Climate Change Impacts on South African Wind Energy Resources

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Abstract

Consideration of the potential risks posed by climate change to the wind energy sector is critical for its development in South Africa. This study determines if future wind speeds might change under two climate change projections by employing climate model data at 0.44°latitude (~45km)×0.44°longitude (~50km) resolution. Ensembles of historically modelled winds compare well with observed wind climate, but wind speeds are over-estimated in the southern regions of South Africa. Projected increases in mean daily wind speeds vary, but never exceed six per cent. Wind speeds within a predetermined range appropriate for power generation are projected to increase in the north-eastern region of South Africa. It is concluded that wind power density will remain low in future, which suggests that wind energy may complement energy supply, but is unlikely to become a major contributor to energy in South Africa.

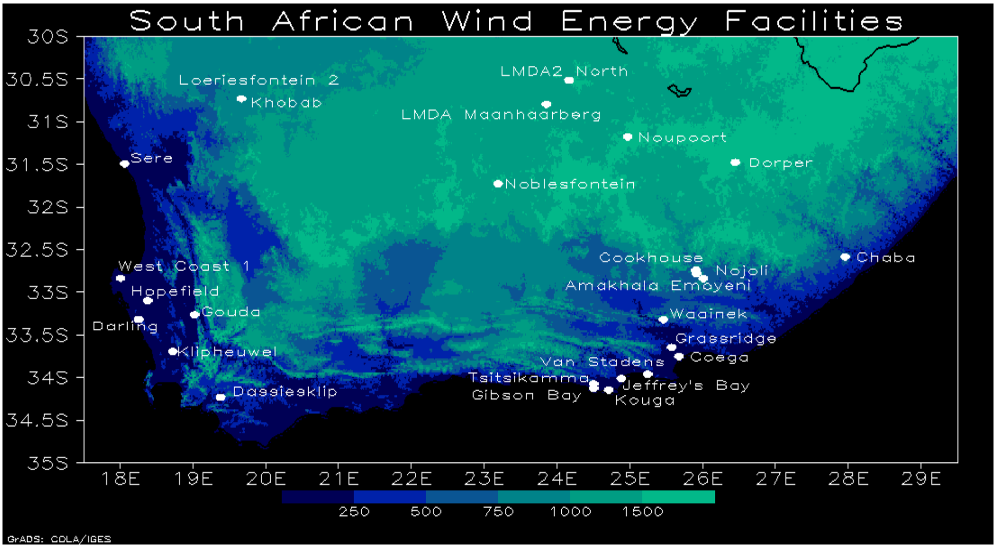
Introduction

The South African Department of Energy is investing a great deal of resources into research and development, installation and grid integration of wind energy. Between 1996 and 2012,[1] wind generating capacity has shown a 27 per cent annual growth rate globally, and the wind energy market is expected to grow by a further six to 10 per cent annually from 2014 onwards.[2] Countries around the globe are advocating the deployment of wind power using a variety of arguments that differ in degree of importance in each country. These include: climate change mitigation policies;[3] ageing electricity generation facilities;[4] the need to diversify current electricity sources and its management;[5] the increased availability, cost effectiveness, and learning rate of the technology;[6]

job creation;[7] foreign business opportunities;[8] less severe environmental impact compared to other energy resources, based on life cycle assessments;[9,10] feed-in tariffs;[11] and scientific research.[12]

In South Africa alone, approximately 25 wind energy facilities are either under construction, in commercial operation, or in the financing stage of deployment. The majority of wind energy projects in SA have been commissioned by the Renewable Energy Independent Power Producer Procurement Programme.[13] Eskom, SA's major electricity supply utility, currently manages two wind energy farms, the Sere (100 MW) and the Klipheuwel (3 MW) wind farms. Some of the wind farms under construction are the Kouga[14] and Gouda[15] facilities. Completed constructions include the wind farms at Noblesfontein, Jeffrey's Bay,[16,17] Van Stadens,[18] Cookhouse and Hopefield.[19] Projects still in the initial phase include those at Nojoli,[20] Gibson Bay, Longyuan Mulilo De Aar Maanhaarberg, Longyuan Mulilo De Aar 2 North, Khobab, Noupoort and Loeriesfontein 2.[21] (See Figure 1.)

Figure 1: Location of current and future planned South African wind energy facilities (LMDA=Longyuan Mulilo De Aar)



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 influence this sector. The functioning of wind farms depends on specific local climatic conditions, making them vulnerable to climate change. The susceptibility of wind energy to climate change is critical and must be quantified, in order to assess adaptation capacity to possible, but uncertain, effects on wind energy production.[22]

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.[23] In the last two decades, a number of studies have been conducted globally on the impact of climate change on the energy sector,[24,25,26,27] renewable energy in general,[28,29,30] wind energy,[31,32,33,34,35,36,37,38,39] and wind climates in southern Africa.[40,41,42]

According to climate projections summarised from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), some risks and opportunities for wind power generation can be expected in the future. The distribution, timing and magnitude of wind resources might change over the projected 20-30 year lifetime of a wind turbine,[43] but, more importantly, wind farms are planned to come online in the long-term as wind energy reaches grid parity in South Africa.

However, Russo et al.[44] noted that few significant changes in wind speed are expected in the near future in the African region. This, and similar assessments of climate change impact on wind behaviour in SA, have mostly been performed using Global Climate Models (GCMs), which have spatially coarser resolutions than Regional Climate Models (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. It is important to note that model simulated winds are susceptible to large errors,[45] if few models and emissions scenarios are used; this emphasises the importance of considering multi-model ensemble comparisons.[46] In this study, two CO2 emissions scenarios are considered in eight dynamically down-scaled GCM simulations, in order to determine the influence of global warming on South African winds, and the anticipated impact on wind power potential.

Models

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.

Climate Change Projections

In the IPCC's AR5, greenhouse gas (GHG) emissions scenarios considered were expressed in terms of the atmospheric heat based Representative Concentration Pathways (RCPs). Previously used IPCC SRES scenarios that were based on CO2 concentrations were updated in the AR5 to heat based RCPs, thanks to new information on emerging technology, economies, land use, land cover change and environmental factors of almost a decade.[47] The new AR5 GHG forcing for future projections used in this study included CO2 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 word 'representative' indicates each RCP's reference to one of numerous possible scenarios that lead to particular radiative forcing characteristics. 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 purposes of driving global warming climate model simulations.

In more detail, RCP4.5 (RCP8.5) represents: a radiative forcing of ~4.5 W.m-2 at stabilisation after 2100 (>8.5 W.m-2 in 2100); and a ~650 ppm CO2-equivalent concentration at stabilisation after 2100 (>1370 ppm CO2-equivalent in 2100). The RCP4.5 therefore represents a pathway that stabilises without overshoot, and RCP8.5 resembles a rising pathway. The RCP4.5 scenario was developed using the Global Change Assessment Model from the Pacific Northwest National Laboratory in the USA; the RCP8.5 was developed using the Model for Energy Supply Strategy Alternatives and their General Environmental Impact from the International Institute forApplied Systems Analysis in Austria.

Table 1: Institutions and countries from which the GCMs used in RCA4 downscaling originated

Institute	Country	GCM
Canadian Centre for Climate Modelling and Analysis (CCCma)	Canada	CanESM2
Centre National de Recherches Météorologiques and Centre Européen de Recherché 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

Aim and Objectives

The aim of this study was to explore the variability in seasonal near-surface winds in SA and to project possible future changes in these winds. The objectives of the study are to: a) determine if historical seasonal near-surface winds over SA, as generated by a regional model, are realistically reproduced (using boundary conditions supplied from coupled GCMs - during the reference period (1981-2005)); b) establish if differences exist between seasonal near-surface winds calculated for the historical period versus a projected period (2051-2075) while incorporating two future CO2 RCPs (RCP4.5 and RCP8.5); and c) determine the most likely impact of projected climate change on wind power density in SA. Results serve not only as an addition to the current understanding of the impact of increasing GHG concentrations on wind patterns, but also on the potential consequences for wind power generation in the wind energy industry in the South African region.

