Comparison of Mann-Kendall and Şen's Innovative Trend Method for Climatic Parameters Over Nigeria's Climatic Zones

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Comparison of Mann-Kendall and Şen's Innovative Trend Method for Climatic Parameters Over Nigeria's Climatic Zones

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Abstract:

Creating innovative ways for the identification of trends is a very vital part of atmospheric studies. Different climatic locations present their unique variations, calling for the dynamism of trend analysis. In addition to the widely adopted Mann-Kendall (MK) trend test, the new Şen's innovative trend analysis (ITA) method has been applied to analyze the trends of refractivity related (atmosphere pressure –AP, vapour pressure – VP, ambient temperature – T) and equivalent potential temperature – EPT related parameters (mixing ratio of air – R, absolute temperature at the lifting condensation level – T_L, potential temperature – PT). This analysis was perfomed using 40 years' data (1981 – 2020) from 4 stations from each climatic zone of Nigeria (Calabar – Tropical monsoon, Ibadan – Tropical Savannah, Kano – Warm semiarid climate, and Kukawa – Warm desert climate). The MK trend test identified monotonic (entirely increasing or decreasing) trends for specific parameters across the climatic locations; the Şen's ITA method was important in the identification of trends even for parameters that showed non-monotonic variations. Other comparisons between both methods were outlined and explained; correlation heat maps were used to show the relationship between all parameters for each climatic location, describing the effect of climate on the variations of these parameters. The low, medium and high values revealed from the Şen's ITA method can be informative for telecom and renewable energy applications, guiding engineers and system designers to understand the trends within range of values for a particular climatic parameter.

Keywords: Şen's Innovative trend test**;** Mann-Kendall test; equivalent potential temperature parameters; refractivity parameters; Nigeria; Climate zones.

Manuscript Highlights:

- The Mann-Kendall (MK) test shows that there is no parameter across the four climatic locations that have significant monotonic trends
- The results from the heat maps shows that there is a high coefficient of correlation between parameters for all climatic locations, but especially in the Warm desert climate of Kukawa.
- The Sen's Innovative trend analysis (ITA) method is better than the Mann-kendall test for the identification of trends for the low, medium and high values across all parameters.
- Trend results can be identified with the Sen's ITA method even if they are non-monotonic

1. Introduction

Several industrialization and infrastructural developmental processes like telecommunication design, building of good road networks, etc., depends greatly (directly or indirectly) on the variations of meteorological and climatic conditions of a particular location. The climate of a particular region plays an integral role in many of the local meteorological conditions faced there which eventually relates to equipment design, applications and utilization of varying meteorological parameters for renewable energy (Badal et al. 2019) and engineering applications. Conditions ranging from radio wave propagation to solar radiation reception, long term temperature and heat waves, vegetation and soil quality, air quality, etc., are affected by local or regional meteorological conditions. Basic meteorological variables like temperature, vapour pressure, and atmospheric pressure, etc. directly or indirectly affects most of these aforementioned conditions on the long-term, and understanding their trends will go a long way in identifying the gaps in the knowledge for the regions in study (Agbo et al. 2021a; Dagang et al. 2021).

It has been established by various studies that refractivity for example, is affected by the water vapour contents of the atmosphere (Edlén 1966; Colavita et al. 2004; Ojo 2015; Agbo et al. 2021b, c); meaning that regions with high humidity or vapour pressure will refract or bend radio waves more. This knowledge has given telecomm engineers and operators a better understanding on the design and application of local instruments for signal propagation. In extension, parameters that relates to equivalent potential temperature (EPT) which include; potential temperature (PT), mixing ratio of air (R), absolute temperature at the lifting condensation level - LCL (T_L), etc., are all studied to bring a better understanding of the behavior of air parcels in the atmosphere at various reference levels. Equivalent potential temperature (EPT) is an important parameter to study because it is a combination of relative humidity and ambient temperature (Song et al. 2022); this has a key role to play even more than ambient temperature in the long term analysis and identification of a change in climate.

Applying analysis techniques on atmospheric variables has led to innovations and discovery of new and better methods of analysis, leading to the better interpretation and presentation of results. Distribution dependent (parametric) and distribution free (non-parametric) methods have been mostly applied for the study of various atmospheric variables (Mann 1945; Kendall 1975; Gorbunova and Lemeshko 2012; Ashraf et al. 2021; Asadi and Karami 2022). There have been some studies of the trend analysis of atmospheric parameters in some locations in Nigeria using the non-parametric Mann-Kendall (MK) test (Amadi et al. 2014; Salami et al. 2014; Alhaji et al. 2018; Agbo 2021; Agbo and Ekpo 2021), but together with this, this study also will adopt the new (Şen 2012) method for the trend analysis of long term refractivity and EPT parameters. The method is being applied in the analysis of trends for atmospheric variables in locations around the world (Güçlü 2018; Ali et al. 2019; Malik et al. 2019, 2020; Serinaldi et al. 2020; Seenu and Jayakumar 2021; Mallick et al. 2021; Danandeh Mehr et al. 2021).

(Zhou et al. 2018) employed ITA to find the trend in the solar radiation in China over a period ranging from 1962 to 2015. In the investigation of spatio-temporal trends as exuded by extreme temperature and precipitation in the Indian Rajasthan region using Sen's slope and Mann-Kendall tests shows negative and positive trends in the urban centres of the Rajasthan (Pingale et al. 2014). In a study using innovative trend analysis for Ibadan, Nigeria, for hydro-meteorological variables with data spanning a period of 45 years, the results obtained indicated an increasng trend with the highest being at a 10% significance level (Ahmed et al. 2022). The results obtained from applying Sen slope and Mann-Kendall (M-K) tests for variability in evaporation and hydro-meteorological parameters in Ibadan, Nigeria, revealed a trend in which solar radiation, wind speed, and evaporation were significantly reduced while rainfall, temperature, and relative humidity did not indicate a significant change over the four decade interval being considered (Oguntunde et al. 2012).

The importance of trend analysis cannot be overemphasised because it is important that the water cycles and the accompanying climate variations are studied and documented for purposes that relate to environment protection, agriculture and urban development. This is evident in the study that tries to find the impact of climatic variations and the associated trend in the cultivation of rice in Nigeria (Akinbile et al. 2015), and application of non-parametric Mann-Kendall test on the implications of trends and precipitation cycles in agricultural and water resources of the tropical climate of Nigeria (Alli et al. 2012)

The relevance of this study will stem from the fact that results of the MK test and Şen's test will be compared for specific locations over the four climatic zones of Nigeria, and the low, medium and high values of the Şen's innovative trend analysis (ITA) test will be evaluated. The identification of the low, medium and high values for parameters like refractivity for example, will not only reveal the trend for all range of values, but give engineers and researchers a big picture understanding of the trends with respect to each range of value. This will help build dynamic systems to curb delays in signal propagation irrespective of the value range (low, medium or high values) in a location. The Şen's ITA method will identify the trend for all value ranges (low, medium and high) in addition to the MK test; this is why this study is significant over climatic locations. The Sen's ITA method identifies trends even when these trends are not monotonic; this is in contrast to the MK test which only identifies monotonically (increasing or decreasing) trends. For better understanding, a monotonic trend is one that the variable or series in study is increasing or decreasing *'consistently'*. A non-monotonic trend on the other hand, is one that is ‘*sometimes’* increasing and decreasing and this is what the Sen’s ITA method can identify, proving the significance of this study. The objective of the study will be to (a) understand how different climates have an effect on the water vapour contents of the atmosphere, ultimately refractivity and EPT (b) demystify the relationship between all the variables in study over all climatic locations, while understanding how the variation of one affects the other (c) detect the long term trends for all parameters and draw proper conclusions (d) compare the results of the MK test and Sen’s ITA test for the same data.

