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Time Series Modelling of Three-Dimensional Temperatures Across Nigeria Using Data from Cosmic

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ABSTRACT

This study examined time series modelling of three-dimensional temperatures across Nigeria using data from COSMIC. A preliminary check on the time series plot of the data showed seasonal variation suggesting that the series was not stationary. Time Series methodology was employed. In order to test the stochastic fluctuation of daily temperature, the researcher used the Q-Q plot to examine the normality of the difference of the temperature. Similarly, daily temperature fluctuations exhibit randomness and continuous change as temperatures vary throughout the day. From the graphical analysis it can be observed that there will be an upward trend of temperature with time from the 2021 to 2030. Hence, there will be a positive relationship between temperature and time for the same period of time. From the graph also, it showed that 98% of temperature can be accounted for by time. The result suggests that the predicted temperature is increasing over the years. From 2006 to 2020, there was a strong negative and significant relationship between temperature and altitude. Also, the mean temperature is increasing in many stations. Hence, the temperature exhibit elements of time-varying characteristics over the study period. At the end, it was recommended that studying and carefully applying mathematical models could help track future rise in monthly temperatures.

INTRODUCTION

One of the primary responsibilities of any meteorological services is to provide information on weather warnings and forecasts to the general public for necessary precaution and prevention. This necessitated a better understanding of the underlying dynamics in weather parameters for modelling, prediction and control. This research examines trend of meteorological parameters such as temperatures across Nigeria using data from Constellation Observing Systems for Meteorology, Ionosphere and Climate (COSMIC).

The earth's climate system and its changes control life on earth and have a substantial influence on the society and economy. Climate is commonly defined as the synthesis of weather averaged over a long period. It is the statistically appreciable variations of weather parameters that stay for a long period, which could be decades or longer. This is the frequency and magnitude shift of sporadic weather events as well as the slow continuous rise in global mean surface temperature. Climate change can be due to natural and anthropogenic effects. It is very important that these can be separated (Volker & Ingeborg, 2006). Today, the entire global community has started suffering from the unfriendly climatic condition, the gradual disappearance of rain forest in the tropics, the loss of plant and animal species, changes in rainfall patterns, and global warming resulting from climate change. Climate change has the potential to affect all natural systems, thereby becoming a threat to human development and survival socially, politically, and economically (Oluwafemi et al, 2011).

Climate change is in many countries in the world, one of the biggest environmental threats to food production, water availability, forest biodiversity and livelihoods (Nury et al, 2012). Moreover, it is widely believed that developing countries in tropical regions of the world, e.g. Nigeria, will be impacted more severely than developed ones. The climate of Nigeria is tropical however; there are wide climatic variations in different regions of the country. Near coast temperatures rarely exceeds 32^0C (90^0F) but humidity is very high and nights are very hot. In land there are two different seasons. A wet season from

April to October with lower monthly temperatures and a dry season from November to March with a midday temperature that rises above 38^0C(100^0F) but relatively cool, dropping as low as 12^0C(54^0F). The variability in the temperature has been observed by several researchers (Chisimkwuo et al., 2014; Ragatoa et al., 2018; Bahari & Hamid, 2019). The temperatures had an increasing trend in some stations (Ulutan et al., 2009) and a decreasing trend in some other stations.

The purpose of the use of climate data differs but the standard averaging period is 30 years (World Meteorological Organization (WMO), 2017) The anomaly of climate parameters degenerates to climate change which is one of the greatest environmental, social, and economic threats facing our world today (Chomitz et. al., 2006). Climate change occurs because of changes to Earth's environment, like changes in its orbit around the sun or human modification of the atmosphere. There is nothing inherently wrong with climate change. It has happened in the past and will happen again. The current concern stems from the rate of change – how quickly changes are happening that is beyond human provision for adaptation. Scientists have found that the current rate of temperature increase is higher than any previously seen in the last 800,000 years. The most meteorological variables used in climatic trend studies are rainfall and temperature (Medori et al., 2012).