Methods

Model Verification

In order to identify the bias in the RCA4 RCM output, it has to be assessed through comparison with observational fields such as the European Centre for Medium-range Weather Forecasts' (ECMWF) ERA-Interim reanalysis data; this is a global atmospheric reanalysis dataset that is available for the period 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, in order to comply with the World Meteorological Organisation's 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. This was then compared to a projected period (2051 to 2075). Calculations were performed for the seasons December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). Providing results in seasonal portions elucidates model performance, by reducing the smoothing effect of taking means over, for instance, an entire year. In this study, however, results are shown only for DJF and JJA, for the sake of succinctness.

ERA-Interim Reanalysis Data

Model performance was evaluated by calculating the differences between 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-wind and v-wind components were obtained from the ERA-Interim reanalysis databank for the 25-year period 1981 to 2005, across the domain 18° to 42°S and 14° to 37°E. 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 bilinearly 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*-components and *v*-components as follows:

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

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.[48] The first 28 days of each month were then selected for further calculation. Residual days could not be used in the analysis, as some model fields consist of 30-day months only, while others include leap years. A uniform month-day number for all 12 months of the year (in this case 28 days) was introduced for purposes of calculating cross-model ensemble averages. Seasonal wind speeds were then obtained after categorising daily data into four groups: DJF, MAM, JJA and SON. From this, seasonal daily mean wind speeds for each season were calculated.

Model Data

Data from the eight GCMs that were dynamically downscaled using the RCA4 RCM were obtained. Daily historical near-surface wind speeds (10m agl) were extracted for each model for the 25 years extending from 1981 to 2005. The domain defined for the study extended from 22° to 35°S and 16.2° and 33°E. For each of the eight model files, data was 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 which daily mean wind speeds for each of the seasons were calculated.

Statistical Evaluation of Model Performance

In order to verify model performance, the Root Mean Square Error (RMSE) of seasonal daily mean wind speeds was calculated using the ERA-Interim and the ensemble RCA4 RCM data. The RMSE was calculated as follows:[49]

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

where:

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

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

n is the number of values.

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.

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). In order to obtain appropriate wind speed limits for electricity generation (that is, above cut-in speed and below cut-out speed) – 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 in order for them 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 height agl declines. The wind speed at 90 m agl, as well as the cut-in and cut-out speeds specified, will be lower at 10m agl, if the atmosphere is assumed to be stable. The cut-in and cut-out speeds at 10 m were calculated using the so-called 'log law', which is often employed in the wind energy industry to extrapolate wind speeds from various heights, i.e.:

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

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} is the reference height, taken here as 10m; and

z_0 is the roughness length.

Roughness length can be defined as the height (in metres) agl at which the wind speed is theoretically equal to zero.[50] In the wind extrapolation, the reference height z_{ref} was taken as 90 m, the wind speed at that height was taken as either the cut-in (3 m.s-1) or cut-out (25 m.s-1) speed, and the required extrapolated height z was taken as 10 m. The roughness length z_0 was taken as 0.05 m, which corresponds with 'crops, tall grass prairie'.[51] In Table 2, the resulting cut-in and cut-out speeds at 10 m agl are shown. The reader should consider that there is an implicit systematic error of ± (1-13 per cent) in the use of the log-law when wind shear is predicted.[52]

Three categories of wind frequency were defined:

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

$$0 < ws \leq 2.1 \text{ m.s}^{-1}$$

- Frequency of days when the wind blows within the valid speed range:

$$2.1 < ws \leq 17.6 \text{ m.s}^{-1}$$

- Frequency of days when the wind blows above cut-out speed:

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

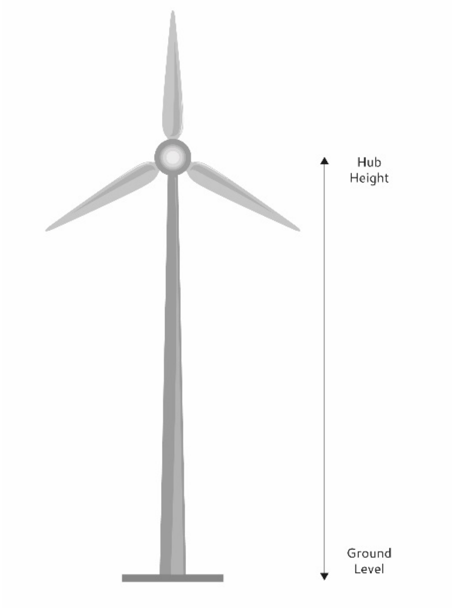
Table 2: Cut-in speed and cut-out speed definitions and their respective values at 90 m and 10m agl

Term	Definition	Source	At 90 m	At 10 m
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[53] Chambers and Kerr,[54] respectively	3 m.s-1	~2.1 m.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[55]	25 m.s-1	~17.6 m.s-1

Subsequently, the frequency of days with wind speeds of below 2.1 m.s^{-1}, between 2.1 m.s^{-1} and 17.6 m.s^{-1}, and above 17.6 m.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 17.6 m.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 (2.1 m.s-1 and 17.6 m.s-1) had to be adjusted in the RCA4 RCM data, so as 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 finding the RCA4 RCM equivalent to the 2.1 m.s-1 and 17.6 m.s-1 ERA-Interim values.

Figure 2: Generic onshore wind turbine and its hub height (©Marina Herbst)



The corresponding model values were found to be:

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

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

- Frequency of days when the wind blows within the valid speed range:

$$2.9 < ws \leq 13.2 \text{ m.s}^{-1}$$

- Frequency of days when the wind blows above cut-out speed:

$$ws > 13.2 \text{ m.s}^{-1}$$

Using the RCA4 RCM data, the percentage frequencies of days were calculated 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. This allows for comparing ERA-Interim and RCA4 RCM frequency percentages for the reference period.

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 located 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 between 1981 and 2005. These three-times-daily observations were averaged to obtain single daily wind averages, which were then employed in calculating seasonal average wind speeds. Model values to be used for purposes of comparison were selected from the grid boxes in model data within which the particular weather station's coordinates lie. These coordinates are shown in Table 3, together with the period for which data were available. Note that data from two stations were considered for the Upington area, as the periods of availability differed.

Table 3: SAWS weather station particulars

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

Change in Wind Speed

Daily means of seasonal wind speeds in the model projected period were calculated using RCA4 RCM projections under conditions of the RCP4.5 and RCP8.5 pathways. Projected frequencies were determined in the same manner as for the reference period. 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 then calculated from the valid range of electricity generation, as per the model data according to the categories specified previously. In this case, anomalies are shown as differences in frequency percentages, as the simulations from which they were calculated were provided as percentages.

Future Wind Power Density

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 bias necessitated bias correction 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.[56] where bias in the mean and variability of the model output is 'corrected' according to observational data:

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

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

Wind power density was calculated as follows:

$$\frac{P}{A} = \frac{1}{2}\rho v^3$$

where:

$\frac{P}{A}$ is the wind power in Watts per m2;

ρ is the air density in kg.m-3, taken here as 1.225 kg.m-3 (as per standard conditions at sea-level and 15°C); and

v is the wind speed in m.s-1

Using the bias-corrected RCA4 RCM projections, wind power density was calculated for SA.

