WIND SPEED TREND ANALYSIS AND INTER-ANNUAL VARIABILITY IN SOUTH AFRICA

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Abstract: Precise projections of long-term linear wind speed patterns provide a useful predictor of shifts in air circulation. Additionally, they are vital for the planning and financing of sectors such as wind power. Trend analysis and inter-annul variation (IAV) of wind speed were executed to examine long-term wind speed patterns and variations in historical mean wind speed data as an index of climate change in South Africa. The examinations were performed on annual mean wind speed data. The variations and patterns, however, are not the result of one factor. They are the result of the interactions of several climatic elements and variables. Thus, the study of wind speed patterns reveals climatic changes. The data used for the analysis was obtained from Wind Atlas of South Africa's (WASA) website. WASA collected data since 2010 at 19 metrological stations (WM01-WM19). Trend analysis was performed using the non-parametric Mann-Kendell's test. The results showed an increasing trend at WM01 and a decreasing trend at WM08. There were no trends at other stations. From the trend analysis results, the magnitude at which wind speed changes per year for the period in investigation varied between 0.003 and 0.111 m/s/year. The lowest change was at WM05, and the highest at WM11. IAV values were calculated by dividing the standard deviation of the annual mean and long-term mean wind speed. IAV values ranged between 1.088% and 3.353%. The industrial standard is 5.4%, but in South Africa it is between 2% and 6% in the study that was conducted in 2019. Stations that had IAV values below 2% are WM03, WM09, WM10, WM14 and WM15, and that implies that the degree at which mean annual wind speed changes at these stations is low. It is recommended that further work be done with long term period (e.g. 20 years).

Keywords: Wind speed; WASA; Wind analysis; Inter-annual variability; trend analysis; Mann-Kendell's test

1. Introduction

Wind speed varies due to climatic changes, which is problematic because wind speed is directly proportional to energy production, so variability in wind speed, means variability in wind energy. Calculating inter-annual variability (IAV) reveals these variations, as it was done in the study of [1-9]. These variability calculations help Independent Power Producers (IPPs) with planning and financing of their wind projects. Trends in wind speed are also essential. To date, no research has been performed in South Africa using meteorological data to investigate trends and inter-annual variability in historic mean wind speed. Previous studies used MERRA, ERA-I and ground station datasets.

This study intends to examine patterns and variations in historical mean wind speed data as an index of climate change in South Africa - trend analysis and inter-annul variation of wind speed. Ghaedi [2] notes that only one of the climatic elements has been the subject of several climate change studies. Many variations and patterns, however, are not the result of one factor alone, but are the result of an interaction of several climatic elements and variables. Wind speed shows the influence of different elements impacting each other. Thus, the study of wind speed patterns will reveal climatic changes [2]. Wind is not only a measure of general air circulation characteristics, but it is also a source of climate-related renewable energy. Long-term variations in the measurement of wind speed are scrutinized to consider the potential impact of climate change on wind speed, hence the justification for this paper.

Since wind resources are rarely consistent, and vary with the time of day, season of the year, altitude, terrain, and from year to year, careful and full research should therefore be carried out. Earlier research shows that the annual average wind speed varies from year to year, but is within 10% of the long-term average. Because a 10% difference in the average wind speed results in a

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30% difference in wind energy, it is important to verify variations in the annual average wind speed in order to measure wind energy efficiently at a candidate location [4] . Several recent studies [1,2,9-14] were carried out on trends.

The non-parametric Mann-Kendell test was used to detect patterns in long-term annual mean wind speed. The reason for using the non-parametric Mann-Kendell test is that, in cases of non-normality of distribution, it has been shown to have higher statistical power as it is robust against outliers and missing data. The Mann-Kendell test, however, is unable to provide an estimation of the trend magnitude, it only detects trends. Particular studies, [10,11], used linear regression and Sen's slope respectively. The method of linear regression is based on the calculation of the slope of a regression line that matches a collection of data elements (x, y) based on an approximation of least squares. For data elements that do not suit a straight line and are also responsive to outliers, this method is inaccurate. Sen's slope is a non-parametric slope estimator and is said to be robust against outliers [20].