The towns considered are located in different climate zones in the country; Calabar is situated in the South-Eastern part of the country and represents the Tropical Monsoon climate marked by less heavy rainfall, Ibadan is situated in the South-Western part of the country and represents the Tropical Savannah marked by heavy grassland and tall trees, Kano is Situated up North-Central representing the Warm Semi-Arid regions that are marked by less rainfall short grasses and sparse trees, and lastly Kukawa is situated in the North-East while representing the Warm Desert regions that are marked by very small amount of rainfall as well as dry climate conditions.

Results are presented with tables, heat maps, Sen’s graphical representation, etc., in section 4, section 2 describes the study location and data, the theory of refractivity and EPT, as well as the description of the analysis technique for the study has been presented in section 3.

2. Study Area and Data

Nigeria is a country that has land mass that spreads over a number of distinct climate zones. With borders at the Atlantic Ocean and the Sahara Desert, the degree of dryness increases as one moves from the southern region away from the coast of the Atlantic towards the North where the Sahara Desert is located. The variations in climate conditions, caused majorly by anthropogenic activities which have continuously stroked the embers of climate change campaingn, are increasingly becoming unpredictable (Houghton 1996)

Figure 1. Map of Nigeria showing climatic zones and exact locations of stations.

Nigeria is a country located north of the equator and is characterized by strong latitudinal zones; she lies between the longitudes of 3 degrees and 14 degrees and the latitudes of 4 degrees and 14 degrees. The climate becomes progressively drier as we approach the north from the coastal regions of the south. Nigeria is characterized by 4 major climatic zones, the Tropical Monsoon climate in the far south, the tropical savannah climate in the west and middle belt, the warm semiarid climate in the north and the warm desert climate in the far northeast. (Akande et al. 2017). Nigeria has a tropical climate, with rainy and dry seasons that vary depending on where you are (Willoughby et al. 2002). The southeast is hot and humid for the majority of the year, whereas the southwest and the farther interior lands are more dry. The north and west have a savanna climate with distinct wet and dry seasons, whereas the extreme north has a steppe environment with limited precipitation. From south to north, the length of the wet season often decreases; this wet season lasts from March to November in the south, but only from mid-May to September in the extreme north. In the southern states, the rain abruptly stops in August, resulting in a brief dry season known as the "*August break*" (Ogungbenro and Morakinyo 2014). In the southern region, temperature and humidity are usually stable throughout the year, whereas in the north, seasons vary greatly; during the northern dry season, the daily temperature variation becomes even greater. Figure 1 shows the distribution of the 4 major climatic zones of Nigeria. This study will pick one location from each climatic zone and study the refractivity and equivalent potential temperature parameters over them. Table 1 shows the coordinates of the locations in each climatic zone,

Forty (40) years data from 1981 to 2020 for mean annual surface (earth skin) temperature, relative humidity, and atmospheric pressure were obtained from the NASA POWER DATA repository for Kukawa (warm desert), Kano (semiarid), Ibadan (tropical savannah), and Calabar (tropical monsoon); these locations can be seen from figure 1. Other parameters like refractivity, vapour pressure (VP), EPT, PT, MR, temperature at LCL (T_L) were calculated from the obtained data, with equations described in the methodology section.

Data was obtained in CSV format, converted and cleaned with MS Excel, analyzed and results visualized with the python programming language. The MK test and Sen's ITA test was used to detect for trends in the data, heat maps were used to show the relationship between parameters in each climatic location, tables were presented to easily present results. The code for the analysis have been provided through a link at the end of this study.

3. Methodology

The goal of trend analysis is to determine if data values are increasing, decreasing, or staying unchanged over time. Because of the properties of data, detecting a trend is a difficult task, furthermore, according to the IPCC, statistical cases of variables (meteorological, hydrological, and climatological data, etc.) reveal change over time (mean, median, variance, autocorrelation, skewness, or nearly any other element of data) (Data 2009; Kisi and Ay 2014). This fluctuation may be cyclical with the seasons, continuous (a trend), abruptly jumps, or other well-known changes (Bathiany et al. 2018). Seasonality, skewness, serial correlation, non-normal data, "less-than" (censored) values, outliers, and missing values are only a few examples of these properties. (Machiwal and Jha 2006; Nalley 2020)

Popular trend detection tests include the Mann-Kendall (MK) (Mann 1945; Kendall 1975) and the Spearman's rho tests. It has been argued that the validity for these trend detection tools are based on certain conditions. such as the time series' independent structure, normality of the distribution, and data length (Şen 2012, 2014); detection of the slope of a trend for these methods is not possible except through regression approach. The MK test can be inaccurate in some cases (Yue and Wang 2002; Yue et al. 2002; Collaud Coen et al. 2020; Hu et al. 2020); it becomes more effective as the absolute magnitude of the trend increases. As the sample size for the MK test increases, the tests becomes more powerful, and as the amount of variance within a time series increases, the power of the tests decreases. Other concerns for accurate trend detection have been described by various studies like the effect of the adoption the MK pre-whitening test which has been argued to remove a portion of the trend (Yue and Wang 2002; Bayazit and Önöz 2007). To bring balance to results, the new method presented by (Şen 2012) also be adopted together with the Mann-Kendall trend test. The dynamics of both these trend tests will be explained in the succeeding sub-sections.

3.1 Mann-Kendall trend test

When analyzing time-series data, we apply the MK test. The test is non-parametric, which means it doesn't require the data to fit into a specific distribution (Agbo 2021). This test is used when a set of data corresponds with a linear relationship. The test is usually adopted when analyzing climatological, meteorological, and hydrological time series (Mann 1945; Kendall 1975; De Luca et al. 2020).

The test statistic (S) of this test is calculated using the following equations,

$$S = \sum_{k=1}^{n-1} \sum_{j=k=1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where;

$$\operatorname{sgn}\left(x_j - x_k\right) = \begin{cases} +1; & if \left(x_j - x_k\right) > 0 \\ 0; & if \left(x_j - x_k\right) = 0 \\ -1; & if \left(x_j - x_k\right) < 0 \end{cases} \tag{2}$$

The number of data values is denoted by the letter n. A positive S value denotes an upward trend, while a negative S value denotes a downward trend. Higher positive values in S on the other hand, indicates an upward pattern, while lower negative values indicate a declining trend. If the number of data values n is greater than 10, the normal approximation (Z statistic) is always utilized. It's also worth noting that when there are tied/equal values, the Z statistic's accuracy suffers if the data values are close to 10. The variance of S '*VAR(S)*' is used to calculate the value of the Z statistic (Agbo 2021)

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{g} t_p (t_p - 1)(2t_p + 5)\right] \tag{3}$$

g represents the number of tied groups in the series (showing that the test takes the tied or equal values into consideration. The number of data values in the p^{th} the group is represented by t_p.We can now obtain the test statistic Z, using the values of *VAR(S)* and *S*; (Agbo 2021).

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}; & S > 0 \\ 0; & S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}; & S < 0 \end{cases} \tag{4}$$

To interpret results; when the Z value is negative, a falling trend is recognized, and when the Z value is positive, a rising trend is discerned. If and when the data's p-value is less than the significance level (in this case, 5% = 0.05), both interpretations can be considered to have a significant trend and the null hypothecs (H_o) is rejected. If the p-value is greater than the level of significance, the trend is not significant and H_o is accepted. (Chu et al. 2016; Agbo et al. 2021b)

3.2 ITA test (Şen 2012)

This method which was proposed by (Şen 2012, 2014) was first applied for hydro-meteorological time series data and has been applied for various trend tests of various parameters (Kisi and Ay 2014; Ay and Kisi 2015; Demir and Kisi 2016; Alashan 2020; Phuong et al. 2020; Ashraf et al. 2021).

