Climatic zoning of Ghana using selected meteorological variables for the period 1976–2018

Enoch Bessah¹,² | William Amponsah¹,² | Samuel Owusu Ansah³ | Andrews Afrifa¹ | Bashiru Yahaya³ | Cosmos Senyo Wemegah⁴,⁵ | Michael Tanu³ | Leonard K. Amekudzi²,⁵ | Wilson Agyei Agyare¹,²

¹Department of Agricultural and Biosystems Engineering, College of Engineering, KNUST, Kumasi, Ghana
²WASCAL Climate Change and Land Use, College of Engineering, KNUST, Kumasi, Ghana
³Hydrometeorological Unit, Ghana Meteorological Agency, Accra, Ghana
⁴Earth Observation Research and Innovation Centre, UENR, Sunyani, Ghana
⁵Department of Physics, College of Science, KNUST, Kumasi, Ghana

Correspondence
Enoch Bessah, Department of Agricultural and Biosystems Engineering, College of Engineering, KNUST, Kumasi, Ghana.
Email: enochbessah@knust.edu.gh, enoch.bessah@gmail.com

Abstract
Periodic climate zoning is an essential classification of land cover to account for anthropogenic activities resulting from population increase and urbanization that affect key climate response parameters. Rainfall, relative humidity (RH), maximum (Tmax) and minimum temperature (Tmin) data from the Ghana Meteorological Agency were used to zone Ghana by adopting cluster and PCA analysis methods and verifying the groupings with the seasonal trend and Tukey Honestly Significance Difference (HSD) analysis. The cluster analysis grouped the synoptic stations into four major homogenous clusters while the PCA distributed them into three sub-divisions with reference to 1976–2018. Rainfall, RH, Tmax and Tmin were characterized by five, three, two and three factors with factor loadings in the range of 0.71–0.78, 0.53–0.70, 0.54–0.74 and 0.50–0.72, respectively. HSD found transition stations like Bole and Kete Krachi in cluster 1 and 2 to have no significant difference with cluster 1, while Wenchi, Sunyani, Sefwi Bekwai and Koforidua in cluster 2 had no significant difference with cluster 3. Accra station which was classified in cluster 3 showed the seasonal pattern of cluster 4 and was confirmed by HSD to belong in cluster 4. Therefore, Ghana-based on-point analysis is climatically grouped into Savannah (11°0′0″N–7°46′11″N), Forest (from 7°46′11″N to the coast) and Coastal (about 30 km from the Gulf of Guinea coastline) based on the assessed parameters. These findings are vital for planners and decision-makers especially for industries that depend on weather and climatic conditions for their activities.

KEYWORDS
climatic zoning, cluster analysis, Ghana, rainfall, relative humidity, temperature

1 | INTRODUCTION

Climatological zones are of global importance, even more intensely, since the population keeps increasing which affects land use and land cover. A climatic zone is a region generally characterized by a consistent climate. These regions are distinct to latitudinal belts globally ranging from tropical, arid, Mediterranean, temperate to...
polar regions (IPCC, 2013). Several climatic zones have been located worldwide, which seem to vary amongst continents and even within countries. Temperature is one key climatic parameter that plays an extensive distinct role in this variability. In addition, it is its relation to latitude and altitude (Aigang et al., 2009). Other parameters mostly considered include rainfall, relative humidity, radiation and wind speed. For instance, Peel et al. (2007) used these climatic variables to update the Köppen-Geiger climate classification for the different continents on the globe.

The need for developing countries such as Ghana to clarify these zones to assist research and governmental planning is without debate. Climatic zones are factored in urban planning, and this helps in setting-up smart environment and green human-friendly cities, landscape and global climate change investigation. The World Health Organization (WHO) helps define the zones of various vector-borne diseases, many enteric illnesses, and certain water-related diseases. The WHO has projected an approximated additional 250,000 lives to be lost per year from malnutrition, malaria, diarrhea and heat stress alone due to climate change over the period 2030-2050. Climate is one of several factors that can influence the spread of infectious diseases. Research has continuously identified the relationships between variations in climate and infectious diseases, evidenced primarily on vulnerable populations (Amuakwa-Mensah et al., 2017; Githeko et al., 2000; Lazenby et al., 2014; Patz et al., 1998).

Extreme weather events and variable climates that affect ecosystem changes, food and water supplies all contribute to global warming and pose several health risks. Another sector where climatic zones play an important role in the agricultural sector since it helps farmers in decision making as different types of crops respond to specific climatic conditions (Darfour & Rosentrater, 2016). Drought and flood are existing issues concerning farmers globally, especially amongst developing countries. It is also a major concern in Ghana, especially to the rural farmers of the northern areas. The issue of crop produce being damaged, especially during storage, due to periods of extreme heat and heavy rains is some of the evidence. Crop yield, biodiversity, water use, and soil health receive direct influence from the evolving climate. Furthermore, compounded climatic factors can cause a reduction in plant productivity, usually resulting in price increments for many important crops.

The widely known classification in Ghana is the seven agro-ecological zones established by FAO (2005): Sudan Savannah, Guinea Savannah, Transitional, Deciduous forest, Moist Evergreen, Wet Evergreen and Coastal Savannah. Abass (2009), also categorized Ghana into four climatic regions: Tropical Continental or Savannah, Wet semi-Equatorial, South-western Equatorial and Dry Equatorial (Figure S1). Comparatively, the Sudan Savannah, Guinea Savannah and Transitional agro-ecological zones fall within the Tropical Continental climatic region while the Deciduous Forest and Moist Evergreen agro-ecological zones fall within the Wet Semi-equatorial climatic region. The South-western Equatorial and Dry Equatorial climatic zones are in the same location as the Wet Evergreen and Coastal Savannah agro-ecological zones respectively (Abass, 2009; Darfour & Rosentrater, 2016; FAO, 2005). Amekudzi et al. (2015) used the Meteorological Agency's (GMeT) weather forecasting zoning to study rainfall onset, cessation and length of rainy days in Ghana.

