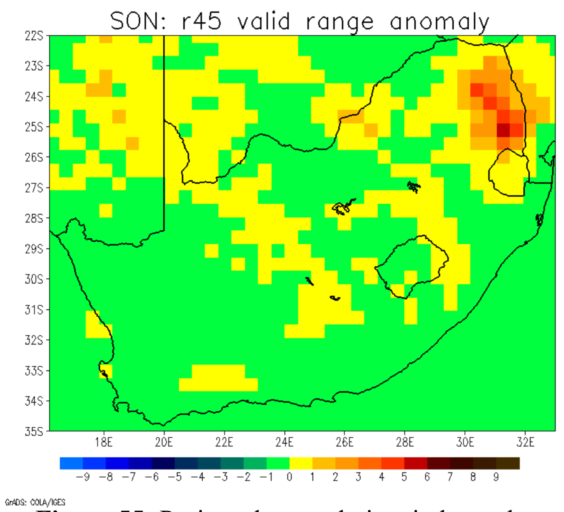

Figure 55: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for SON (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

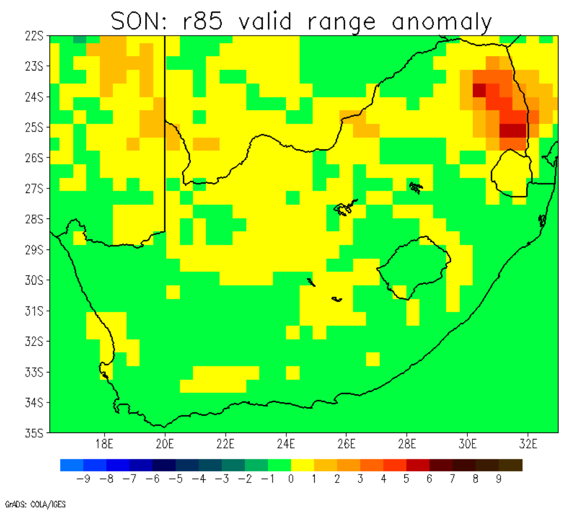

Figure 56: Projected anomaly in wind speed frequencies (%) in the valid wind speed range for SON (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

Occurrences of winds below the cut-in speed during the DJF-season are mostly expected to remain between -2% and 0% change in the RCP4.5 pathway, except for a small region between Swaziland and Lesotho, where such winds may occur up to 2% more (Figure 57). In the RCP8.5 pathway, these winds are also projected to generally decrease by -2% and 0%, but a larger part than in the RCP4.5 pathway projection (between Swaziland and Lesotho) could expect these winds to occur up to 4% more often (Figure 58).

During the MAM-season, up to 10% fewer occurrences of below cut-in wind speeds in the eastern half of the country are projected in the RCP4.5 pathway (Figure 59). Minor increases can be expected during MAM for the RCP4.5 pathway in the southwestern Northern Cape,

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the Western Cape and the coastal Eastern Cape Provinces (Figure 59). Below cut-in speed winds are projected to decrease by up to 14% in north-eastern South Africa under the RCP8.5 pathway (Figure 60). These winds could occur by up to 2% more frequently along the coast in the Western Cape and Eastern Cape Provinces (Figure 60).

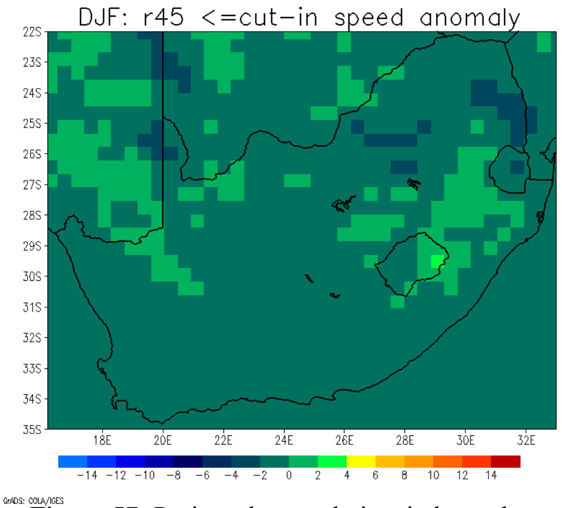

Figure 57: Projected anomaly in wind speed frequencies (%) below cut-in speed for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

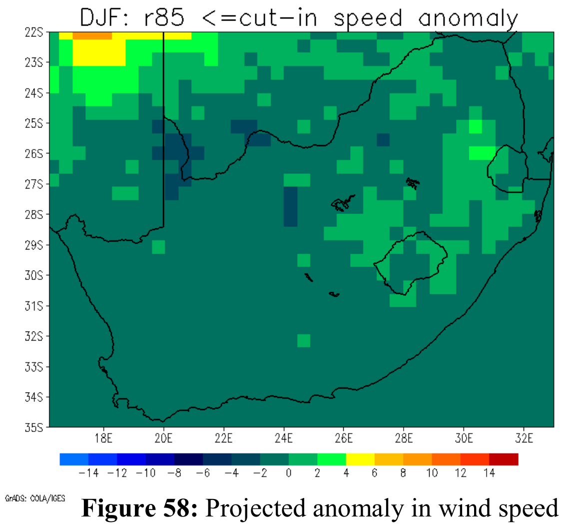

Figure 58: Projected anomaly in wind speed frequencies (%) below cut-in speed for DJF (2051-2075 relative to 1981-2005) under the RCP8.5

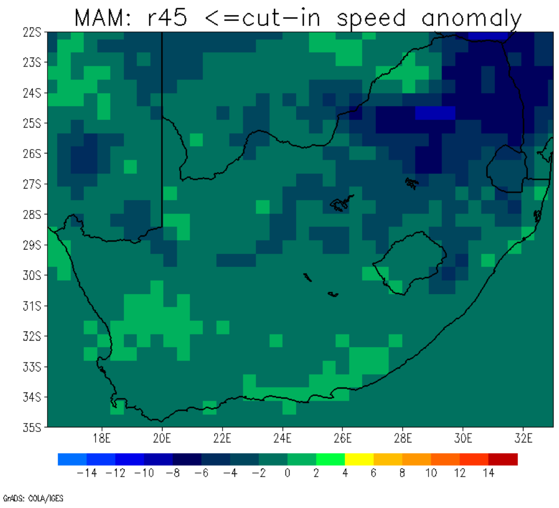

Figure 59: Projected anomaly in wind speed frequencies (%) below cut-in speed for MAM (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

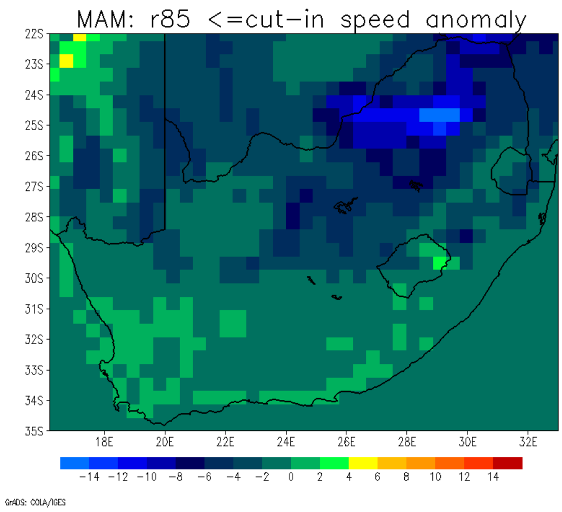

Figure 60: Projected anomaly in wind speed frequencies (%) below cut-in speed for MAM (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

Below cut-in speed winds could occur 2% more often in scatterred areas in the Western Cape and Eastern Cape Provinces in the JJA-season under the RCP4.5 pathway (Figure 61). These winds are projected to occur up to 10% less often in north-eastern South Africa in the RCP4.5 pathway. Below cut-in speed winds could occur 2% more often under the RCP8.5 pathway in the Northern Cape and Eastern Cape Provinces (Figure 62). Large parts of north-eastern

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South Africa could expect these winds to decrease by 12% under the RCP8.5 pathway (Figure 62).