The technique is based on the fact that when two (2) time series are identical, plotting them against each other results in a scatter of points along the 1:1 (45°) line on the Cartesian coordinate system, as seen in the figure 2. Similarly, from the beginning to the end of a recorded time series (say temperature), it can be separated into two equal halves, and each sub-series is sorted independently in ascending or descending order. From figure 2, based on the Cartesian coordinate system, the first sub-series (x_i) is positioned on the X-axis, while the second sub-series (y_i) is located on the Y-axis. When plotting the time series, regardless of whether they are monotonic, as long as they are trendless, they all fall on the 1:1 line (Şen 2012). A monotonically increasing trend is observed when all the data points from the plot are above the 1:1 line; the same way, a monotonically decreasing trend is observed when all the data points are below the 1:1 line. In unique cases, some data points can fall below, above and on the 1:1 line; this will be separated into the low, medium, and high values as shown in figure 2.

Figure 2: Illustration of the innovative trend method showing low, medium and high values. Reproduced from (Meng et al. 2021) Copyright 2022. Springer Nature, Switzerland AG. Part of Springer Nature. https://www.springernature.com/

3.3 Theory of Refractivity

The refractive index n, which is connected to the speed of the signal in free space V_f and the speed of the signal in the given medium V_m, is the term we will be studying in part.

$$n = \frac{V_f}{V_m} \tag{5}$$

The signal's speed in the atmosphere will be less than that in free space because some parameters impede the speed of the EM wave in the atmosphere. Refractivity is related to refractive index by

$$N = (n-1)\times 10^6 \,(N-Units) \tag{6}$$

Refractivity is always measured with refractometers, but an equation has been recommended by the ITU and applied in various research.

$$N = 77.6\frac{P}{T} + 3.73\times 10^5 \frac{e}{T^2}(N-units) \tag{7}$$

where P is the atmospheric pressure in hPa, T is the absolute temperature in Kelvin, e is the atmospheric vapour pressure in hpa which is related to the relative humidity (H) and saturated vapor pressure e_s by: $e = \frac{e_s H}{100}(hPa)$

The Clausius-clapeyron relation is adopted as follows;

$$e_s = 6.11\exp\left(\frac{17.26(T-273.16)}{T\ -35.87}\right)(hPa)$$

Refractivity as a dependent variable is related to independent parameters like the atmospheric pressure, ambient temperature, vapour pressure, and all these variables will be investigated in this article.

3.4 Equivalent Potential Temperature (EPT) and Potential Temperature (PT)

The EPT, is related to variables such as the temperature at the LCL (T_L), the MR (r), the PT (θ), the equivalent temperature, among others. (Bryan 2008). Climate and effects of climate are affected by the movement of parcels of air in the atmosphere, these variations are as a result of movement of these air parcels and are responsible for condensation, humidity, cloud movement, long term climate, etc. (Sherwood et al. 2010).

Water produced through condensation is discharged as heat or water vapor in a pseudo-adiabatic process, which is a saturated process. The heat is added back to the air parcel since it is not gained or lost (adiabatic process) (Bechtold 2009). This indicates that a saturated air parcel loses heat at a considerably slower pace than unsaturated air during an adiabatic operation. To understand EPT and PT we define some parameters.

The absolute temperature at the lifting condensation level is the temperature a given air parcel would reach if it was lifted dry to its LCL adiabatically (Romps 2017). The T_L occurs when an air parcel is cooled by dry adiabatic lifting; the lifting condensation level (LCL) is formally defined as the height at which the relative humidity (RH) of an air parcel reaches 100% with regards to liquid water.

The T_L is gotten by the relation (Bolton 1980);

$$T_L = \frac{2840}{3.5InT_k - Ine - 4.805} + 55 \tag{8}$$

where e is the vapour pressure in hPa and T is the absolute temperature in kelvin

The mixing ratio of air which is the amount of water vapour in a given amount of dry air; it related to the vapor and atmospheric pressure by;

$$r = 621.97\frac{e}{P-e} \tag{9}$$

The PT is basically described as the temperature a parcel of air has to attain when it moves up or down to 100hPa (the movement is adiabatic and dry). This parameter is related to the atmospheric pressure, temperature and mixing ratio by;

$$\theta = T\left(\frac{1000}{P}\right)^{0.2854\left(1-0.28\times10^{-3}r\right)} \tag{10}$$

Related to the PT is the EPT, having the equation

$$\begin{aligned}\theta_E &= T\left(\frac{1000}{P}\right)^{0.2854\left(1-0.28\times10^{-3}r\right)}\times\exp\left[\left(\frac{3.376}{T_L}-0.00254\right)\times r\left(1+0.81\times10^{-3}r\right)\right]\\ &=\theta\times\exp\left[\left(\frac{3.376}{T_L}-0.00254\right)\times r\left(1+0.81\times10^{-3}r\right)\right]\end{aligned} \tag{11}$$

To explain the EPT, we take an air parcel and lift it dry adiabatically to its LCL, this will make the moisture in that parcel of air to condense out in what we call a pseudo-adiabatic process (without loss or gain of heat); this air parcel is now adiabatically brought back to 1000hpa. The temperature in which this sample of air will have at when brought back to 1000hpa after the afore explained process is called the EPT.

(Gao and Cao 2007) studied the application of EPT and PT in cyclone tracks in non-uniformly saturated atmospheres, (Zhou et al. 2009) studied comparisons of generalized PT in a humid atmosphere with the EPT in a saturated moist atmosphere, and (Heimann 1992) studied EPT and PT trends at cold fronts with pre-fontal foehn. This emphasizes the significance of this research in relation to other parameters.

4. Applications and Discussion

Results from the analysis of all climatic locations have been presented in this section. Graphics from the Sen's ITA method have been presented as well as tables comparing the Sen's ITA test to the MK test for each location. Low, medium and high values were identified for the Sen's ITA test which buttressed results of the MK test. Heat maps for all locations have been presented to help readers understand the relationship between all parameters for all climatic locations.

The basic statistics, describing results for each parameter across all the 4 climatic zones have been presented in table 1. The table shows the standard deviation, mean, median, minimum, and maximum values for each parameter in each station. By observing results from this table, it can be seen that the climates of the northern regions (Warm desert and Warm Semiarid) are relatively similar; the same could be said for the climates in the southern zones (Tropical savannah and Monsoon).

Careful observation shows that as we head towards the south from the northern climates, the seasons become less dry and more wet. This is characterized by the lower temperature values in the Monsoon and Savannah Climate; this also leads to a higher vapour and atmospheric pressure values for these climatic zones – the reverse is the case for the Warm Semiarid and Desert Climates located in Kano and Kukawa respectively.

The refractivity values across each climatic zone shows that the locations in the warm climates (Kano, Kukawa and even Ibadan provinces) have lower values of refractivity. This is in contrast to Calabar (Tropical Monsoon Climate), which has higher values of refractivity due to its higher vapour and atmospheric pressure values. The same could be observed for other parameters like the $T_{L,}$ *EPT, and PT;* as the values are lower for the warm climates.