The first attempt at climate zoning was reported in Aryee et al. (2018); here, the authors only used thirty years of rainfall climatology of Ghana for this purpose (Figure S1). It is, therefore, evident that at the time of this study, there were no established climatic zones over Ghana from multi-climate parameters. This confusion could be responsible for the reference made to the four agro-ecological zones demarcated by Amekudzi et al. (2015) as climatic zones by Asilevi et al. (2019) in their assessment of global solar radiations over Ghana. The agro-ecological zones of Ghana play a crucial role necessary for planning, especially in the agricultural and scientific research sectors. The current version of the Köppen-Geiger climate classification (Beck et al., 2018) of Ghana shows an extended area of Tropical Monsoon compared to Peel et al. (2007) Updated classification. This could be due to the current version's increased resolution (1 km) (Figure S2). There is a need to establish or group the synoptic stations based on their climatic characteristics and the appropriate techniques to inform policy and planning, especially in adapting to climate change. Therefore, this study focused on using only climatic parameters from the 22 synoptic stations in Ghana for the zoning. The parameters were; rainfall, relative humidity, maximum and minimum temperature on a daily scale. The work was limited to point analysis of each parameter at each station to prevent irregular gridding point data with wide spatial variation, such as in Ghana.

Clustering has been the standard method for climatic zoning and weather conditions classification ( Stocksbury & Michaels, 1991; Davis & Walker, 1992; Gong & Richman, 1995; Yao, 1997; Kidsen, 2000; DeGaetano, 1996; Steinbach et al., 2003; Straus et al., 2007; Vrac & Naveau, 2007). This approach has further been improved by addressing the issue of autocorrelation and seasonality by Lund and Li (2009). Other methods that have been explicitly applied for rainfall zoning include L-moments.
(Guttman, 1993), spatial correlation functions (Sen & Habib, 2001), empirical orthogonal functions (Jebari et al., 2009), harmonic analysis (Suhaila & Jemain, 2009), multivariate regression (Sabziparvar et al., 2015), spatial interpolation (Gupta et al., 2017), k-means clustering (Machiwal et al., 2017), Pearson’s correlation (Haines & Olley, 2017), regional frequency analysis (Medina-Cobo et al., 2017) and support vector machines (Lin et al., 2017) and, combined cluster analysis (CA) and Principal Component Analysis (PCA) (Amissah-Arthur & Jagtap, 1999; Machiwal et al., 2019; Modarres & Sarhadi, 2011). Specifically, Amissah-Arthur and Jagtap (1999) used CA and PCA methods to cluster seasonal rainfall patterns in Nigeria into six groups based on datasets from 23 stations. Nnaji et al. (2016) subsequently used hierarchical cluster analysis (HCA) to zone 24 rainfall stations into five groups according to their co-efficient of variation. Cluster analysis helps group the dataset based on homogeneous factors while PCA is used to identify the factors characterizing or responsible for the homogeneity in the dataset.

Therefore, this study used cluster analysis and principal component analysis to zone or group the 22 synoptic stations in Ghana based on long-term (1976–2018) daily rainfall, relative humidity, and maximum and minimum temperature data. Specifically, the study addressed the following objectives:

1. determining the assessed parameters’ patterns at the 22 synoptic stations.
2. assess the factors responsible for the identified patterns or clusters
3. determine the variation and significance within and between them.

**FIGURE 1** Map of Ghana showing the 16 regions and digital elevation model (DEM)
2 | METHODOLOGY

2.1 | Study area

Ghana is located in West Africa between latitudes 4° 71’ N and 11° 20’ N and longitudes 1° 20’ E and 3° 28’ W covering a land area of about 235, 000 km² (Figure 1). Long-term mean annual rainfall is between 700 mm and 2030 mm while average minimum and maximum temperatures are 22°C and 32°C respectively (Kabo-Bah et al., 2016). About 60% of the population is in the agricultural sector, mainly practising rainfed crop production and are vulnerable to climatic changes (Bessah et al., 2021; GSS, 2011). The largest artificial lake (Volta) and natural lake (Bosomtwe) in Africa and West Africa are located in Ghana. These natural features and the vegetation and relief contribute to the climatic conditions experienced in the country.

2.2 | Data sources

Daily rainfall, relative humidity (RH), maximum (Tmax) and minimum (Tmin) temperature data were acquired from the Ghana Meteorological Agency (GMet) for the period 1976–2018 (43 years). Twenty-two synoptic stations distributed across the country with missing data for rainfall, RH, Tmax and Tmin in the range of 0.004%–13.00%, 1.76%–24.61%, 1.05%–18.12% and 1.94%–20.0% respectively were used (Figure 1, Table S1). The study used RH recorded at 15:00 GMT because of less missing data than the other synoptic hours (9:00 and 12:00 GMT). RClimDex package was used for the quality control assessment of the data, identifying and removing negative precipitations, and crosschecking minimum temperatures that were higher than the maximum temperature for the same location and day.

2.3 | Data analysis

The Statistica software version 13 was used to run the cluster and Principal Component Analysis (PCA). The tree clustering approach was adopted using Ward’s method Amalgamation linkage rule and Euclidean distance measure to cluster the climatic stations (as the variables) for each of the parameters assessed. Factor analysis (PCA) with a minimum eigenvalue of 1.00 and five (5) maximum factors was set under the Varimax normalized factor rotation to assess the factors influenced by similar phenomena across the clustered climatic stations. Both tree clustering and factor analysis were performed on monthly mean data and daily data due to the similarities in the results and the aim to show the seasonal variation in the stations. The factor loading threshold was set at 0.5 to flag all factor loadings greater than the threshold.

A pivot table was used to determine the monthly mean of RH, Tmax, Tmin and total rainfall and graphically plotted for each station. The 22 synoptic stations were grouped into the four identified clusters to assess the pattern of the parameters as a factor explaining similarities in the groups. The R software was used to carry out the Analysis of Variance (ANOVA) and Tukey Honestly Significant Difference (HSD) based on monthly totals (rainfall) and means (for RH, Tmax and Tmin) of the datasets for the 22 synoptic stations. The FAO (2005) agro-ecological zones were the basis for the spatial classification of the climatic zones. ArcGIS 10.7 was used for the demarcation based on the findings of this study.

