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Wind Atlas for South Africa (WASA)

Atlas of extreme wind and gust for South Africa

Final Report for WASA Phase III

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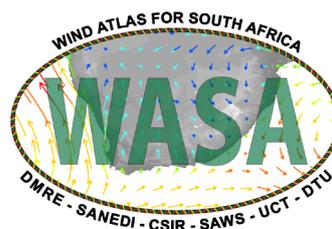
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1. Introduction

This report outlines the final results for the Wind Atlas of South Africa project for the extreme wind and gust statistics for planning of wind farms (Work Package 5).

In addition to an extreme wind atlas based on meteorological measurements, the following relevant products were produced in terms of modelling in WASA Phases I and II:

- 1) The 50-year wind at 10 m, 50 m and 100 m from WRF modeling at a spatial resolution of 4 km for two areas in South Africa.
- 2) The 50-year wind at 10 m from the spectral correction method in connection with the use of the reanalysis data CFSR I, at a special resolution of 40 km.
- 3) Generalized 50-year wind from 1) over the two areas that can be further applied to microscale, linear computational model LINCOM, to obtain local extreme wind at a resolution of tens of meters.
- 4) Generalized 50-year wind from 2) over South Africa that can be further applied to the microscale, linear computational model LINCOM, to obtain local extreme wind statistics at a resolution of tens of meters.

In WASA Phase III, benefiting from the long term, high spatial resolution (3.3 km) mesoscale modeled data over the entire country, we obtained

- 5) The 10-min values of 50-year wind at 10 m, 50 m, 100 m and 200 m. The 10 m winds were not one of the direct outputs from the mesoscale modeling but serve as output for this project. The output of the 10m wind speed was used to estimate the 1:50 year wind statistics and these were critically compared to the outputs from historical observations, also at 10 m height.
- 6) Generalized 50-year wind from 5) that can be further applied to microscale, linear computational model LINCOM, to obtain local extreme wind statistics at a resolution of tens of meters.

WASA III benefitted from the ongoing GASP project, where the method outlined in 4) is applied to the whole globe and downscaled using LINCOM to a spatial resolution of 250 m. Thus we estimated

- 7) The 10-min values of 50-year wind at 50 m, 150 m and 200 m at a spatial resolution of 250 m over South Africa.

The results from the two mentioned WASAIII datasets were compared to earlier WASA datasets as well as measurements.

In addition to the above, final calculation was done of

- 8) The 3-s values of the 50-year gust at 10 m at a spatial resolution of 3.3 km.

The methods for 5) – 8) are briefly summarized in section 2. The results are presented in section 3, followed by discussion and conclusion.

2. Methods

The methods introduced here are for the calculations in WASA III.

2.1. WRF-modeling and the estimation of the extreme wind

The details of the WRF setup and modeling can be found in Hahmann et al. (2020). Briefly, the model was forced by ERA5 data and it ran for the period from 1990 to 2019. The spatial resolution for the innermost model domain is 3.3 km, covering entire South Africa. The outputs are saved every 30 minutes.

The annual wind maxima at each mesoscale grid point are identified. For the 30 samples of the annual maximum values, we apply the Gumbel distribution and obtain the 50-year value. The winds at 50 m, 100 m and 200 m are obtained through interpolation of values at the relevant model levels. The wind at 10 m is not an output, here we use the values from other heights and a logarithmic fit to obtain it, see Fig. 1. As mentioned earlier, these values are for comparison with the many historical measurements that were made at this height. Fig 1 shows that (1) it is not a good method to use data from all the three levels in connection with a 2nd order polynomial regression. (2) When using a linear fit, there are some differences between using data from three levels and data from the first two levels.

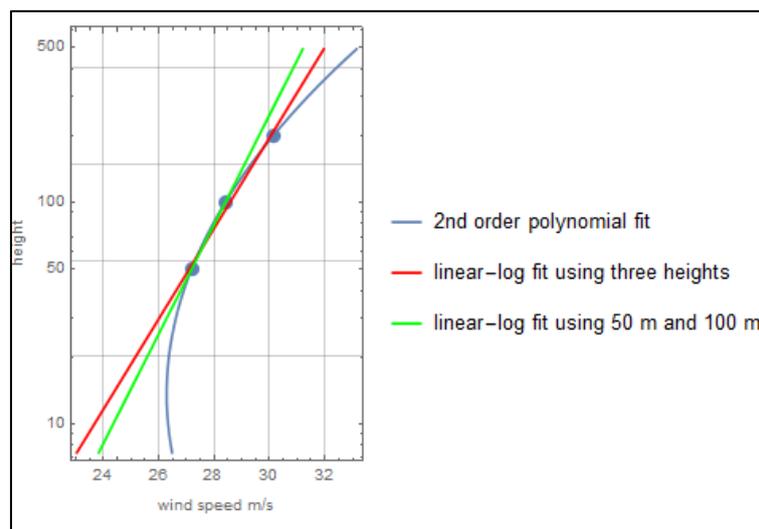


Fig. 1. Obtaining wind speed at 10 m using data from other heights.

Primarily we use the values at 10 m derived from 50 m and 100 m. The values are compared with those derived using all three heights (50 m, 100 m and 150 m).

Products 5) and 6) listed in Section 1 were produced using this method.

Product 6) was obtained from the so-called “generalization”, which cleans the speed-up effects caused by mesoscale topography and roughness length change, and convert the winds to a homogeneous surface with a roughness length of 5 cm (see Larsén and Kruger (2016) for the details). The “cleaning” is done sectorwise. For each WRF grid point, the wind time series is grouped into 36 sectors. Each sector has its own speedup effect depending on the upwind orography and roughness length change. Here we used the data prepared in WP3. Afterwards, after assuming the same

geostrophic wind, the winds are converted from the WRF roughness length (used in the modelling) to a standard 5 cm.

2.2. The GASP method

The details of the method can be found in the report Larsén et al. (2020). Briefly, the global reanalysis data are used in connection with the spectral correction method, as done in Larsén and Kruger (2015), and in addition, the calculation is continued using the microscale flow model LINCOM for downscaling to a spatial resolution of 250 m.

2.3. Observations

The 50-year winds at 111 stations have been prepared by the South African Weather Service. Table 1 shows the station names, coordination, and 1:50 year gust estimations at 10 m. In the estimation process the roughness length was considered (observations have to be done in fairly open terrain), topography and statistical estimation method. More information on the approach can be found in Kruger (2011).

Table 1. Observational estimates of the 1:50 year gusts for 111 South African Weather Service stations with at least 10 years of data. The stations are arranged according to latitude.