The difference in seasonality of the mean wind speed indicates how the change in seasons (summer, autumn, winter and spring) influences wind speed. The monthly variation of the mean wind speed shows how the wind speed changes monthly. IAV of mean wind speed gives confidence in the long-term availability of wind intensity and thus helps to obtain reliable wind energy estimates from wind turbines. IAV is a calculation of the degree to which wind speeds differ yearly [3]. IAV is specified as the standard deviation over several years of annual mean wind speed, and is usually represented as a percentage. The variance in wind speeds is proportional to the variance in energy yield, and the IAV value is therefore a significant input for a wind farm to determine confidence in an energy yield forecast [3]. From literature, the current industry standard IAV value is approximately 5.4 % [6].

Behrens [3] published an IAV study in 2016 and recommended that further work on this topic of IAV should cover the following areas: "addition of further data sources in South Africa, especially from long-term tall meteorological masts, to improve confidence in the results.

2. Data

Wind speed data from the Wind Atlas for South Africa (WASA) was used for this study. WASA provided wind data from 19 locations in South Africa. The details and information of wind stations are tabulated in Table 1. WASA data includes average wind speed, minimum wind speed, maximum wind speed, and wind direction at four different heights, namely: 62m, 60m, 40m and 20m. The WASA project was launched in 2009 with the objective of mapping South African wind resources, which in turn will enable stakeholders in the wind energy sector and industry to investigate and plan for the utility-scale exploitation of wind power for electricity generation.

Table 1. Stations information and data details (WM stands for Wind Mast [16]

Station	From	Latitude (S)	Longitude (E)	Temporal resolution
WM01	2010-06	28°36'06.7"	1'6°39'51.9"	10 minutes
WM02	2010-06	31°31'29.7"	19°21'38.7"	10 minutes
WM03	2010-06	31°43'49.4"	18°25'10.1"	10 minutes
WM04	2010-05	32°50'41.2"	18°06'34.5"	10 minutes
WM05	2010-05	34°36'41.6"	19°41'30.3"	10 minutes
WM06	2010-09	32°33'24.4"	20°41'28.7"	10 minutes
WM07	2010-05	32°58'00.2"	22°33'23.8"	10 minutes
WM08	2010-08	34°06'32.0"	24°30'49.0"	10 minutes
WM09	2010-09	31°15'05.8"	25°01'50.2"	10 minutes
WM10	2010-08	32°05'26.5"	28°08'09.0"	10 minutes
WM11	2015-10	30°48'51.6"	28°04'25.3"	10 minutes
WM12	2015-10	29°51'00.4"	30°31'42.8"	10 minutes
WM13	2015-10	27°25'34.2"	32°09'58.1"	10 minutes
WM14	2015-10	27°52'54.1"	29°32'36.4"	10 minutes
WM15	2015-10	28°37'11.9"	27°07'23.4"	10 minutes
WM16	2018-10	29°26'39.2"	19°21'25.1"	10 minutes
WM17	2018-11	29°45'29.1"	23°31'12.6"	10 minutes
WM18	2018-11	27°35'50.5"	23°39'19.4"	10 minutes
WM19	2018-10	27°43'36.1"	20°34'06.0"	10 minutes

WASA has been collecting data for the past ten years. It has had three project phases, namely: WASA 1, WASA 2 and WASA 3. WASA 1 included ten meteorological stations in Northern Cape, Western Cape and Eastern Cape. WASA 2, phase two of WASA project, included five meteorological stations in KwaZulu-Natal, Free State and Eastern Cape. Currently, WASA is in phase 3, which includes four meteorological stations in north-western part of South Africa. All stations are shown in Figure 1.