The $T_{L,}$ is lower for the warm semiarid climate compared to other climates, this shows that the temperature that a given air parcel would attain if it was lifted dry adiabatically to its lifting condensation level is lower compared to other regions. This shows that for a given air parcel in the warm semiarid climate, the temperature required to raise this given air parcel to its LCL is lower than other climatic zones. This is mainly because this climate is less humid and therefore, less humidity (low moisture) means a lower lifting condensation level because the air mass is drier. This shows why the mixing ratio is lower for the climate when compared to other regions.

These observations show why the Warm semiarid and Warm desert climate in Kano and Kukawa respectively are hotter and less humid. The Tropical Monsoon and Tropical savannah climates are more humid in comparison. The Tropical Monsoon climate for instance, has a more uniform weather condition throughout the year.

Table 1: Basic statistics, numbers, units and data ranges of the stations over the four climatic zones of Nigeria.

4.1 MK test

For the examination of the annual trend of all metrics across all climatic zones, we avoided assumptions such the Mann-Kendall (MK) pre-whitening procedure. This was done to preserve the series' authenticity; we used the original recorded and calculated data for the analysis. (Douglas et al. 2000; Yue et al. 2002; Şen 2012; Piyoosh and Ghosh 2017; Almazroui and Şen 2020).

From this perspective, the MK test results for all parameters in the 4 climatic zones have been presented in table 2. This table summarizes the MK original test which was calculated with a significance level if 5% (0.05). The tables show the Z-value, test statistic (S), the results of the *Ho* hypothesis as well as the trend (increasing or decreasing). The p-values of the observation which were less than the significance level (0.05) were interpreted to have rejected the null hypothesis which postulates that there is no trend in the time series. Positive z-values show increasing monotonic trends, while negative z-values shows decreasing monotonic trends.

Results from the MK test show that most of the parameters in the Tropical Monsson (Calabar) and tropical savannah climate (Ibadan) rejects the null (*Ho*) hypothesis. Only the atmospheric pressure of the Tropical Monsoon climate (Calabar) accepted the *Ho* hypothesis which means that there was no trend detected in the series; this meant that other parameters rejected the null hypothesis which meant that there was trend detected in the annual variation of these other parameters. For the Tropical Savannah Climate in the Ibadan province, only the surface temperature (T), potential temperature, and atmospheric pressure (AP) parameters all show no trend (accepts *Ho*), other parameters in this region show trends (increasing only).

The warm semiarid and warm desert climate of Kano and Kukawa respectively show similar MK test results. Only the surface temperature and PT results show trends (rejects Ho); the other parameters do not show trends at 5% (0.05) significance level as they all accepted the Ho hypothesis.

Based on the MK test of all parameters for all climates zones, we can observe from table 2 that for the parameters that have trends, none of these detected trends are decreasing, but they're all increasing.

Table 2: Results from the MK test at 5% significance levels for all parameters across the stations over the four climatic zones of Nigeria.

↑- Indicates increasing trend

↓- Indicates decreasing trend

4.2 Sen's ITA test

Figures 3 - 10 shows the scatter graphics for the Sen's ITA test results. Each figure shows results for each parameter for all climatic zone (a) Calabar – Tropical Monsoon (b)Ibadan – Tropical Savannah (c)Kano – Warm

Semiarid and (d)Kukawa – Warm desert. Results were presented in table 3 for the Sen's ITA method as the low, medium and high values.

Figure 3 shows that the low, medium and high values for atmospheric pressure in Calabar and Ibadan (3a and 3b) have no trend. However, increasing trends are observed in the low and high values of Kano and Kukawa (3c and 3b) with no trends in their medium values.

Figures 4 and 5 show similar results for the vapor pressure and mixing ratio parameters in the same locations. The high, medium and low values for the Calabar and Ibadan locations for both parameters are all increasing. The low values for both parameters in Kano and Kukawa show no trend. However, decreasing trends are observed for the medium and high values for both parameters in Kano (Warm Semiarid climate). For Kukawa (Warm desert climate), both parameters had decreasing trends were observed for medium values and increasing trend for high values. The similarity in the Sen's trend results for the vapor pressure and missing ratio parameters for each location shows that both parameters are related to each other by the water vapor contents.

Figure 6 shows the Sen's graphic representation results for temperature parameters. The trend is all increasing in the Tropical Monsoon climate of Calabar for low, medium and high values (figure 3a). The same results can be observed in the warm semiarid climate of Kano (6c). The low and medium values of the Tropical savannah climate and is increasing, while the high values are decreasing (6b). However, there is no trend for the low temperature values of the Warm desert climate of Kukawa; however, the medium and high values are all increasing (6d).

Figure 7 displays the Sen's ITA results for refractivity. It reveals that the refractivity trend is increasing for all values in the tropical monsoon and savannah climates of Calabar (7a) and Ibadan (7b) repectively. Conversely, all values of the warm semiarid climate of Kano show decreasing trends. Decreasing trends are also observed for the medium and low values of the warm desert climate in Kukawa. This shows that refractivity is increasing steadily in climate zones that have high water vapour contents.

The trend results for the temperature at LCL (T_L) is shown in figure 8. Results are quite similar to that of the refractivity trends as the tropical climates of Calabar and Ibadan both show increasing trends for all values. The warm semiarid climate of Kano reveals shows decreasing trends for all values. Only the medium values of the warm desert climate of Kukawa shows a trend (decreasing). Results reveal that the temperature at LCL is consistently increasing over the years for the tropical climates and is doing the opposite for the warm climates.

The EPT trends are shown in figure 9. Increasing trends have been observed for all values in the tropical climate locations (Calabar and Ibadan), increasing trends are also observed for the low values of the warm climate locations (Kano and Kukawa); other values for these warm locations show no trend.

Figure 10 shows the PT trend results for the Sen's test method. Majority of values for these parameter show an increasing trend for all locations. Only the high values of the tropical semiarid climate of Ibadan (decreasing trend) and the low values of the warm desert climate of Kukawa (no trend) show different trend results.

Figure 3: Atmospheric Pressure results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 4: Vapour pressure results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 5: Mixing Ratio (*R*) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 6: Surface Temperature (*T*) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 7: Refractivity (*N*) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 8: Lifting condensation temperature (T_L) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 9: Equivalent Potential Temperature (Θ_T) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

Figure 10: Potential Temperature (Θ) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

4.3 Relationship Between Climatic Variables

Figure 11 is correlation matrixes or heat maps showing the relationship between the parameters in each location/climate zone. The purpose of these heat maps is to show how the variation of some parameters affect the changes of others.

A careful observation of figure 11 shows that the VP, refractivity, temperature at LCL (T_L), mixing ratio (R), and EPT all have a very strong positive relationship between themselves for all zones. It is more strong in the warm desert climate of Kukawa, other locations like the Tropical Monsson climate of Calabar. This strong positive correlation shows how strong refractivity, mixing ratio, temperature at LCL, and EPT is affected by the vapour pressure (a derivative of relative humidity or atmospheric water vapour content). Part of this result was captured in Agbo et al. (2021) study of refractivity and EPT relationship. The atmospheric pressure variation has a very weak correlation for all climatic locations, revealing that its variation does not necessarily have an effect on the variation of other parameters in study.

These results give an accurate idea on the variations of parameters that relate to each other irrespective of their location. Showing that although different climate zones have different variations, the variations of related parameters in the same climatic location is relatively similar.