Results and Discussion

Model Verification

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

Near-surface wind speeds in the JJA-season are projected at no less than 2.5 m.s^{-1} in the north-eastern quarter of the country in the RCA4 RCM ensemble run (Figure 6) – 0.5m.s^{-1} higher than the ERA-Interim run (Figure 5). 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: the ERA-Interim run shows that these winds range from 3 m.s^{-1} to 5 m.s^{-1}, while the RCA4 RCM ensemble run shows it could range from 3.5m.s^{-1} to 6m.s^{-1}.

The RMSE of seasonal mean daily wind speeds (m.s-1) is shown in Figures 7 and 8. The high RMSE values on the south-eastern tip of the country demonstrate overestimations identified in the previous paragraphs. The RCA4 RCM generally performs best over central SA. The highest RMSE-values of 2.8 m.s-1 occur in the JJA-season in the Cape Town region and over Lesotho

Figure 3: DJF mean seasonal wind speed(m.s-1) from ERA-Interim data (1981-2005)

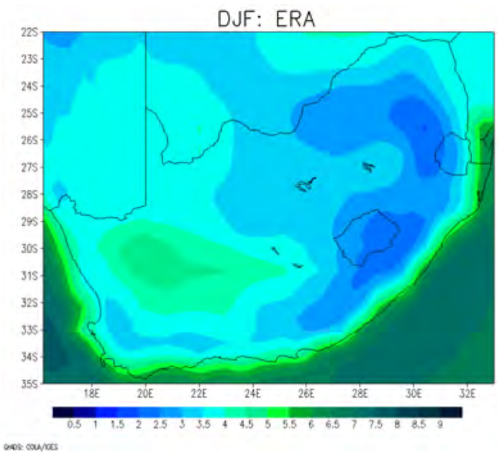


Figure 4: DJF mean seasonal wind speed (m.s^{-1}) from Model ensemble data (1981-2005)

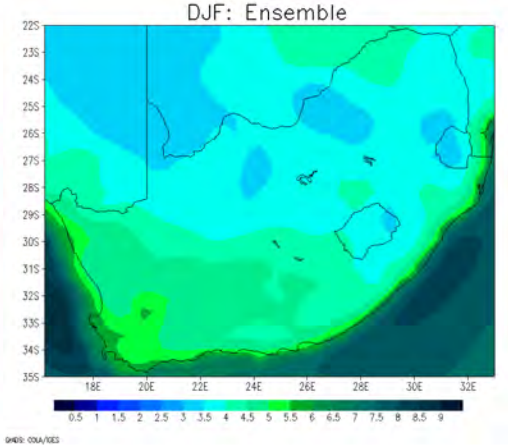


Figure 5 JJA mean seasonal wind speed (m.s^{-1}) from ERA-Interim data (1981-2005)

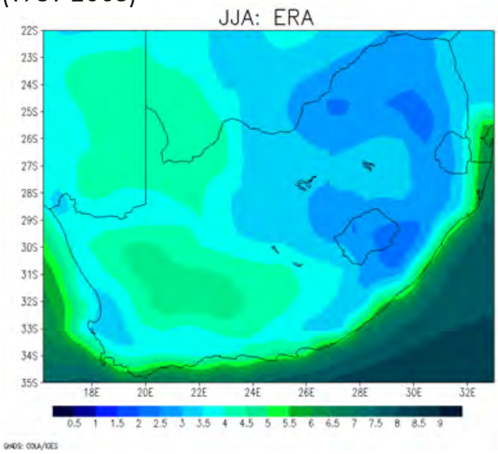
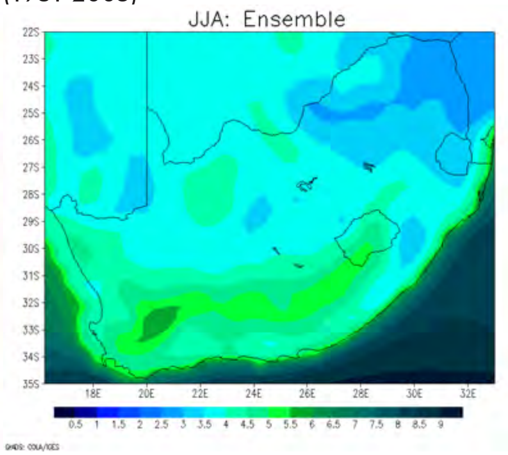


Figure 6: JJA mean seasonal wind speed (m.s^{-1}) from Model ensemble data (1981-2005)



In terms of wind speeds occurring within a range acceptable for electricity generation, the results from the RMSEs become more apparent in Figures 9 to 12 – in particular, the over-estimation perceived in the southern half of South Africa in Figures 4 and 6. The RCA4 RCM results (Figure 10) show that, for DJF, wind speeds within a valid range occur close to 100 per cent across the entire country. According to the ERA-Interim output (Figure 9), however, wind speeds within the valid range do not occur as often in the north-eastern part of the country. The valid range estimation in JJA is similar for ERA-Interim (Figure 11) and model (Figure 12) output in its estimation of fewer occurrences of wind speed within valid range in the Limpopo Province only, albeit of slightly different magnitudes. Fewer occurrences (as little as 75 per cent 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 11), whereas the RCA4 RCM output suggests that winds blow within the valid range 100 per cent of the time in the Western Cape Province (Figure 12).

Figure 7: Root Mean Square Error (RMSE) for the DJF wind speeds (m.s^{-1}) (1981-2005)

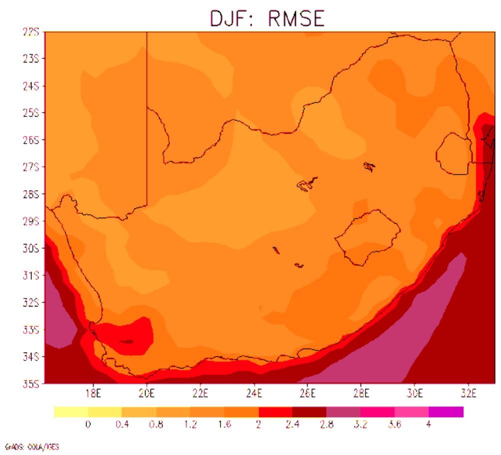


Figure 8: Root Mean Square Error (RMSE) for the JJA wind speeds (m.s^{-1}) (1981-2005)

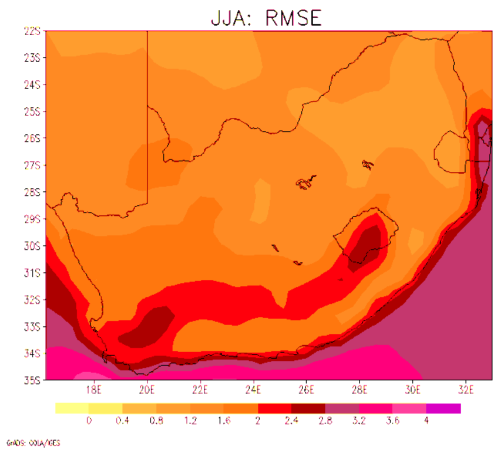


Figure 9: Frequency of days (%) when the wind blows within the valid speed range in DJF (ERA-Interim data) (1981-2005)