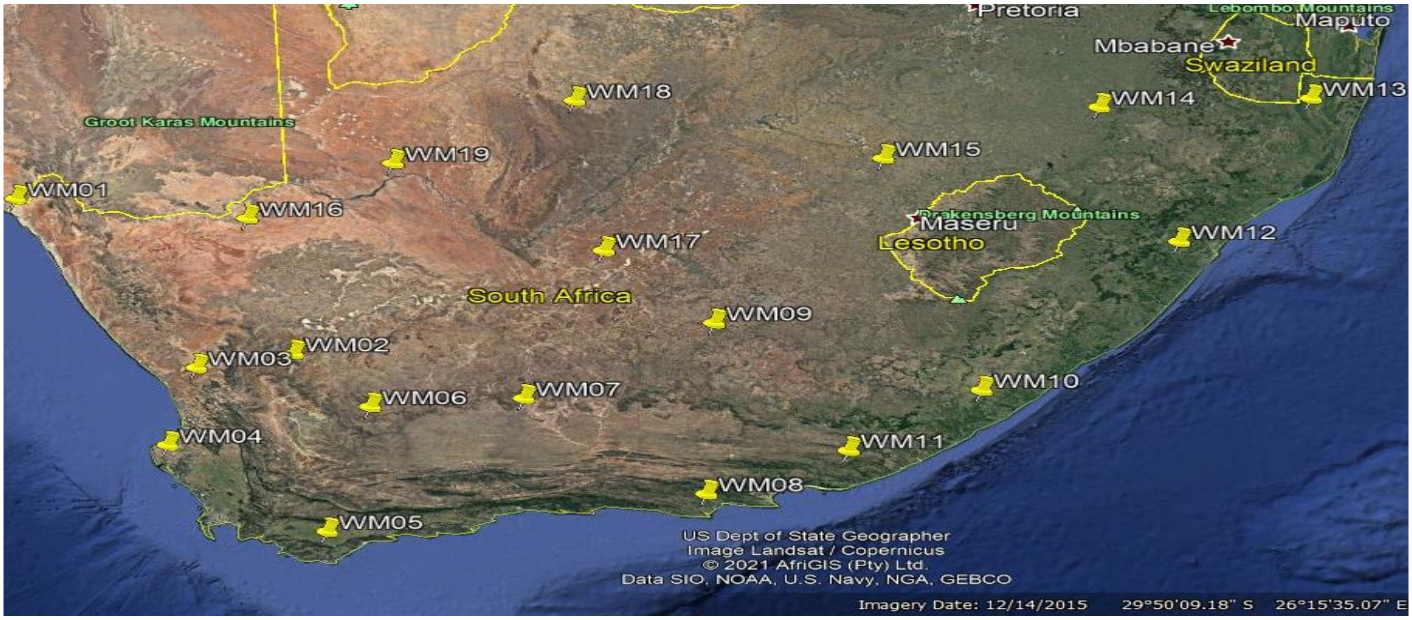

Figure 1. Meteorological stations [10]

Stations are grouped according to the year in which data observation began at that specific station. The stations are organized into three categories. The first category is G1, it is made of meteorological stations falls under WASA 1 project. G1 has stations where data observation began in 2010. G2, the second category, is made of WASA 2 meteorological stations where data observation began in 2015. And lastly, G3 includes stations that falls under WASA 3 project - data observation started in 2018 at these stations. The groups are shown in Table 2. WM04 will not be considered in the analysis because data collection was aborted in 2013.

Table 2. Grouping of stations according to year observations started (in years)

G1 (WASA 1)	G2 (WASA 2)	G3 (WASA 3)
WM01	WM11	WM16
WM02	WM12	WM17
WM03	WM13	WM18
WM04	WM14	WM19
WM05	WM15	
WM06		
WM07		
WM08		
WM09		
WM10		

3. Methodology

Python was used as programming language to conduct all the calculations and plotting of graphs. The Mann-Kendall test is used to detect if trends exist in the results. The test compares time series data values with other values in the sequential order. Additionally, the test uses the statistical term Z for n>10, that is defined as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S-1}{\sqrt{VAR}} & if\ S > 0 \end{cases} \tag{1}$$

The Z value is used to analyse the frequency of a statistically significant pattern. A positive Z value denotes a positive trend, while a negative Z value denotes a downward trend. The null hypothesis (H_o), which asserts that there is no trend, is rejected if |Z| is greater than the critical Z value, Z_α, which is obtained from the cumulative standard normal distribution table [17]. The table can be found at Gilbert [18]. S, from Equation 1, is the statistical term defined as follows:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(x_i - x_j) \tag{2}$$