3 | RESULTS AND DISCUSSION

3.1 | Characterization of climatic zones

3.1.1 | Cluster analysis of rainfall, RH and temperatures

The four-cluster demarcation from the analysis based on monthly total records is presented in Figure 2. Rainfall, RH, Tmax and Tmin at four cluster distinctions were at euclidean linkage distance of 400, 200, 10 and 12. Rainfall distribution was grouped into three major areas: North, central and coast. However, Axim, a coastal station, was significantly different from the rest and was classified as one group (to give four clusters [Figure 2]). The cluster analysis suggests that these stations have the same rainfall characteristics. The same results were reported by Aryee et al. (2018) when rainfall dataset (GMet v1.0 at 0.5°× 0.5° spatial resolution) for the period 1990–2012 were clustered by k-means over Ghana. GMet v1.0 was generated with 113 rainfall stations data across the country (Aryee et al., 2018). It can be deduced from the results that the 22 synoptic stations are rightly distributed to account for the variations in rainfall in Ghana.

Relative humidity was grouped latitudinally from the north to the coast with three stations as the transition between the north and south (south here refers to stations above the coastal stations latitudinally) (Figure 2). Kete Krachi, which was clustered as part of the north, was now in the transition. This could be due to the effect of the Volta Lake over Kete Krachi. Accra on the coast was clustered with the southern stations under cluster
3, possibly due to urban heat islands resulting from the industrial activities of the city (Wemegah et al., 2020). Moreover, the station located at the Kotoka International Airport is surrounded by vegetation, which may mimic the atmospheric conditions of deciduous forests. This could be the proximity to the sea velocity convergence.

**FIGURE 2** Clustered rainfall, relative humidity, maximum and minimum temperature stations classified into four groups
The dendrogram of maximum and minimum temperature at four cluster levels of varying positions could be influenced by local factors. For maximum temperature, four stations above latitudes 9°0’00”N were clustered together while below latitude 9°0’00”N has no pattern of clustering (Figure 2). The maximum temperature was not homogenously distributed below latitude 9°0’00”N. Factors such as the Volta Lake (water bodies), high elevations (mountains) in the Eastern Region and vegetation could significantly affect mid-day temperatures (Hanamean Jr. et al., 2003; Revadekar et al., 2013). For instance, Abetifi (in the mountainous region) showed similar Tmax with most coastal stations (cluster 4). This could be attributed to the vegetation and highest altitude of Abetifi (594.7 m asl). Similarities with the coastal stations could be due to the Afram River; however, in terms of altitude, the coast is low-lying (Aigang et al., 2009; Planchon, 2000; Revadekar et al., 2013).

The minimum temperature within the northern part of the country was clustered together (Cluster 1) with Kete Krachi at about latitude 9°0’00”N which was far below Bole station (cluster 2). T min between latitude 5°30’00”N and 9°0’00”N from the West towards the Greenwich meridian (0°0’00”W) could be explained by similar factors (clusters 2). Coastal stations and eastern stations below latitude 7°0’00”N had significantly different T min except for Tema and Ada on the east coast (Figure 2). The eastern ocean current and its diurnal temperature trend could be the reason for the variation of stations on this part of the coast from the West (Scheitlin, 2013).

### 3.1.2 Climatic zoning of stations

Scoring of the clusters based on the four parameters showed three distinct classes with the same or similar climatic characteristics as presented in Table 1. Navrongo, Wa, Tamale, and Yendi had a common factor defining rainfall, RH, Tmax and Tmin. Tmax and Tmin of Bole were more identically to cluster 2, and that of Kete Krachi found to be in cluster 2 were RH and Tmax. Factor 2 of PCA ranging between 0.55 and 0.70 (Table S2) showed a high level of similarities in rainfall characteristics amongst five stations except for Kete Krachi, which was not significant. However, it was highest in cluster 2 at 0.398. For RH, PCA factor ranged between 0.86 and 0.88 (Table S3). Factors showing similarities in Tmax for

| Synoptic station | Latitude | Longitude | Altitude (m) | Cluster 1 | Cluster 2 | Cluster 3 | Cluster 4 |
|------------------|----------|-----------|-------------|-----------|-----------|-----------|-----------|
| Navrongo         | 10.90    | −1.09     | 201.3       | 4/4       | 0/4       | 0/4       | 0/4       |
| Wa               | 10.06    | −2.50     | 322.7       | 4/4       | 0/4       | 0/4       | 0/4       |
| Tamale           | 9.58     | −0.86     | 168.8       | 4/4       | 0/4       | 0/4       | 0/4       |
| Yendi            | 9.45     | −0.03     | 195.2       | 4/4       | 0/4       | 0/4       | 0/4       |
| Bole             | 9.03     | −2.49     | 299.5       | 2/4       | 2/4       | 0/4       | 0/4       |
| Kete Krachi      | 7.83     | −0.03     | 122.0       | 2/4       | 2/4       | 0/4       | 0/4       |
| Wenchi           | 7.74     | −2.11     | 338.9       | 0/4       | 2/4       | 2/4       | 0/4       |
| Sunyani           | 7.34     | −2.38     | 308.8       | 0/4       | 2/4       | 2/4       | 0/4       |
| Sefwi Bekwai     | 6.19     | −2.32     | 170.8       | 0/4       | 2/4       | 2/4       | 0/4       |
| Koforidua        | 6.11     | −0.26     | 166.5       | 0/4       | 2/4       | 2/4       | 0/4       |
| Kumasi           | 6.71     | −1.60     | 286.3       | 0/4       | 1/4       | 3/4       | 0/4       |
| Ho               | 6.61     | 0.47      | 157.6       | 0/4       | 1/4       | 3/4       | 0/4       |
| Akuse            | 6.10     | 0.10      | 17.4        | 0/4       | 1/4       | 3/4       | 0/4       |
| Akim Oda         | 5.93     | −0.98     | 139.4       | 0/4       | 1/4       | 3/4       | 0/4       |
| Abetifi          | 6.67     | −0.75     | 594.7       | 0/4       | 1/4       | 2/4       | 1/4       |
| Akatsi           | 6.14     | 0.80      | 53.6        | 0/4       | 1/4       | 2/4       | 1/4       |
| Axim             | 4.86     | −2.24     | 37.8        | 0/4       | 1/4       | 1/4       | 2/4       |
| Accra            | 5.56     | −0.16     | 67.7        | 0/4       | 0/4       | 3/4       | 1/4       |
| Ada              | 5.77     | 0.62      | 5.2         | 0/4       | 0/4       | 1/4       | 3/4       |
| Saltpond         | 5.27     | −1.06     | 439         | 0/4       | 0/4       | 1/4       | 3/4       |
| Takoradi         | 4.88     | −1.75     | 4.6         | 0/4       | 0/4       | 1/4       | 3/4       |
stations in the north (0.83–0.86) were also significant at Abetifi, Ho, Kumasi, Sefwi Bekwai, Kete Krachi, Sunyani and Wenchi (Table S3) at the transition or central part of Ghana. Factors explaining the characteristics of \( T_{\text{min}} \) in the north in the range of 0.84–0.90 were also significant at Kete Krachi, Sunyani and Wenchi (Table S4).