Temperature plays an important role in electricity demand and generation; heat waves and cold waves represent potential threats to the energy system due to the sustained nature of such events. Globally, the symptoms of the climate change problem are manifesting through, flora and fauna, melting glaciers, and decreasing mountain snow caps. For example, the mosquito belt has considerably expanded to higher elevations due to the temperature increase, frequency, and droughts. From the aggregate of the past events of the earth, climate (global, regional, and local) has never been static. The non-static natures are in various magnitudes ranging from variability through fluctuation, trends, and abrupt to gradual changes (Ayoade, 2003). Evidence of global climate change in the past 100 years are shown in the empirical observations and climate models and will likely change more rapidly in the future (Adeleke et al., 2018). There is a term ″climate normal″. The World Meteorological Organization (WMO) describes climate normal as lubber line used by the Climatologists to relate current climate trends to that of the past (Normal) so as to predict for the future. Scientists traditionally define it as an average over a recent 30- year period (World Meteorological Organization (WMO) (2017). Increase in temperature; rainfall variation; rise in sea level and flooding; drought and desertification; loss of biodiversity; frequent extreme weather events occurrence has been the evidences of changing climate in Nigeria (Elisha et. al, 2017; Akande et al, 2017). It is widely projected that as the planet warms, climate and weather variability will increase. Changes in the frequency and severity of extreme climate events and in the variability of weather patterns will have significant consequences for human and natural systems. Increasing frequencies of heat stress, drought and flooding events are projected for the rest of this century, and these are expected to have many adverse effects over and above the impacts due to changes in mean variables alone (IPCC, 2012).

There is no gainsaying in the fact that the earth is warming. Detailed observations of surface temperature assembled and analyzed by several different research groups showed that the planet's average surface temperature was 1.4°F (0.8°C) warmer during the first decade of the 21st century than during the first decade of the 20th century, with the most pronounced warming over the past three decades (Hood, 2019; Herrig & Lindsey, 2020).Since 1980s, temperature has increased significantly (Federal Ministry of Environment, 2014). Also, weather events in different ecological zones revealed that temperature will continue to increase in the foreseeable future (Akande et al, 2017). There have been records of farmlands reduction, poor crop yields and lower agricultural productivity, because of higher temperatures, lower rainfall, drought and desertification (Ogbuabor & Egwuchukwu, 2017). Understanding the nature and scale of possible climate changes in South Eastern Nigeria using the temperature data from Constellation Observing Systems for Meteorology, Ionosphere and Climate (COSMIC) is of importance to agricultural production and human health. For this purpose, time series modelling of weather data can be a valuable tool to investigate its variability pattern and, maybe, even to predict short and long term changes in the time series.

The theoretical framework of this study is the model that describes the daily average temperature behaviour using the mean-reverting Ornstein-Uhlenbeck process. The unknown parameters of the process were estimated with 16 years (2006-2020) of daily average temperature from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC). The daily average temperature is calculated by averaging each day's maximum and minimum temperature from midnight-to-midnight. Given a weather station, let us note by T_i^{max} and T_i^{min}, respectively, the maximum and minimum temperatures measured in one day i. We define the mean temperature of the day i by

$$T_i = \frac{T_i^{\max} + T_i^{\min}}{2} \qquad (1)$$

Considering the seasonal variation and long-term trends of temperature, we used the mean-reverting Ornstein-Uhlenbeck process to model the temperature behaviour. In the long run, the variation of daily average temperature intends to revert to a mean temperature. In order to test the stochastic fluctuation of daily temperature, we used the Q-Q plot to examine the normality of the difference of the temperature. If we denote by T_t the average temperature at date t, the dynamics of the process T_t are described by the stochastic differential equation:

$$dT_t = dT_t^m + \alpha\left(T_t^m - T_t\right) + \sigma_t dW_t \qquad (2)$$

where T_t^m is the long-term mean of the process, α is the rate of mean reversion, σ_t is the volatility square root time of the fluctuations and W_t is a Brownian motion.

In order to simulate trajectories of this process, we need to discretize this equation. Equation (2) can be written as:

$$T_t - T_t^m = \alpha\left(T_{t-1} - T_{t-1}^m\right) + \sigma_t \varepsilon_t, \qquad (3)$$

where, $\varepsilon_t \sim N\left(0,1\right)$.