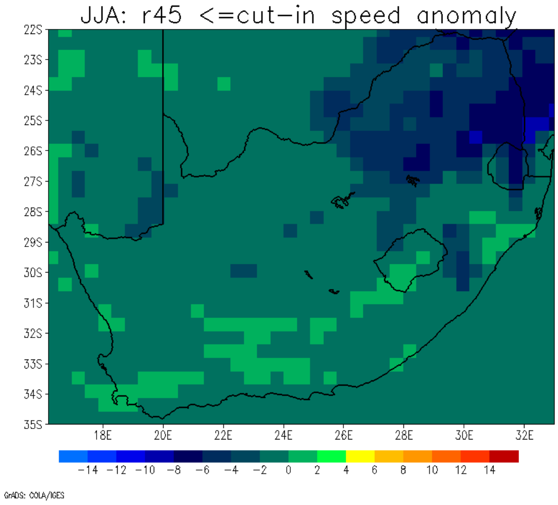

Figure 61: Projected anomaly in wind speed frequencies (%) below cut-in speed for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

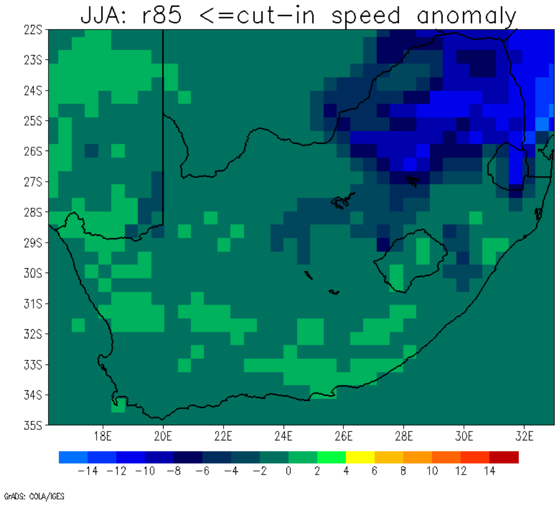

Figure 62: Projected anomaly in wind speed frequencies (%) below cut-in speed for JJA (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

During the SON-season for the RCP4.5 pathway, frequencies of below cut-in speed winds could increase by up to 2% in parts of the North-West, Free State, Northern Cape and Eastern Cape Provinces (Figure 63). Below cut-in speed winds could decrease by 6% in a small area north of Swaziland (Figure 63). In the RCP 8.5 pathway, these winds are projected to change primarily by -2% to 0%, apart from the same area north of Swaziland for which the winds could occur 6% less frequently as well (Figure 64). Small areas in which these winds could occur up to 2% more often are scatterred around the eastern interior of the country and parts of the Western Cape coast under the RCP8.5 pathway (Figure 64).

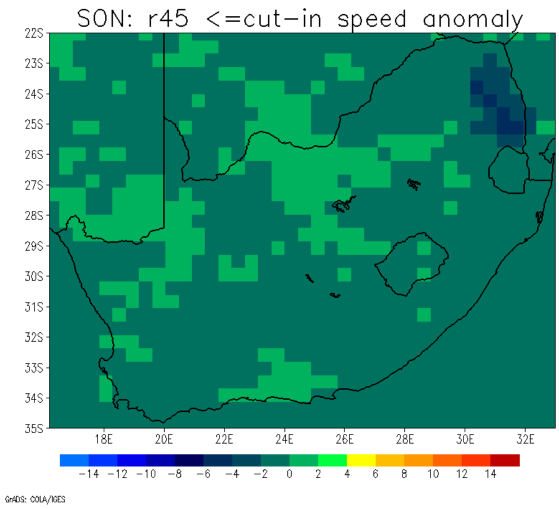

Figure 63: Projected anomaly in wind speed frequencies (%) below cut-in speed for SON (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

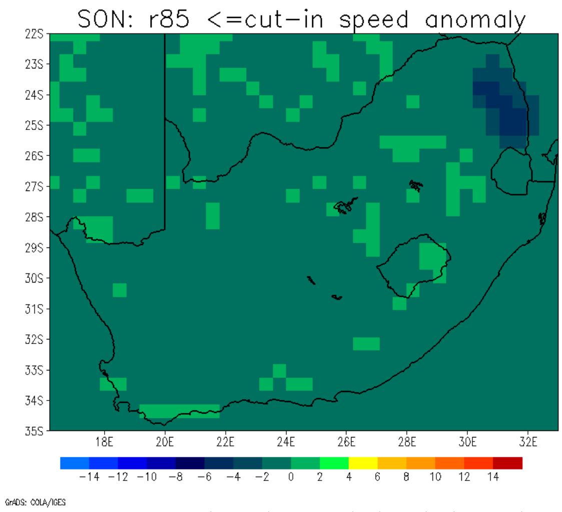

Figure 64: Projected anomaly in wind speed frequencies (%) below cut-in speed for SON (2051-2075 relative to 1981-2005) under the RCP8.5 pathway.

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4.2.3 Mean seasonal wind directions

In the DJF-season, the north-easterlies over the Gauteng region (Figure 65) are projected to deviate towards the east in the RCP4.5 (Figure 66) and the RCP8.5 pathway. Over the western half of the country, the southerlies (Figure 65) are projected to deviate in an east to south-eastern direction in the interior of the country under both pathways (Figures 66 and 67). The southerlies close to the coast in the Western Cape Province (Figure 65) are projected to deviate to the west in both pathways as well (Figures 66 and 67). The south-easterlies simulated in the far eastern corner of the country are projected to devaite to the east in the RCP4.5 pathway (Figure 66) and are projected to deviate in an easterly to north-easterly direction in the RCP8.5 pathway (Figures 67).

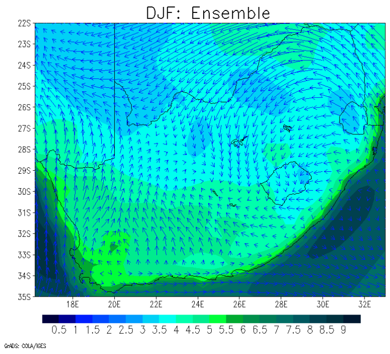

Figure 65: DJF mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

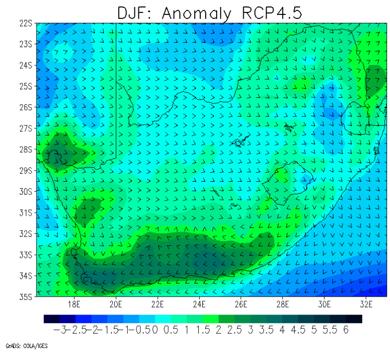

Figure 66: Projected anomaly in mean wind speed (%) and direction for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

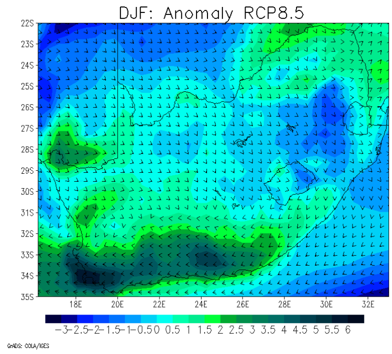

Figure 67: Projected anomaly in mean wind speed (%) and direction for DJF (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

In the MAM-season, the primarily southern direction in which winds blow over the Eastern Cape and Western Cape Provinces (Figure 68) are projected to deviate in a western direction in the RCP4.5 (Figure 69) and the RCP8.5 (Figure 70) pathways where current wind farm developments are underway. In the RCP4.5 pathway, winds are not projected to deviate (Figure 69) much from their dominant directions (Figure 68) in central South Africa. However, in the western expanses of the country, the northerlies (Figure 68) are projected to deviate in an eastern direction in thr RCP4.5 pathway (Figure 69). Winds in the Limpopo area are projected to remain fairly unchanged in the both the RCP4.5 (Figure 69) and RCP8.5 pathways (Figure 70). North-westerlies along the Eastern Cape coast (Figure 68) are projected to deviate in the opposite direction i.e. to the southwest in both pathways (Figures 69 and 70).

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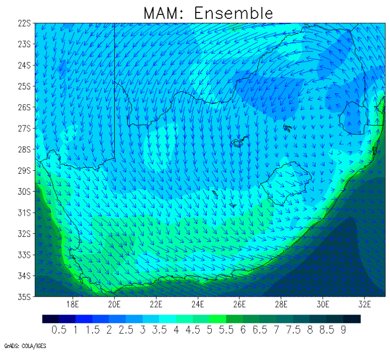

Figure 68: MAM mean seasonal wind speed ($m.s^{-1}$) from RCA4 RCM ensemble data (1981-2005).