Most of the stations scoring half or more out of the four parameters under cluster two are identified in the forest areas (either deciduous or transitory). PCA of rainfall showed that Akatsi, Kete Krachi, Sunyani and Wenchi were insignificant under factor 3, explaining the similarities in rainfall characteristics (Table S2). However, Sunyani and Wenchi had similar characteristics under factor 5, which other classification may have been used to group them under transitional zone like Amekudzi et al. (2015). Factors explaining similar characteristics in RH for forest areas (southern part of Ghana) were significant in the range of 0.53–0.74; however,

### Table 2: ANOVA of rainfall, RH, \( T_{\text{max}} \) and \( T_{\text{min}} \) on monthly basis

| Synoptic station | Rainfall | RH   | \( T_{\text{max}} \) | \( T_{\text{min}} \) |
|------------------|----------|------|-------------------|-------------------|
| **Cluster 1**    |          |      |                   |                   |
| Navrongo         | 80.90    | 40.67| 35.26             | 22.91             |
| Wa               | 80.71    | 44.03| 33.81             | 22.61             |
| Tamale           | 88.77    | 45.04| 34.39             | 22.80             |
| Yendi            | 101.26   | 46.97| 33.97             | 22.39             |
| Bole             | 89.17    | 49.70| 33.13             | 21.08             |
| Kete Krachi      | 111.76   | 55.58| 32.83             | 23.37             |
| **Cluster 2**    |          |      |                   |                   |
| Bole             | 89.17    | 49.70| 33.13             | 21.08             |
| Kete Krachi      | 111.76   | 55.58| 32.83             | 23.37             |
| Wenchi           | 102.12   | 57.65| 31.32             | 21.55             |
| Sunyani          | 97.53    | 58.10| 31.24             | 21.46             |
| Sefwi Bekwai     | 116.94   | 60.41| 32.62             | 22.70             |
| Koforidua        | 108.36   | 62.78| 32.05             | 22.18             |
| **Cluster 3**    |          |      |                   |                   |
| Wenchi           | 102.12   | 57.65| 31.32             | 21.55             |
| Sunyani          | 97.53    | 58.10| 31.24             | 21.46             |
| Kumasi           | 111.24   | 59.24| 31.34             | 22.14             |
| Abetifi          | 93.04    | 64.72| 28.59             | 20.95             |
| Ho               | 103.79   | 59.83| 32.41             | 22.89             |
| Sefwi Bekwai     | 116.94   | 60.41| 32.62             | 22.70             |
| Akatsi           | 60.07    | 65.05| 32.10             | 23.60             |
| Koforidua        | 108.36   | 62.78| 32.05             | 22.18             |
| Akuse            | 85.98    | 61.30| 33.22             | 23.25             |
| Akim Oda         | 117.42   | 65.01| 31.62             | 22.44             |
| Accra            | 62.38    | 67.33| 31.13             | 24.04             |
| **Cluster 4**    |          |      |                   |                   |
| Ada              | 63.09    | 74.15| 31.20             | 25.12             |
| Tema             | 55.55    | 76.19| 30.07             | 24.64             |
| Accra            | 62.38    | 67.33| 31.13             | 24.04             |
| Saltpond         | 78.47    | 78.98| 29.65             | 23.45             |
| Takoradi         | 90.77    | 77.46| 30.24             | 23.45             |
| Axim             | 156.98   | 76.09| 29.60             | 24.01             

Note: Italicized rows are transitional. NB: Means sharing the same superscript are not significantly different from each other (Tukey's HSD, \( P<0.05 \)
stations like Kete Krachi, Wenchi, Sunyani, Abetifi and Kumasi had significant characteristics under factor 1 (Table S3). PCA of $T_{\text{max}}$ and $T_{\text{min}}$ at Kete Krachi, Sunyani and Wenchi showed that the linking factor is the same at the forest areas and another factor similar to $T_{\text{max}}$ and $T_{\text{min}}$ in the northern part of Ghana explaining temperature in these three stations (Table S4 and S5). Therefore, it is evident that factors explaining rainfall, RH, $T_{\text{max}}$ and $T_{\text{min}}$ at Kete Krachi, Sunyani and Wenchi can be identified with the stations transit between the northern part of Ghana and the forest areas or south (Tables S2–S5).

Ada, Accra, Tema, Saltpond, Takoradi and Axim could be classified into one group with Akatsi as a transition between the forest or southern stations and coastal stations (Table 2). Two factors separated rainfall characteristics at the coast, grouping Accra, Ada and Tema together as one and Axim, Saltpond and Takoradi as another while Akatsi was not significant in any of the five factors characterizing rainfall (Table S2). Akatsi further had a different factor explaining RH than the other stations in the coastal areas (Table S3) but similar to the stations in the south. Therefore, based on rainfall, RH, maximum and minimum temperatures, the climate of Ghana from point assessment of climatic stations could be classified into three groups. Moreover, Bole and Kete Krachi are transitions between the northern and forest areas, while Akatsi is a transition between the forest and coastal areas.

