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Observed Soil Temperature Trends in Enugu Metropolitan City, Nigeria

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Abstract

Trends in soil temperature are important but rarely reported indicators of climate change; yet this has received little attention, even when the non-attention to soil investigation by the Enugu Capital Territory Development Authority has been confirmed to contribute partly to the increasing cases of collapsed buildings in the area. This study analysed soil temperature trends in Enugu metropolitan city, using secondary subsoil temperature and surface air temperature data sets that were sourced from the Nigerian Meteorological Agency over 21 years (2000-2020). The statistical techniques employed were the interwoven statistics – correlation and regression. The study showed that, while the annual soil temperature has been decreasing (0.012 °C per year), the soil-air temperature differences have been increasing (0.037 °C per year), although both of these trends were nonsignificant. The study acknowledged an inherent possible drawback due to the use of nonhomogenised data sets and recommends that the penalised maximal F test should be employed in further research aimed at validating the findings presented here.

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Introduction

"Trends in soil temperature are important, but rarely reported, indicators of climate change" because the soil is a buffered system that can slowly respond to changes in atmospheric weather [1-3]. Comparatively, little attention has been given to soil temperature in the investigation of climatic variables with trends due to limited availability of the data, as such studies in Enugu have mainly focused on surface air temperature (SAT) and rainfall even when the non-attention to soil investigation by the Enugu Capital Territory Development Authority has been confirmed to contribute partly to the increasing cases of collapsed buildings in the area [4-6]. Papers from different continents across the world including North America, Europe and Asia have reported trends in soil temperature [1-4,7-9]. Elsewhere, other studies have focused on the temporal trend of soil-air temperature difference (SATD, representing the soil temperature with the ground surface temperature (GST) in most cases [2,10-12].

Soil temperature (including GST) and groundwater temperature are the two main indicators of urban subsurface temperature [13,14]. SAT and the underlying soil temperature are among the important elements of the Earth's energy balance and their difference is key for the comprehensive determination of climate change [10,15]. Numerous attempts to define the GST have been done. According to, GST extends from "0-5 cm beneath the surface cover" [16]. For the thermistor to be protected from bad weather and direct solar radiation, measured GST at a depth of 3-5 cm in the ground [17]. Because GSTs were not recorded in the Russian data set in their analysis of the Northern Hemisphere permafrost region from 1980-2000, tested how effective it is to represent GST with the 20 cm depth and they found no qualitative differences [18]. Using only the 5 cm depth to represent the GST in their analysis of SATDs over selected stations of North America, Various authors have used either 0 cm or 20 cm in their analysis of SATDs [11,12,15,19]

Both observations and models can be used to obtain soil temperature [20]. There exists a disparity in the literature between simulation and observation techniques, and some authors have argued that due to the lack of observational data with sufficient spatial and/or temporal coverage, it is often difficult to use observational data for these investigations [2,21]. Owing to the expensive nature of monitoring subsurface temperature continuously, cheaper alternative ways have been adopted via the use of analytical methods and computer technologies. But many factors contribute to influencing underground temperature field, including solar radiation, SAT, wind speed, rainfall, soil properties and shelter [22,23]. Most of these factors change irregularly and as a result, the prediction and estimation of underground temperature are complex, explaining the underestimation of magnitudes reported in a previous study [21,24].

Using in-situ data presents a better temporal resolution [25,26], making it ideal for this study. Also, the focus is only on the shallow layer (<10 m), without regard to the deep (10-100 m) and very-deep (>100 m) layer respectively because natural in-situ temperatures do not substantially vary beyond this depth [27,28]. Hence, the present study aims to analyse soil temperature trends in Enugu metropolitan city. Towards achieving this aim, two objectives are pursued. One is to determine the extent of change in time of soil temperature in the study area. And two is to ascertain the temporal trend of the SATDs in the study area.

Materials and Methods

Study Area

The study area is Enugu urban, which is the capital of Enugu State in Southeastern Nigeria. It is composed of Enugu East, Enugu North and Enugu South Local Government Areas (LGAs), and is bounded by various LGAs in the following directions: in the north by Igbo-Etiti and Isi-Uzo, south by Nkanu West, east by Nkanu East and west by Udi. It lies approximately within Latitudes 6°21'N and 6°29'N of the Equator and Longitudes 7°26'E and 7°35'E of the Greenwich meridian (Figure. 1).