For n>10, S is approximately normally distributed. S is the product of subtracting the number of positive differences from the number of negative differences. When S is positive, there is an increasing trend and when S is negative, the trend is of decreasing nature [17]. VAR is the variance, and it is defined as:

$$VAR = \frac{n(n-1)(2n+5)}{18} - \frac{\sum_{p=1}^{q} t_p(t_p-1)(2t_p+5)}{18} \quad (3)$$

VAR is the variance of S where q is the number of connected groups and t_p is the number of connections to the p^{th} value. For 4≤n≤10, the conclusion of rejecting or accepting the null hypothesis is based on the statistical term S only. If the probability (p-value) at S is less than the significance level (α), the null hypothesis is rejected and if S is greater than the significance level then the null hypothesis is accepted [11].

The trend magnitudes are quantified by a Sen's slope for a set of pairs (i, x_i) where x_i is the mean wind speed. Sen's slope is defined as follows:

$$Sen's\ slope = median\left\{\frac{x_j - x_i}{j-i}; j > i\right\} \quad \text{[m/s/year]} \quad (4)$$

x_i and x_j are the sequential data for the i^{th} and j^{th} term, respectively. The larger the absolute value of the Sen's slope, the more obvious the variation trend is. The IAV of wind speed is calculated using calendar years. It is calculated as follows:

$$IAV = \frac{\sigma_{\mu_a}}{m_{lt}}$$

σ_{μ_a} = annual mean wind speed's standard deviation

m = long term mean wind speed

4. Results and discussion

The findings of this study would be useful for wind energy industry stakeholders, including analysts of wind resources, developers, owners, operators, meteorologists, research institutes, and financial investors. Wind speed at the height of 62m was used. Before doing trend analysis and inter-annual variation, wind analysis was performed at each wind mast station to show wind speed characteristics.

4.1. Wind speed statistics

From Table 3 it is evident that the CV varies considerably with location. CV values across stations are low compared to those found in [6]. The low CV indicates low wind speed variability across the stations. Table 3 further portrays WM05 and WM09 as the windiest stations with mean wind speed of 8.4 m/s and 8.0 m/s, respectively. CV of 12.9% and 14.9% are high at WM01 and WM04, respectively. The CV shows the extent of variability of wind speed in a term relative to the long-term mean wind speed. The annual mean wind speed is relatively low at WM01 and WM02, with mean wind speeds of 6.2 m/s and 6.1 m/s respectively, as shown in Table 3. The long-term mean wind speed is high in WM05. A variety of possible triggers varying from orographic, orogenic and topographic characteristics may be due to the variation of wind speed across the stations as observed in Table 3.

Table 3. Statistics of wind speed for all G1 stations

Station	Min speed [m/s]	Max speed [m/s]	Mean speed [m/s]	Standard deviation	CV (%)
WM01	4.3	7.9	6.2	0.8	12.9
WM02	5.0	7.5	6.1	0.5	8.2
WM03	5.5	9.1	7.1	0.7	9.9
WM04	5.2	8.1	6.7	1.0	14.9
WM05	6.9	10.3	8.4	0.8	9.5
WM06	6.0	10.0	7.4	0.9	12.2
WM07	5.8	8.2	6.9	0.4	5.8
WM08	5.7	8.8	7.2	0.6	8.3
WM09	5.9	10.4	8.0	1.0	12.5
WM10	6.0	7.8	6.6	0.5	7.6

From Table 4, it is clear that the CV vary between 7.8% and 19.0% due to location. The highest CV values were recorded at WM11 (19.0%), and the lowest at WM12 (7.8%). Table 4 further shows WM11 and WM14 as the windiest stations with spectacular mean wind speed of 7.9 m/s and 7.4 m/s, respectively. The annual mean wind speed is relatively low at WM12 and WM13, with mean wind speeds of 5.1 m/s and 5.0 m/s, respectively.