### 3.2 Seasonal climatic pattern of the different clusters

#### 3.2.1 Rainfall

Figure 3 reports the patterns of mean monthly rainfall from the different synoptic stations within the climatic zones. All the stations classified under each cluster showed similar trends except cluster 2 (Figure 3). The rainfall trends show a unimodal pattern for Cluster 1 (Figure 3a), and bimodal for Cluster 3 and 4 (Figure 3c–d), while cluster 2 had both unimodal and bimodal patterns (Figure 3b).

The bimodal rainfall patterns showed varying trends, especially with the peaks in the major and minor rainfall seasons. Cluster 3 showed a bi-modal rainfall pattern of the major seasons (March–July) peaking in June and minor season (September–November) peaking in October. The peak rainfall amount for both major and minor season was 150–220 mm (Figure 3c). Cluster 4 also showed the bi-modal pattern just like cluster 3, though the peak amount of monthly rainfall differed (Figure 3d). The peak in the major season was generally greater than 100 mm compared to the minor season in cluster 4 and recorded the lowest annual rainfall (Owusu & Waylen, 2009). Axim station showed the seasonal trend of cluster 4, however, the amount of monthly rainfall in the major season was significantly higher than all other
stations and that of the minor season was similar to the rainfall amount in the cluster 3. This peculiarity of Axim could be the reason for its classification under the forest zone in the FAO and other agro-and/or ecological zoning in Ghana (Amekudzi et al., 2015; FAO, 2005). About 60% of rainfall is received in the major season (March – July) and the remaining 30% are during the minor season (September – November). The results show that Bole and Kete Krachi belong to cluster 1 and Koforidua, Sefwi Bekwai, Sunyani and Wenchi fit into cluster 3 based on seasonal patterns (Figure 3).

3.2.2 | Relative humidity

Relative humidity varied in trends and levels or amounts from one group to another. Figure 4 reports the mean monthly relative humidity patterns from the different synoptic stations within the four clusters. The patterns observed indicate that relative humidity increases as we move from north to south. Cluster 1 in the north recorded lower relative humidity values below 30% from December to March, indicating how dry the atmosphere can be in the driest months. Lowest RH (20%) for Cluster 1 was recorded in January and the highest (70%) was in August (Figure 4a). The trend in Cluster 2 followed a similar pattern as cluster 1, however, the lowest RH in January was higher than that of cluster 1 (~30%) and the peak RH was about 72%. Furthermore, the trend does not show a sharp decline from October to December as was observed in cluster 1 (Figure 4b), except for Bole, which appeared in both Clusters. Cluster 3 recorded RH in the range of 30%–80%, with January recording the lowest (Figure 4c). The mean monthly RH of cluster 3 was above 70% from June to September. The mean monthly relative humidity for cluster 4 was consistently between 68% and 80% throughout the year except for Accra station, which showed more transition between clusters 3 and 4. Cluster 4, which consists of stations along the coast, recorded maximum relative humidity values across the four clusters, showing a trend with little variation between 60% and 85% (Figure 4d). Accra showed the same pattern as cluster 4, however, RH values were more within the range of cluster 3 due to the heat island effect in the city (Wemegah et al., 2020).

3.2.3 | Maximum and minimum temperature

Figure 5 reports the patterns of the mean monthly maximum temperatures from the different synoptic stations within the four clusters. For the pattern of the maximum temperature, the highest values were recorded in cluster 1, with around 34–40°C from November to April and the lowest values in the month of August at a mean value of

![Figure 4](image-url)
about 29°C (Figure 5a). $T_{\text{max}}$ in cluster 2 was averagely between 28°C (August) and 35°C (February) (Figure 5b). The pattern of $T_{\text{max}}$ in cluster 3 was slightly smoother compared to the others with an average range of 28°C–34°C (February). Abetifi recorded the lowest $T_{\text{max}}$ in cluster 3 at about 3°C–5°C from the other
stations’ records (Figure 5c). This could be due to the altitude (Table 1) and the high dense vegetation of the area. Moreso, the Volta Lake plays a role in the climatic dynamics at the Abetifi station contributing to the low $T_{\text{max}}$ readings. The lowest values were recorded for cluster 4 (Figure 5d), with less than 30°C from July to September across the stations. The lowest and highest $T_{\text{max}}$ in cluster 4 were about 27°C (August) and 32°C (March). Generally, the lowest mean monthly maximum temperatures were recorded during the wet season (June to October), at less than 33°C. The period of low $T_{\text{max}}$ is a period of significant rainfall amount (Figures 3, 5).

The pattern of the $T_{\text{min}}$ was different amongst the groups (Figure 6). The cluster 1 and 2 generally showed a similar pattern but at different temperature levels (Figure 6a,b). Average $T_{\text{min}}$ less than 21°C were recorded from November to January in cluster 1 and from December to January in cluster 2. The highest $T_{\text{min}}$ was recorded in April (~25°C) and March (~23°C) in clusters 1 and 2, respectively. In cluster 3, mean $T_{\text{min}}$ was between 21°C (January) and 23°C (April) with a seasonal pattern of all stations in the range of 20°C–25°C (Figure 6c). The coastal areas recorded the highest mean monthly $T_{\text{min}}$ over the assessed period at about 25°C (March). Cluster 3 and 4 showed a similar pattern, however, the temperature curve from June to September is more profound in the cluster 4 (Figure 6c,d). Abetifi station showed the lowest $T_{\text{min}}$ in cluster 3 as was in the $T_{\text{max}}$ due to similar factors of altitude and vegetation. The results showed that temperature had little variations in seasonal trends amongst transition stations within the two clusters they were grouped into.
3.3 | Statistical significance of climatic zoning