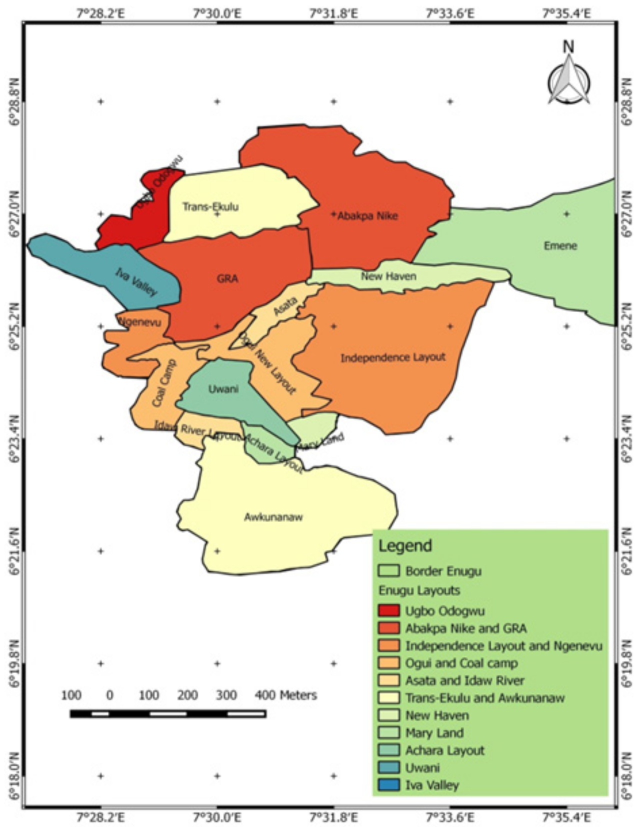

Figure 1: The wards in Enugu urban. (Source: GIS Lab, Department of Geography & Meteorology, NAU, Awka)

The past census figures confirm the growth of this city. Enugu urban had a population of 464,514 and 717,291 in 1991 and 2006 respectively as well as an estimated population of 833,373 in 2011 [29]. The city is an ideal location for this study; besides being the ninth most populous city in Nigeria, it is the largest city in Enugu State [6,30].

Enugu urban is located in the Tropical Rainforest zone that relates to the Tropical Wet and Dry (Aw) climate of the Köppen-Geiger-Pohl classification system [31]. The general relief comprises a gently undulating plain with low hills and steep valleys, creating a dual division of escarpment and lowland zones. It lies below 300 m northwest on the Cross River basin and is characterised by a dendritic drainage pattern that is dominated by two major river systems: the larger, Ekulu river system (northwards) and the Nyaba river system (southwards).

Human activities have reduced Enugu's vegetation from tropical rainforest to derived guinea savanna vegetation, otherwise described as a "rainforest-savanna ecotone", with a hydrologic ratio of less than 0.75 [32-34]. The city's well-developed transportation network plays an important role in stimulating production. It is an hour's drive from Onitsha, one of the biggest commercial cities in Africa, and takes two hours from Aba, another very large commercial city, both of which are trading centres in Nigeria [30].

Data Need

Temperature is the observed meteorological variable required. Two temperature data sets were collected and examined: soil temperature and SAT. The temperature data that were collected are the monthly soil temperature (at depth of 5, 10, 20, 30, 50 and 100 cm, respectively) and the monthly SAT over 21 years. These depths were chosen because they are the depths at which soil temperatures are measured at the Nigerian Meteorological Agency (NIMET), Enugu (see Fig. 2) and fall within the "shallow layer" definition given earlier [27]. Unlike SAT, the soil temperature is not commonly available [1]. This informed the choice of the study's duration, which is considered suitable for this analysis. Records from January 2000 to December 2020 was selected for this study.

Figure 2: Soil thermometers at NIMET, Enugu.

The thermometers are spaced roughly 65 cm apart and arranged orderly to allow for easy reading of the soil temperature at six depths (from left to right): 5, 10, 20, 30, 50 and 100 cm. As the soil temperature increases, the mercury in the bulb extends and rises. When the soil temperature drops, the mercury shrinks and falls down the tube.

