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# ANALYSIS OF ATMOSPHERIC STABILITY AND CONVECTIVE ACTIVITIES FOR RADIO APPLICATIONS OVER SELECTED LOCATIONS IN NIGERIA

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**ABSTRACT**

*This study investigates the thermodynamic structure of the convective atmosphere during the rainy period of March to October, and the dry period of November to February, in the southwestern part of Nigeria. Eight (8) years of re-analysis data, spanning January 2011 to December 2018 across five stations in southwestern Nigeria were employed for the study. The stability indices employed for the analysis include Humidity Index (HI), K-index (KI), Boyden-index (BI) and the Total-totals index (TT). Frequency of occurrence, spatial distribution, monthly variation and time series analyses of the indices established the predominance of thunderstorm activities at the locations during the rainy months of March to October. This underscores the high suitability of the stability indices for predicting atmospheric convective activities in these locations. The results play important role in providing relevant data for radio link designers, meteorologists, and aerospace practitioners, for effective planning and design of atmospheric operational activities.*

## 1. Introduction

Understanding atmospheric stability conditions is important for proper planning of radio communication links, weather forecasting and meteorological applications. Hence, the analysis of atmospheric convective activities is of paramount importance to radio engineers, weather forecasters and operational meteorologists. In radio meteorology, convection refers primarily to atmospheric motions in the vertical direction. As the earth is heated by the sun, different surfaces absorb different amounts of energy, and convection may occur where the surface heats up very rapidly.

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As the surface warms, it heats the overlying air, which gradually becomes less dense than the surrounding air and begins to rise. The process of convection begins at sunrise when the sun's radiation strikes the ground, heating it. As the ground's temperature warms, it heats the layer of air directly above it through conduction (the transfer of heat from one substance to another). But, since barren surfaces like sand, rocks, and pavement become warmer faster than ground covered by water or vegetation, air at and near the surface heats unevenly. As a result, some pockets of air get warm faster than others. The faster warming pockets become less dense than the cooler air that surrounds them and they begin to rise. These rising columns or currents of air are called "thermals." As the air rises, heat and moisture are transported upward (vertically) into the atmosphere. The stronger the surface heating, the stronger and higher up into the atmosphere the convection extends.

Forecasting and issuance of warnings on possible adverse weather phenomena form the primary concern of every weather forecaster and operational meteorologist. Also, radio engineers have the primary responsibility of designing telecommunication architecture that can withstand any kind of weather, hence their stake in understanding atmospheric convective activities and thermodynamic processes. Consequently, knowledge of atmospheric thermodynamic structure and convective activities is sacrosanct for weather forecasting and radio planning operations. Convective activities also play significant roles in the sustenance and preservation of life processes, especially in terms of thermal regulation within the atmosphere, weather forecasting for agricultural, telecommunications, aviation and military reconnaissance activities, among others [1-4]. Thorough understanding of atmospheric convective events and thermodynamic processes helps with adequate preparation and prevention of adverse weather phenomena occurrences. Atmospheric instability cannot be unconnected with factors that fuel convective activities, hence the degree and frequency of occurrence of the latter can be characterized using properties of the former known as stability indices. Atmospheric instability has significant implication for wireless radio propagation such as altering the trajectory and strength of a signal as it travels from the transmitting antenna to the receiving station. Depending on the condition of atmospheric constituent parameters like temperature, pressure and water vapour pressure, at different atmospheric layers, signals may bend away from, or towards the horizon, or get trapped within an atmospheric layer. These phenomena are referred to as sub-refraction, super-refraction or ducting respectively [4,5].

Convective weather development is dependent mainly on two factors, namely: atmospheric instability and moisture availability in the troposphere. Another factor, apart from the first two, is the existence of a triggering mechanism that allows air parcels to be lifted to a point in which free flow is attained, which is especially important for in-depth convection development during severe weather [5]. The study of atmospheric stability begins with the notions of static stability and the parcel technique, progressing to related images of conditional, absolute, latent, and potential/convective instability. The stability indices were created in this context to provide an indicator of the first two convective-generating mechanisms (individually or in combination), and they are commonly utilized by operational forecasters for very-short-range (a few hours) prediction.