Number	Name	lat	lon	1:50 yr gust
3108	STRUISBAAI	-34.8008	20.0589	41
6386	HERMANUS	-34.4325	19.2247	44
10682	STILBAAI	-34.3708	21.3964	30
7699	TYGERHOEK	-34.1497	19.9031	37
5609	STRAND	-34.1411	18.8489	44
14545	PLETTENBERGBAAI	-34.0939	23.3289	31
14123	KNYSNA	-34.0594	23.0914	34
15692	TSITSIKAMMA	-34.0269	23.9086	28
12661	GEORGE WO	-34.0167	22.3832	33
35209	PORT ELIZABETH	-33.9844	25.6108	40
21178	CAPE TOWN WO	-33.97	18.6	38
20618	ROBBENEILAND	-33.7989	18.3744	29
33556	PATENSIE	-33.7653	24.8233	33
21823	PAARL	-33.7217	18.9719	31
34763	UITENHAGE	-33.7142	25.435	39
22729	WORCESTER	-33.6639	19.4186	42
41388	MALMESBURY	-33.4725	18.7183	33
56917	GRAHAMSTOWN	-33.2906	26.5028	32
40192	GEELBEK	-33.1961	18.1242	29
59572	EAST LONDON WO	-33.03	27.83	36
41841	PORTERVILLE	-33.0125	18.9769	39
0061298-8	LANGEBAAANWEG-AWS	-32.97	18.16	29
0063807-2	EXCELSIOR-CERES	-32.96	19.43	30
0060620-9	CAPE-COLUMBINE	-32.83	17.86	34

78227	FORT BEAUFORT	-32.7881	26.6294	38
0088293A6	SUTHERLAND	-32.4	20.66	34
92081	BEAUFORT-WES	-32.3572	22.5775	39
96072	GRAAFF - REINET	-32.1933	24.5431	31
0084671-0	CLANWILLIAM	-32.18	18.89	29
0098190B6	CRADOCK-MUN	-32.17	25.63	34
83572	LAMBERTSBAAI	-32.03	18.3298	28
0113025A2	FRASERBURG	-31.92	21.51	35
123685	QUEENSTOWN	-31.92	26.88	44
0106880A2	VREDENDAL	-31.67	18.5	27
127272	UMTATA WO	-31.53	28.67	41
0134479A3	CALVINIA-WO	-31.48	19.76	32
150620	ELLIOT	-31.3381	27.845	44
0144791_2	NOUPOORT	-31.19	24.96	33
0148517A9	JAMESTOWN	-31.12	26.81	32
0155394A5	PORT_EDWARD	-31.07	30.23	35
0182591A4	MARGATE	-30.85	30.33	32
0182465_7	PADDOCK	-30.75	30.26	32
0169880-1	DE-AAR-WO	-30.67	23.99	42
0173032-4	GARIEP-DAM	-30.56	25.53	36
0190868-1	BRANDVLEI	-30.46	20.48	33
0184491-4	KOINGNAAS	-30.2	17.29	28
0210099A7	IXOPO	-30.15	30.07	27
0240808A2	DURBAN_SOUTH_AWS	-29.97	30.95	33
0232654_4	WEPENER	-29.92	26.85	33
241076	VIRGINIA	-29.767	31.05	31
0291570-1	FAURESMITH	-29.75	25.32	32
0241072_9	MOUNT_EDGEcombe	-29.7	31.05	24
0214700B2	SPRINGBOK-WO	-29.67	17.88	35
0224400-8	PRIESKA	-29.67	22.74	35
0239699_7	ORIBI_AIRPORT	-29.65	30.4	34
0239698_5	PIETERMARITZBURG	-29.63	30.4	29
0268016AX	GIANTS_CASTLE_AWS	-29.27	29.52	42
0268883_6	MOOI_RIVER	-29.22	30	36
0247668A4	POFADDER	-29.12	19.39	29
261516	BLOEMFONTEIN WO	-29.1	26.3	36
0270155_9	GREYTOWN	-29.08	30.6	34
0304357_6	MTUNZINI	-28.95	31.7	32
0296709AX	FICKSBURG	-28.83	27.9	35
0290468A9	KIMBERLEY-WO	-28.81	24.77	37
0276196-8	VIOOLSDRIF-AWS	-28.77	17.62	29
0305134_6	RICHARDS_BAY_AIRPORT	-28.73	32.08	29
0281606A5	AUGRABIES-FALLS	-28.6	20.34	32
274034	ALEXANDERBAAI	-28.5728	16.5364	32

0300454_3	LADYSMITH	-28.57	29.77	36
0317475A8	UPINGTON-WO	-28.41	21.26	36
0333682A9	VAN_REENEN	-28.38	29.39	36
0321110_7	POSTMASBURG	-28.35	23.08	33
0337738_2	ULUNDI	-28.3	31.42	31
0331585_9	BETHLEHEM_WO	-28.25	28.33	33
339732	CHARTERS CREEK	-28.2	32.417	28
364300	WELKOM	-27.9947	26.6658	40
0372527_1	VRYHEID	-27.78	30.8	28
0370856_3	NEWCASTLE	-27.77	29.98	36
356880	KATHU	-27.6719	23.0106	33
0365398_8	KROONSTAD	-27.67	27.31	36
0362189_7	BLOEMHOF	-27.65	25.62	34
0360453A0	TAUNG	-27.55	24.77	34
0412148_6	MBAZWANA_AIRFIELD	-27.48	32.6	33
0393806-4	KURUMAN	-27.43	23.45	27
0405326A9	VREDE	-27.42	29.17	32
0410175_X	PONGOLA	-27.41	31.59	30
441416	STANDERTON	-26.93	29.23	34
0436204-1	KLERKSDORP	-26.9	26.62	31
0437104A4	POTCHEFSTROOM	-26.74	27.08	32
0438784-3	VEREENIGING	-26.57	27.96	33
0479870-X	ERMELO-WO	-26.5	29.98	33
0461208-4	TWEE-RIVIEREN	-26.47	20.61	36
0476762A3	SPRINGS	-26.21	28.44	21
0476399-0	JOHANNESBURG-INT-WO	-26.14	28.23	32
0472278-0	LICHTENBURG	-26.13	26.16	33
0513239_0	GRAND_CENTRAL	-25.98	28.13	33
0513385A2	IRENE-WO	-25.91	28.21	33
0515320-8	WITBANK	-25.83	29.19	34
0508047-0	MAFIKENG-WO	-25.8	25.54	31
0517041-2	BELFAST	-25.69	30.03	31
0511399-X	RUSTENBURG	-25.66	27.23	30
0520691-2	KOMATIDRAAI	-25.51	31.91	30
0594626B9	GRASKOP-AWS	-24.94	30.84	31
0585341-8	MADIKWE-GAME-RESERVE	-24.69	26.2	32
0587725CX	THABAZIMBI	-24.58	27.41	29
0633882-7	MOKOPANE	-24.2	29.01	31
0677802BX	POLOKWANE-WO	-23.86	29.45	35
0679194-5	TZANEEN-WESTFALIA-ESTATE	-23.74	30.11	20
0674341-8	LEPHALALE	-23.68	27.71	29
0675666-2	MARKEN	-23.59	28.39	29
0723664-6	THOHOYANDOU-AWS	-23.08	30.38	33

Out of 19 WASA stations (Fig. 2), at eight stations the measurements of winds at 60 m are sufficiently long to be used for estimation of the 50-year wind.