To achieve Objective I, the monthly soil temperature data set were averaged to obtain the annual mean. The annual mean for all the soil depths was averaged to obtain a single value for each year. For Objective II, the monthly SAT data set were averaged to get the annual mean. Also, the annual mean of three soil depths (5, 10 and 20 cm) was averaged to obtain a single value that was used in addition to the annual mean SAT to obtain the SATDs (SATD: soil temperature − SAT). Although the GST ranges from 0 to 5 cm, it has been confirmed that no qualitative difference exists between the GST and the 20 cm soil temperature [16,18]. This implies that any depth (and all depths) between 0 and 20 cm can effectively be employed, and informed the decision to use the 5-20 cm annual average.

Data Sources and Method of Collection

All the data sets used in this study were sourced from the NIMET headquarters in Abuja as secondary data. At the observatory unit of NIMET, Enugu, regular meteorological observations are provided, including soil temperatures and SAT. These variables are collected hourly (SAT) and every six hours (soil temperature) by the meteorological observers. The SAT is collected at all the 24 meteorological hours (ordinary, minor synoptic and major synoptic hours, given in GMT) from the Stevenson screen that is placed at about 1.5 to 2 m above the ground, and recorded on "Form Met 131". On the other hand, the soil temperature is only collected during the four major synoptic hours (0000, 0600, 1200 and 1800 GMT). A mercury-in-glass soil thermometer (Casella-London immersion) that is spaced at about 65 cm apart (see Fig. 2) was used to measure the soil temperature at 5, 10, 20, 30, 50 and 100 cm depth points, and recorded on "Form Met 113". The daily mean soil temperatures are calculated for each soil depth and averaged to get the monthly mean required for this study. Similarly, the daily mean SATs are calculated and averaged to obtain the monthly mean used in the study.

Method of Data Analysis

The innovative trend analysis, successive average methodology, and Mann-Kendall and Sen's slope methods are other options for estimating trends but some of these methods have been questioned [35,36]. For this study, the commonest method of finding a trend in a time series was employed. This method involves the use of the interwoven statistics: correlation and regression. To clarify their main difference, correlation refers to when both measurements (usually in interval or ratio scale) are random variables but regression is when the independent variable can be chosen because it is fixed [37,38]. A scatterplot (also known as a scatter diagram) is very important and was used to represent the predictor variable (X-axis) and the criterion variable (Y-axis) graphically. Because such a graph makes it difficult to determine the general trend due to so many fluctuations, a smoothing function was applied to dampen the fluctuations. A 5-year moving average was used to smoothen the noise off the time series and, given a set of values (Y_1, Y_2, Y_3, Y_4...), a moving average of order N is given as shown in Equation 1 [39,40].

$$\frac{Y_1 + Y_2 + \cdots Y_N}{N}, \frac{Y_2 + Y_3 + \cdots Y_{N+1}}{N}, \frac{Y_3 + Y_4 + \cdots Y_{N+2}}{N} \quad (1)$$

With this method, each of these null hypotheses (H_0) was tested. One, "There is no significant trend in the soil temperature within the study period". Two, "There is no significant trend in the SATDs within the study period". The Pearson's product-moment correlation coefficient (denoted as r, Eq. 2) is a parametric statistic and it is the most commonly used to measure the relationship between two interval or ratio variables. It gives the strength (–1 to +1) and direction (negative or positive) of the trend and, to interpret the level or strength of the correlation, the "coefficient of determination" (C/D) in Equation 3 was employed because arbitrary benchmarks (such as the one in should not be applied rigidly [39,41].

$$r = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sqrt{\left(\sum x^2 - \frac{(\sum x)^2}{n}\right)\left(\sum y^2 - \frac{(\sum y)^2}{n}\right)}} \quad (2)$$

$$C/D = r^2 \quad (3)$$

where, r: Pearson's product-moment correlation coefficient, x and y: two studied sets of observation, n: sample size, ∑: summation, C/D: coefficient of determination.