Many studies have reported their findings on thunderstorm forecasting using stability indices, and their skill ratings have been classified. In most cases, instability indices are used to calculate atmospheric instability [5-12]. By measuring the thermodynamic instability with satellite, reanalysis, and radiosonde data, stability indices have been produced and utilized to improve both research and operational forecasting of severe weather and thunderstorms. Similarly, [13] observed with the equatorial atmosphere radar, the convective activities associated with intra-seasonal variation over Sumatera, Indonesia, and reported that convective activities that played out over the study area in the month of June, 2002 were in tandem with the general observations during TOGA COARE. The work also reported that the increase in convective activities, which is due mainly to local circulatory system, may be significant in providing moisture for the middle and upper atmosphere of that location. Likewise, [14] employed radiometric observations to investigate convective activities and atmospheric instability at Kolkata, India, and obtained the short-term variation of brightness temperature (BT) at 22 GHz, and lifting index (LI) that is effective for providing real-time update on convective activities at the location. More recently also, [15] studied atmospheric convection, dynamics and topography shape the scaling pattern of hourly rainfall extremes with temperature globally, and reported that local features of atmospheric convection, larger-scale dynamics and orography, affect the dependence of extreme rainfall on surface temperature. Similar studies that investigated and reported the significance of convective activities on diverse atmospheric conditions and phenomena include – [16-23], among several others.

However, the study of atmospheric convective activities and thermodynamic processes over Nigeria as a geographical space or any of its constituent locations has not enjoyed significant attention from local or foreign researchers, leading to paucity of research output from Nigeria, on this premise, neither has much study been conducted on the comparison of the instability indexes. This paucity of research output may not be unconnected with the poor existing radiosonde facilities and network, leading to data deficit. Consequently, research works in this and related fields are compelled to depend on reanalysis data.

All of the instability indices - Humidity Index (HI), K-index (KI), Boyden-index (BI) and the Total-totals index (TT), in general, represent the propensity for the occurrence of convective activities. Also, these parameters determine, to a large extent, some radio propagation impairment mechanisms, such as multipath fading, tropo-scatter, rain and gaseous attenuations and anomalous propagation phenomena [13,15,16]. This follows the significant role played by increased atmospheric moisture content, and dynamic temperature and pressure variation, in inducing wireless radio channel impairments through absorption and scattering of the radio waves [20-23]. Their threshold values are approximate and may change depending on geographic location, season, and synoptic situation. The Boyden Index [8], the K-index [7], and the Lifted Index [6] are employed in this study, as well as the Humidity Index and the Total Totals Index.

Because radiosonde observations are required to understand the vertical distribution of temperature and water vapor, few worldwide measurements are available [24]. The goal of this research is to employ satellite remote sensing intervention to enhance accurate forecasting of severe weather phenomena by measuring atmospheric instability at the regional and local levels of southwestern Nigeria. Therefore, the spatial distribution of five instability indices across selected stations in southwestern Nigeria was conducted to examine atmospheric instability and thermodynamic processes over the region. The variables of interest which include temperature, humidity, and geopotential height profiles were obtained from the archive of Era-5 satellite (reanalysis) database.

A thunderstorm is defined as a cumulonimbus cloud that is energetic enough to produce lightning and thunder [25]. Thunderstorms are convective clouds that form when moist air rises and condenses into liquid water, releasing latent heat and feeding the updraft. The vertical dimension of a thunderstorm cloud has the same order of magnitude as its horizontal dimension, which is its distinguishing feature. Thunderstorm clouds are significantly taller than regular clouds. Thunderstorms feature strong vertical motions, with updraft speeds of up to 50 m/s recorded during severe thunderstorms [26]. Thunderstorms are caused by atmospheric convection that is deep and wet. Convection is defined by [27] as a group of small-scale, thermally directed circulations caused by gravity acting on an unstable vertical distribution of mass. Even with this narrow definition, a wide range of atmospheric phenomena on various scales are included. Convection is a difficult subject in atmospheric sciences because of the interconnections between bigger and smaller scales and the important influence of water phase shifts.

## 2. Material and Method

The thermodynamic structure of the atmosphere was studied over five (5) stations in south-western Nigeria (Akure: 7.2571’N, 5.2058’E), (Ibadan: 7.3775’N, 3.9470’E), (Osogbo: 7.7827’N, 4.5418’E), (Ado: 7.6124’N, 5.2371’E), and (Lagos: 6.5344’N, 3.3792’E) considering both the rainy (March-October) and dry season month (November-February) using ERA-5 Satellite data. Eight years (2012-2020) data was obtained from the archive of European Centre for Medium Range Weather Forecast (ECMWF) with resolution of 0.25 degrees. The indices examined in this study include K Index (KI), Total Totals Index (TT), Humidity Index (HI) and Boyden-index (BI).