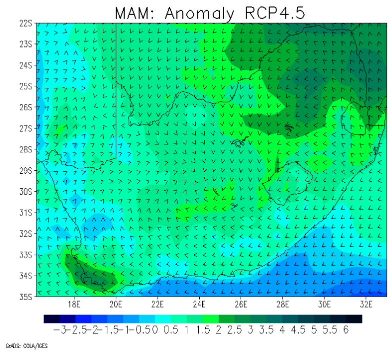

Figure 69: Projected anomaly in mean wind speed (%) and direction for MAM (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

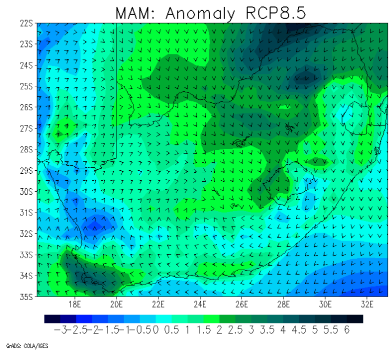

Figure 70: Projected anomaly in mean wind speed (%) and direction for MAM (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

The north-easterlies in Limpopo (Figure 71) are projected to deviate in a southern direction in both the RCP4.5 (Figure 72) and RCP8.5 (Figure 73) pathways in the JJA-season. The north-westerlies over the Western Cape and Eastern Cape Provinces (Figure 71) are projected to deviate very little in the RCP4.5 pathway (Figure 72), but are projected to deviate in a northern direction under the RCP8.5 pathway (Figure 73).

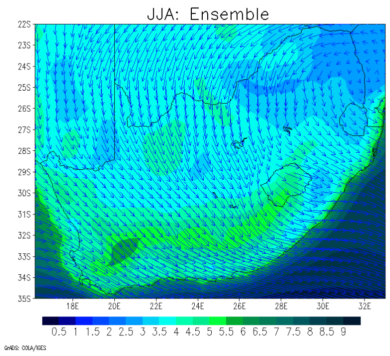

Figure 71: JJA mean seasonal wind speed ($m.s^{-1}$) from RCA4 RCM ensemble data (1981-2005).

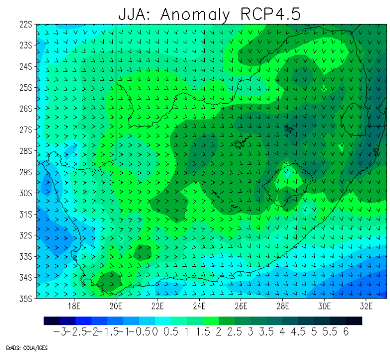

Figure 72: Projected anomaly in mean wind speed and direction (%) for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

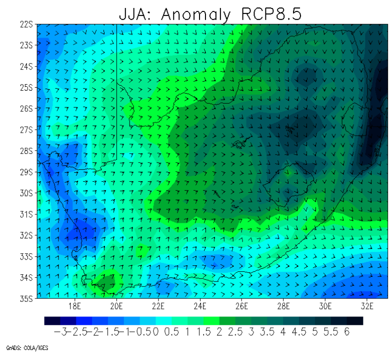

Figure 73: Projected anomaly in mean wind speed (%) and direction for JJA (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

While wind directions in the eastern half of the country (Figure 74) are projected to remain relatively unchanged in the SON-season under both the RCP4.5 (Figure 75) and RCP8.5 (Figure 76) pathways, they are projected to deviate to the west along the coasts of the Western Cape and Eastern Cape Provinces under both pathways (Figures 75 and 76). South-westerly winds in the Northern Cape Province (Figure 74) are projected to deviate in an eastern direction in both pathways (Figures 75 and 76).

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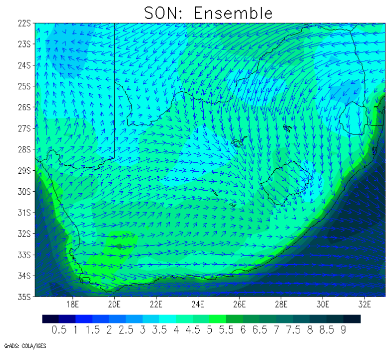

Figure 74: SON mean seasonal wind speed (m.s^{-1}) from RCA4 RCM ensemble data (1981-2005).

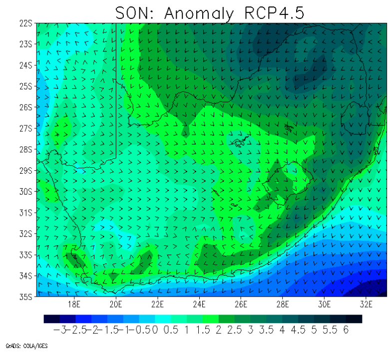

Figure 75: Projected anomaly in mean wind speed (%) and direction for SON (2051-2075 relative to 1981-2005) under the RCP4.5 pathway.

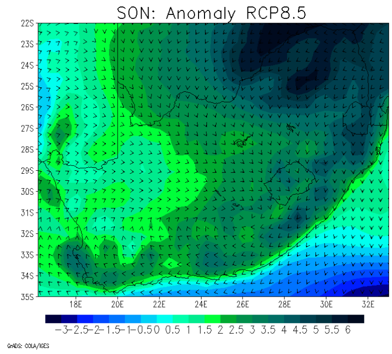

Figure 76: Projected anomaly in mean wind speed (%) and direction for SON (2051-2075 relative to 1981-2008) under the RCP8.5 pathway.

4.3 VALUE OF FINDINGS

In the DJF-season, wind speeds are projected to increase under both RCPs in the north-eastern quarter of the country. However, during the MAM-season, increased wind speeds are projected for the north-eastern corner of the country as well as the Cape Town region. This potential increase in wind speeds grows to the south-west in the JJA-season, but recedes again in the SON-season. Changes in wind speeds are similar under both RCPs, but the magnitude of changes differs, usually being more extreme under the RCP8.5 pathway than the RCP 4.5 pathway. In the DJF- and SON-seasons, wind speeds generally are projected to increase by up to 6% in the areas which are currently being exploited for wind farm development. However, in the MAM- and JJA-seasons, wind speeds are projected to increase by a maximum of 2%, or to decrease by no more than 1%. Therefore, according to these primarily increasing wind speeds year-round, the South African wind farms could expect to be affected quite positively in the projected period. As for the rest of the country, especially to the north-east, wind speeds are projected to increase by up to 6% in all of the seasons except for the DJF-season. The South African wind resource is therefore generally projected to improve.

Projected changes in winds within the speed range appropriate for wind power generation are small in the majority of the country, and seldom exceed an increase or decrease of 1%, especially in the Western Cape and Eastern Cape Provinces where wind farms are being developed at present. In north-eastern South Africa, these winds could blow by up to 9% more often in the MAM- and JJA-seasons under both pathways. In the DJF- and SON-

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seasons, these winds are also projected to occur more often, but by a maximum of 6% more than in the historical period.

Winds below cut-in speed are projected to remain mostly unchanged in all seasons for the largest part of the country, but are projected to decrease in north-eastern South Africa. Scattered areas where these winds occur up to 2% more frequently are present in the areas important for current wind power developments in all seasons except the DJF-season, for which 0% to 2% decreases in these winds are projected.

Deviations from dominant wind directions in the country are fairly similar under both RCP4.5 and RCP8.5 pathways. Wind directions are projected to change in the western half of the country in the DJF-season from coming predominantly from the south in the historical period, and deviating to the west in the projected pathways. Wind directions are projected to remain similar in the MAM- and JJA- and SON-seasons in the Limpopo Province. In the MAM- and SON-seasons, wind directions are projected to change to the opposite direction along the Western Cape and Eastern Cape Provinces. These wind direction changes would have a limited effect on the South African wind resource as they are fairly minor.

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CHAPTER 5

Wind power resource impacts

5.1 PROJECTED WIND POWER DENSITY RESULTS

Bias corrected wind speed projections are required to correct for shortcomings of the forcing GCMs from which the RCA4 RCM projected wind fields. After ERA-Interim reanalysis data were used to correct bias, near-surface wind speeds were more realistically represented. Resulting bias corrected wind speed projections for the RCP4.5 pathway are shown in Figures 77, 79, 81, and 83 and are labelled as "[Season]: r45_bc". Bias corrected wind speed projections for the RCP8.5 pathway are shown in Figures 78, 80, 82, and 84 and are labelled as "[Season]: r85_bc".