A line of best fit, known as the ordinary least square line (OLS line), was drawn on the scatterplot. The OLS line aims to fall in the middle of the points such that there is an equal (or roughly equal) number of points above and below the line (these outlying points are the anomalies). The equation for this regression line (OLS line) is given in Equation 4. Also, a legitimate version of the Student's t-test (Eq. 5) was used to test the significance of the correlation coefficient [37,39]. This method described has been applied successfully in recent meteorological studies (for example and inclusive of the stepwise guide, exist in the literature [12,41].

$$y = a + bx \quad (4)$$

$$a = \bar{y} - (\bar{x} \times b) = \left(\frac{\sum y}{n}\right) - \left(\left[\frac{\sum x}{n}\right] b\right) \quad (4.1)$$

$$b = \frac{\sum xy - \frac{(\sum x)(\sum y)}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}} \quad (4.2)$$

where, a: intercept (Eq. 4.1), b: slope (Eq. 4.2), x and y and $\sum$ and n: the same as denoted in Eq. 2.

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (5)$$

where, t: Student's t-test statistic, r and n: the same as denoted in Eq. 2.

Both inferential analyses were judged at a 5% (0.05) level of significance (denoted as α or alpha). Each statistic had an associated probability value (p-value or abbreviated as "Sig."). If the p-value is less than or equal to the α ($p \leq 0.05$), then the H_0 will be rejected, implying that the result is statistically significant. However, if the p-value is greater than the α ($p > 0.05$), then the H_0 will be accepted. This will mean that the result is statistically nonsignificant.

Results and Discussion

On one hand, Objective I is "To determine the extent of change in time of soil temperature in the study area" (see Section 1) and its complementary H_0 states that "There is no significant trend in the soil temperature within the study period". The scatterplot (with interpolation line), as presented in Fig. 3, indicates that the movement of the time series was characterised by fluctuations.

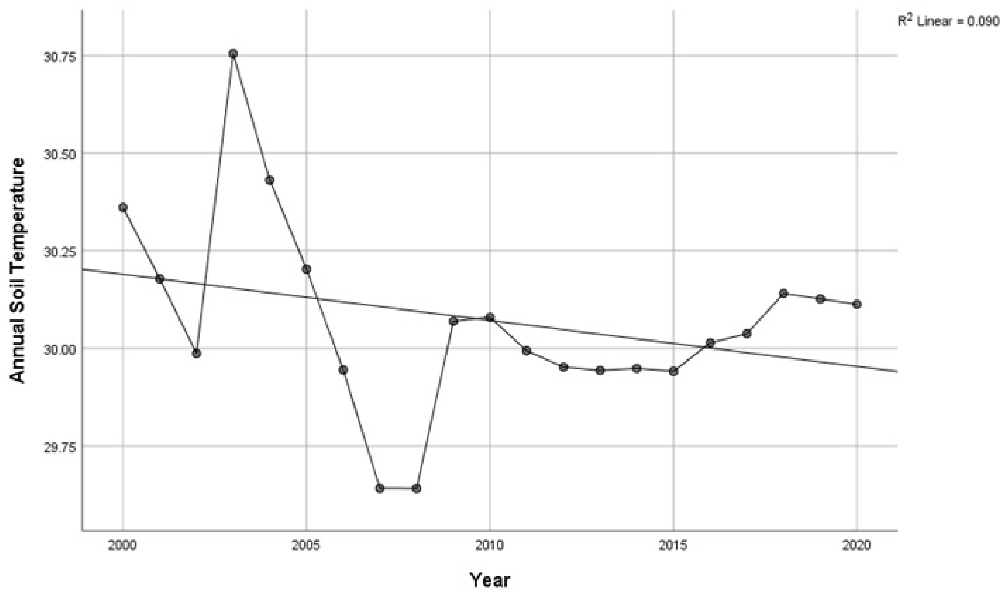

Figure 3: Scatterplot of soil temperature in Enugu.

Due to these fluctuations, it was necessary to apply a smoothing function (as shown in Fig. 4). From Pearson's correlation estimation as shown in Table 1 ($r = -0.301$, $p = 0.093 > 0.05$), there is a nonsignificant negative relationship between change in time and soil temperature and thence the H_0 was accepted. Therefore, "There is no significant trend in the soil temperature within the study period". The implication is that, even though the annual soil temperatures have been decreasing by 0.012 °C per year, it is not significant at 0.05 since this decrease could be due to other external factors (including SAT and soil type). Hence, it became necessary to conclude at this point without the need to further interpret the correlation or regression result because it is statistically nonsignificant. The remaining SPSS output of this analysis can be found in Appendix A.