The temperature movement has strong seasonality. Thus, we guess that this seasonal dependence should be modelled with a sine-function of the form, $sin(wt + \varphi)$, where t denotes the time measured in days. Since we know that the period of the oscillation is one year, we have $\omega = 2\pi/365$. Besides, owing to global warming all over the world and the urban heating effect, another component of the mean temperature that should be added to the model is a positive trend. The mean temperature T_t^m at time t has the following form:

$$T_t^m = A + Bt + C[sin\,(\omega t)\,cos\phi + cos\,(\omega t)\,sin\,\phi] \qquad (4)$$

We can rewrite T_t^m under the following form:

$$T_t^m = A + Bt + Csin\,(\omega t + \phi) \qquad (5)$$

Then, it is possible to estimate the parameters by operating some changes of variables and renaming the constant. We can then write

$$T_t^m = \beta_1 + \beta_2 t + \beta_3\, sin\,(\omega t) + \beta_4\, cos\,(\omega t)\,, \qquad (6)$$

where

$$A = \beta_1,$$
$$B = \beta_2,$$
$$\phi = \tan^{-1}\left(\frac{\beta_4}{\beta_3}\right), \qquad (7)$$
$$C = \frac{\beta_3}{\cos\left(\phi\right)}.$$

By applying the method of ordinary least squares to the observations of the daily temperatures, we can find the parameters.

Time series analysis and forecasting have become a major tool in numerous hydro-meteorological applications to study trends and variations in variables like rainfall, humidity, temperature stream flow and many other environmental parameters. It is therefore important to forecast how quickly the temperatures are going to increase as temperatures in excess of 40^0C may predispose both human and livestock to heat related diseases (Agrometeorological Bulletin, 2010). The main focus of this study is to carefully and rigorously study the past observations of a time series to develop an appropriate model that can predict future values of the series. The aim of this study was to investigate time series modelling of three-dimensional temperatures across Nigeria using data from COSMIC. Specifically, the study sought to:

i. Investigate how atmospheric temperatures have changed over the years (2006-2021) using data from COSMIC.
ii. Forecast possible trend for upcoming years across Nigeria using data from COSMIC.

MATERIALS AND METHODS

The area of this study was Nigeria. Nigeria is a country located in West Africa. It lies between 4^0N and 14^0N latitude and 4^0E and14^0E longitude and is bordered in the South by the Atlantic Ocean and the North by the Sahara Desert. Atmospheric temperature data used in this study are radio occultation (RO) measurements from the COSMIC mission. Measurements from both COSMIC I and COSMIC II missions were used. The data were obtained as second level (wetPrf and wetPf2) files from website of the University Corporation for Atmospheric Research (UCAR). Available data from May 2006 to September 2020 were used. Data from the website are available in Tape Archive (TAR) format. The data obtained were analyzed using statistical methods. Inputs that used for the neural network training are mainly time series indicators and 3-dimensional space indicators. For time series indicators were hour of the day (in universal time, UT), the day of the year, and the year. For 3-D space indicators, we used longitude (in degrees), latitude (in degrees), and altitude (in km). The hour of the day was introduced to facilitate the neural network's learning of diurnal variations. The day of the year was introduced to facilitate the network's learning of seasonal variations, and the year was introduced to facilitate the network's learning of long-term variations over the years. The 3-D space indicators were respectively introduced to facilitate the network's learning of spatial variations across the longitudes, latitudes and altitudes. The feed-forward back-propagation neural network method was used for the training, and the training algorithm used was the Levenberg-Marquardt back-propagation algorithm (Levenberg, 1944).

RESULTS AND DISCUSSION

Results

The average climate parameters is presented (Table 1).