The corrected wind speeds were then used to calculate wind power density for each of the four seasons under the RCP4.5 and RCP8.5 pathways. The projected wind power densities in RCP4.5 are shown in Figures 85, 87, 89, and 91 and are labelled as "[Season]: r45 WPD". The projected wind power density for the RCP8.5 pathway is shown in Figures 86, 88, 90, and 92 and are labelled as "[Season]: r85 WPD".

5.1.1 Bias corrected mean seasonal wind speeds

The strongest mean seasonal wind speeds are projected in the Northern Cape and could reach a maximum of 5.5m.s^{-1} under both the RCP4.5 (Figure 77) and RCP 8.5 (Figure 78) pathways. The lowest wind speeds are clearly projected for the eastern half of the country, where wind speeds range from 1.5m.s^{-1} to 4m.s^{-1} in the RCP4.5 and RCP8.5 pathways, for which mean wind speeds are projected to be fairly similar. The highest wind speeds that could be important for wind energy generation are projected just off the coast of South Africa, reaching 6m.s^{-1} in both pathways.

Mean wind speeds in the MAM-season are also projected similarly in both pathways, save for a continuous strip on the north-east of the country with a wind speed of 2m.s^{-1} to 2.5m.s^{-1} in the RCP4.5 pathway (Figure 79) that is broken into two separate "patches" under the RCP8.5 pathway (Figure 80). Nevertheless, mean wind speeds are projected between 2m.s^{-1} and 3.5m.s^{-1} in the eastern half of the country, as well as along the coast of the remainder of the country. Higher wind speeds of up to 4.5m.s^{-1} are projected in the western part of the country.

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Off the coast of the country, the highest wind speeds are again projected as in the DJF-season and could reach 6m.s^{-1} in both pathways.

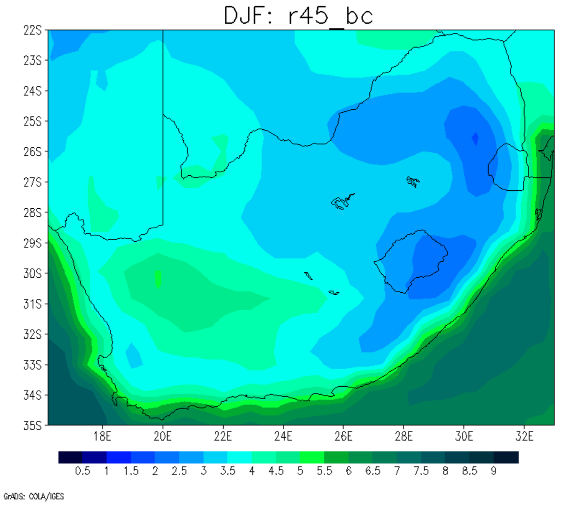

Figure 77: Bias corrected mean wind speed (m.s^{-1}) for DJF under the RCP4.5 pathway (2051-2075) from RCA4 RCM ensemble data.

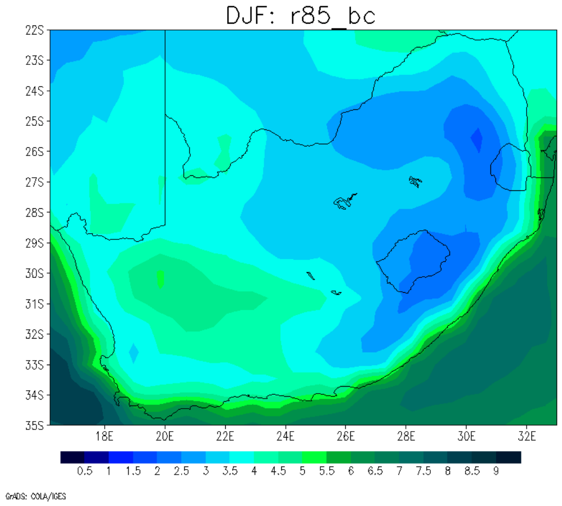

Figure 78: Bias corrected mean wind speed (m.s^{-1}) for DJF under the RCP8.5 pathway (2051-2075) from RCA4 RCM ensemble data.

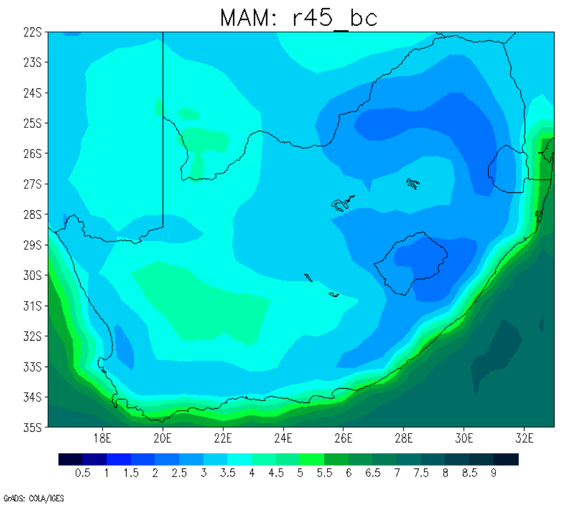

Figure 79: Bias corrected mean wind speed (m.s^{-1}) for MAM under the RCP4.5 pathway (2051-2075) from RCA4 RCM ensemble data.

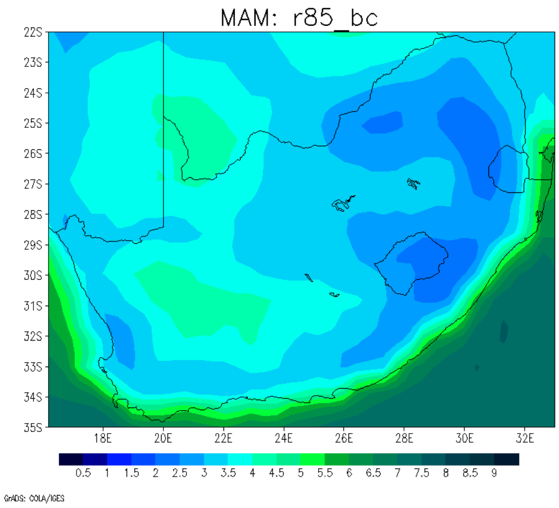

Figure 80: Bias corrected mean wind speed (m.s^{-1}) for MAM under the RCP8.5 pathway (2051-2075) from RCA4 RCM ensemble data.

Mean wind speeds are also strongest in the western half of the country in the JJA-season in both the RCP4.5 (Figure 81) and RCP8.5 (Figure 82) pathways. Wind speeds reach 5.5m.s^{-1} in the western interior in the RCP4.5 pathway (Figure 81) and 5m.s^{-1} in the RCP8.5 pathway (Figure 82) but wind speeds of a slightly smaller magnitude are then projected along the west coast and parts of the Western Cape Province (not lower than 3m.s^{-1}).

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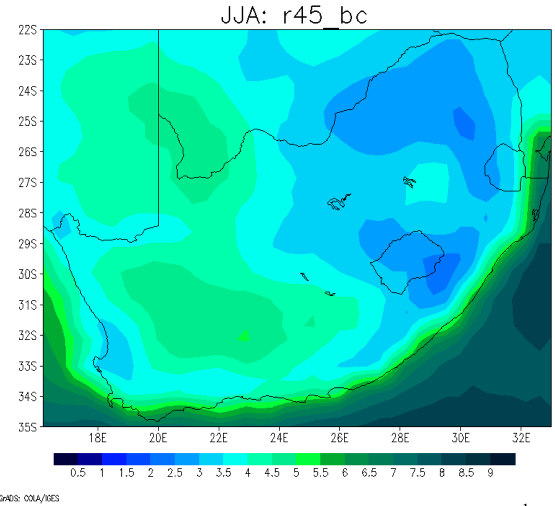

Figure 81: Bias corrected mean wind speed (m.s^{-1}) for JJA under the RCP4.5 pathway (2051-2075) from RCA4 RCM ensemble data.