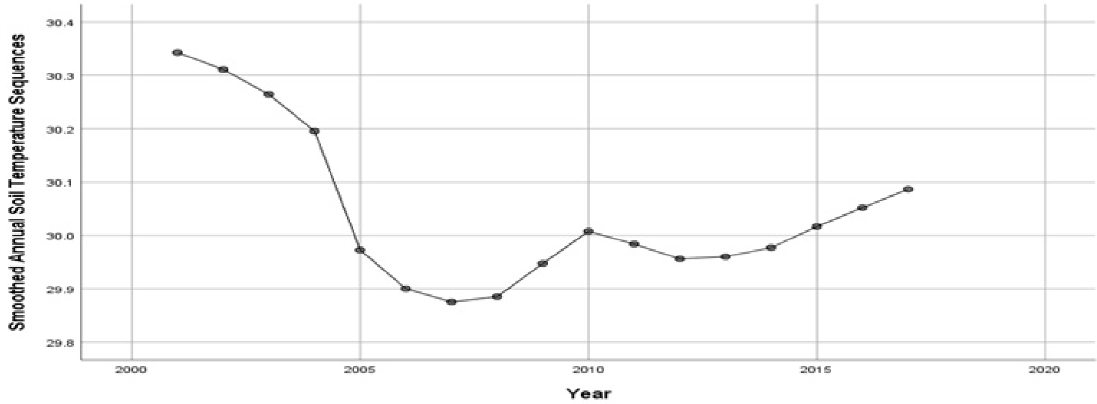

Figure 4: 5-year moving average of soil temperature in Enugu.

Table 1: Correlation result of Objective I.

	Year		Annual Soil Temperature
Year	Pearson Correlation	1	-0.301
	Sig. (1-tailed)		0.093
	N	21	21
Annual Soil Temperature	Pearson Correlation	-0.301	1
	Sig. (1-tailed)	0.093	
	N	21	21

On the other hand, the intention of Objective II is "To ascertain the temporal trend of the SATDs in the study area" and its equivalent H_0 states that "There is no significant trend in the SATDs within the study period". The scatterplot (with interpolation line and dashed line; Fig. 5) shows that the movement of the time series was characterised by fluctuations, hence the need to reduce it through a smoothing function (Fig. 6).

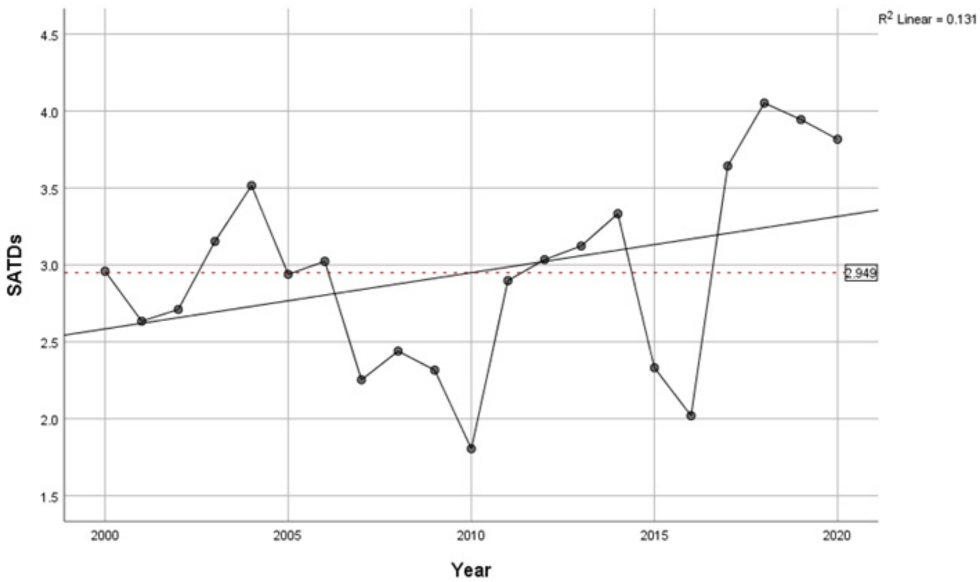

Figure 5: Scatterplot of SATDs in Enugu.