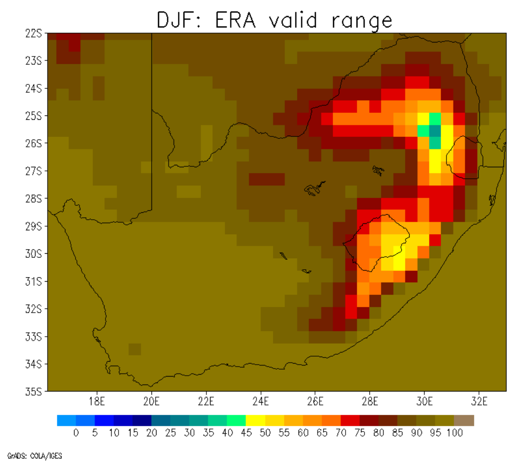
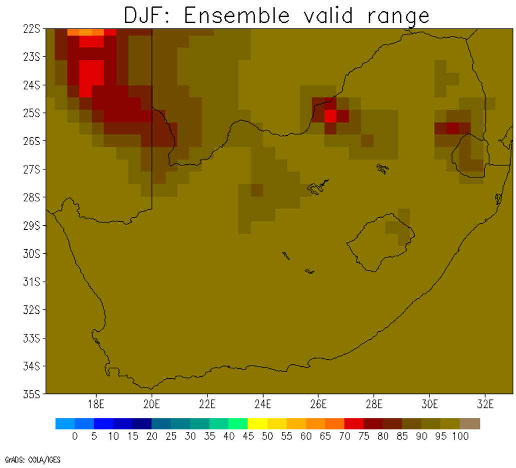


Figure 10: Frequency of days (%) when the wind blows within the valid speed range in DJF (Model ensemble data) (1981-2005)



According to Figure 13, ERA-Interim data projects that wind speeds occur below cut-in speed, up to 65 per cent of the time in the eastern half of the country in the DJF-season. The RCA4 RCM run (Figure 14), projects that winds occur below cut-in speed, 0-5 per cent 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 per cent of the time).

The ERA-Interim simulation shows that winds could blow below cut-in speed up to 55 per cent of the time just east of Lesotho in the JJA-season (Figure 15). The RCA4 RCM simulation, however, only projects it to occur up to 20 per cent of the time in this area (Figure 16). 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 per cent of the time) (Figure 16), while the ERA-Interim projection shows a maximum frequency of 45 per cent of winds blowing below cut-in speed (Figure 15).

There were zero instances of wind speed occurring above cut-out speed on land for ERA-interim and model ensemble data. This was the case for both seasons.

Figure 11 Frequency of days (%) when the wind blows within the valid speed range in JJA (ERA-Interim data) (1981-2005)

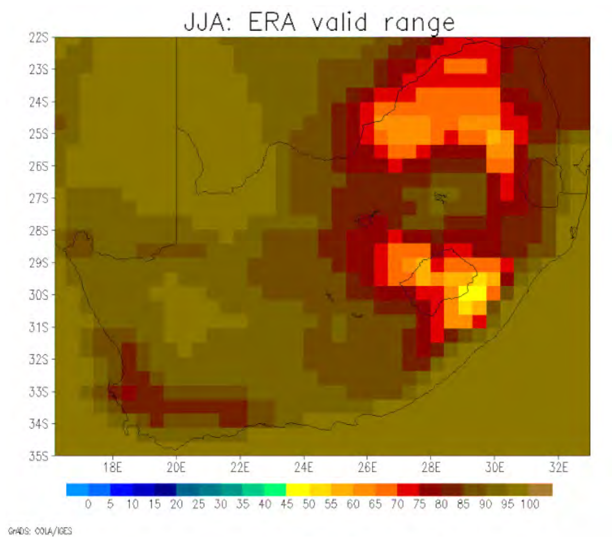


Figure 12: Frequency of days (%) when the wind blows within the valid speed range in JJA (Model ensemble data) (1981-2005)

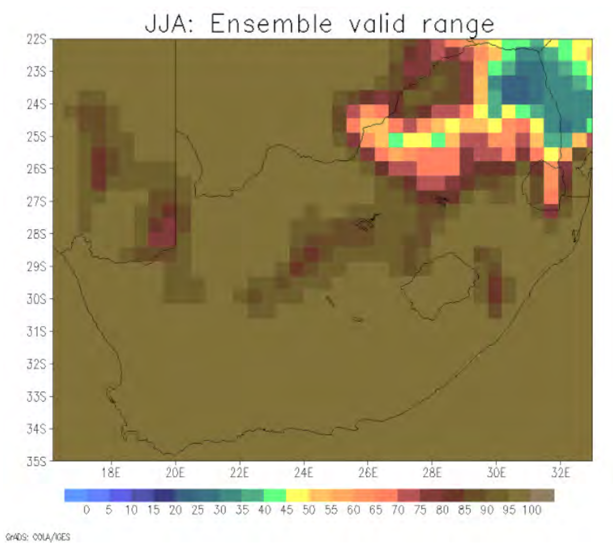


Figure 13: Frequency of days (%) when the wind blows below cut-in speed in DJF (ERA-Interim data)

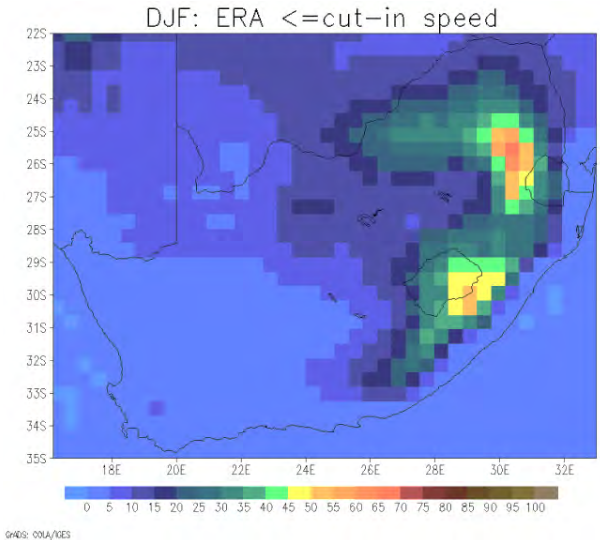


Figure 14: Frequency of days (%) when the wind blows below cut-in speed in DJF (Model ensemble data)

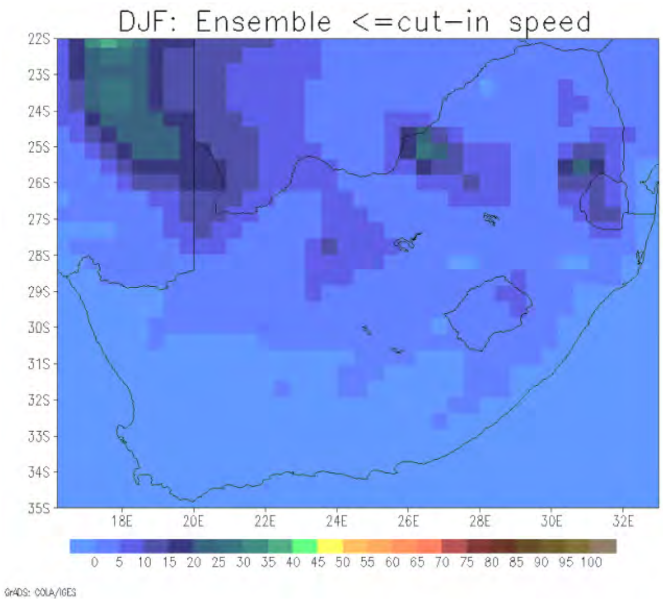


Figure 15: Frequency of days (%) when the wind blows below cut-in speed in JJA (ERA-Interim data)