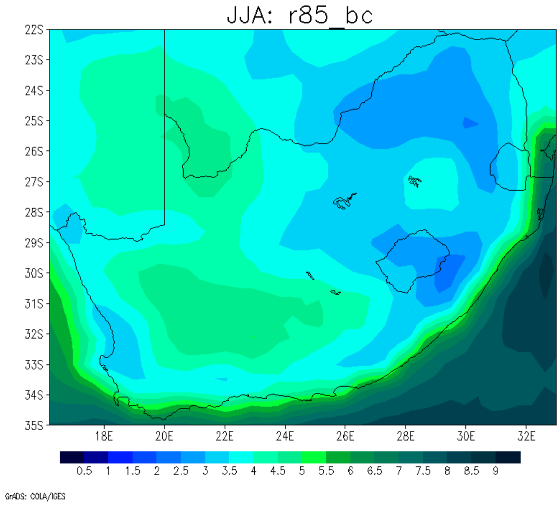

Figure 82: Bias corrected mean wind speed (m.s^{-1}) for JJA under the RCP8.5 pathway (2051-2075) from RCA4 RCM ensemble data.

In the SON-season, wind speeds are projected to reach 5.5m.s^{-1} in only a tiny portion of the Northern Cape Province in the RCP4.5 pathway (Figure 83), whereas under the RCP8.5 pathway (Figure 84), the areas which could experience wind speeds of up to 5.5m.s^{-1} is somewhat larger, as is the portion in the centre of the country which could experience wind speeds of 4m.s^{-1} to 4.5m.s^{-1}. Lower wind speeds (no lower than 2m.s^{-1}) are projected along the east of the country under both pathways.

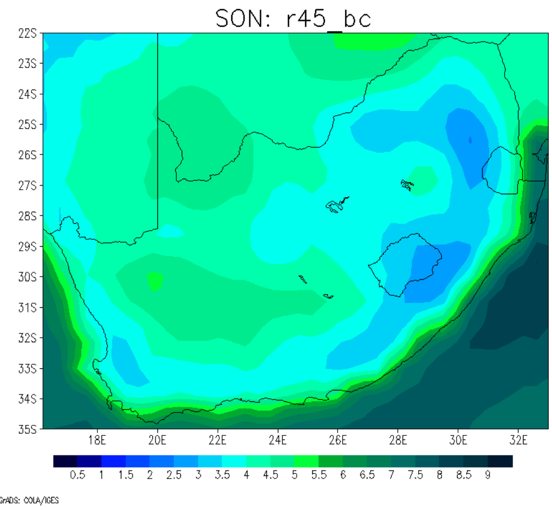

Figure 83: Bias corrected mean wind speed (m.s^{-1}) for SON under the RCP4.5 pathway (2051-2075) from RCA4 RCM ensemble data.

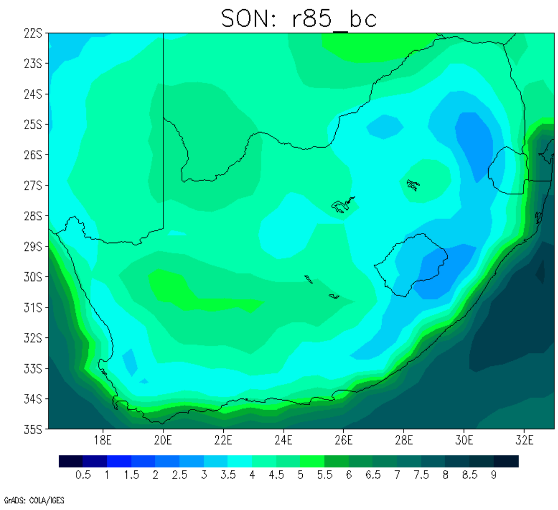

Figure 84: Bias corrected mean wind speed (m.s^{-1}) for SON under the RCP8.5 pathway (2051-2075) from RCA4 RCM ensemble data.

5.1.2 Projected wind power density

In the DJF-season in the interior of the country, wind power density is projected to be the highest in the central Northern Cape at 90W.m^{-2} for both the RCP4.5 (Figure 85) and the RCP8.5 (Figure 86) pathways, but the region of 90W.m^{-2} is larger in the RCP4.5 pathway. A

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very low wind power density is projected for the eastern half of the country, due to the low mean wind speeds projected for this area under both pathways. Wind power densities of up to 150 W.m^{-2} are projected along the coast in both pathways.

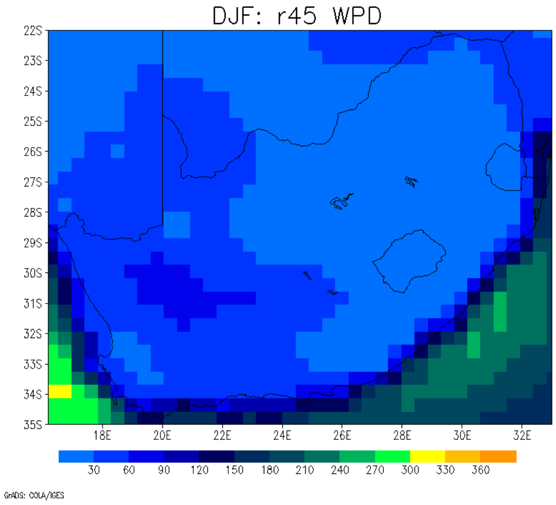

Figure 85: Wind power density (W.m^{-2}) for DJF under the RCP4.5 pathway (2051-2075).

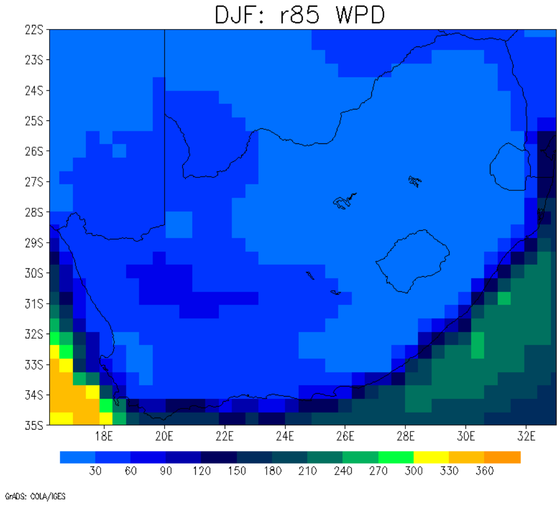

Figure 86: Wind power density (W.m^{-2}) for DJF under the RCP8.5 pathway (2051-2075).

Wind power densities in the MAM-season look fairly similar despite the two different RCPs. Because of the low mean wind speeds projected for this season, wind power densities only reach 60W.m^{-2} in the Northern Cape, and these patches are larger in the RCP8.5 pathway (Figure 88) than in the RCP.5 pathway (Figure 87). Wind power densities of up to 150W.m^{-2} are projected for areas along the entire coast of South Africa, except the West Coast.

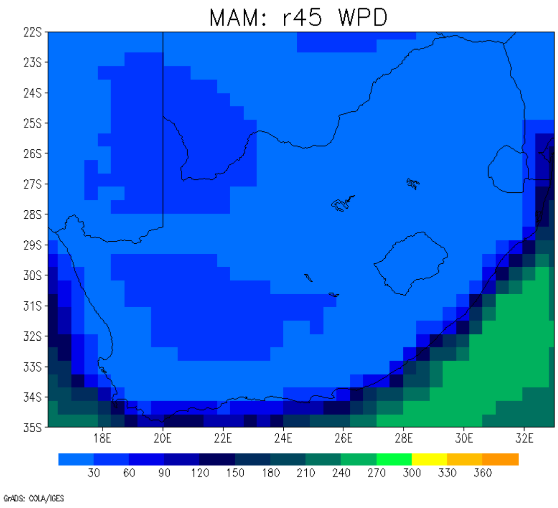

Figure 87: Wind power density (W.m^{-2}) for MAM under the RCP4.5 pathway (2051-2075).

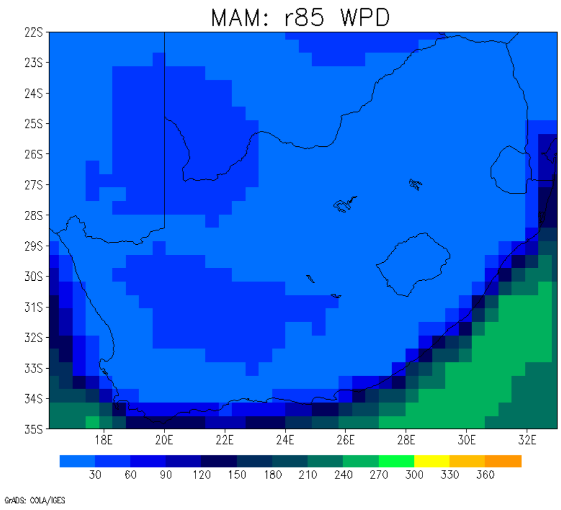

Figure 88: Wind power density (W.m^{-2}) for MAM under the RCP8.5 pathway (2051-2075).