Figure 11: Correlation matrixes showing the relationships between the following parameters [Temperature T(K), vapour pressure (VP), atmospheric pressure (AP), refractivity (N), mixing ratio (R), temperature at lifting condensation level (T_L), equivalent potential temperature (Θ_T), potential temperature (Θ)] for the following stations and climatic zones (a) Calabar –Tropical Monsoon, (b)Ibadan – Tropical Savannah, (c)Kano – Warm Semiarid, and (d) Kukawa – Warm desert

4.4 Comparison between MK test and Sen's ITA test

The summary of results for the MK test and the Sen's ITA trend tests are displayed in table 3, the table shows the results for the low, medium and high values from the Sen's ITA test. It can be seen from this table, that although the MK test does not detect trends for some parameters over some climatic locations, the Sen's method detects trends for some low, medium and high values. The MK test detects trends in 16 of the total 32 parameters across all locations/climatic regions. The Sen's ITA method however, detects trends for an average of about 27 parameters for all low, medium and high values. MK results for parameters across climatic zones that show no trends are demystified by the Sen's ITA method with increasing and/or decreasing trends across low, medium or high values; consequently, parameters that show trends from the MK test have monotonically increasing trends (where all low, medium and high values are above the 1:1 (45^{o}) line) for the Sen's ITA test. The Sen's ITA method presents a more precise way to understand the variations of parameters across various values and change points. This is in agreement with studies by (Alifujiang et al. 2020; Mallick et al. 2022).

Table 3: Comparison of MK results and Sen's trend method for all parameters across the stations over the four climatic zones of Nigeria.

↑- Indicates increasing trend

↓- Indicates decreasing trend

5. Conclusion and General Remarks

Due to the activities, both natural and anthropogenic, that trigger changes in the climate conditions of the country, it has become pertinent to find a trend in hydro-meteorological parameters that determine the climate conditions. An accurate estimated trend will be invaluable in making policies that encourage environmental protection. This study analyzed the trends of refractivity alongside its related parameters (vapour pressure, atmospheric pressure, ambient temperature) and EPT and its parameters (temperature at LCL, mixing ratio, potential temperature) for stations from each climatic zone in Nigeria. The stations and climate zones include: Calabar in the Tropical Monsoon, Ibadan in the Tropical Savannah, Kano in the Warm Semi-Arid, and Kukana in the Warm Desert climate. The analysis of these trends were done for annual data for 40 years (1981-2020) to identify the discrepancies across climatic zone by adopting the MK trend test and, the new Sen's ITA test which has been applied in this region for the first time. Results obtained from this study were presented by comparing parameters in the same climatic zone, comparing the MK and Sen results, understanding how the variations of some parameters affects others. The following are the concluding remarks:

a. For long term variations, the MK trend test results show that there is no parameter across all climatic locations that has significantly decreasing trends. All significant trends that rejects the null hypothesis is increasing, with most of these parameters in the Tropical Monsoon and savannah climates of Calabar and Ibadan respectively. The atmospheric pressure is the only parameter that shows no significant trend across all climatic locations. Other parameters vary based on climatic locations. The MK results from the tropical monsoon climate of Calabar shows that the climate of this location and even the tropical savannah climate is almost uniform, agreeing with (Roth 2007; Agbo et al. 2021c). The MK test shows significance for the temperature and PT parameters in the warm semiarid and warm desert climates of Kano and Kukawa respectively. The Sen's ITA test was also applied to detect trends for the low, medium and high values for each parameter. This test gives a broader knowledge and a better understanding of the results presented by the application of the MK test as the low, medium and high values of this test brings the MK test into context.
b. The correlation heat maps show the parameters within each climatic locations that have the same variations. Results show that since all refractivity and EPT related parameters are affected by the vapour content and air parcels in the atmosphere, their relationships are strong and positive. One thing to note is the similarity in the trends of ambient temperature and potential temperature across all locations, after showing a coefficient of correlation value of unity (1), agreeing with a study by (Song et al. 2022) that temperature and PT are closely related; they presented results that the PT be used for the analysis of long term climatic variation in temperature, instead of using temperature itself because the PT relates the relative humidity and temperature. The mixing ratio of air and the vapour pressure also have the same results (coefficient of correlation of 1) across all locations; this is so because they are both related to the amount of water vapour or water molecules in the atmosphere. Also agreeing with a study by (Alnaser and Barakat 2000; Boucher et al. 2004; Agbo et al. 2021b), refractivity and EPT are closely related by their variation, this clearly seen by their strong positive correlation of across all locations. The hear map shows the uniform warm conditions of the climate in Kukawa.
c. Results reveal that there are advantages when applying the Sen's ITA method with the MK test. The MK test requires more data to be more accurate, and this is not the case for the Sen's method. The presentation of trends for the low, medium and high values in the Sen's method makes it easy to identify trends than

the MK test. Results show that a monotonic trend (all data points are in one area of the 45^o line) is observed in the Sen's ITA result when the MK test is significant. The Sen's results detect different trends for the low, medium and high values when the MK trend test shows no significant result.

d. Results presented reveals an important information about the variation of refractivity and EPT parameters and can serve as an important source of information for the design of equipment that are affected by the water vapor and air parcel contents of the atmosphere. In extension, the MK test and Sen's ITA test can be applied together to bring better context to trend results.

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Statements and Declarations

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Author Contributions:

E. P. Agbo Conceived and designed the analysis; Collected the data; Analysed the data using analysis tools; Performed the analysis, and wrote the first draft. U. Nkajoe interpreted the results and wrote the paper. C. O. Edet reviewed results for scientific relevance, supervised the study, reviewed and wrote some sections. All authors read and commented on the previous versions of the manuscript, and unanimously approved the final manuscript.

Code Availability: The code associated with this analysis can be assessed from https://github.com/Emmaestro001/Innovative-Trend-Analysis-of-Climatic-Zones-over-Nigeria

Data Availability: The data associated with this study was obtained from the NASA POWER repository for the specific locations in study at https://power.larc.nasa.gov/data-access-viewer/.

FIGURES AND TABLES

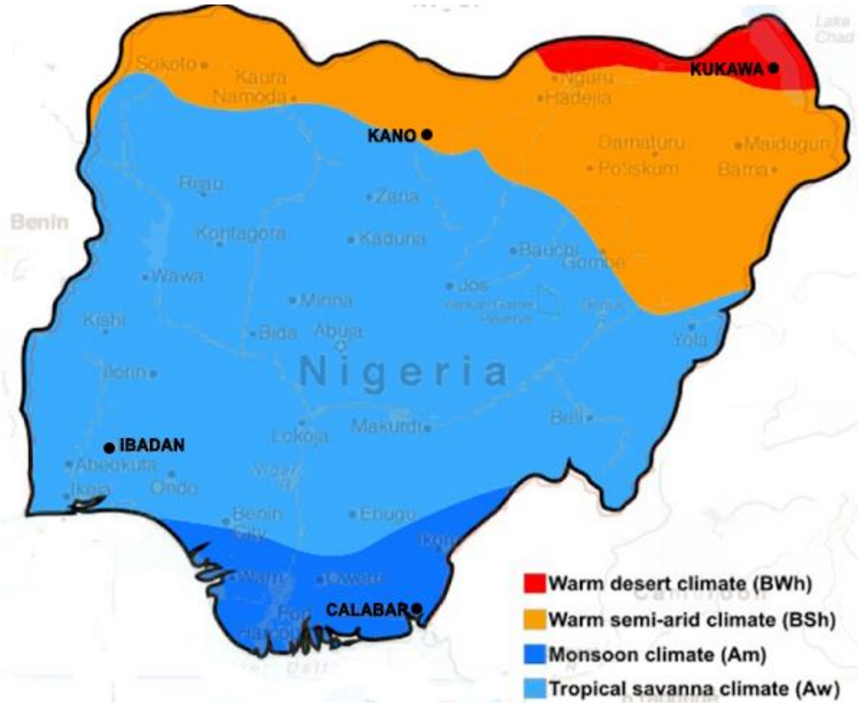


Figure 1. Map of Nigeria showing climatic zones and exact locations of stations.