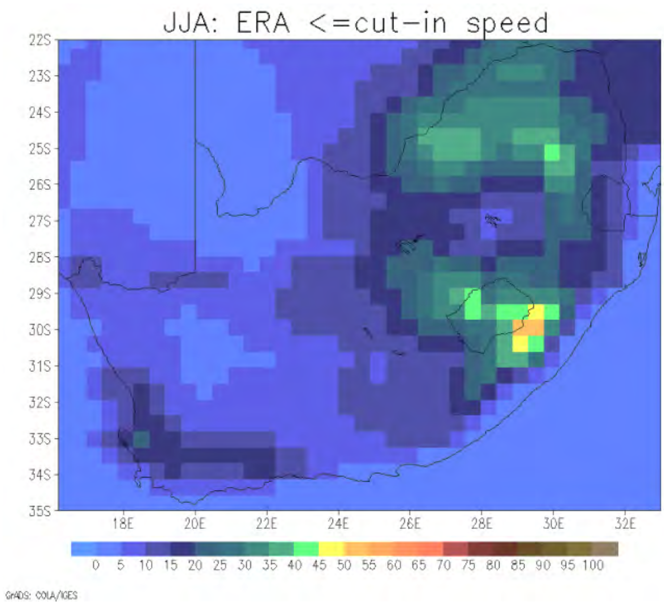


Figure 16: Frequency of days (%) when the wind blows below cut-in speed in JJA (Model ensemble data)

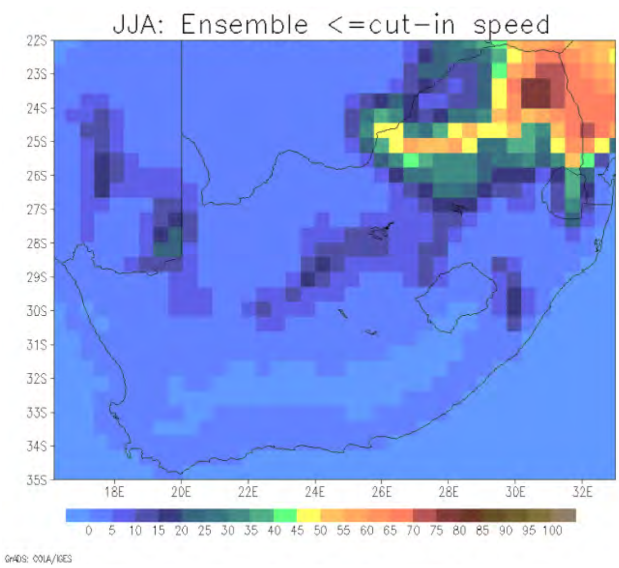
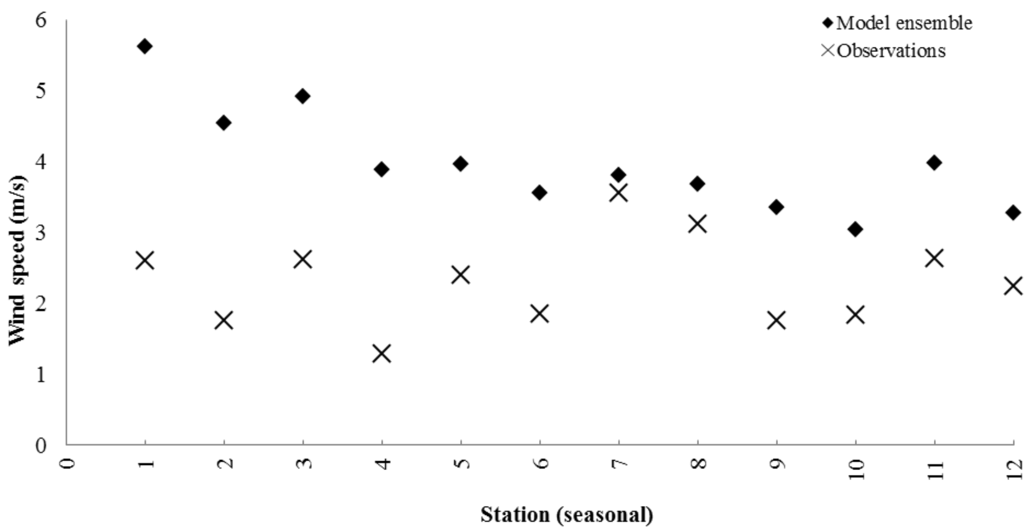


Figure 17 shows mean daily wind speeds as simulated from RCA4 RCM data, plotted together with mean daily wind speeds calculated from ground station data recorded at six SAWS weather stations. Two separate values were plotted per location according to the DJF- and JJA-seasons. Wind speed from model ensemble data at all of the points chosen was higher than that of the observational data taken from the SAWS weather stations. Wind speed varies on scales smaller than the grid resolution of model data of 0.44° × 0.44° (0.44° latitude translates to roughly between 40 and 45 km; and 0.44° longitude translates to 49 km). Minor topographical variations, land cover and temperature variations can intensify or slow wind.[57] Furthermore, wind speed measurement instruments can deliver uncertainties ranging from ± (2.5-5 per cent). The model performs best in the Upington and Mokopane regions (location 7-8 and 11-12, respectively in Figure 17). The over-estimation of winds demonstrated by the high RMSE-values in previous figures for the Western Cape Province are supported by the large the differences seen in Figure 17 between the Malmesbury and Vredendal observations versus model output (locations 1-2 and 3-4, respectively)

Figure 17: Comparison of wind speeds from SAWS station data with RCA4 RCM ensemble data. Location numbers 1 to 2 denote Malmesbury DJF and JJA; location numbers 3-4 denote Vredendal DJF, JJA, etc. They are in the same order as in Table 3.



Change in Wind Speed

Mean Seasonal Daily Wind Speed

Mean daily wind speed per season and frequency in the three categories were used to calculate anomalies. For the DJF-season, it is shown that in Figure 18 that wind speeds are expected to increase by up to four per cent along the southern parts of the Western and Eastern Cape Provinces under RCP4.5. Decreases in wind speeds of up to 1.5 per cent might be expected in the Highveld under the RCP4.5 pathway. In the RCP4.5 pathway in the JJA-season, wind speeds are projected to increase for the majority of the country (Figure 19). Specifically the eastern half of the country could expect wind speeds to increase by up to 4.5 per cent, but central South Africa and the Cape Town region could expect wind speeds to increase by up to three per cent. Decreased wind speeds of up to 1 per cent are projected in the same pathway over the coastal Eastern Cape Province and the West Coast.

For the RCP8.5 pathway, a decrease in wind speeds of up to 2.5 per cent might be expected during DJF (Figure 20) in the central-east of the country and in the Northern Cape Province respectively. Wind speed may increase by up to 6 per cent in the Cape Town region and the Eastern Cape Province during DJF. In JJA, wind speeds are projected to increase by up to 6 per cent in the far east of South Africa, and in the region of one to three per cent in the interior (Figure 21). Wind speeds are projected to decease along the West Coast by up to two per cent, and could decrease by 1.5 per cent in the Eastern Cape Province.

Seasonal Daily Wind Speed Frequency

During DJF, a decrease of 1 per cent of wind speed frequency of winds within valid speed 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 22) and RCP 8.5 (Figure 23) pathways . Up to 3 per cent 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 22). Under the RCP8.5 pathway these wind speeds are projected to occur by up to 3 per cent less frequently in a small area west of Swaziland (Figure 23). In the majority of the country, however, the frequency of winds blowing within the appropriate speed range is projected to remain fairly unchanged. In the JJA-season, valid speed range winds are projected to occur more often over the Limpopo Province by between three and nine per cent in the RCP4.5 pathway (Figure 24). The Western Cape and Eastern Cape Provinces could expect these winds to occur up to 1 per cent less frequently in the RCP4.5 pathway. In the RCP8.5 pathway, a large region in north-eastern South Africa could expect nine per cent more valid speed range winds (Figure 25). These winds are projected to occur up to three per cent more often in central South Africa, and to occur up to 1 per cent less often in the Eastern Cape and parts of the Western Cape Province (Figure 25).