Table 1: Average Climate Parameters (Temperature (^{0}C), Altitude (km)) and Time (year) using Data from COSMIC from 2006 to 2020

Year	DOY	Hr(UT)	Alt(km)	Lat(dg)	Lon(dg)	SSN	Temp(ºC)
2006	132	5.834865	8.69	10.09068	8.38233	30.86408	-24.5238
2007	1	7.9147	3.25	12.93087	9.49	38	6.895
2008	1	23.3031	29.45	4.04587	9.563478	9	-46.6539
2009	1	17.6139	5.25	8.666304	10.9537	0	-3.33217
2010	1	4.8092	4.55	4.771957	13.22109	18	1.17
2011	1	13.7339	6.35	7.069348	9.238913	48	-9.02196
2012	2	10.2817	3.75	7.075217	5.778478	92	5.78587
2013	1	13.2083	3.5	4.905319	5.324043	99	6.92617
2014	5	14.9028	4.45	5.466957	6.123913	134	1.925217
2015	1	9.627948	3.19	10.41522	10.13565	104	8.401522
2016	1	11.6975	3.15	9.930217	12.42761	37	9.993696
2017	1	16.8206	2.95	7.624783	9.310652	12	11.55217
2018	2	19.5138	4.35	5.347391	10.58348	0	2.653913
2019	274	1.7933	2.08	12.25957	13.49261	7	18.72478
2020	16	9.1299	2.85	11.39739	5.995217	0	11.11587

Table 1 presents the average climate parameters and time (year) using data from COSMIC from 2006 to 2020. This is illustrated in the graph below.

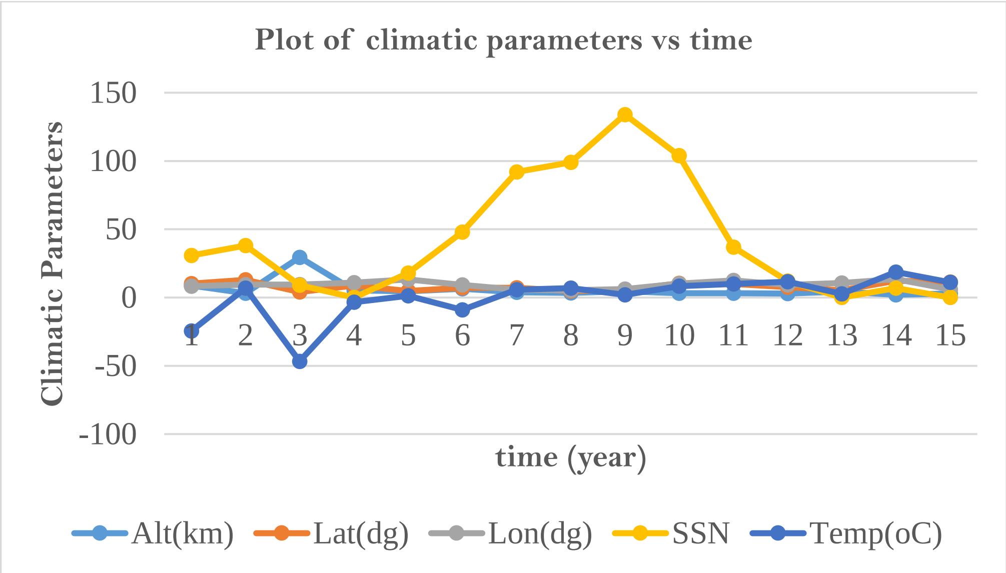

Figure 1: Plot of Climatic Parameters against Time

Figure 1 shows the graphical relationship between the climatic parameters with time from 2006 to 2020, the graph shows series of positive and negative relationships between the parameters and time. However, the relationship between temperature and altitude is shown below.