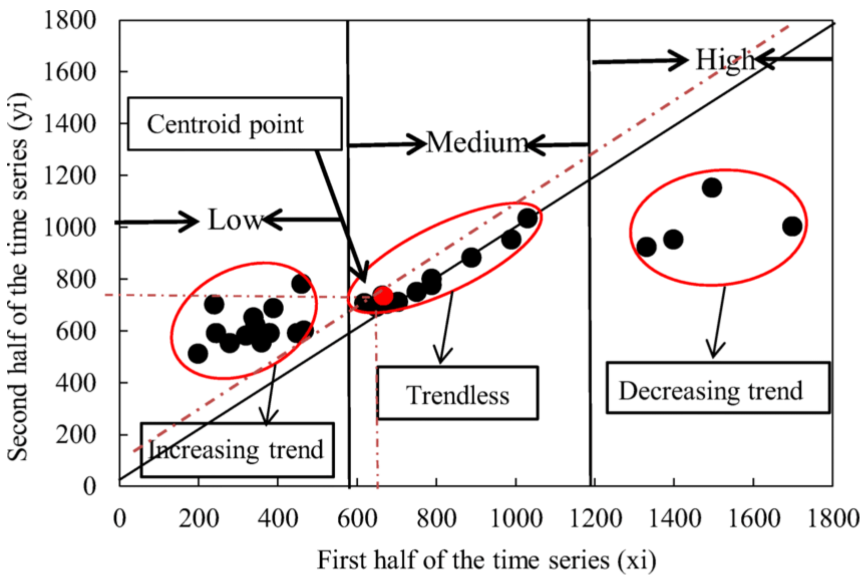
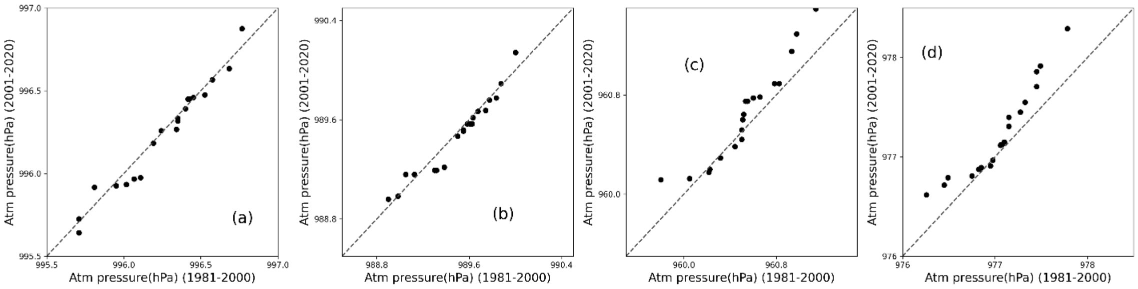


Figure 2: Illustration of the innovative trend method showing low, medium and high values. Reproduced from (Meng et al. 2021) Copyright 2022. Springer Nature, Switzerland AG. Part of Springer Nature. https://www.springernature.com/



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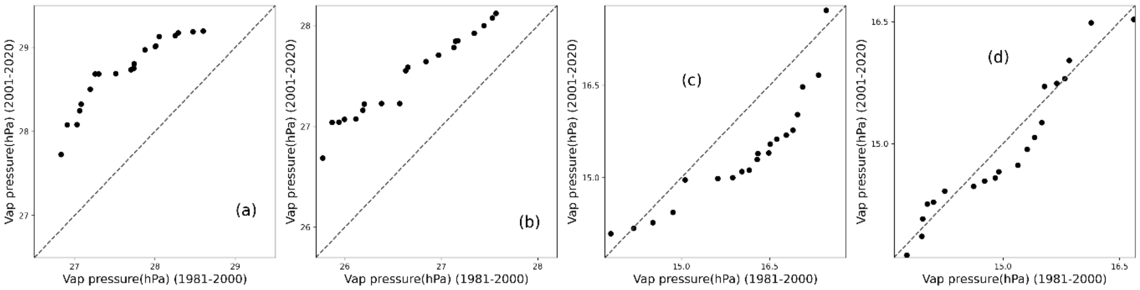

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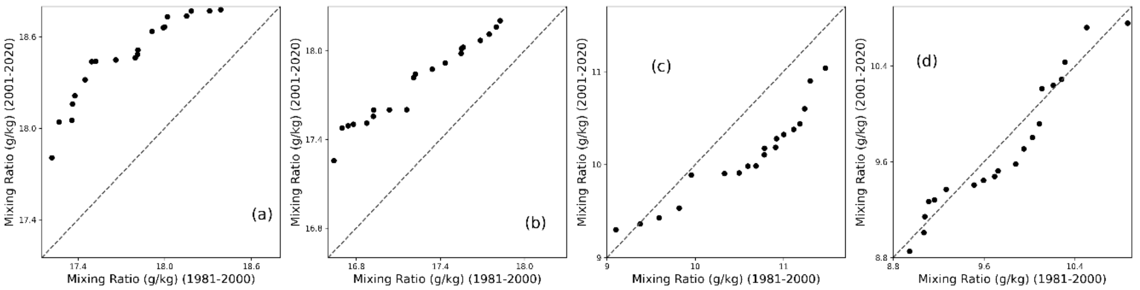

Figure 5: Mixing Ratio (R) results for (a) Calabar – Tropical Monsson (b)Ibadan – Tropical Savannah (c)Kano – Warm Semiarid and (d)Kukawa – Warm desert, using Sen's ITA method

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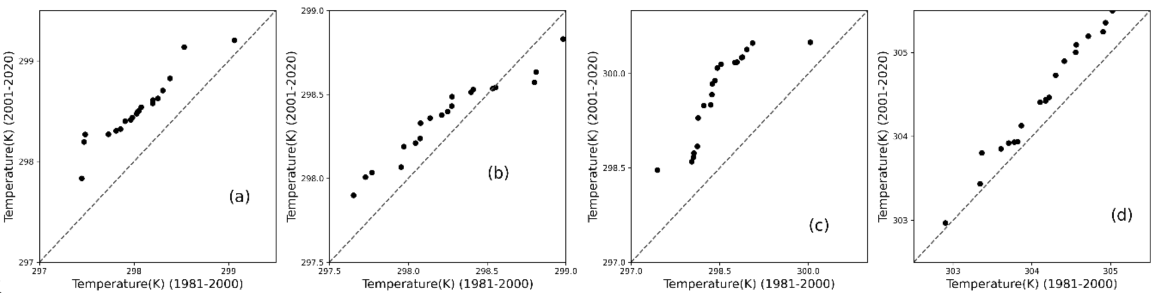

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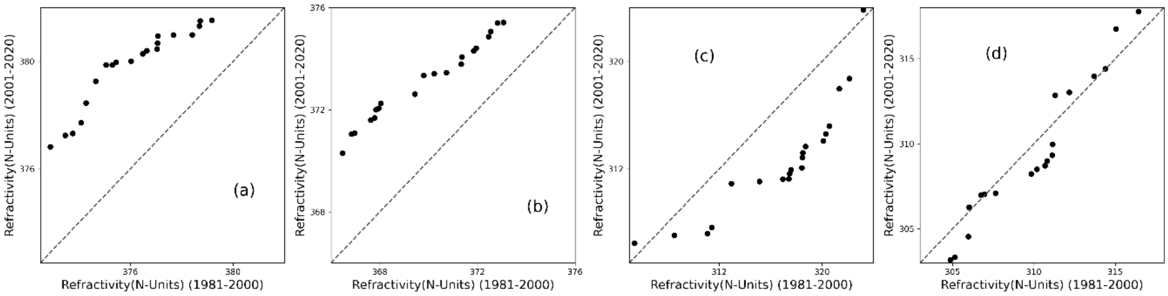