Occurrence of wind below the cut-in speed during DJF are generally expected to remain between -2 per cent and 0 per cent change in the RCP4.5 pathway, except for a small region between Swaziland and Lesotho, where such winds may occur up to 2 per cent more often (Figure 26). In the RCP8.5 pathway, these winds are also projected to generally decrease by -2 per cent and 0 per cent, but a larger part than in the RCP4.5 pathway projection (between Swaziland and Lesotho) could expect these winds to occur up to 4 per cent more often (Figure 27).

Below cut-in speed winds could occur 2 per cent more often in scattered areas in the Western Cape anv d Eastern Cape Provinces in the JJA-season under the RCP4.5 pathway (Figure 28). These winds are projected to occur up to 10 per cent less often in north-eastern South Africa in the RCP4.5 pathway. Below cut-in speed winds could occur 2 per cent more often under the RCP8.5 pathway in the Northern Cape and Eastern Cape Provinces (Figure 29). Large parts of north-eastern South Africa could expect these winds to decrease by 12 per cent under the RCP8.5 pathway (Figure 29).

Figure 18: Projected anomaly in mean wind speed (%) for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

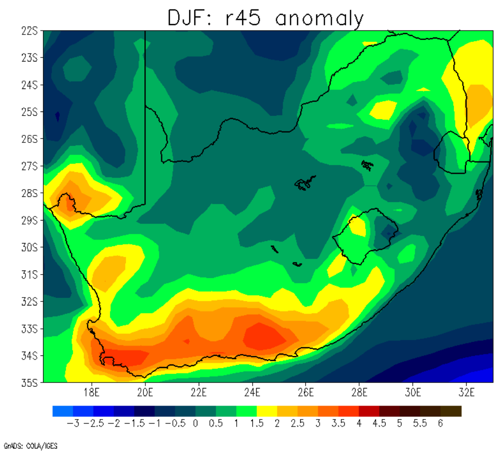


Figure 19: Projected anomaly in mean wind speed (%) for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

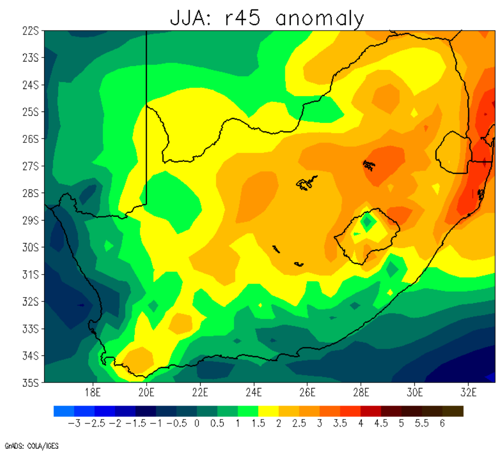


Figure 20: Projected anomaly in mean wind speed (%) for DJF (2051-2075 relative to 1981-2008) under the RCP8.5 pathway

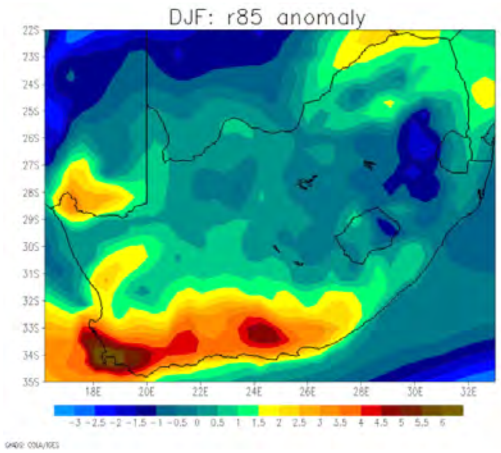


Figure 21: Projected anomaly in mean wind speed (%) for JJA (2051-2075 relative to 1981-2008) under the RCP8.5 pathway

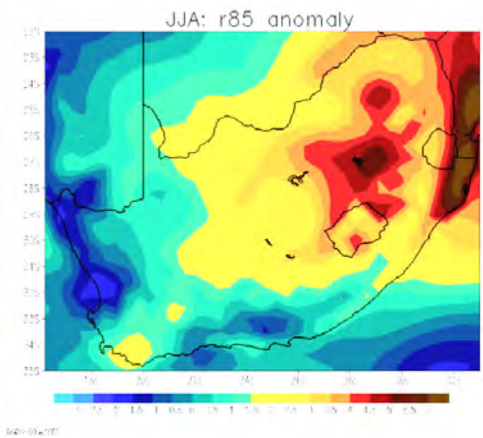


Figure 22: Projected anomaly in wind speed frequency (%) in the valid wind speed range for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

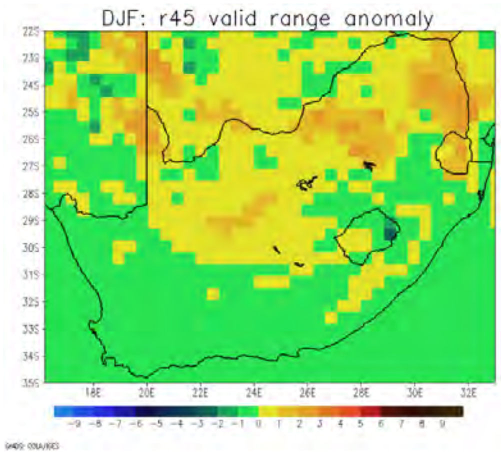


Figure 23: Projected anomaly in wind speed frequency (%) in the valid wind speed range for DJF (2051-2075 rela-tive to 1981-2005) under the RCP8.5 pathway

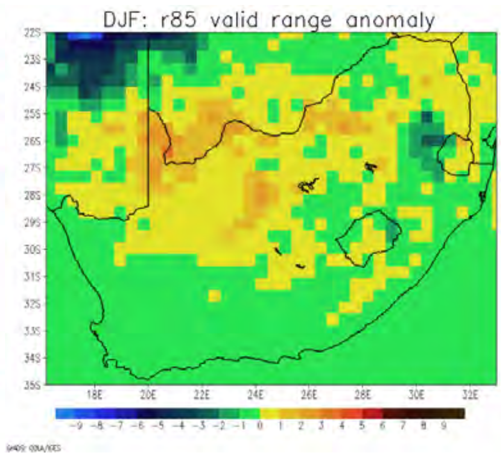


Figure 24: Projected anomaly in wind speed frequency (%) in the valid wind speed range for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

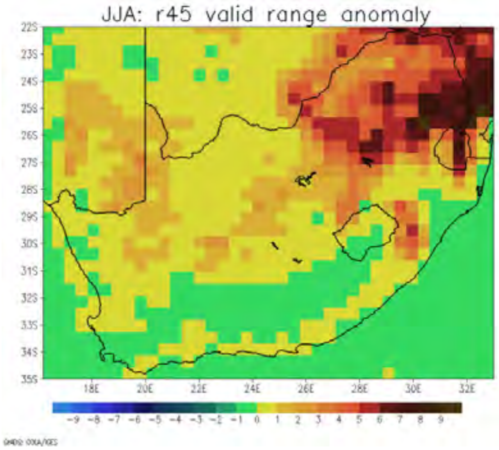


Figure 25: Projected anomaly in wind speed frequency (%) in the valid wind speed range for JJA (2051-2075 relative to 1981-2005) under the RCP8.5 pathway