Table 4. Statistics of wind speed for all G2 stations

Station	Min speed[m/s]	Max speed [m/s]	Mean speed [m/s]	Standard deviation	CV(%)
WM11	5.6	10.9	7.9	1.5	19.0
WM12	4.3	5.9	5.1	0.4	7.8
WM13	3.9	6.0	5.0	0.6	12.0
WM14	5.1	10.4	7.4	1.2	16.2
WM15	4.3	7.6	6.1	0.9	14.8

In G3 stations, WM16 has the highest mean wind speed (7.041 m/s). This means it is windiest G3 station, as seen from Table 5. The CV value ranges between 5.8% and 8.9%, with the highest at WM19, and the lowest at WM17. WM19 has the lowest mean wind. Again, a variety of possible triggers varying from orographic, orogenic and topographic characteristics may be due to the variation of wind speed across the stations

Table 5. Statistics of wind speed for G3 stations

Station	Min speed [m/s]	Max speed [m/s]	Mean speed [m/s]	Standard deviation	CV(%)
WM16	6.4	8.1	7.0	0.5	7.1
WM17	5.9	7.5	6.9	0.4	5.8
WM18	5.8	7.3	6.5	0.5	7.7
WM19	4.6	6.4	5.6	0.5	8.9

4.2. Trend Analysis

Trend in wind speed was examined using the Mann-Kendall's test. The results for both G1 and G2 stations are shown in the table below. Trend was not examined on G3 stations as they have one complete year of data, yet the Mann-Kendall's test requires a minimum four. WM04 was also not considered as it has two complete years. Inter-annual variability will also not be done for these stations.

4.2.1.G1 stations

The sample size is nine (n=9) so only the statistical term S is used as mentioned in section 3. The Mann-Kendall's test results for G1 are in Table 7. Annual trend exists at WM01 and WM08 because the p-value is less than the significance level, so null hypothesis is rejected. At WM01, an increasing trend is detected because S is positive and at WM08 decreasing trend is detected because S is negative. The magnitudes at which wind speed changes annually are also shown below. The slope indicates annual wind speed changes. At WM01 and WM08 mean wind speed changes by 0.05 m/s/year and 0.03 m/s/year, respectively.

Table 6. Mann-Kendall's test results trend magnitude (Sample size for G1 stations (n) is 9).

Station	*Period*	***Sen's slope*** ***[m/s/year]***	S	p-value	$H_o$rejected/ accepted
WM01	Annual	0.05	18	0.038	Rejected, increasing
WM02	Annual	0.02	6	0.306	Accepted, no trend
WM03	Annual	0.01	-8	0.238	Accepted, no trend
WM05	Annual	0.003	2	0.46	Accepted, no trend
WM06	Annual	0.05	12	0.130	Accepted, no trend
WM07	Annual	0.04	14	0.090	Accepted, no trend
WM08	Annual	0.03	-18	0.038	Rejected, decreasing
WM09	Annual	0.03	8	0.238	Accepted, no trend
WM10	Annual	0.02	12	0.130	Accepted, no trend

4.2.2.G2 stations

Sample size for G2 stations (n) is 4. Results are tabulated below. There is no distinctive annual trend at all G2 stations.

Table 7. Mann-Kendall's test results trend magnitude (Sample size for G2 stations (n) is 4).

Station	***Sen's slope*** ***[m/s/year]***	S	p-value	$H_o$rejected/ accepted
WM11	0.11	4	0.167	Accepted
WM12	0.03	0	0.625	Accepted
WM13	0.10	-4	0.167	Accepted
WM14	0.001	0	0.625	Accepted
WM15	0.02	-2	0.375	Accepted

4.3. Inter-annual variation

4.3.1.G1 stations

Before doing IAV calculations, annual mean wind speeds for G1 stations were plotted (Figure 4) to visualize the annual mean wind speed changes over a nine-year period (2011-2019). From Figure 2, it is seen that there is no clear trend in annual mean wind speed in most of the stations except at WM01 and WM08, thus verifying trend analysis results. At WM01, in 2011,2012 and 2013 the mean wind speed is around 6.1 m/s then slightly decreases to approximately 6 m/s in 2014 and 2015. Then increases from 6 m/s to 6.45 m/s from 2015 to 2019 showing an increasing trend which was detected by the Mann-Kendall's test. At WM08, the annual mean wind speed starts from 7.4 m/s in 2011 and decreases to 7 m/s in 2015 then slightly increase in 2016 and 2017 then decrease again. At other stations, the mean wind speed fluctuates, there is no clear trend.