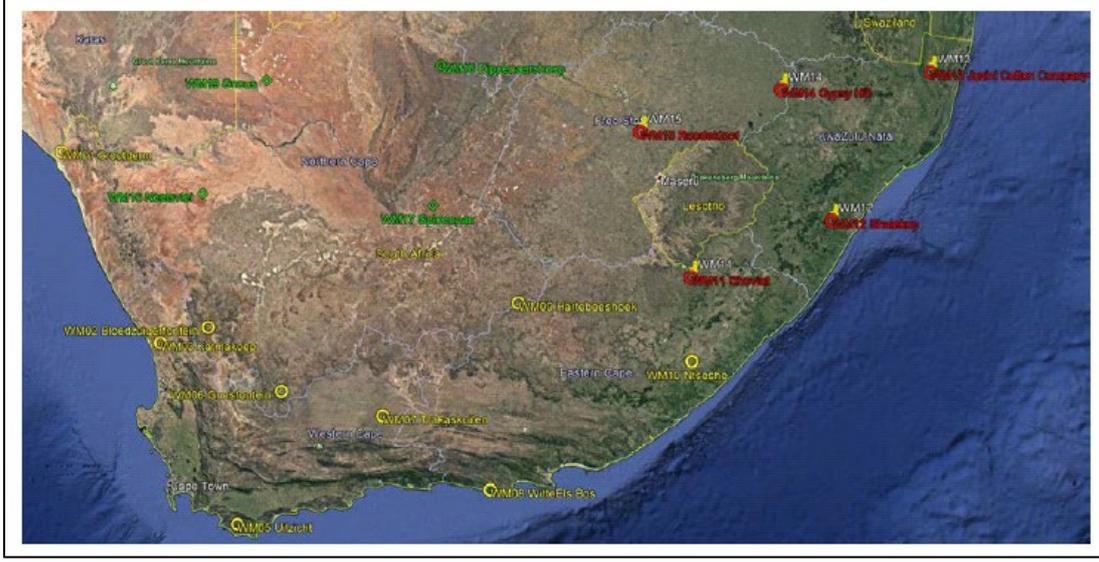


Fig. 2. 19 met stations from WASA project (from Mortensen et al. 2021)

2.4. Calculation of the extreme gust values

The corresponding gust values are obtained based on the 50-year wind at 10 m using a boundary-layer turbulence model, the Kaimal model for the along-wind components:

$$fS(f) = \frac{102u_*^2(fz/U)}{(1+33fz/U)^{5/3}} \quad (1)$$

where u_* is the friction velocity and it can be approximately calculated through $\kappa U/u_* = \ln(z/z_0)$ for neutral conditions, here $\kappa = 0.4$ is the von-Kármán constant. We use the 30-min values (as the WRF model output) of 50-year wind as input for U in Eq. 1. The spectrum is used to calculate the zero and second-order spectral moments following

$$m_i = \int_{f_1}^{f_2} f^i S(f) df$$

with $i = 0$ and 2 , respectively. Here f_1 determines the period over which the gust is calculated and f_2 determines to what resolution the calculation will be done. The time scales we apply here are $f_1 = 1/1800$ s, and f_2 the Nyquist frequency for a temporal resolution of 3 s, namely 0.1667 Hz.

The spectral moments are used to obtain the peak factor

$$k_p = \sqrt{2 \ln \left(T_0 \sqrt{\frac{m_2}{m_0}} \right)} + \frac{0.577}{\sqrt{2 \ln \left(T_0 \sqrt{\frac{m_2}{m_0}} \right)}}$$

where T_0 is the period the gust is calculated over and the gust is obtained through

$$V_{50,gust} = U_{50} + k_p \sqrt{m_0}$$

3. Results

3.1. The 50-year gust

Most regions in South Africa are affected by thunderstorms. As a consequence, using the typical boundary-layer turbulence model underestimates the turbulence and therefore the gust values. We tested using coefficients larger than 102 in connection with the use of Eq. 1 for these areas, which improves the overall estimation of gust values at stations in these areas. However, differential estimations over adjoining regions caused artificial discontinuities and therefore the original modelled values were revisited. It was established by categorizing the estimated gusts and increasing the estimated values to the top category value for conservativeness. For example, all 1:50 year wind gusts estimated lower than 36 m/s were designated a value of 36 m/s, 36 to 40 m/s a value of 40 m/s, 40 to 44 m/s a value of 44 m/s and all values above 44 m/s were categorized as the top-most category. Regions in the highest category should be treated with caution for any infrastructure development, including wind farms. In the modelling process some point estimations in these regions were well above 50 m/s.

The categorization of wind gust values in the intervals above made it convenient to compare the new map to a recent map developed from only observations, for the revision of the South African loading code. The last mentioned map, presented in Fig 4, indicates somewhat higher values over the central interior but due to the lack of sufficient observations over higher lying areas did not fully succeed to reflect the very high values likely over the escarpment. In addition, the spatial resolution of the observations necessitated to provide estimates for municipal districts, with the additional motivation that it makes reference to design wind speed values explicit.

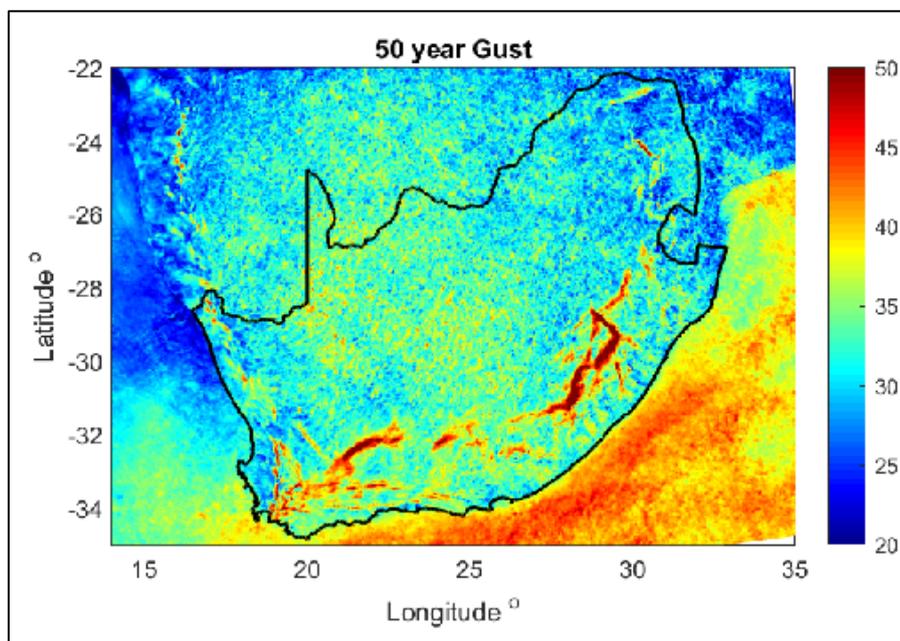


Fig. 3. The original 3 s value of the 50-year gust at 10 m.