In the JJA-season, an area with a projected 90W.m^{-2} wind power density is projected once more in the Northern Cape under the RCP4.5 pathway (Figure 89), but it extends further

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south than does the same area in, for instance, the DJF-season. This area is also larger in the RCP4.5 pathway than it is in the RCP8.5 pathway (Figure 90). Wind power density in most of eastern South Africa is projected at no more than 30W.m^{-2}.

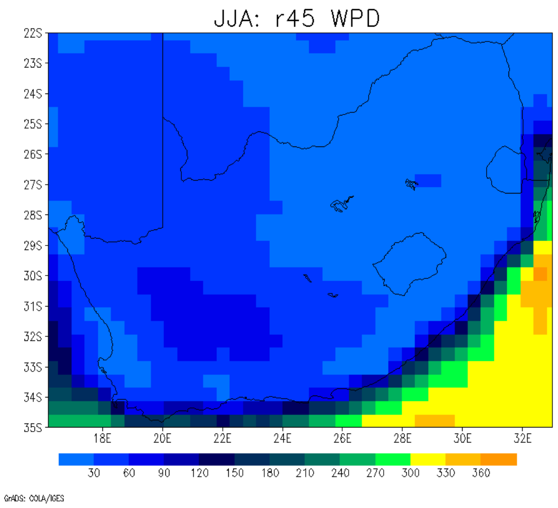

Figure 89: Wind power density (W.m^{-2}) for JJA under the RCP4.5 pathway (2051-2075).

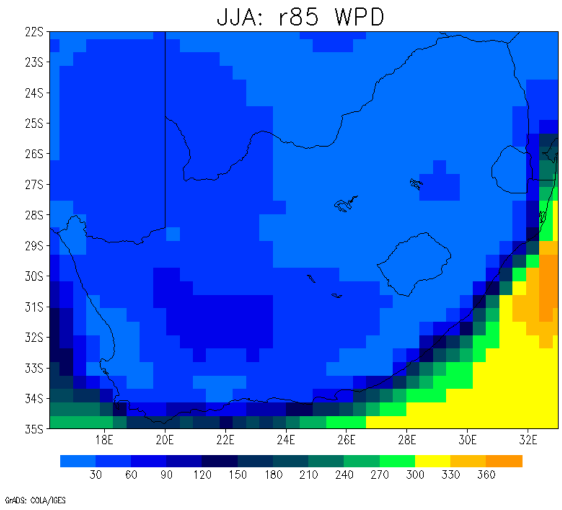

Figure 90: Wind power density (W.m^{-2}) for JJA under the RCP8.5 pathway (2051-2075).

In the SON-season, wind power density is projected at 90W.m^{-2} in two parts of the Northern Cape under both pathways, the areas being slightly smaller in the RCP4.5 pathway (Figure 91) than in the RCP8.5 pathway (Figure 92). Along the South African coast, wind power densities are projected at 60W.m^{-2} to 150W.m^{-2} in both pathways.

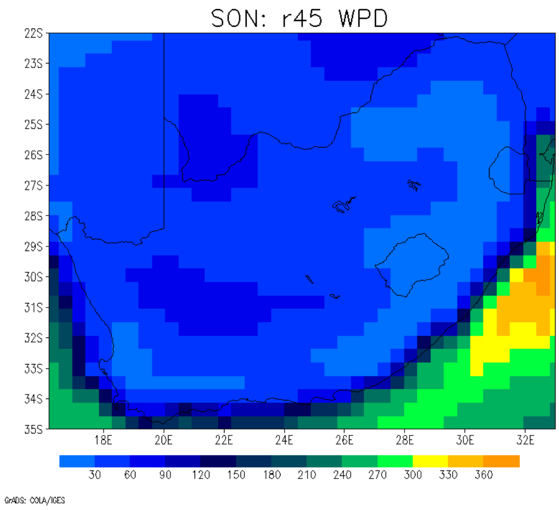

Figure 91: Wind power density (W.m^{-2}) for SON under the RCP4.5 pathway (2051-2075).

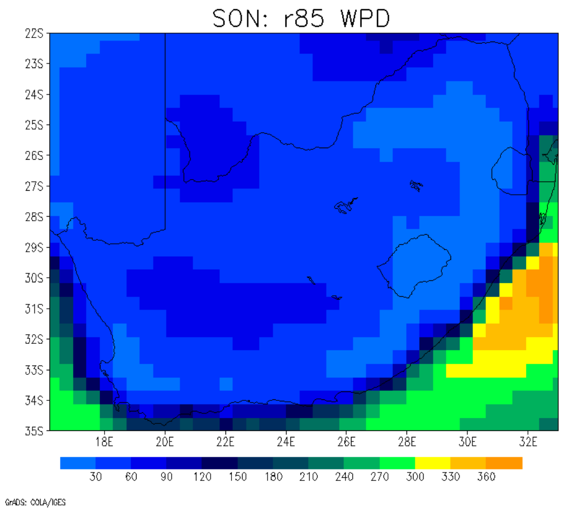

Figure 92: Wind power density (W.m^{-2}) for SON under the RCP8.5 pathway (2051-2075).

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5.2 VALUE OF FINDINGS

Bias corrected seasonal mean wind speeds could be used in the estimation of wind power densities in South Africa in the projected period of 2051 to 2075. Using only the projected data would have provided results which were affected by inherent RCA4 RCM inconsistencies. Bias corrected projections of mean wind speeds did not differ a great deal from observations (ERA-Interim data) of mean wind speeds in the historical simulations, suggesting that wind energy resources are not projected to be affected severely by climate change.

Wind power densities are projected to be the highest (90W.m^{-2}) in a region in the Northern Cape Province in all seasons and under both pathways except in the MAM-season, where the highest wind power density in the country is projected at 60W.m^{-2}. These projections are low in terms of wind resource estimation: wind power densities are required to be above 100W.m^{-2} by industry standards to make the installation of wind power generation facilities profitable. However, these calculations were performed at 10m agl, and wind turbines function at heights of >90m agl, therefore the wind power density will be estimated at smaller magnitudes than is typical for wind power generation facilities.

Wind power density was calculated in this study using mean wind speeds. Since wind turbines have a limited useful wind speed range from which to generate electricity (3m.s^{-1} to 25m.s^{-1}), values beyond this range causes the wind power density estimation to produce lower values than would have been obtained if a mean of the wind speeds in the valid speed range was used to calculate the wind power density.

The results provide useful insights of the South African wind resource potential in 2051 to 2075. It shows that wind resources are not severely affected by different CO_2 RCPs, and that the eastern interior has a relatively low wind resource in comparison to the western half, especially around the Northern Cape. As expected due to relatively high projected wind speeds, wind power densities have been projected to be the highest at the coast.

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CHAPTER 6

Conclusions

6.1 DISCUSSION

The wind energy industry is experiencing rapid growth globally as prompted by climate change adaptation strategies and the unsustainable use of non-renewable energy resources. The progression of developments in this exciting field has spilt over to the South African energy sector. Considering potential hazards to wind energy projects is critical, and climate change could pose a threat to long term investments. The aim of this study was to explore the variability of winds in South Africa as they occurred in a historical period from 1981 to 2005, to determine whether climate change could affect winds in South Africa in a projected period from 2051 to 2075, and to estimate the wind power resource in this projected period. Three objectives were subsequently developed:

a. determine whether seasonal near-surface winds over South Africa, as generated by a regional model using boundary conditions supplied from coupled state-of-the-art GCMs during the reference period of 1981 to 2005, are realistically reproduced;
b. establish whether differences exist between seasonal near-surface winds calculated for the historical period versus a projected period (2051-2075) incorporating each of two future CO_2 RCPs (RCP4.5 and RCP8.5); and
c. determine the most likely impact of projected climate change on wind power density in South Africa.