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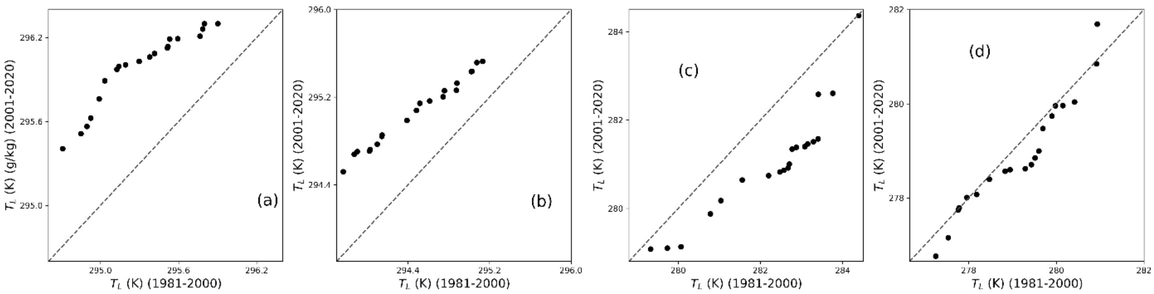

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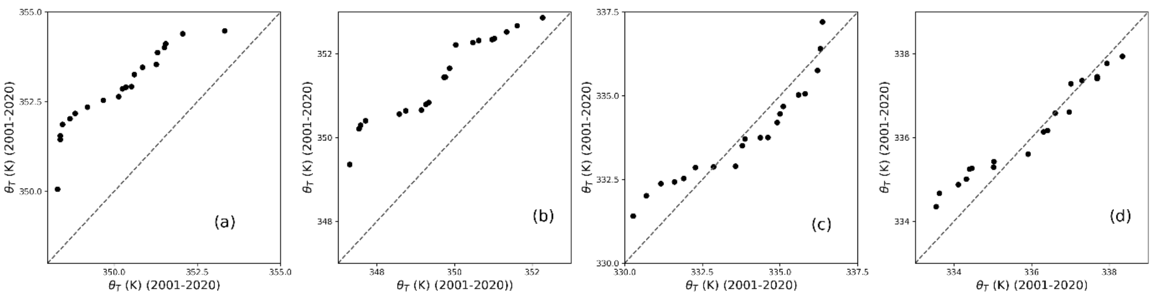

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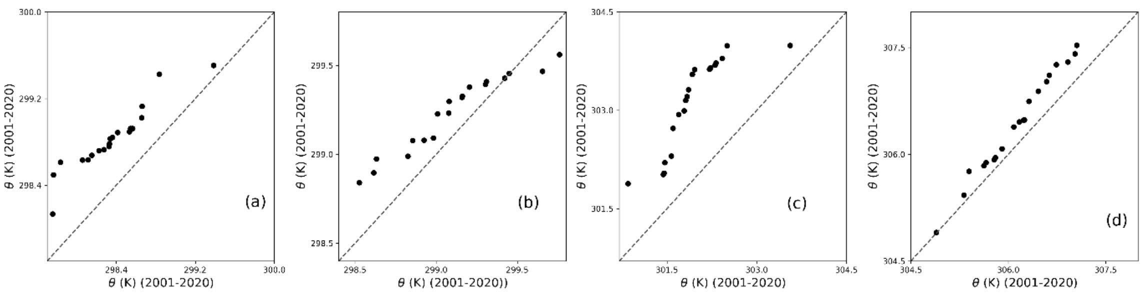

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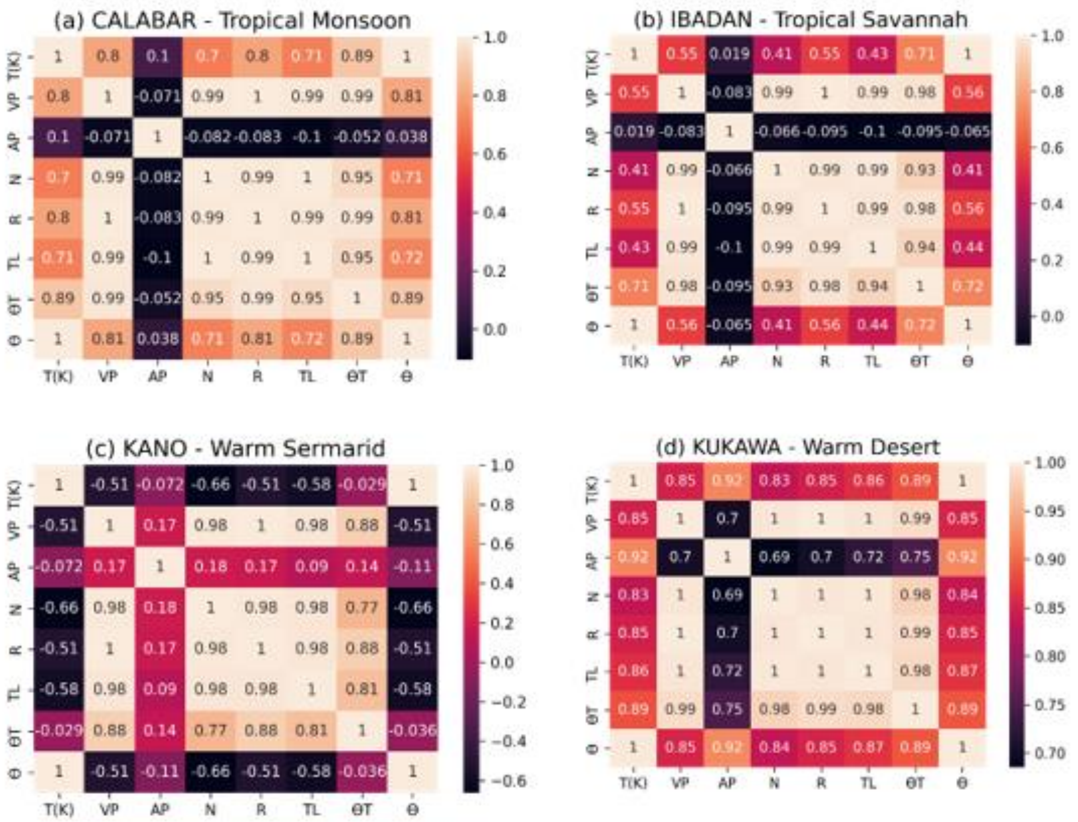

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Table 1: Basic statistics, numbers, units and data ranges of the stations over the four climatic zones of Nigeria.