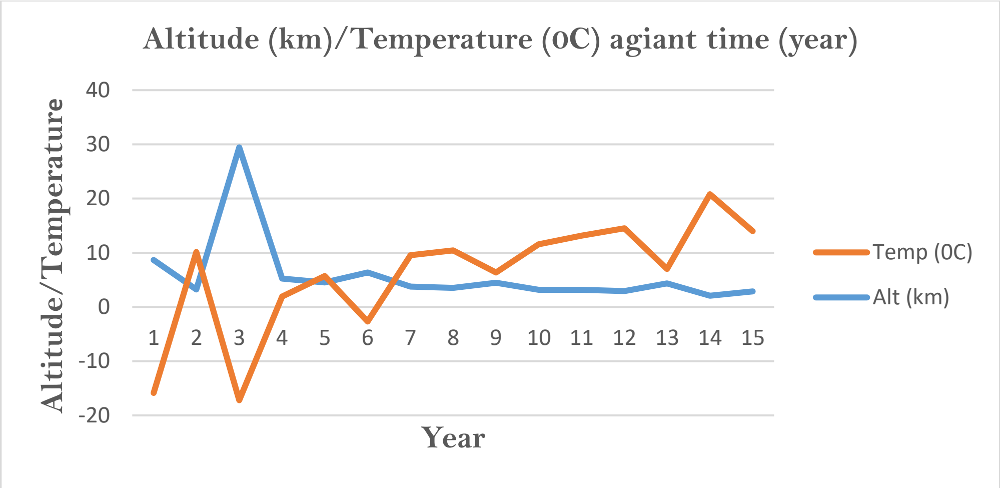

Figure 2: A Graph of Climatic Parameters (Temperature and Altitude) and Time

Figure 2 shows the graphical relationship between the temperature and altitude with time from 2006 to 2020, the graph shows series of positive and negative relationships between the parameters.

Table 2: Correlation between Temperature and Altitude using Data from COSMIC from 2006 to 2020

		Altitude	Temperature	time
Altitude	Pearson Correlation	1	-.912**	-.457
	Sig. (2-tailed)		.000	.087
	N	15	15	15
Temperature	Pearson Correlation	-.912**	1	.664**
	Sig. (2-tailed)	.000		.007
	N	15	15	15

Table 2 shows the correlation coefficient between temperature and altitude using data from COSMIC from 2006 to 2020. From 2006 to 2020, there is a strong negative and significant relationship between temperature and altitude ($R = -.912$, p-value = 0.000). However, there is a change in this pattern from 2006 to 2020 where a massive positive relationship was observed.

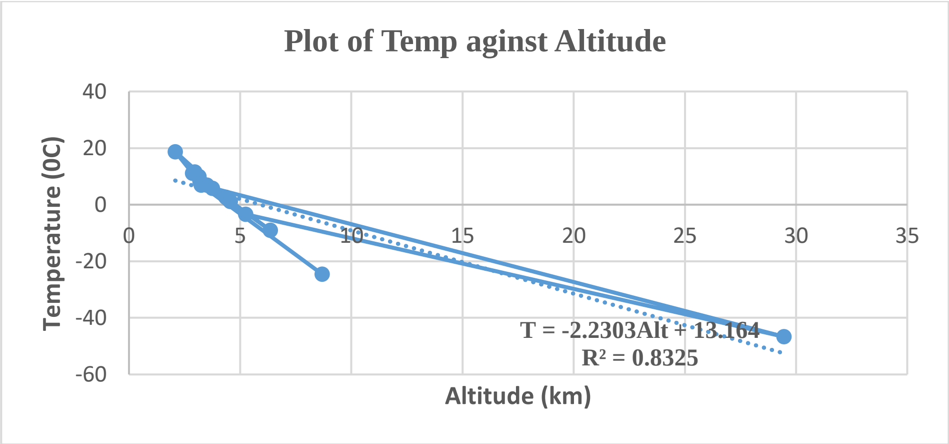

Figure 3: Graph of Temperature against altitude

Figure 3 shows the **g**raph of temperature against altitude. It is clear that temperature has an inverse relationship with altitude using data from COSMIC from 2006 to 2020.

Result from the Model

$$Temp_t = 13.164 - 2.2303Alt_t \quad (1)$$

Equations (1), shows the temperature on altitude, a negative forcing of 2.2303 can be seen on altitude by temperature. The positive constant however indicates that the temperature is reacting directly to altitude. The R^2 value on Figure 3 is 0.8325, this means that 83.3% of temperature can be accounted for by altitude. It indicates that changes in altitude can largely predict or explain the variations in temperature. This suggests a strong relationship between altitude and temperature, and the altitude can be considered a good predictor of temperature changes.