Table 2 present the Tukey HSD results of monthly total rainfall, RH, T\text{max} and T\text{min} of the stations assessed for 1976–2018. Results showed that Bole and Kete Krachi in Cluster 2 are significantly indifferent with stations in cluster 1 and therefore are merged to cluster 1 as was represented by the FAO (2005) agro-ecological zone of Ghana. Moreover, the difference between Wenchi, Sunyani, Sefwi Bekwai and Koforidua with others in Cluster 3 was not significant, therefore, they can be scientifically combined as having similar climatic properties (Table 2). Accra was classified into clusters 3 and 4, however, HSD analysis shows that rainfall, RH, T\text{max} and T\text{min} are not significantly different from stations classified under cluster 4. Therefore, in this study, the climatic zones of Ghana adopted from the FAO (2005) agro-ecological zones are Savannah, Forest and Coastal (Figure 7). Sudan Savannah and Guinea Savannah agro-ecological zones were merged to form the Savannah climatic zone (Figure S1) and the Coastal Savannah was modified based on a digital elevation model of the coast to form the Coastal climatic zone at about 30 km from the Gulf of Guinea coastline. The remaining agro-ecological zones were merged to form the Forest climatic zone (Figure 7).

The introduction of relative humidity, maximum and minimum temperature nullified the high-rainfall records at Axim which created the fourth zone according to Aryee et al. (2018) and Abass (2009) (See Figure S1). Also, the transition zone in FAO (2005) and Amekudzi et al. (2015) could be purely a result of vegetation in the agro-ecological zoning. Aryee et al. (2018) and Abass (2009) had no transition which was in line with the findings of this study. The savannah climatic zone with the largest coverage is comparable to the Tropical Savannah in the Köppen-Geiger climate classification (Beck et al., 2018; Peel et al., 2007). However, the findings of the present study showed a significant difference between the Savannah and Forest zones (Figure 7) which is missing at the global scale due to resolution and rainfall thresholds set for the Köppen-Geiger climate classification (Beck et al., 2018; Peel et al., 2007). Axim with the highest rainfall amount recorded less than 60 mm in the driest month of January (~37 mm) and could not qualify as a rainforest but a tropical monsoon according to Köppen-Geiger climate classification (Figures 3, 7 & S2). The Coastal climatic zone has similar rainfall patterns with the Savannah as captured by the Köppen-Geiger climate classification (Figures 7, S2). However, the significant variation in relative humidity, maximum and minimum temperature qualifies it to be a cluster to inform agricultural and infrastructural decision-making amongst others. This study reveals details lost under the global Köppen-Geiger climate classification for Ghana.

4 | CONCLUSION

This study delineated the climatic zones of Ghana from rainfall, relative humidity, maximum and minimum temperature records for the period 1976–2018 using the cluster and principal component analysis. Seasonal trend and Tukey Honestly Significance Difference (HSD) were used to verify the classification from the cluster analysis. Cluster analysis classified the 22 synoptic stations into four groups. Ranking the four parameters showed three major climatic groupings of the stations with cluster 2 as a transition between 1 and 3 and Accra as a transition between cluster 3 and 4. PCA showed that the transition stations belonged to one of the 3 major groups. The seasonal or monthly patterns confirmed that the transition stations are aligned to one of the major groups and are explained by similar factors. Turkey HSD further confirmed that Bole and Kete Krachi station in cluster 2 are statistically not different from cluster 1 stations.

In contrast, Accra, under cluster 3 was not statistically different from cluster 4, which is located on the coast. The variation in rainfall and RH was along latitudes, while temperature has no specific trend in classification. Therefore, the climatic zones of Ghana from latitude 7.78°C northward are classified as Savannah climatic zone and about 30 km from the coast of the Gulf of Guinea upward is the Coastal climatic zone. Between the two zones is the forest climatic zone. The findings are useful for policymakers to formulate adequate guidelines for planning and to manage climate-related interventions in Ghana. For instance, the climatic zones in this study would inform the implementation team of the planting-for-food-and-jobs initiative of the Government of Ghana, where to extend cash crops like cocoa or rubber to in the country and new locations that would be climatically favorable for the introduction of new crops. Moreover, proven adaptation strategies to climate change may be softly adopted in other locations in the same zones.

Further studies should consider the inclusion of wind speed, and solar radiation for the classification. And also adopt a good skill satellite dataset for a spatial classification to know the actual demarcations of the clusters when climatic parameters are combined for zoning.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to the Data Processing Department of the Ghana Meteorological Agency, Accra, for making the rainfall, temperature and relative humidity data available for this work. Data have
been collected in the framework of the H2ATLAS project, a BMBF-WASCAL partnership project for the assessment of Green Hydrogen Generation Potential in Africa. Special thanks to the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL), HQ Accra and KNUST, Kumasi for providing the enabling environment for the study.

AUTHOR CONTRIBUTIONS
Enoch Bessah: Conceptualization (lead); data curation (equal); formal analysis (lead); methodology (lead); software (equal); writing – original draft (lead); writing – review & editing (equal). William Amponsah: Conceptualization (equal); data curation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). Samuel Oweisu Ansah: Conceptualization (equal); data curation (equal); writing – original draft (equal); writing – review and editing (equal). Andrews Afrifa: Data curation (equal); formal analysis (supporting); methodology (supporting); writing – original draft (equal); writing – review and editing (equal). Bashiru Yahaya: Conceptualization (equal); data curation (equal); methodology (supporting); writing – original draft (equal); writing – review and editing (equal). Cosmos Senyo Wemegah: Conceptualization (equal); data curation (equal); writing – original draft (equal); writing – review and editing (equal). Michael Tanu: Conceptualization (equal); data curation (equal); supervision (equal); writing – review and editing (equal). Leonard K. Amekudzi: Formal analysis (equal); methodology (equal); supervision (equal); writing – review and editing (equal). Wilson Agyei Agyare: Conceptualization (equal); data curation (equal); formal analysis (supporting); methodology (supporting); project administration (lead); supervision (equal); writing – review and editing (equal).

DATA AVAILABILITY STATEMENT
Data would be provided upon request.