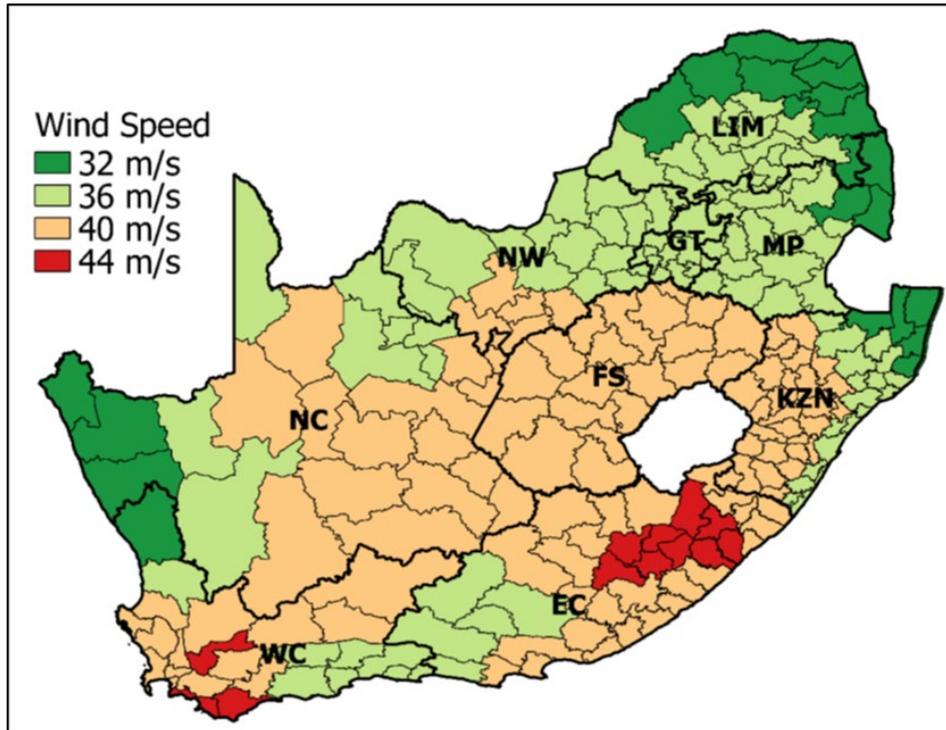


Fig. 4. Developed map of fundamental value of basic wind speed (developed for revision of SANS wind loading code), provides the 1:50 yr gust values closest to values estimated from measured data (Kruger et. al, 2017).

Fig 5 presents the final WASA III map for the 50-year gust, V_{50} . A critical comparison between Fig 4 and Fig 5 and comparison of the results from the analysis of 111 stations show that the final map compares well to the updated design values in Figure 4, considering the following:

- The East Coast: most stations along the KwaZulu-Natal coast estimate a 1:50 year gust in the region of 35 m/s, therefore 35 m/s or 36 m/s (as in the case of the SANS map) is appropriate. Towards the south at the Eastern Cape coast wind speeds are somewhat higher and in northern KwaZulu-Natal somewhat lower.
- Top of escarpment should be higher than the 40 m/s of the SANS map, as indicated by measurement estimations and provision for conservativeness. Modelling shows values much higher than 44 m/s in isolated areas.
- The interior, excluding the escarpment, influenced by thunderstorms and synoptic-scale systems to varying degrees - SANS map and results from measurements provide most reliable input, and is significantly higher than modelling in places. Therefore a design value of not lower than 36 m/s is indicated for the interior.
- Eventually most of the country is close to a value of 36 m/s with the remainder mostly between 36 and 40 – therefore a common interval of 4 m/s could be used (36, 40, 44 m/s, and greater than 44); the latter category additional to those in the SANS map.

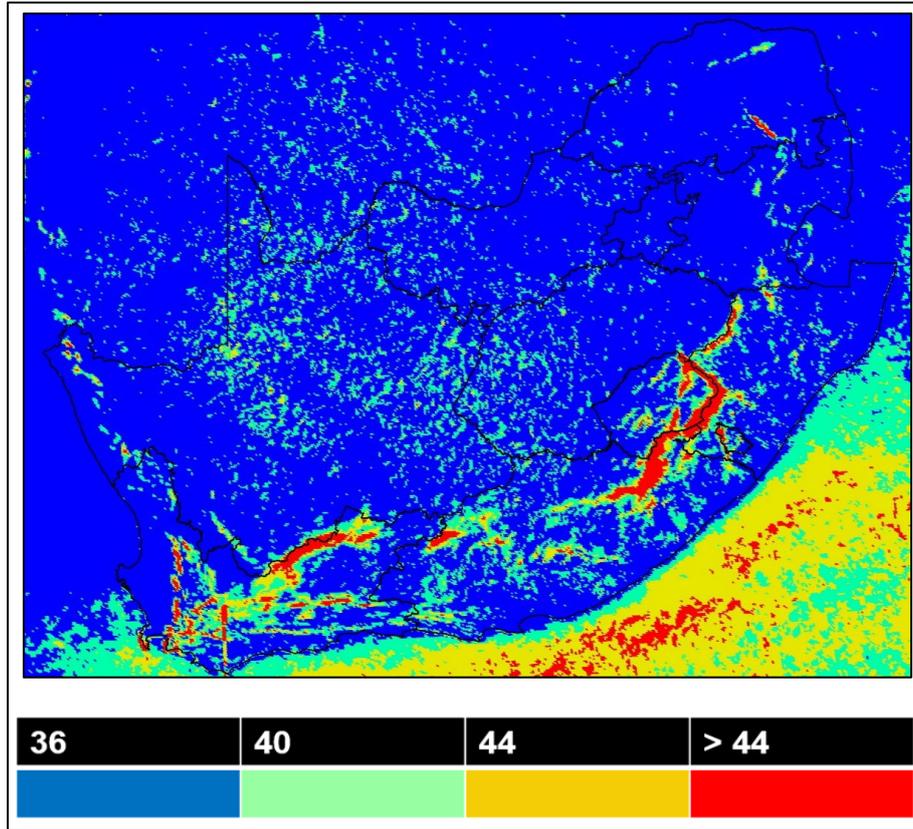


Fig. 5. Final WASA III map for the 50-year 3-s gust V_{50} at 10 m, derived from modelling and verified by measurements.