Table 3: Estimation of Mean Temperature

Model	**Unstandardized Coefficients**	**Standardized Coefficients**	**t**	**Sig.**		
	B	Std. Error	Beta			
1	(Constant)	-16.673	6.832		-2.440	.033
	time	2.402	.829	.653	2.898	.014
	sinwt	-1.930	5.139	-.084	-.376	.714
	coswt	1.061	5.046	.047	.210	.837

Table 3 shows the estimation of mean temperature. The mean temperature T_t^m at time t has the following form:

$$T_t^m = A + Bt + C[\sin(\omega t)\cos\phi + \cos(\omega t)\sin\phi] \quad (2)$$

We can rewrite T_t^m under the following form:

$$T_t^m = A + Bt + C\sin(\omega t + \phi) \quad (3)$$

Then, it is possible to estimate the parameters by operating some changes of variables and renaming the constant. We can then write

$$T_t^m = \beta_1 + \beta_2 t + \beta_3 \sin(\omega t) + \beta_4 \cos(\omega t), \quad (4)$$

where

$$A = \beta_1, \quad B = \beta_2, \quad \phi = \tan^{-1}\left(\frac{\beta_4}{\beta_3}\right), \quad C = \frac{\beta_3}{\cos(\phi)}. \quad (5)$$

By applying the method of ordinary least squares to the observations of the daily temperatures, we can find the parameters as follows:

β_1 = -16.673,
β_2 = 2.402, (6)
β_3 = -1.930,
β_4 = −1.061.

Then, the mean temperature is obtained as:

$$T_t^m = -16.673 + 2.402t - 1.930\sin(\omega t) + 1.061\cos(\omega t) \quad (7)$$

The equation describes a temperature (T_t^m) that is influenced by several components: a baseline value -16.673, a linear change with time $2.402t$, and oscillatory behaviour involving trigonometric functions with angular frequencies ω and a reference angle ϕ. The equation represents a mathematical model that can be used to describe mean temperature variations at a specific location (m) over time (t) and incorporates both linear and oscillatory influences. Therefore, the performance of the mean temperature model for forecasting the temperature series appears to be more favourable to the model identified by other researchers. This is evident in Figures 6 and 7. Hence, the temperature exhibit elements of time-varying characteristics over the study period. As a result, it is an indication that the climatic data may be best estimated using non-linear time series methodologies. The Q-Q plot of daily temperature difference is shown below.

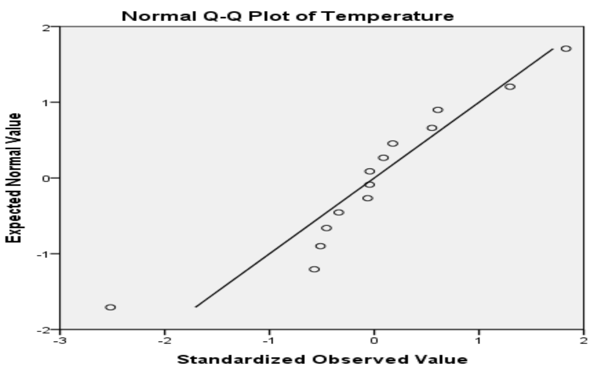

Figure 4: Q-Q Plot of Daily Temperature Difference

Considering the seasonal variation and long-term trends of temperature, we used the mean-reverting Ornstein-Uhlenbeck process to model the temperature behaviour. In the long run, the variation of daily average temperature intends to revert to a mean temperature. In order to test the stochastic fluctuation of daily temperature, we used the Q-Q plot to examine the normality of the difference of the temperature. If the distribution of the difference sequence is normal, the Q-Q plot should be a line. Figure 4 shows the difference of the temperature is approximately normal, so we consider the fluctuation of daily temperature as a Brown motion. In a Brownian motion, the random movement occurs continuously and is often described by a normal distribution. Similarly, daily temperature fluctuations exhibit randomness and continuous change as temperatures vary throughout the day.