ORCID
Enoch Bessah https://orcid.org/0000-0002-2187-2022
William Amponsah https://orcid.org/0000-0002-1010-1206
Samuel Oweisu Ansah https://orcid.org/0000-0001-5375-8876
Bashiru Yahaya https://orcid.org/0000-0001-8754-100X
Cosmos Senyo Wemegah https://orcid.org/0000-0002-5936-0268
Michael Tanu https://orcid.org/0000-0002-3184-7314
Leonard K. Amekudzi https://orcid.org/0000-0002-2186-3425

Wilson Agyei Agyare https://orcid.org/0000-0002-4028-7961

REFERENCES
Abass, K. (2009) A regional geography of Ghana for senior high schools and undergraduates. Accra: Piccis Publications.
Aigang, L., Tianming, W., Shichang, K. & Deqian, P. (2009) On the relationship between latitude and altitude temperature effects. Proceedings - 2009 international conference on environmental science and information application technology, ESIAT 2009, 2, 55–58. https://doi.org/10.1109/ESIAT.2009.335
Amekudzi, L.K., Yamba, E.I., Preko, K., Asare, E.O., Aryee, J., Baidu, M. et al. (2015) Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of Ghana. Climate, 3, 416–434. https://doi.org/10.3390/cli3020416
Amissah-Arthur, A. & Jagtap, S.S. (1999) Geographic variation in growing season rainfall during three decades in Nigeria using principal component and cluster analyses. Theoretical and Applied Climatology, 63, 107–116.
Amuakwa-Mensah, F., Marbuah, G. & Mubanga, M. (2017) Climate variability and infectious diseases nexus: evidence from Sweden. Infectious Disease Modelling, 2(2), 203–217. https://doi.org/10.1016/j.idm.2017.03.003
Aryee, J.N.A., Amekudzi, L.K., Quansah, E., Klutse, N.A.B., Atiah, W.A. & Yorke, C. (2018) Development of high spatial resolution rainfall data for Ghana. International Journal of Climatology, 38, 1201–1215. https://doi.org/10.1002/joc.5238
Aslief, P.J., Quansah, E., Amekudzi, L.K., Amoako, T. & Klutse, N. A.B. (2019) Modeling the spatial distribution of global solar radiation (GSR) over Ghana using the Ångström-Prescott sunshine duration model. Scientific African, 4(2), 1–12. https://doi.org/10.1016/j.sciaf.2019.e00094
Beck, H., Zimmermann, N., McVicar, T.R., Vergopolan, N., Berg, A. & Wood, E.F. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. Science Data, 5, 180214. https://doi.org/10.1038/sdata.2018.214
Bessah, E., Boakye, E.A., Agodzo, S.K., Nyadzi, E., Larbi, I. & Awotwi, A. (2021) Changes in seasonal rainfall in the 21st-century over Ghana and its implication for agriculture productivity. Environment, Development and Sustainability, 23(8), 12342–12365. https://doi.org/10.1007/s10668-020-01171-5
Darbour, B. & Rosentrater, K.A. (2016) Agriculture and food security in Ghana. Agricultural and Biosystems Engineering Conference Proceedings and Presentations, 478, 1–16. https://lib.dr.iastate.edu/abe_eng_conf/478, https://doi.org/10.13031/aim.20162460507
Davis, R.E. & Walker, D.R. (1992) An upper-air synoptic climatology of the western United States. Journal of Climate, 5, 1449–1467.
DeGaetano, A.T. (1996) Delineation of mesoscale climate zones in the northeastern United States using a novel approach to cluster analysis. Journal of Climate, 9, 1765–1782.
FAO. (2005) Fertilizer use by crop in Ghana. Rome: Food and Agriculture Organization of the United Nations.
Githeso, A.K., Lindsay, S.W., Confalonieri, U.E. & Patz, J.A. (2000) Climate change and vector-borne diseases: a regional analysis. Bulletin of the World Health Organization, 78(9), 1136–1147.
Gong, X. & Richman, M.B. (1995) On the application of cluster analysis to growing season precipitation data in North America east of the Rockies. Journal of Climate, 8, 897–931.
Gupta, A., Kamble, T. & Machiwal, D. (2017) Comparison of ordinary and Bayesian kriging techniques in depicting rainfall variability in arid and semi-arid regions of north-West India. *Environmental Earth Sciences*, 76, 512. https://doi.org/10.1007/s12665-017-6814-3

Guttmann, N.B. (1993) The use of L-moments in the determination of regional precipitation climates. *Journal of Climate*, 6, 2309–2325.

Haines, H.A. & Olley, J.M. (2017) The implications of regional variations in rainfall for reconstructing rainfall patterns using tree rings. *Hydrological Processes*, 31, 2951–2960.

Hanamean, J.R., Jr., Pielke, R.A., Sr., Castro, C.L., Ojima, D.S., Reed, B.C. & Gao, Z. (2003) Vegetation greenness impacts on maximum and minimum temperatures in Northeast Colorado. *Meteorological Applications*, 10, 203–215. https://doi.org/10.1017/S1350482703003013

IPCC. (2013). Annex III: Glossary [Planton, S. (ed.)]. In: Climate change 2013: the physical science basis) In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. et al. (Eds.) *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Jebari, S., Berndtsson, R., Uvo, C. & Bahri, A. (2009) Regionalizing fine time-scale rainfall affected by topography in semi-arid Tunisia. *Hydrological Sciences Journal*, 52(6), 1199–1215.

Kabo-Bah, A.T., Diji, C.J., Nokoe, K., Mulugeta, Y., Obeng-Ofori, D. & Akpoti, K. (2016) Multiyear rainfall and temperature trends in the Volta River basin and their potential impact on hydropower generation in Ghana. *Climate*, 4(4), 49. https://doi.org/10.3390/cli40400496

Kidson, J.W. (2000) An analysis of New Zealand synoptic types and their use in defining weather regimes. *International Journal of Climatology*, 20, 299–316.

Lazenby, M.L., Landman, W.A., Garland, R.M. & DeWitt, D.G. (2014) Seasonal temperature prediction skill over southern Africa and human health. *Meteorological Applications*, 21, 963–974. https://doi.org/10.1002/met.1449

Lin, G.-F., Chang, M.J. & Wu, J.T. (2017) A hybrid statistical downscaling method based on the classification of rainfall patterns. *Water Resources Management*, 31(1), 377–401.