3.2. The 10-min 50-year wind

The 10-min values of the 50-year wind at turbine hub height are one of the key design parameters for deciding which kind of turbine to be used for a particular site (see Table 2). For instance, a turbine class using e.g. annual average wind speed of class III and turbulence category B, together with 10-min values of the 50-year wind of class II is designated class IIIB,II.

In sections 3.2.1 and 3.2.2, the 10-min 50-year winds are presented from the WASA III project as well as from the GASP project.

Table 2: Basic parameters for wind turbine classes¹

Wind turbine class		I	II	III	S
V_{ave}	(m/s)	10	8,5	7,5	Values specified by the designer
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{ref,T}$	57	57	57	
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			
<p>The parameter values apply at hub height and</p> <p>V_{ave} is the annual average wind speed;</p> <p>V_{ref} is the reference wind speed average over 10 min;</p> <p>$V_{ref,T}$ is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones;</p> <p>A+ designates the category for very high turbulence characteristics;</p> <p>A designates the category for higher turbulence characteristics;</p> <p>B designates the category for medium turbulence characteristics;</p> <p>C designates the category for lower turbulence characteristics; and</p> <p>I_{ref} is a reference value of the turbulence intensity (see 6.3.2.3).</p>					

3.2.1. WRF-WASAIII

The WRF model outputs are 30-min instantaneous values at a spatial resolution of 3.3 km. The eventual 50-year winds need to be corrected to 10-min values. We applied the spectral analysis to the 10-min values of measured and modeled time series from 19 stations from the WASA I-III projects (see Fig. 2 for the locations of these WASA stations). We found that on average the spatial smoothing effect between the model output and the targeted 10-min resolution is 6% using the method from Larsén and Kruger (2014). Fig. 6 shows such an example of the spectral smoothing effect in the modeled data for the relatively high frequencies, showing as the tapered-out tail in the power spectrum in comparison with the measurements (blue). We will simply apply 6% on top of the 30-min model outputs to obtain the corresponding 10-min values.

However, the model not only misses the high frequency fluctuations, it could also introduce systematical bias in the calculation, such as overestimation or underestimation. Such a systematical bias is more difficult to correct as the whole physics system is involved, including the input data, model setup and model physics. This part is not corrected.

¹ IEC FDIS 61400-1 (2017), INTERNATIONAL ELECTROTECHNICAL COMMISSION

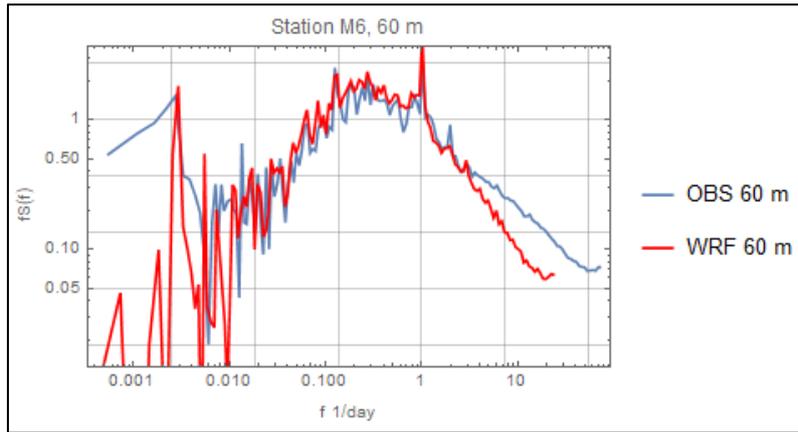


Fig. 6. Comparison of the power spectrum of wind speed at 60 m, from 10-min time series of measurements and 30-min time series of WRF modeled data.

Fig. 7 is the map of the 50-year wind at 10 m of 10-min values, obtained using values from 50 m and 100 m using the method shown in Fig. 5. The 10-m values obtained from 50 m, 100 m and 200 m are systematically smaller than those from 50 m and 100 m for the extrapolation (see Fig 1 for the difference). So there is additional uncertainty from the method of obtaining the 10-m values. In connection with the use for design parameters, we choose the more conservative estimates, namely using 50 m and 100 m.

In Fig. 8 the map of the so-called basic wind velocity is presented, the 10-min values of 50-year winds that are generalized to $z = 10$ m over a homogeneous surface with roughness length of 5 cm. This is a parameter that is often used in building standards, such as the Eurocode EN 1991-1-4. In our method, this variable is used as forcing for the microscale LINCOM model to resolve the local topographical and roughness length effect.

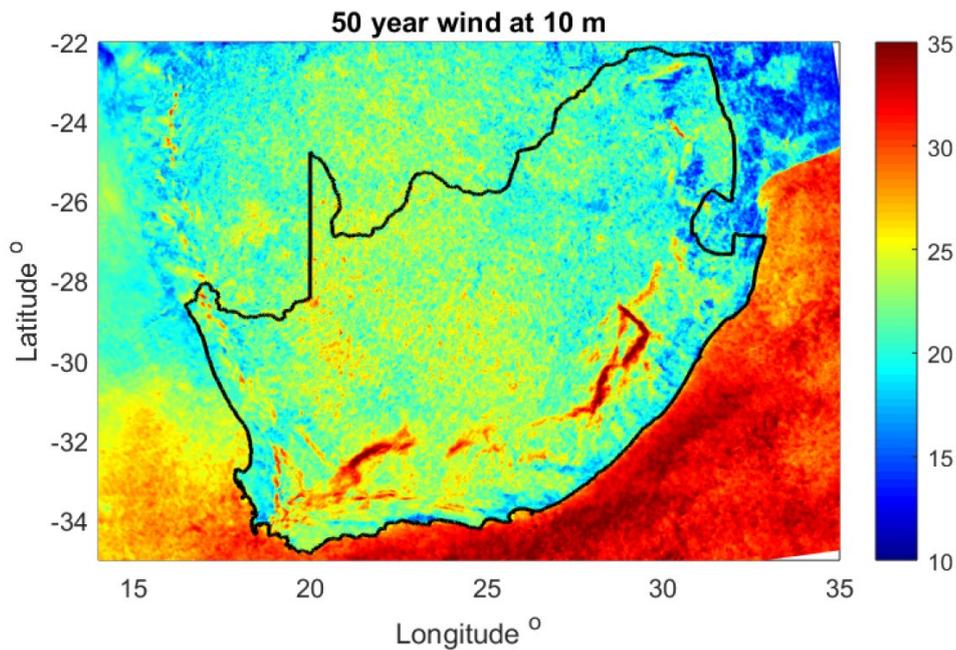


Fig. 7. The 50-year wind at 10 m at a spatial resolution of 3.3 km, from 30-year mesoscale modeled wind (1990-2019), with spectral correction, shown for the range 10 – 35 m/s.