Discussion

This study showed that there are variabilities of the temperature over time during the period 2006-2020. The variability in the temperature has been observed by several researchers (Chisimkwuo et al., 2014; Ragatoa et al., 2018; Bahari & Hamid, 2019). The temperatures had an increasing trend in some stations (Ulutan et al., 2009) and a decreasing trend in some other stations. From the graph it can be observed that there will be an upward trend of temperature with time from the 2021 to 2030. Hence, there will be a positive relationship between temperature and time for the same period of time. From the graph also, it shows R^2-value on of 0.98, this means that 98% of temperature can be accounted for by time. Therefore, the general trend for upcoming years across Nigeria using data from COSMIC was found to be increasing.

The result of this study suggests that the temperature data collected over a specific study period shows elements of time-varying characteristics. In other words, the temperature is not constant throughout the study period and exhibits changes over time. Time-varying characteristics in temperature data can be observed in various ways. Temperature tends to follow seasonal patterns, with distinct changes between different seasons like summer, winter, spring, and autumn. This is commonly observed in many regions and is attributed to the tilt of the Earth's axis. Over an extended period, temperature data might exhibit an upward or downward trend, indicating global warming or cooling trends, respectively. Temperature typically fluctuates throughout the day, with cooler temperatures during the night and warmer temperatures during the day. This is mainly due to the variation in solar radiation. Certain climate oscillations, such as El Niño and La Niña, can lead to irregular and periodic changes in temperature patterns over specific regions and time frames. Periods of unusually high or low temperatures, like heatwaves or cold snaps, can occur over different periods and significantly influence the overall temperature characteristics. Temperature data might also exhibit random fluctuations over short time frames due to various factors, including local weather systems and atmospheric disturbances.

From 2006 to 2020, there is a strong negative and significant relationship between temperature and altitude. Studies have consistently shown a strong negative relationship between temperature and altitude, commonly referred to as the "altitude-temperature" relationship or the "lapse rate." As one increases in altitude, the temperature generally decreases. This relationship is crucial in understanding climate patterns and is a fundamental principle in meteorology and climatology. The primary reason for this relationship is the adiabatic cooling effect, which is a consequence of changes in air pressure and volume as air rises or descends in the atmosphere. As air moves higher in the atmosphere, it experiences lower atmospheric pressure, leading to an expansion in volume. The expansion of air results in a decrease in temperature, and conversely, as air descends to lower altitudes, it experiences higher pressure and compression, leading to an increase in temperature.

Several studies support the existence of the altitude-temperature relationship. An analysis of some key questions (National Research Council, in Adedotun et al., 2020). This report by the National Research Council of the National Academies emphasizes the significance of understanding the lapse rate and its implications for climate change research and predictions. Bahari and Hamid (2019) discuss the correlation between temperature and altitude, elaborating on how adiabatic cooling and heating influence temperature variations with elevation. Baboo and Shereef (2010) provides a comprehensive analysis of atmospheric physics, including the concept of lapse rates and their importance in explaining temperature changes with altitude. This also corroborates the results of Clemens et al in Bahari and Hamid (2019) who investigated the relationship between temperature and altitude using global satellite observations and models, supporting the strong negative correlation between the two variables. Curtis et al. as cited in Ayeni and Oloukoi (2022) focused on regional-scale temperature-altitude relationships in mountainous regions and validates the existence of the altitude-temperature relationship. Oluwafemi, et al (2010) analyzed temperature variations with altitude across different regions and confirms the expected decrease in temperature with increasing elevation.

CONCLUSION

The study concludes that temperature dynamics in Nigeria are characterized by complex interactions between atmospheric conditions and temporal changes, reflecting the inherently variable nature of the climate system. The observed behaviour of temperature over the study period demonstrates that climatic processes are neither static nor purely deterministic, but are influenced by underlying environmental factors and random fluctuations. Consequently, robust mathematical and stochastic modelling approaches provide a valuable framework for understanding temperature behaviour and improving the reliability of climate prediction and long-term environmental planning.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this study. No financial, personal, institutional, or professional relationships influenced the design, data collection, analysis, interpretation of findings, or the preparation of this manuscript.

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