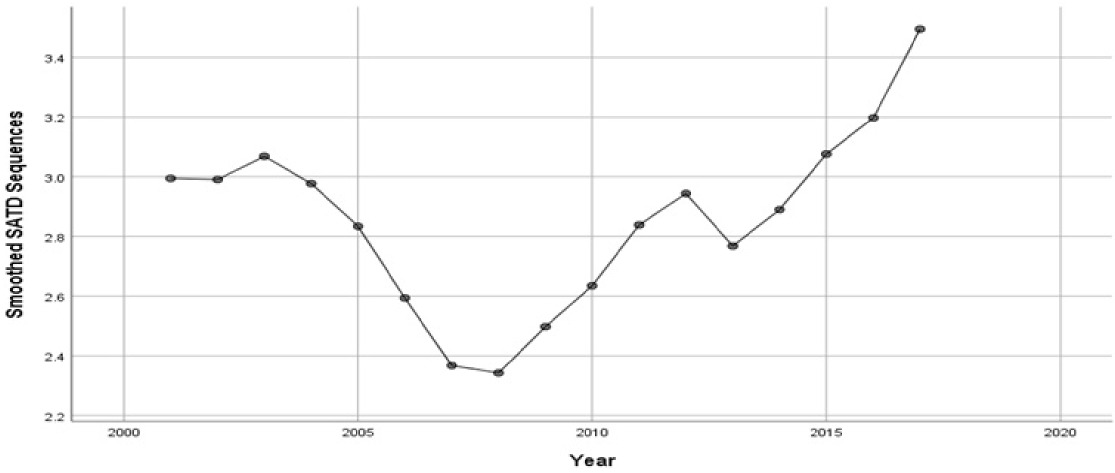

Figure 6: 5-year moving average of SATDs in Enugu.

From Pearson's correlation estimation presented in Table 2 (r = 0.362, p = 0.053 > 0.05), there is a nonsignificant positive relationship between change in time and SATDs. Hence, the H0 was accepted. This implies that "There is no significant trend in the SATDs within the study period". This result means that, although the SATDs have been increasing by 0.037 °C every year, it is not significant at 0.05 because some external factors (like soil type, and buildings among others) could have caused this increase. Consequently, further interpretation was deemed unnecessary having concluded that the result is not statistically significant. For reference, Appendix B shows the part of this analysis output not presented here.

Table 2: Correlation result of Objective II.

		Year	SATDs
Year	Pearson Correlation	1	0.362
	Sig. (1-tailed)		0.053
	N	21	21
SATDs	Pearson Correlation	0.362	1
	Sig. (1-tailed)	0.053	
	N	21	21

The soil temperature trend (Fig. 3) suggests general cooling while that of the SATDs (Fig. 5) indicates general warming, although both of them are nonsignificant. However, for reported linear trend estimates to be reliable, the data sets need to be homogeneous [42-44]. For example, indicated a significant linear warming trend in the SATDs of China but reanalysed it with a homogenised data set and revealed a significant linear cooling trend; they attributed the observed disparity to be due to the homogenisation effect [11,12]. It should be pointed out that the data used in this study was not homogenised. Also, from the dashed line in Fig. 5, it can be stated that the 5-20 cm annual mean soil temperature (used loosely here as the "soil temperature," better referred to as the GST) can be estimated by adding 2.9°C to the annual mean SAT; this value is the mean SATD. This finding is within the range of 2-4 °C reported elsewhere [45,46].

Conclusion, Limitations and Suggestions for Further Studies

This study showed that, at the rate of 0.012 °C per year, there is a nonsignificant cooling trend in the annual soil temperature of Enugu between 2000 and 2020. It was also observed that, although nonsignificant, the trend of the SATDs in this area has been increasing at the rate of 0.037 °C per year within the study duration.

However, the nonhomogenised data sets used present an inherent possible drawback. The homogeneity of climate data is essential for many aspects of climate research. Although there is a stepwise guide to use R, it was not done because the authors have limited proficiency in using the statistical package [47]. It should be pointed out that using a homogenised version of these data could improve the reliability of the findings.

From the foregoing challenge, the present study suggests that follow-up research can be conducted with a homogenised version of the data used here to see how it agrees or disagrees with the findings presented. To homogenise the data sets, the penalised maximal F test accounting for autocorrelation can be employed [47-49].

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