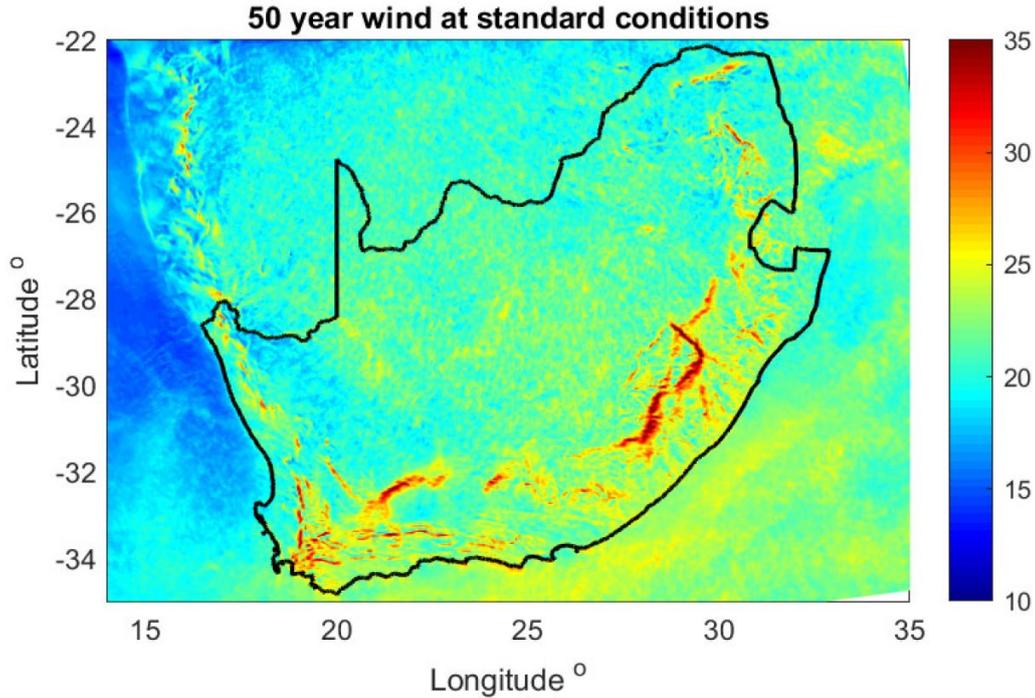


Fig. 8. The 10-min values of 50-year wind at standard conditions (10 m, over roughness length of 5 cm) at a spatial resolution of 3.3 km, from 30-year mesoscale modeled wind (1990-2019), with spectral correction, shown for the range 10 – 35 m/s.

The figures of the 50-year winds at 50 m, 100 m and 200 m can be found in Appendix.

3.2.2. GASP

The results from GASP are 50-year winds of 10-min values at 50 m, 100 m and 150 m. The spatial resolution is 250 m, much finer than the data from the WRF output. The 10 m values can be extrapolated in a similar way as described in section 2. The corresponding map for 10 m was not produced here due to the large amount of data. It can easily be done for particular sites, as done for validation here (see Fig 9).

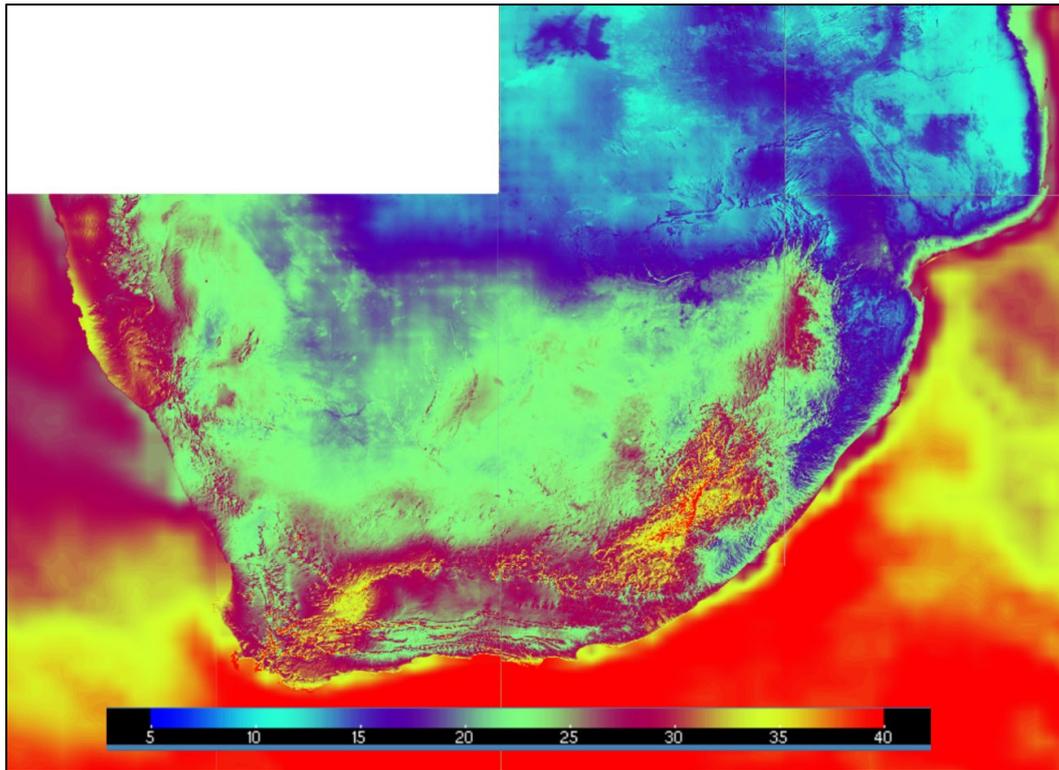


Fig. 9. The 10-min values of the 50-year wind at 50 m at a spatial resolution of 250 m, shown for the range 5 – 40 m/s (GASP project output).

4. Comparison of measurements and model data

The modeled and measured 50-year 10-min as well as 3-s gust values are compared briefly in the following.

4.1. Comparison between WRF-WASAI, WRF-WASAI and observations

The scatter plot in Fig. 10 include four groups of data, of which WASA III 10m and WASA 60 m correspond to the modeled data as described here with 3.3 km and 33-year long, and the WASA I and WASA II correspond to the mesoscale modeling performed in WASA I and II with a spatial resolution of 4 km and half the length of simulation.