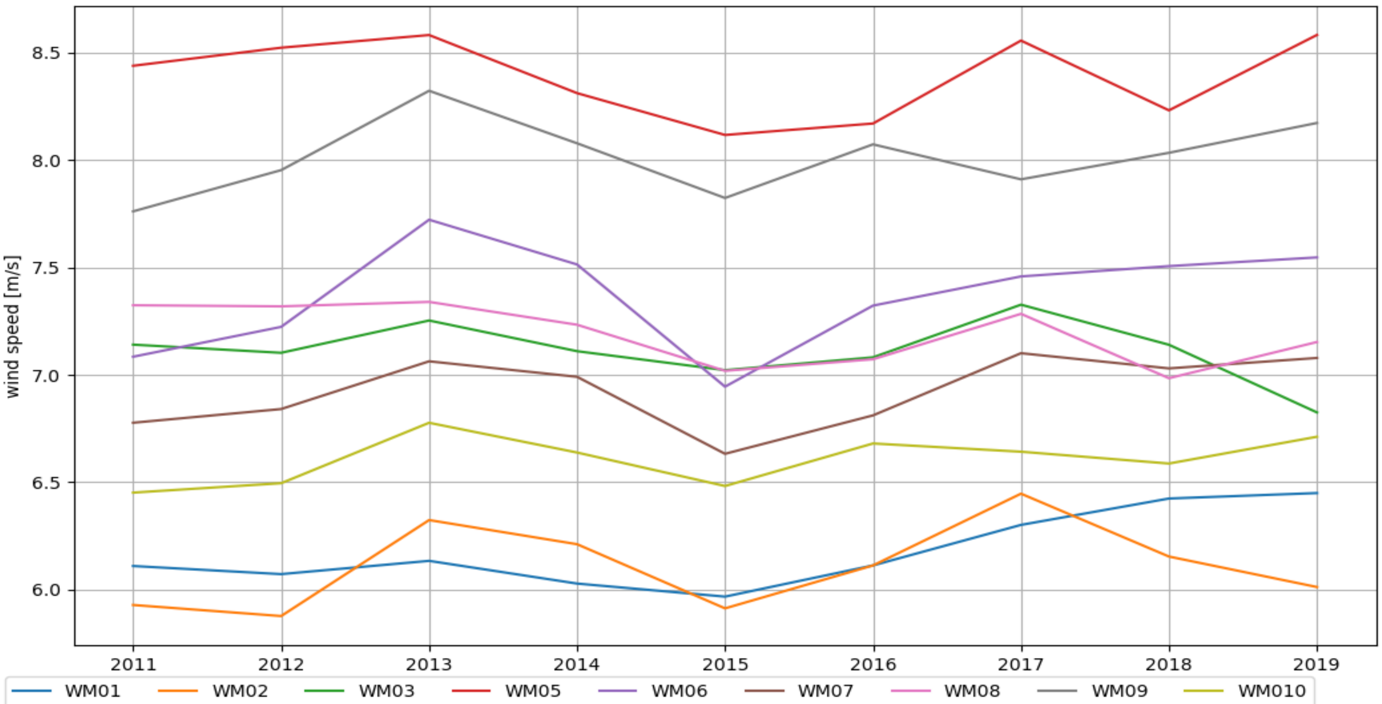

Figure 2 Annual average wind speed at G1 stations

IAV values for G1 stations are shown in Table 9. The IAV values for G1 stations range between 1.7% and 3.4%. This is lower than the industrial standard of 5.4%. In [1], the IAV for the whole of South Africa, IAV ranged between 2% and 6%. This means G1 IAV values, except WM08 and WM10, may be considered accurate since they fall within this range. At WM08 and WM10 IAV values are relatively low this means the degree at which annual mean wind speed changes is low. If the values are rounded to one significant digit, all IAV values would fall in the range.