Location and Coordinates	Parameter	Units	Data Range (1981-2020)	Mean	Standard Deviation	Minimum Value	Median Value	Maximum Value
KANO **Warm Semiarid Climate** (Lat. 11.9455, Long. 8.5884)	T	K	40	299.08	0.85	297.44	298.86	300.50
	VP	hPa	40	15.71	1.02	13.80	15.66	17.72
	AP	hPa	40	960.56	0.38	959.80	960.53	961.49
	$REF-(N)$	N-Units	40	314.70	4.89	305.40	314.35	323.83
	R	g/kg	40	10.39	0.68	9.10	10.35	11.73
	T_L	K	40	281.65	1.46	279.08	281.49	284.39
	$EPT-(\Theta_T)$	K	40	333.83	1.72	330.27	333.77	337.21
	$PT-(\Theta)$	K	40	302.53	0.86	300.85	302.30	303.99
IBADAN **Tropical Savannah Climate** (Lat. 7.507, Long. 3.8478)	T	K	40	298.30	0.31	297.65	298.30	298.98
	VP	hPa	40	27.08	0.66	25.77	27.15	28.12
	AP	hPa	40	989.49	0.31	988.90	989.56	990.14
	$REF-(N)$	N-Units	40	371.48	2.52	366.47	371.89	375.42
	R	g/kg	40	17.51	0.44	16.64	17.55	18.20
	T_L	K	40	294.77	0.48	293.76	294.81	295.53
	$EPT-(\Theta_T)$	K	40	350.52	1.52	347.30	350.63	352.87
	$PT-(\Theta)$	K	40	299.20	0.31	298.53	299.22	299.87
CALABAR **Tropical Monsoon Climate** (Lat. 5.0118, Long. 8.4676)	T	K	40	298.27	0.42	297.45	298.29	299.20
	VP	hPa	40	28.18	0.72	26.83	28.25	29.20
	AP	hPa	40	996.25	0.31	995.64	996.33	996.88
	$REF-(N)$	N-Units	40	377.94	2.51	372.89	378.06	381.54
	R	g/kg	40	18.11	0.48	17.22	18.16	18.78
	T_L	K	40	295.65	0.46	294.71	295.69	296.30
	$EPT-(\Theta_T)$	K	40	351.50	1.84	348.30	351.55	354.48
	$PT-(\Theta)$	K	40	298.59	0.42	297.76	298.63	299.51
KUKAWA **Warm Desert Climate** (Lat. 12.9566, Long. 13.6256)	T	K	40	298.30	0.31	297.65	298.30	298.98
	VP	hPa	40	27.08	0.66	25.77	27.15	28.12
	AP	hPa	40	989.49	0.31	988.90	989.56	990.14
	$REF-(N)$	N-Units	40	371.48	2.52	366.47	371.89	375.42
	R	g/kg	40	17.51	0.44	16.64	17.55	18.20
	T_L	K	40	294.77	0.48	293.76	294.81	295.53
	$EPT-(\Theta_T)$	K	40	350.52	1.52	347.30	350.63	352.87
	$PT-(\Theta)$	K	40	299.20	0.31	298.53	299.22	299.87

Table 2: Results from the MK test at 5% significance levels for all parameters across the stations over the four climatic zones of Nigeria.

↑- Indicates increasing trend

↓- Indicates decreasing trend

Location and Coordinates	Parameter	P-value	Z-value	MK test statistic (S)	H_o Hypothesis	Trend (↑↓)
CALABAR **Tropical Monsoon Climate** (Lat. 5.0118, Long. 8.4676)	T	4.65E-08	5.46	470	REJECT	YES (↑)
	VP	4.69E-08	5.46	505	REJECT	YES (↑)
	AP	0.83	-0.21	-19	ACCEPT	NO
	$REF-(N)$	8.59E-08	5.35	495	REJECT	YES (↑)
	R	4.62E-09	5.86	504	REJECT	YES (↑)
	T_L	2.09E-08	5.60	482	REJECT	YES (↑)
	$EPT-(\Theta_T)$	1.97E-09	6.00	516	REJECT	YES (↑)
	$PT-(\Theta)$	4.07E-08	5.49	472	REJECT	YES (↑)
IBADAN **Tropical Savannah Climate** (Lat. 7.507, Long. 3.8478)	T	0.36	0.92	80	ACCEPT	NO
	VP	1.04E-04	3.88	359	REJECT	YES (↑)
	AP	0.89	-0.14	-13	ACCEPT	NO
	$REF-(N)$	5.53E-05	4.03	373	REJECT	YES (↑)
	R	2.88E-05	4.18	360	REJECT	YES (↑)
	T_L	8.62E-05	3.93	338	REJECT	YES (↑)
	$EPT-(\Theta_T)$	9.50E-05	3.90	336	REJECT	YES (↑)
	$PT-(\Theta)$	0.31	1.01	88	ACCEPT	NO
KANO **Warm Semiarid Climate** (Lat. 11.9455, Long. 8.5884)	T	8.11E-06	4.46	384	REJECT	YES (↑)
	VP	0.47	-0.72	-67	ACCEPT	NO
	AP	0.21	-1.25	108	ACCEPT	NO
	$REF-(N)$	0.25	-1.15	-107	ACCEPT	NO
	R	0.44	-0.78	-68	ACCEPT	NO
	T_L	0.21	-1.26	-105	ACCEPT	NO
	$EPT-(\Theta_T)$	0.20	1.27	110	ACCEPT	NO
	$PT-(\Theta)$	1.12E-05	4.39	378	REJECT	YES (↑)
KUKAWA **Warm Desert Climate** (Lat. 12.9566, Long. 13.6256)	T	8.11E-06	4.46	384	REJECT	YES (↑)
	VP	0.47	-0.72	-67	ACCEPT	NO
	AP	0.21	1.25	108	ACCEPT	NO
	$REF-(N)$	0.25	-1.15	-107	ACCEPT	NO
	R	0.44	-0.78	-68	ACCEPT	NO
	T_L	0.17	-1.39	-120	ACCEPT	NO
	$EPT-(\Theta_T)$	0.20	1.27	110	ACCEPT	NO
	$PT-(\Theta)$	1.12E-05	4.39	378	REJECT	YES (↑)

Table 3: Comparison of MK results and Sen's trend method for all parameters across the stations over the four climatic zones of Nigeria.
↑- Indicates increasing trend
↓- Indicates decreasing trend

Location and Coordinates	Parameter	MK test result	Sen's method		
			Low	Medium	High
CALABAR Tropical Monsoon Climate (Lat. 5.0118, Long. 8.4676)	T	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	VP	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	AP	NO	NO	NO	NO
	$REF-(N)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	R	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	T_L	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	$EPT-(\Theta_T)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	$PT-(\Theta)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
IBADAN Tropical Savannah Climate (Lat. 7.507, Long. 3.8478)	T	NO	YES (↑)	YES (↑)	YES (↓)
	VP	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	AP	NO	NO	NO	NO
	$REF-(N)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	R	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	T_L	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	$EPT-(\Theta_T)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	$PT-(\Theta)$	NO	YES (↑)	YES (↑)	YES (↓)
KANO Warm Semiarid Climate (Lat. 11.9455, Long. 8.5884)	T	YES (↑)	YES (↑)	YES (↑)	YES (↑)
	VP	NO	NO	YES (↓)	YES (↓)
	AP	NO	YES (↑)	NO	YES (↑)
	$REF-(N)$	NO	YES (↓)	YES (↓)	YES (↓)
	R	NO	NO	YES (↑)	YES (↑)
	T_L	NO	YES (↓)	YES (↓)	YES (↓)
	$EPT-(\Theta_T)$	NO	YES (↑)	YES (↓)	NO
	$PT-(\Theta)$	YES (↑)	YES (↑)	YES (↑)	YES (↑)
KUKAWA Warm Desert Climate (Lat. 12.9566, Long. 13.6256)	T	YES (↑)	NO	YES (↑)	YES (↑)
	VP	NO	NO	YES (↓)	YES (↑)
	AP	NO	YES (↑)	NO	YES (↑)
	$REF-(N)$	NO	YES (↓)	YES (↓)	YES (↑)
	R	NO	NO	YES (↓)	YES (↑)
	T_L	NO	NO	YES (↓)	NO
	$EPT-(\Theta_T)$	NO	YES (↑)	NO	NO
	$PT-(\Theta)$	YES (↑)	NO	YES (↑)	YES (↑)

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