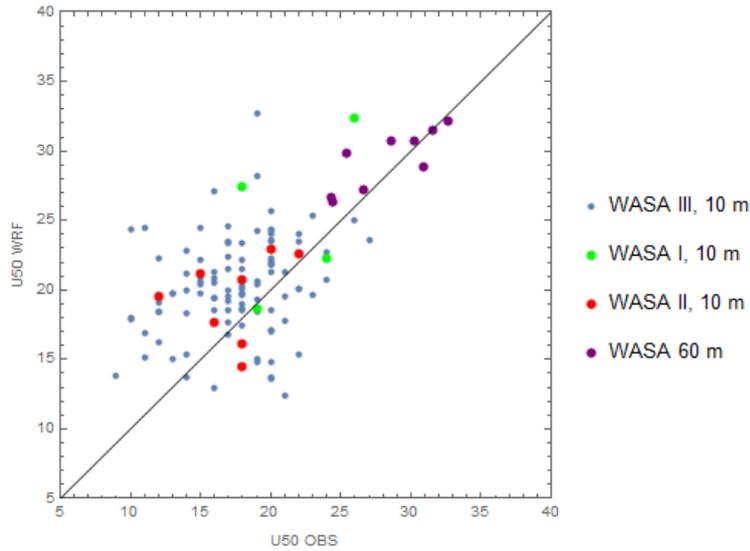


Fig. 10. Comparison of the 50-year wind at 10 m between observation and WRF model, blue: WASAIII-111 stations; red and green: 12 stations from WASAI and II; purple: WASA stations with measurements at 60 m.

4.2. Comparison between GASP results and measurements

For the 111 stations, the 10-m values from the GASP database are extracted and plotted together with the measured ones in Fig. 10. For the WASA stations, the 60-m values are plotted in purple.

Note that in Fig. 10, we used logarithmic extrapolation of winds at 50 m and 100 m to 10 m and we applied an extra 6% for spectral correction. In Fig. 11, we used the same logarithmic extrapolation, though the results are very similar if we use 50 m and 100 m, or 50 m, 100 m and 150 m, or even second order polynomial fit. Overall, the values are on average underestimated in the GASP data by approximately 6%.

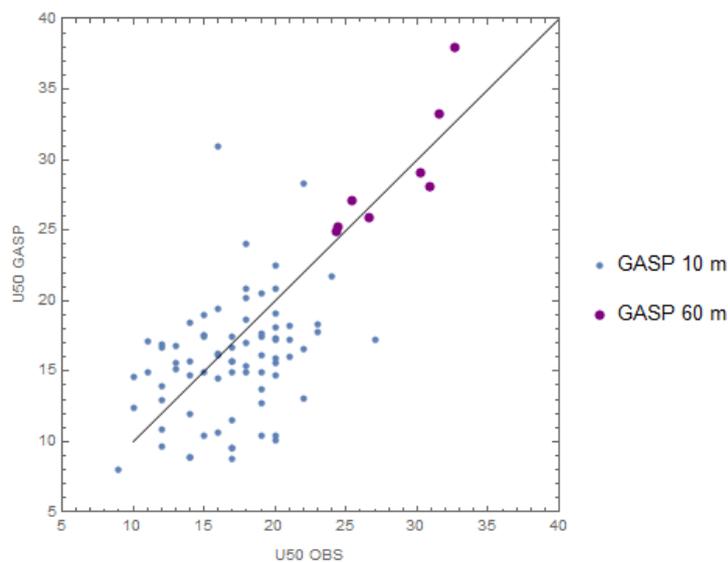


Fig. 11. 10-min values of the 50-year wind at 10 m from measurements versus those from the GASP project.

4.3. The 50-year 3-s gust values

Fig. 12 shows the scatter plot of the 3-s values of the 50-year gust, measured and modeled at the 111 stations from Table 1.

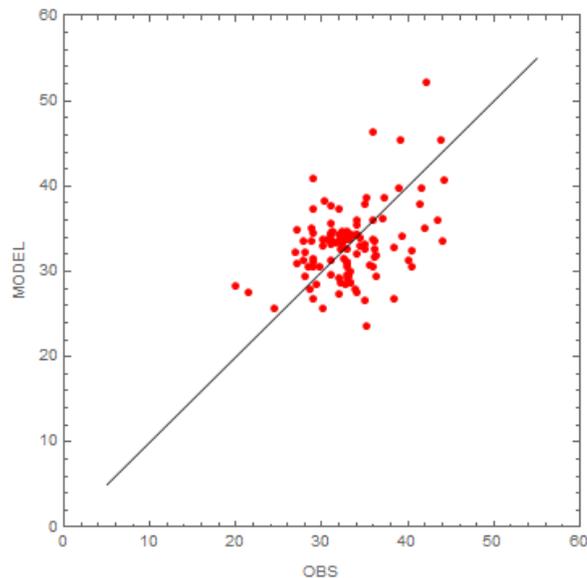


Fig. 12. Comparison of the 3-s values of the original 50-year gust at 10 m at 111 stations, based on Fig. 10.

5. Discussion and conclusion

Extreme winds are key design parameters. The 10-min values of the 50-year wind at turbine hub height are needed together with turbulence intensity and mean wind speed to decide turbine classes. At the same time, the hub height gust magnitude should also be given for the standard wind turbine classes. In addition, for the wider engineering sector and built environment, the extreme wind statistics as included in the national loading code is essential to design for specific extreme winds.

In the WASA III phase, we used the high-resolution mesoscale model results to produce the following products over the entire country:

- a. The 10-min values of the 50-year wind at several heights, including 10 m.
- b. The 10-min values of the 50-year wind of the standard conditions (at 10 m over roughness length of 5 cm).
- c. The 3-s values of the 50-year wind at several heights, including 10 m.

Note that these data are available at a spatial resolution of 3.3 km. The WRF model outputs are at 50 m, 100 m and 200 m, which makes it possible to derive the corresponding values at any hub height between the land surface to 200 m. These data are useful for regional planning. For a particular site, in order to obtain even finer resolution calculation, e.g. at a spatial resolution of 10 m, one can use dataset-b as input to the LINCOM model in WAsP Engineering.

At the same time, the 10-min values of the 50-year wind and turbulence intensity at several heights, as well as turbine classes can also be assessed through the GASP project output over South Africa. This data are available at a spatial resolution of 250 m, and they can be used as reference to the ones calculated in the WASA project.