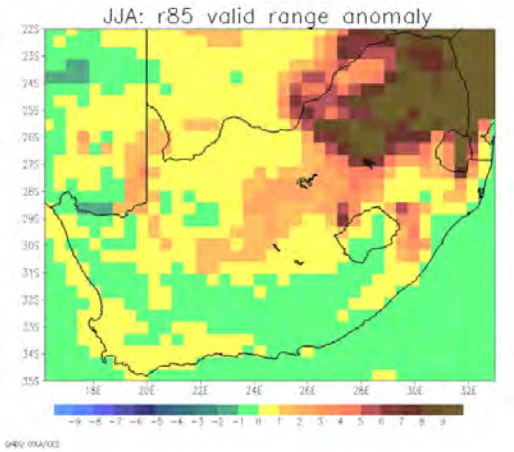


Figure 26: Projected anomaly in wind speed frequency (%) below cut-in speed for DJF (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

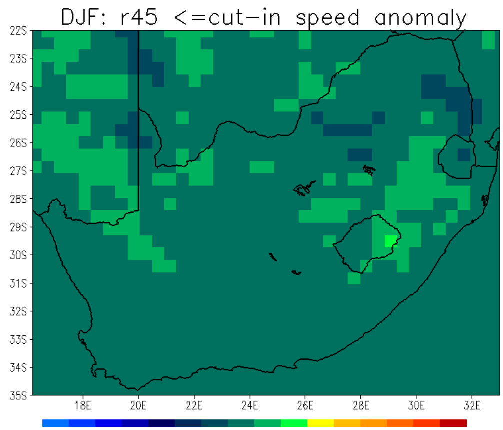


Figure 27: Projected anomaly in wind speed frequency (%) below cut-in speed for DJF (2051-2075 relative to 1981-2005) under the RCP8.5 pathway

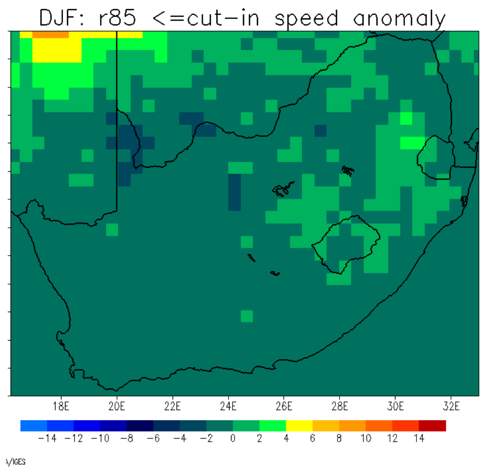


Figure 28: Projected anomaly in wind speed frequency (%) below cut-in speed for JJA (2051-2075 relative to 1981-2005) under the RCP4.5 pathway

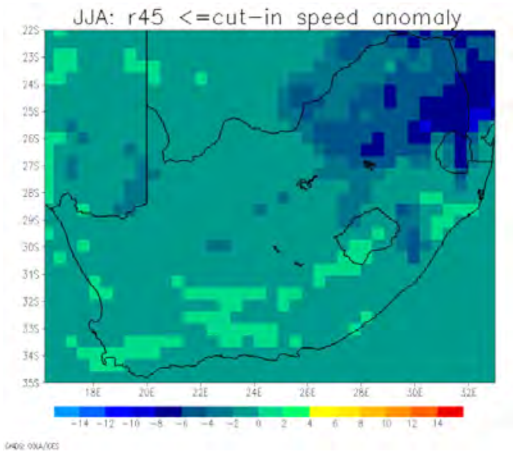
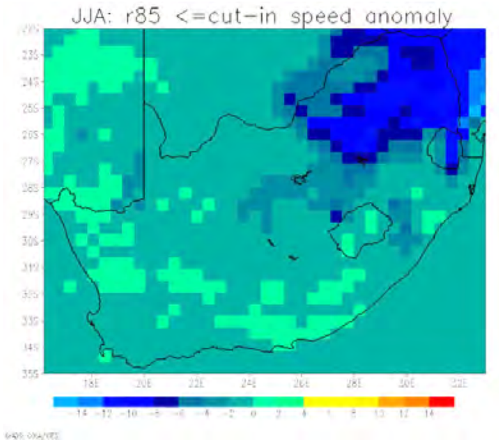


Figure 29: Projected anomaly in wind speed frequency (%) below cut-in speed for JJA (2051-2075 relative to 1981-2005) under the RCP8.5 pathway



Future Wind Power Density

Resulting bias-corrected projections for both seasons and both pathways are shown in Figures 30, 32, 34 and 36. The reader is referred back to Figures 3 and 5 to interpret bias-corrected mean wind speeds: results are now more similar to the ERA-Interim simulations, and thus more accurate in terms of the magnitude in wind speed.

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 31) and the RCP8.5 (Figure 35) pathways, but the region of 90W.m^{-2} is larger in the RCP4.5 pathway. A 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.

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 33), but it extends further 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 37). Wind power density in most of eastern South Africa is projected at no more than 30W.m^{-2}.

Figure 30: Bias-corrected mean wind speed (m.s^{-1}) for DJF under the RCP4.5 pathway (2051-2075) from Model ensemble data

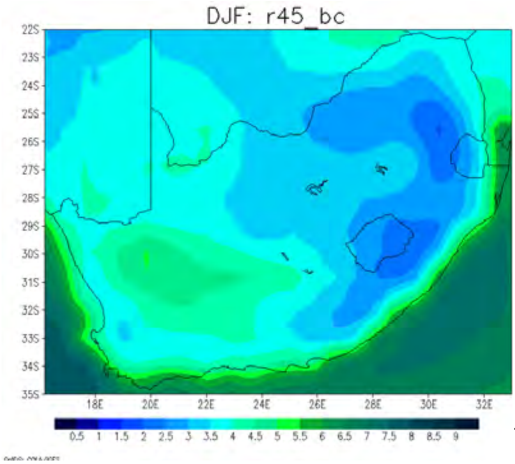


Figure 31: Wind power density (W.m^{-2}) for DJF under the RCP4.5 pathway (2051-2075)

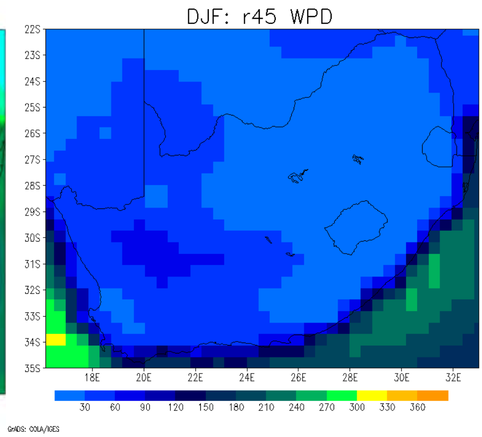


Figure 32: Bias-corrected mean wind speed (m.s^{-1}) for JJA under the RCP4.5 pathway (2051-2075) from Model ensemble data

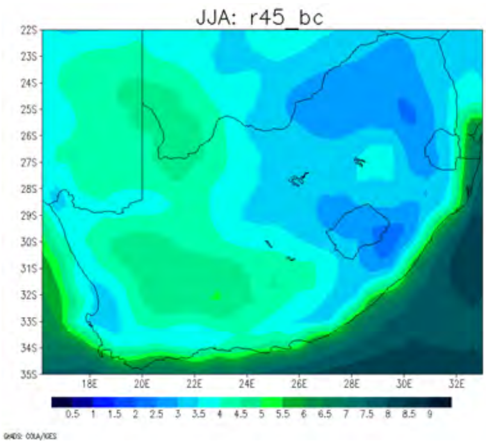


Figure 33: Wind power density (W.m^{-2}) for JJA under the RCP4.5 pathway (2051-2075)