6.1.1 Objective 1: Climate model validation

To achieve the first objective, RCA4 RCM data were evaluated against observed climate data (ERA-Interim reanalysis) as well as point data from SAWS weather stations to provide an independent assessment of the RCA4 RCM output. Model data were obtained from eight GCMs that were dynamically downscaled by the RCA4 RCM.

A substantial volume of processing went into the data before it could be employed in the production of illustrative maps to indicate how realistically RCA4 RCM data reproduce

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winds. An ensemble of RCA4 RCM model data was compiled to create a single output dataset for the 25-year historical period. All datasets were cleaned to ensure consistency in both RCA4 RCM output and in ERA-Interim output.

Mean seasonal wind speeds were calculated from the ERA-Interim dataset, as u- and v-components are provided in the ERA-Interim reanalysis databank, from which the near-surface wind speed could be calculated. ERA-Interim data also had to be regridded due to a difference in its resolution from the RCA4 RCM data. Wind speed data could now be separated into seasonal datasets, and compared accordingly.

Through comparison of ERA-Interim simulations to RCA4 RCM simulations of each season's mean daily wind speeds, it was observed that the model showed a positive bias in its estimation of wind speed in a southern strip stretching from around Cape Town to Lesotho throughout, but this overestimation did not exceed 1.5m.s^{-1} in any of the four seasons. The RCA4 RCM performed well in all seasons in the north-eastern quarter of the country, as well as over northern central South Africa.

A statistical test (RMSE) revealed that the RCA4 RCM performed worse than could be seen from only the projections themselves as RMSE-values reached 2.8m.s^{-1} in some areas in the DJF-, JJA-, and SON-seasons, and up to 2.4m.s^{-1} in the MAM-season. The high RMSE-values occurred in areas that are currently being developed as wind power generation facilities. Fortunately, the areas where the highest RMSE-values were observed were over relatively small areas of the country, and the RMSE-values in the majority of the country were in the range of 0.8m.s^{-1} to 2m.s^{-1}.

To apply data to wind turbine technology, model data was displayed in an alternative manner as well: the frequency of days with winds occurring within a speed range that is appropriate for electricity generation from wind turbines, the frequency of days when winds blow below cut-in speed, and the frequency of days when winds blow at above cut-out speeds were calculated.

The results of the frequencies of seasonal daily winds blowing at speeds within a range that is useful to wind energy shows that the RCA4 RCM generally projected this speed category to occur more often than the ERA-Interim simulations do. In the DJF- and SON-seasons, the RCA4 RCM projected valid speed range winds to occur more frequently in the east of the country than the ERA-Interim simulation. On the other hand, MAM- and JJA-season RCA4

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RCM simulations show valid speed range winds to occur less frequently in the northern half of the country than the ERA-Interim simulations.

The frequencies of winds blowing below cut-in speed show seasonal projections similar to the valid wind speed range category mentioned above. DJF- and SON-seasons are projected by the RCA4 RCM to have winds below cut-in speed less often in the eastern part of the country than the ERA-Interim data. In the MAM-season, the northern half of the country is projected by the RCA4 RCM to have wind speeds below cut-in speeds more often than the ERA-Interim output suggests. In the JJA-season, the RCA4 RCM only projects more frequent below-cut-in speed winds in the north-eastern quarter of the country (around Limpopo), without capturing the ERA-Interim data's simulation of more frequent below cut-in speed winds further south of the Limpopo area.

There were no instances of winds blowing at above cut-out speed on land for both ERA-Interim and RCA4 RCM ensemble data. Even though wind speeds were found to occur in this category over the ocean, oceanic wind data are of little use for this study. RCA4 RCM performance could therefore not be evaluated using this wind speed frequency category and was not assessed further in this study.

The results of high RMSE-values in the Cape Town region were confirmed through the independent comparison of RCA4 RCM data to weather station data. The RCA4 RCM ensemble indeed simulated mean wind speeds at higher magnitudes than they have been recorded at all six ground stations, but were especially high at Malmesbury and Vredendal, both occurring in the area where the highest RMSE-values were found in all four seasons. The RCA4 RCM data were most comparable at the Upington and Mokopane stations.

6.1.2 Objective 2: Climate model projections

To satisfy the second objective, RCA4 RCM data that were forced with two CO_2 RCPs in the projected period of 2051 to 2075 were employed to calculate projected wind climates. RCPs provide possible versions of trajectories of GHGs up to the end of the 21st century, according to evolution in economies, land cover, technology etc., therefore allowing us to consider alternative futures in climate phenomena. Projected increases or decreases in wind speeds were calculated and shown as anomalies: per cent change in mean daily wind speed for each season; and as differences in frequencies of wind speeds within and below the wind speed

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range appropriate for electricity generation. Wind direction anomalies were indicated as deviations form dominant wind directions in the reference period.

In the DJF-season, wind speeds were projected to increase under both RCPs in the north-eastern quarter of the country. Increased wind speeds are projected during the MAM-season for the north-eastern corner of the country as well as the Cape Town region. This potential increase in wind speeds grows to the south-west in the JJA-season, but recedes again in the SON-season. Changes in wind speeds are similar under both RCPs, but the magnitude of changes differs, usually being more extreme under the RCP8.5 pathway than the RCP 4.5 pathway. In the DJF- and SON-seasons, wind speeds are generally projected to increase by up to 6% in the areas which are currently being exploited for wind farm development. In the MAM- and JJA-seasons, wind speeds are projected to increase by a maximum of 2%, or to decrease by no more than 1% in this region. According to these primarily increasing wind speeds year-round, the South African wind energy sector could expect to be affected quite positively in the projected period. As for the rest of the country, especially to the north-east, wind speeds are projected to increase by up to 6% in all of the seasons except for the DJF-season. The South African wind resource is therefore projected to increase.

Projected changes in winds blowing within the speed range appropriate for wind power generation are small in the majority of the country, and seldom exceed increases or decreases of 1%. This small change is important for the Western Cape and Eastern Cape Provinces where wind farms are currently being developed. In north-eastern South Africa, winds in the valid speed range winds could blow by up to 9% more often in the MAM- and JJA-seasons under both pathways. In the DJF- and SON-seasons, these winds are also projected to occur more often, but by a maximum of 6% more than in the historical period. These increases in winds within the appropriate speed range suggest that new areas for potential wind farm development could become exploitable in future.

Winds below cut-in speed are projected to remain mostly unchanged in all seasons for the largest part of the country, but are projected to decrease in north-eastern South Africa. Areas where these winds occur up to 2% more frequently are dispersed around the country and in areas important for current wind power developments in all seasons except the DJF-season, for which these winds are projected to occur 0% to 2% less often.

Deviations from dominant wind directions in the country are fairly similar under both RCP4.5 and RCP8.5 pathways. Wind directions are projected to change in the western half of

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the country in the DJF-season from coming predominantly from the south in the historical period, to deviating to the west in the RCP4.5 and RCP8.5 pathways. Wind directions are projected to remain similar in the MAM-, JJA- and SON-seasons in the Limpopo Province. In the MAM- and SON-seasons, winds are projected to deviate to the opposite direction along the Western Cape and Eastern Cape Provinces. These minor wind direction changes would therefore have a limited effect on the South African wind resource.

6.1.3 Objective 3: Wind power density projections

Bias corrected seasonal mean wind speeds could be used in the estimation of wind power densities in South Africa in the projected period of 2051 to 2075. Bias corrected projections of mean wind speeds did not differ significantly from ERA-Interim data of the 1981 to 2005 historical period, suggesting that wind energy resources are not projected to be affected severely by climate change.

Wind power densities are projected to be the highest ($90W.m^{-2}$) in a region in the Northern Cape Province in all seasons and under both pathways except in the MAM-season, where the highest wind power density in the country is projected at $60W.m^{-2}$.

The results provide useful insights of South African wind resources in 2051 to 2075. It shows that wind resources are not severely affected by different CO_2 RCPs, and that the eastern interior has a relatively low wind resource in comparison to the western half, especially around the Northern Cape. As expected due to relatively high projected wind speeds, wind power densities have been projected to be the highest at the coast.