6. References

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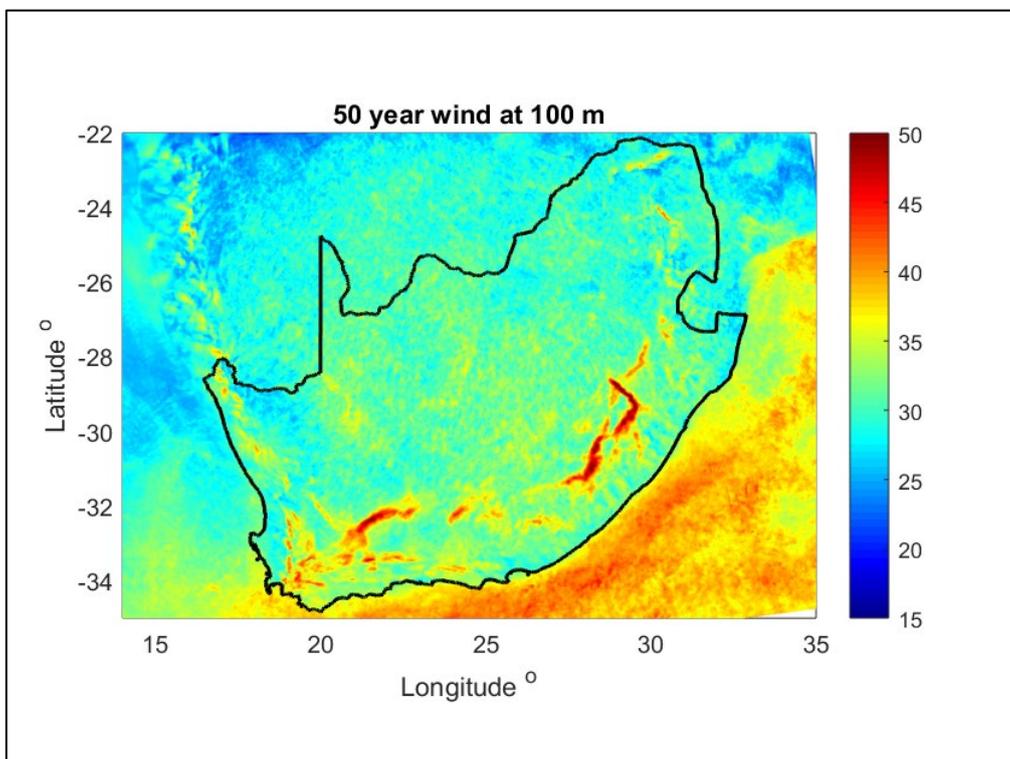
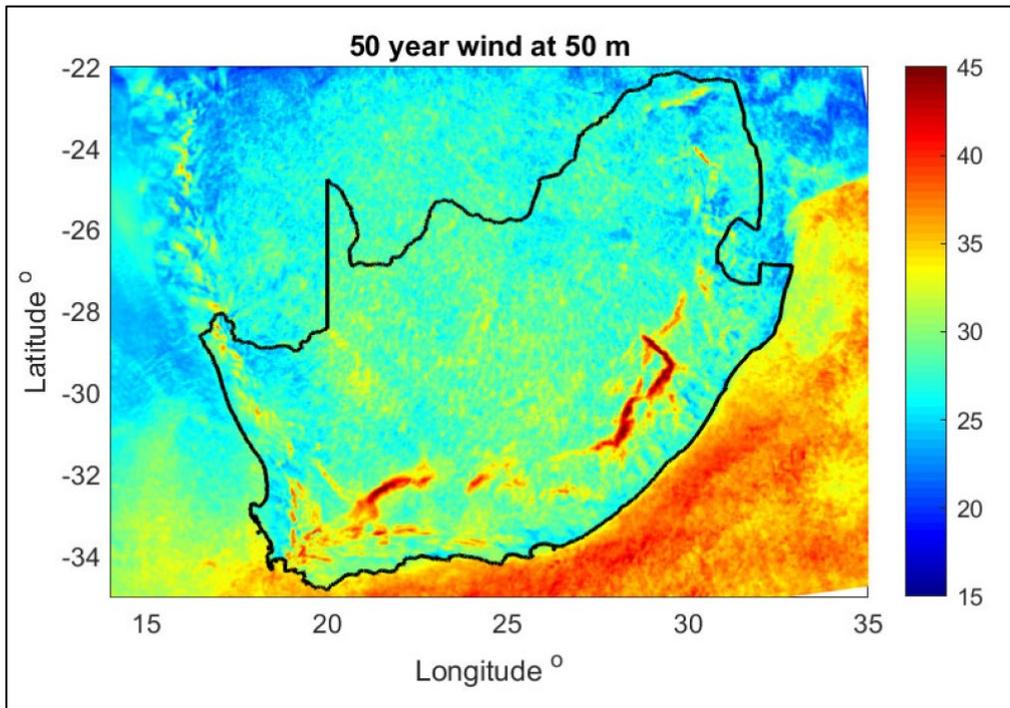
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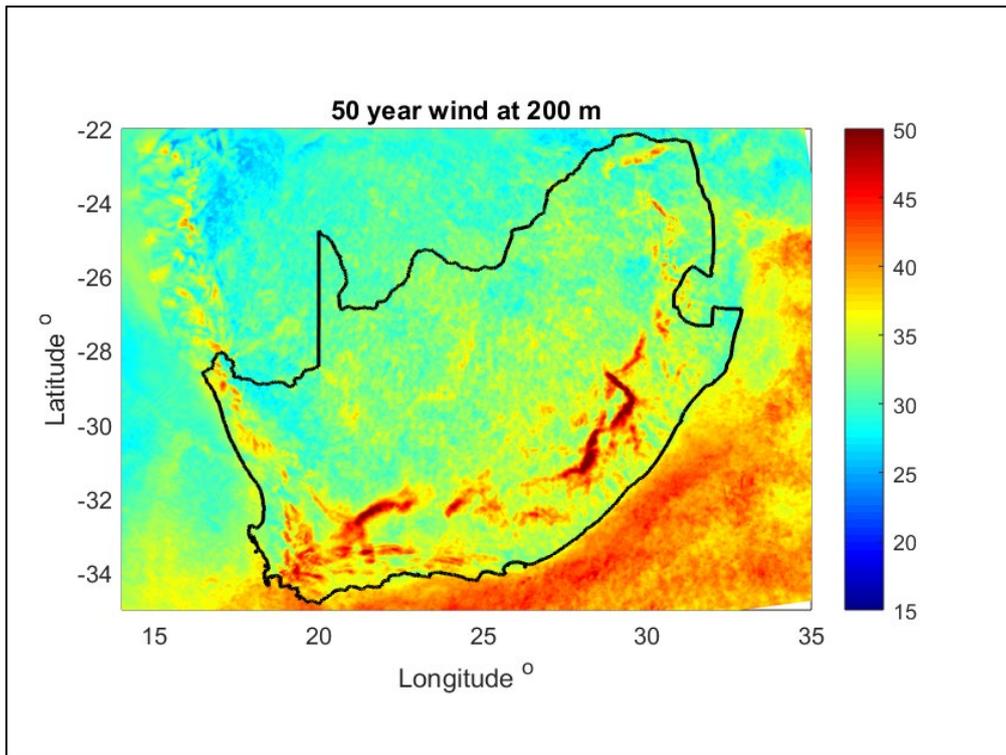
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Appendix: Extreme winds at various heights derived from WRF model output





Atlas of extreme wind and gust for South Africa (WASA Phase III)

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