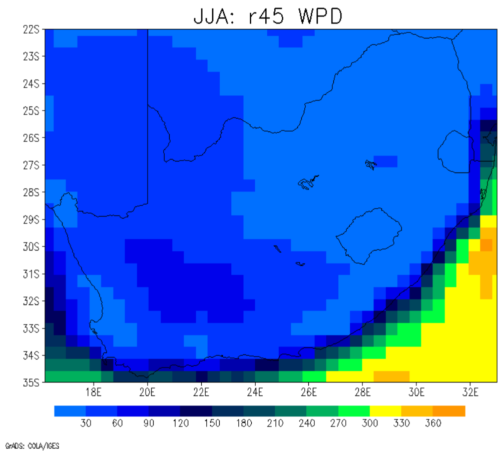


Figure 34: Bias-corrected mean wind speed ($m.s^{-1}$) for DJF under the RCP8.5 pathway (2051-2075) from Model ensemble data

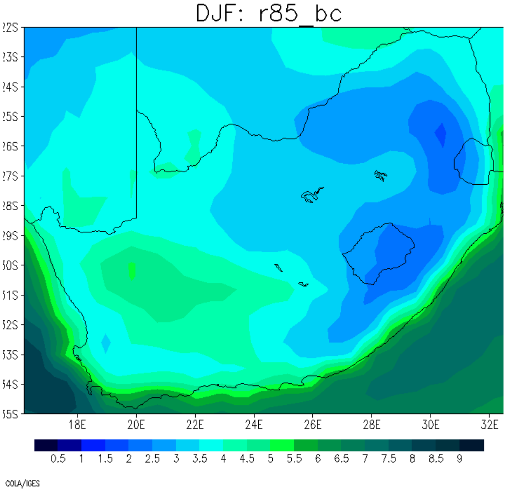


Figure 35: Wind power density ($W.m^{-2}$) for DJF under the RCP8.5 pathway (2051-2075)

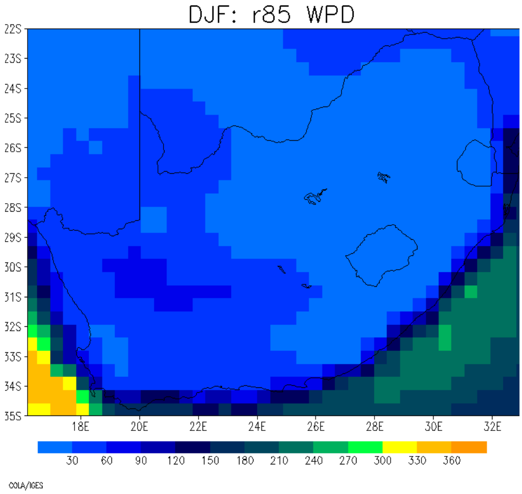


Figure 36: Bias-corrected mean wind speed ($m.s^{-1}$) for JJA under the RCP8.5 pathway (2051-2075) from Model ensemble data

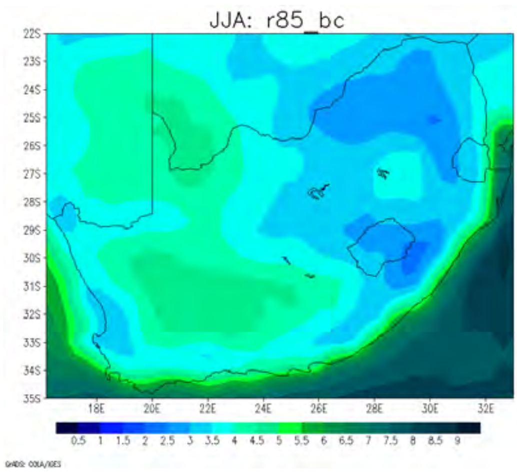
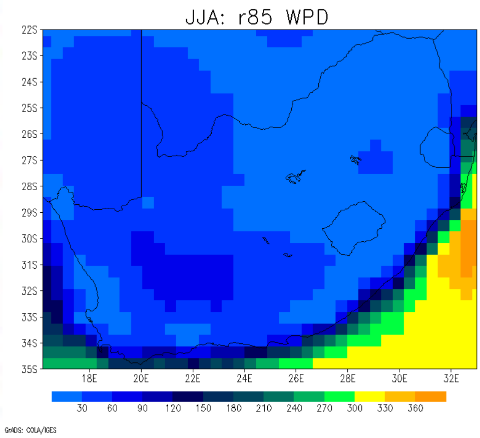


Figure 37: Wind power density ($W.m^{-2}$) for JJA under the RCP8.5 pathway (2051-2075)



Conclusion

The wind energy industry is experiencing rapid growth globally, prompted by climate change adaptation strategies and the unsustainable use of non-renewable energy resources. Developments in this exciting field have spilt over to the South African energy sector. Considering potential hazards to wind energy projects is critical, as climate change could pose a threat to its long term investment potential. 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.

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 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 was re-meshed due to a difference in its resolution from the RCA4 RCM data. Data could then be separated into seasonal datasets and compared.

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 1.5 $m.s^{-1}$ 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. 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 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.

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 appropriate for electricity generation from wind turbines was calculated. The output had to be verified against ERA-Interim data again. The frequency of days with wind speed too low and too high for wind power generation was also calculated. The same trend became evident in these analyses as in the mean calculations. The model ensemble data showed more optimistic results in terms of wind speed within a valid wind speed range for electricity generation across the southern region of the country. Where wind speed was not within the valid wind speed range, it could be assumed that it was lower than this range, rather than higher. This assumption is warranted by model ensemble results that reveal wind speed above the valid speed range occurring very infrequently across the country in all seasons in the 25-year period. The topography of the escarpment is not well captured by model data, as it does not show lower wind speed along this strip. It projects lower wind speed in the north-eastern quarter of the country than the ERA-Interim data during JJA.

To satisfy the second objective, RCA4 RCM data that were forced with two CO2 RCPs in the projected period of 2051 to 2075 were employed to calculate projected wind climates. 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 range appropriate for electricity generation.

In the southern parts of the Western Cape Province and the Eastern Cape Province, an increase in wind speed of up to three and six per cent was projected during DJF in the RCP4.5 and RCP8.5 pathways, respectively. A decreased mean wind speed of one and three per cent (according to the respective pathways) has been projected in this season in the central and eastern regions of the country. Mean daily wind speed is expected to increase over the whole country during JJA, except along the west coast and southern parts of the Western Cape Province and Eastern Cape Province in both pathways. The magnitude of the anomaly is larger in RCP8.5. Mean daily wind speed is projected to increase in regions in which wind farms are currently commissioned, except during JJA in the Eastern Cape.

In terms of the third objective, 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 (90 W.m-2) in a region in the Northern Cape Province in all seasons and under both pathways.

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.

The wind power density projections are lower than the requirement in industry for the wind power density to be above 100 W.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 10 m agl, and could in future work be extrapolated to turbine heights of > 90 m 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 (3 m.s-1 to 25 m.s-1). Furthermore, estimates of wind climate are less robust than that of temperature projections, where the agreement between multiple models is often fairly high.[58] Finally, model output can only be seen as trends, rather than absolute projections – hence the focus on anomalies, rather than projections.

Acknowledgements

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