Lund, R. & Li, B. (2009) Revisiting climate region definitions via clustering. *Journal of Climate*, 22, 1787–1800.

Machiwal, D., Dayal, D. & Kumar, S. (2017) Long-term rainfall trends and change points in hot and cold arid regions of India. *Hydrological Sciences Journal*, 62(7), 1050–1066.

Machiwal, D., Kumar, S., Meena, H.M., Santra, P., Singh, R.K. & Singh, D.V. (2019) Clustering of rainfall stations and distinguishing influential factors using PCA and HCA techniques over the western dry region of India. *Meteorological Applications*, 26, 300–311. https://doi.org/10.1002/met.1763

Medina-Cobo, M.T., García-Marín, A.P., Estévez, J., Jiménez-Hornero, F.J. & Ayuso-Muñoz, J.L. (2017) Obtaining homogeneous regions by determining the generalized fractal dimensions of validated daily rainfall data sets. *Water Resources Management*, 31(7), 2333–2348.

Modarres, R. & Sarhadi, A. (2011) Statistically-based regionalization of rainfall climates of Iran. *Global and Planetary Change*, 75, 67–75. https://doi.org/10.1016/j.gloplacha.2010.10.009

Nnaji, C.C., Mama, C.N. & Ukpabi, O. (2016) Hierarchical analysis of rainfall variability across Nigeria. *Theoretical and Applied Climatology*, 123(1–2), 171–184. https://doi.org/10.1007/s00704-014-1348-z

Owusu, K. & Waylen, P.R. (2009) Trends in spatio-temporal variability in annual rainfall in Ghana (1951-2000). *Weather*, 64(5), 115–120. https://doi.org/10.1002/wea.255

Patz, J.A., Martens, W.A., Focks, D.A. & Jetten, T.H. (1998) Dengue fever epidemic potential as projected by general circulation models of global climate change. *Environmental Health Perspectives*, 106, 147–153. https://doi.org/10.1289/ehp.98106147

Peel, M.C., Finlayson, B.L. & McMahon, T.A. (2007) Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

Planchnier, O. (2000) A study of the coastal climates in France using temperature and precipitation data (1961–1990). *Meteorological Applications*, 7, 217–228. https://doi.org/10.1017/S135048270001481

Revadekar, J.V., Hameed, S., Collins, D., Manton, M., Sheikh, M., Borgaonkar, H.P. et al. (2013) Impact of altitude and latitude on changes in temperature extremes over South Asia during 1971–2000. *International Journal of Climatology*, 33, 199–209. https://doi.org/10.1002/joc.3418

Sabziparvar, A.A., Movahedi, S., Asakereh, H., Maryanaji, Z. & Mosadodian, S.A. (2015) Geographical factors affecting variability of precipitation regime in Iran. *Theoretical and Applied Climatology*, 120(1–2), 367–376. https://doi.org/10.1007/s00704-014-1174-3

Scheitlin, K. (2013) The maritime influence on diurnal temperature range in the Chesapeake Bay area. *Earth Interactions*, 17(21), 1–14. https://doi.org/10.1175/2013El00054.1

Şen, Z. & Habib, Z. (2001) Monthly spatial rainfall correlation functions and interpretations for Turkey. *Hydrological Sciences Journal*, 46(4), 525–535. https://doi.org/10.1080/02626660109492848

Steinbach, M., Tan, P.-N., Kumar, V., Klooster, S. & Potter, C. (2003) Discovery of climate indices using clustering. Proceedings of Ninth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, New York, NY, ACM, pp. 446–455.

Stooksbury, D.E. & Michaels, P.J. (1991) Cluster analysis of southeastern U.S. climate stations. *Theoretical and Applied Climatology*, 44, 143–150. https://doi.org/10.1007/BF00686169

Straus, D.M., Corti, S. & Molteni, F. (2007) Circulation regimes: chaotic variability versus SST-forced predictability. *Journal of Climate*, 20, 2251–2272. https://doi.org/10.1175/JCLI4070.1

Suhaila, J. & Jemain, A.A. (2009) A comparison of the rainfall patterns of Ninth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, New York, NY, ACM, pp. 446–455.

Stooksbury, D.E. & Michaels, P.J. (1991) Cluster analysis of southeastern U.S. climate stations. *Theoretical and Applied Climatology*, 44, 143–150. https://doi.org/10.1007/BF00686169

Suhaila, J. & Jemain, A.A. (2009) A comparison of the rainfall patterns of Ninth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, New York, NY, ACM, pp. 446–455.

Stooksbury, D.E. & Michaels, P.J. (1991) Cluster analysis of southeastern U.S. climate stations. *Theoretical and Applied Climatology*, 44, 143–150. https://doi.org/10.1007/BF00686169

Vrac, M. & Naveau, P. (2007) Stochastic downscaling of precipitation: from dry events to heavy rainfalls. *Water Resources Research*, 43, W07402. https://doi.org/10.1029/2006WR005308

Wemegah, C.S., Yamba, E.I., Aryee, J.N.A., Sam, F. & Amekudzi, L. K. (2020) Assessment of urban heat Island warming in the Greater Accra region. *Scientific African*, 8, e00426. https://doi.org/10.1016/j.sciaf.2020.e00426
Yao, C.S. (1997) A new method of cluster analysis for numerical classification of climate. *Theoretical and Applied Climatology*, 57, 111–118. https://doi.org/10.1007/BF00867982

SUPPORTING INFORMATION
Additional supporting information may be found in the online version of the article at the publisher’s website.

How to cite this article: Bessah, E., Amponsah, W., Ansah, S. O., Afrifa, A., Yahaya, B., Wemegah, C. S., Tanu, M., Anekudzi, L. K., & Agyare, W. A. (2022). Climatic zoning of Ghana using selected meteorological variables for the period 1976–2018. *Meteorological Applications*, 29(1), e2049. https://doi.org/10.1002/met.2049