6.1.4 Recommendations

The wind power density projections are lower than the requirement in industry for the wind power density to be above $100W.m^{-2}$ to justify the development of wind power generation facilities. Mean wind speeds that were employed in the calculation of wind power densities in this study were performed at 10m agl, and could in future work be extrapolated to turbine heights of >90m agl. Furthermore, wind power density could be calculated using mean wind speeds within the speed range that is useful to wind turbines for electricity generation ($3m.s^{-1}$ to $25m.s^{-1}$).

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APPENDIX

Table A1: South African wind energy facilities

Name	Location	Contracted Capacity (Nameplate Capacity) (MW)	Company	Turbine manufacturer	Number of turbines	Turbine capacity (MW)	Hub height (m)	Rotor diameter (m)	Cut-in speed (m/s)	Cut-out speed (m/s)	REI4P Bid Window/ Eskom	Preferred bidder status awarded date	Construction start date	Commercial operation start date	Reference
Red Cap Kouga Wind Farm - Oyster Bay	Port Elizabeth, Eastern Cape	77.6	Red Cap Kouga Wind Farm (Pty) Ltd	Nordex	32	2.5	80	90	3	25	1	13/12/2011	20-Mar-13	Q1 2015	DoE, 2011; NERSA, 2012d
Noblesfontein	Victoria West, Northern Cape	72.8	Coria (PKF) Investments 28 (Proprietary) Limited	Vestas	41	1.8	80/95/120	100	3	20	1	13/12/2011	Nov-12	Jul-14	DoE, 2011; Barradas, 2012; Njobeni, 2012
Jeffreys Bay	Jeffreys Bay, Eastern Cape	135.11	South Africa Mainstream Renewable Power Jeffreys Bay pty Limited	Siemens	60	2.3	80	101	4	25	1	13/12/2011	Dec-12	Jul-04	DoE, 2014; DoE, 2011; Jeffrey's Bay Wind Farm, 2012
MetroWind Van Stadens Wind Farm	Port Elizabeth, Eastern Cape	26.2	MetroWind (Pty) Ltd	Sinovel	9	3	90	113	3	25	1	13/12/2011	Nov-12	Feb-14	DoE, 2014; DoE, 2011; Metrowind, 2012
Cookhouse Wind Farm	Cookhouse, Eastern Cape	135	African Clean Energy Developments	Suzlon	66	2.1	79	88	4	25	1	13/12/2011	Nov-12	Q2 2014	DoE, 2011; African Clean Energy Developments, 2012; Greve, 2013

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Hopefield Wind Farm	Hopefield, Western Cape	65.4	Umoya Energy (Pty) Ltd	Vestas	37	1.8	95	100	3	20	1	13/12/2011	Jul-12	Feb-14	DoE, 2014; DoE, 2011; Creamer Media, 2014; NERSA, 2012a
Dassiesklip Wind Energy Facility	Caledon, Western Cape	26.2	Klipheuwel - Dassiefontein Wind Energy Facility (Proprietary) Limited	Sinovel	9	3	100	113	3	25	1	13/12/2011	Jan-13	Jan-14	DoE, 2014; DoE, 2011; Bigala, 2012; NERSA, 2012c; BioTherm Energy, 2013; Insurance Times and Investments, 2014; The Wind Power, 2014
Dorper Wind Farm	Inkwanca Municipality, Eastern Cape	97 (100)	Dorper Wind Farm (Pty) Ltd	Nordex	40	2.5	80	95-102	3	25	1	13/12/2011	May-13	Jul-14	DoE, 2011; Dorper Wind Farm, 2014; UNFCCC, 2012; Nordex, 2014
Gouda	Gouda, Western Cape	135.5	Blue Falcon 140 Trading (RF) (Pty) Ltd	Acciona	36	3	100	≥100	4/3.5/3	25	2	10/5/2013	Sep-13	2014	DoE, 2013a; ACCIONA, 2012
Wind Farm West Coast 1	Vredenburg, Western Cape	90.82 (94)	Aurora Wind Power (RF) (Pty) Ltd	Vestas	47	2	80/95/105/125	90	3	25	2	10/5/2013	Sep-13	Mid 2015	DoE, 2013a; Windlab, 2014; Vestas, 2014a; Aurora Wind Power, 2013
Waainek	Grahamstown, Eastern Cape	23.28	Waainek Wind Power (RF) (Pty) Ltd	Vestas	8	3	84	112	3	25	2	10/5/2013	N/A	Q4 2014	DoE, 2013a; Creamer Media, 2013b; NERSA, 2012b; Vestas, 2014b

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Grassridge Wind Power	Port Elizabeth, Eastern Cape	59.8	Grassridge Wind Power (RF) (Pty) Ltd	Vestas	20	3	84	112	3	25	2	10/5/2013	Oct-13	Q4 2014	DoE, 2013a; Barradas, 2013; Vestas, 2014b
Chaba	Great Kei Municipality, Eastern Cape	21	Chaba Wind Power (RF) (Pty) Ltd	Vestas	7	3	84	112	3	25	2	10/5/2013	N/A	Q4 2014	DoE, 2013a; NERSA, 2012b; Vestas, 2014b
Amakhala Emoyeni	Bedford, Eastern Cape	133.7	Amakhala Emoyeni Re Project 1 (RF) (Pty) Ltd	Nordex	56	2.4	91/120/141	117	3	20	2	10/5/2013	N/A		DoE, 2013a; Windlab, 2014; Nordex, 2014
Tsitsikamma Community Wind Farm (“TCWF”) Project	Tsitsikamma, Eastern Cape	93	Tsitsikamma Community Wind Farm (RF) (Pty) Ltd	Vestas	31	3	94	112	3	25	2	10/5/2013	Q2 2015	2016	DoE, 2013a; Creamer Media, 2013a; Vestas, 2014b
Nojoli Wind Farm	Eastern Cape	86.6 (88)	Nojoli Wind Farm (RF) (Pty) Ltd	Vestas	44	2	80	100	3	20	3	4/11/2013	Mid 2014	Jun-16	DoE, 2013b; NERSA, 2014e; Deduleasa, 2014
Gibson Bay	Kouga, Eastern Cape	110 (111)	Red Cap	Nordex	37	3	91	117	3	25	3	4/11/2013	Aug-14	Q1 2017	DoE, 2013b; Windpower Intelligence, 2013; NERSA, 2014a
Longyuan Mulilo De Aar Maanhaarberg Wind Energy Facility	Northern Cape	96	Longyuan	United Power	67	1.5	80	82; 86	3	25	3	4/11/2013	N/A	Mar-16	DoE, 2013b; NERSA, 2013b

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Longyuan Mulilo De Aar 2 North Wind Energy Facility	Northern Cape	138.96	Longyuan	United Power	96	1.5	80	86	3	25	3	4/11/2013	N/A	Mar-16	DoE, 2013b; NERSA, 2013a
Khobab	Namakwa, Northern Cape	138 (140)	Mainstream Renewable Power	N/A	107	1-3	80-120	87-120	N/A	N/A	3	4/11/2013	Aug-14	Apr-17	DoE, 2013b; Venzo, 2013; NERSA, 2014b
Noupoort Mainstream Wind	Umsobomvu, Northern Cape	79 (80.5)	Mainstream Renewable Power	N/A	N/A	N/A	60-120	70-130	N/A	N/A	3	4/11/2013	Aug-14	Dec-15	DoE, 2013b; NERSA, 2014d; Almond, 2011
Loeriesfontein 2	Namakwa, Northern Cape	138 (140)	Mainstream Renewable Power	N/A	*180-190	N/A	80-120	87-120	N/A	N/A	3	4/11/2013	Aug-14	Apr-17	DoE, 2013b; NERSA, 2014c; Marais, 2014
Sere Wind Farm	Vredendal, Western Cape	100	Eskom	Siemens	46	2.3	80	108	3; 4	25	Eskom commercial	N/A	Dec-13	Q4 2014	Eskom, 2014; Matthews, 2014; Siemens, 2011
Klipheuwel Wind Energy Facility	Klipheuwel, Western Cape	3.16	Peaking Generation (Eskom Generation Division)	Vestas; Jeumont	3	0.66; 1.75; 0.75	40; 60; 46	47; 66; 48	3; 4	25	Eskom experimental	N/A	2002; 2003	2002; 2003	Eskom, 2013
Darling	Darling, Western Cape	5.2	Darling Wind Power (Pty) Ltd	Fuhrlaender	4	1.3	50	64	2	27	DoE Demonstration	N/A	Sep-07	May-08	Darling Wind Farm, 2014

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