Table 8. Inter-annual variation for G1 stations

Station	σ_{μ_a}	m_{lt}	**IAV (%)**
WM01	0.173	6.178	2.8
WM02	0.196	6.109	3.2
WM03	0.141	7.112	2.0
WM05	0.186	8.391	2.2
WM06	0.247	7.370	3.4
WM07	0.165	6.925	2.4
WM08	0.139	7.192	1.9
WM09	0.174	8.015	2.2
WM10	0.112	6.607	1.7

4.3.2.G2 stations

There is no distinctive trend observed in annual mean wind speeds in G2 stations. This is evident from Figure 6. One cannot say if annual mean wind speed increases or decreases with years. Trend analysis results using Mann Kendell test are thus confirmed.

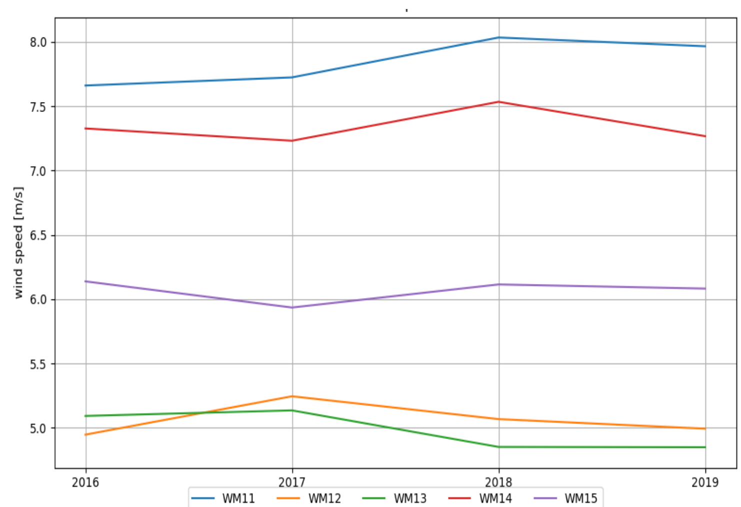

Figure 3. G2 annual mean wind speed

IAV values for G2 stations are shown in Table 10 below. The IAV values for G2 stations range between 1.1% and 2.9% which is lower than the industrial standard of IAV 5.4% also. IAV values at WM14 and WM15 do not fall between the range of 2% and 6% found in [1]. The only stations with IAV values within the range are WM11, WM12 and WM13.

Table 9. Inter-annual variation for G2 stations

Station	σ_{μ_a}	m_{lt}	IAV (%)
WM11	0.182	7.041	3.0
WM12	0.131	6.873	2.1
WM13	0.153	6.528	2.2
WM14	0.135	5.623	1.6
WM15	0.0912	7.041	1.1

5. Conclusion

The aim of this study was to examine patterns and variations in historical mean wind speeds as an index of climate change in South Africa. Trend analysis and IAV of wind speed were conducted at WASA 1 and WASA 2 as they have at least four years of data, which is a requirement for the Mann-Kendall's test that was used to examine trends. Annual mean wind speed at all stations (WM01-WM19) ranged between 5.0 m/s and 8.4 m/s with highest at WM05 and lowest at WM13.

After conducting a Mann-Kendall's test, there was no annual trend at most of the WM stations. The only stations that showed a trend are WM01 and WM08 where WM01, an increasing trend was found with a slope magnitude of 0.05 m/s/year (0.69 %/year) and WM08, a decreasing trend was found with a slope magnitude of 0.03 m/s/year (0.48 %/year). This may be due to the fact that the term (years) in this study is low compared to the term in most of the previous studies. It may also be simply because there is no trend in South African's wind speed. It is thus recommended that further work be done in 10-20 years to establish whether the problem is in the term, or that there is simply no trend.

The IAV values for G1 stations ranged between 1.7% and 3.4%, and for G2 stations, 1.1% and 2.9%. This is lower than the industrial standard of IAV 5.4% implying that mean annual wind speed variation at these stations is low. For South Africa, using satellite data (MERRA and ERA-I datasets), it was shown that the IAV ranged between 2% and 6% [3]. Among G1 stations, WM01, WM02, WM03, WM05, WM06, WM07 and WM09 proved to have IAV values that fall within South African's IAV range. From G2 stations, WM11, WM12 and WM13 also fell within the range. Having low IAV values is good, because it shows that there is no much variation in wind speed; consequently, no variation in wind energy output.

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