### 2.1 K Index (KI)

Based on the vertical temperature lapse rate and the amount and vertical extent of low-level moisture in the atmosphere, the K index is a measure of thunderstorm potential. The K Index (KI) is very useful for detecting convective and heavy-rain situations. Temperatures at 850, 700, and 500 hPa, as well as dewpoints at 850 and 700 hPa, are used to calculate it. The higher the moisture content and the wider the temperature difference between 850 and 500 degrees Fahrenheit, the higher the KI and convection potential.

$$K = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}) \quad (1)$$

Table 1. Possibility of thunderstorms with K-Index

| **KI** | **Thunderstorm Potential** |
|---|---|
| 0-15 | 0% |
| 16-19 | 20% unlikely |
| 20-25 | 35% isolated thunderstorm |
| 26-29 | 50%widely scattered thunderstorm |
| 30-35 | 80% numerous thunderstorm |
| >36 | 100% chance of thunderstorm |

### 2.2 Total Totals Index

The TT was created to identify locations in the United States that could be prone to severe weather [5]. Higher TT levels raise the chance of severe development. The temperature and dewpoint at 850 hPa, as well as the temperature at 500 hPa, are used to calculate it. The greater the instability and the consequent TT value, the higher the 850 hPa dewpoint and temperature and the lower the 500 hPa temperature. The Vertical Totals (VT) and the Cross Totals (CT) make up the Total Totals Index (CT). Static stability, or the lapse rate between 850 and 500 mb, is represented by the VT. The 850 mb dew point is included in the CT. As a result, TT accounts for both static stability and 850 mb moisture, but it is inaccurate in cases where low-level moisture is below 850 mb. Furthermore, if a strong capping inversion is present, convection may be hindered despite a high TT value.

$$TT = T_{850} + T_{d850} - 2T_{500} \quad (2)$$

Table 2. Possibility of thunderstorms with TT-Index

| **TT** | **Thunderstorm potential** |
|---|---|
| 45-50 | Thunderstorm possible |
| 50-55 | Severe thunderstorm possible |
| 55-60 | Severe thunderstorm most likely |

### 2.3 Humidity Index

The humidity Index is simply computed from temperatures at 850, 700, and 500 hPa, and dewpoints at 850, 500 and 700 hPa. It is computed using (3)

$$HI = (T - T_d)_{850} + (T - T_d)_{700} + (T - T_d)_{500} \quad (3)$$

Table 3. Possibility of thunderstorms with HI-Index

| HI | Thunderstorm Potential |
|---|---|
| 25-30 | More probability of thunderstorm |
| 31-35 | Less probability of thunderstorm |

**2.4 Boyden Index**

The Boyden Index (BI) is given by the formula [8]:

$$BI = Z_{700-1000} - T_{700} - 200 \quad (4)$$

where Z is the difference between the geopotential height between 700hPa and 1000hPa, and T is the atmospheric temperature at 700hPa. The BI does not appear to take moisture into account, unlike most instability indices. It simply describes the vertical temperature profile between 1000 and 700 hPa and was created to assess thunderstorm danger during frontal passes over the United Kingdom. Thunderstorm activity in the troposphere is usually indicated by a threshold value of 94 [8].

## 3.0 Results and Discussion

### 3.1 Analysis of the thermodynamic indices.

Figure 1(a-d) depicts the percentage of occurrence of the thermodynamic indices in the South-western region of Nigeria. The stations under consideration cuts across all the major cities of the region and they include: Lagos, Osogbo, Ibadan, Akure, Ado. The discussion of the various indices is presented below.

#### 3.1.1Total Totals Index (TT-Index)

According to [5], the threshold value of the totals total index is estimated to be +44. Figure (1a) presents the range and the percentage of occurrence of the totals total index. The TT-index ranges from values less than 30 to 60 with and interval of 5. The percentage of occurrence is very much high in Lagos which is a coastal region surrounded by the Atlantic Ocean. More probability of occurrence was observed when the values range between 40-45. The totals total index as shown in figure (1a) does not show linear dependency on the convective activity. Therefore, this study affirms that the TT-index alone is not a good predictor of thunderstorm occurrence in the South-western region of Nigeria.

#### 3.1.2 K-Index

The percentage of occurrence of K-index is presented in Figure (1b). The values are at intervals of 5 and range between 0 and values greater than 36. The work of [7] reported that the greater the K-index value above 20, the more unstable the atmosphere and the better the chance of thunderstorm occurrence. Maximum probability of occurrence was found at the range of 30-35 with probability of 76%, 70%, 78%, and 62% for Ibadan, Lagos, Osogbo, and Akure respectively.

#### 3.1.3 Humidity-Index (HI)

The occurrences and severity of thunderstorm increases as the value of HI decreases, as indicated in Figure (1c). More probability of occurrence was obtained when HI values ranges below 30 for all the stations observed. This shows that HI is a comparatively good predictor for convective activities. Li et al., [10] recorded a +30 threshold value for the HI.

#### 3.1.4 Boyden-Index(BI)

The higher the value of the BI, the greater the risk of the thunderstorm. A threshold value of 94 is indicative of thunderstorm activity in the troposphere [8]. Most of the station observed in the study location is below the threshold of 94, indicating less probability for thunderstorm occurrence.

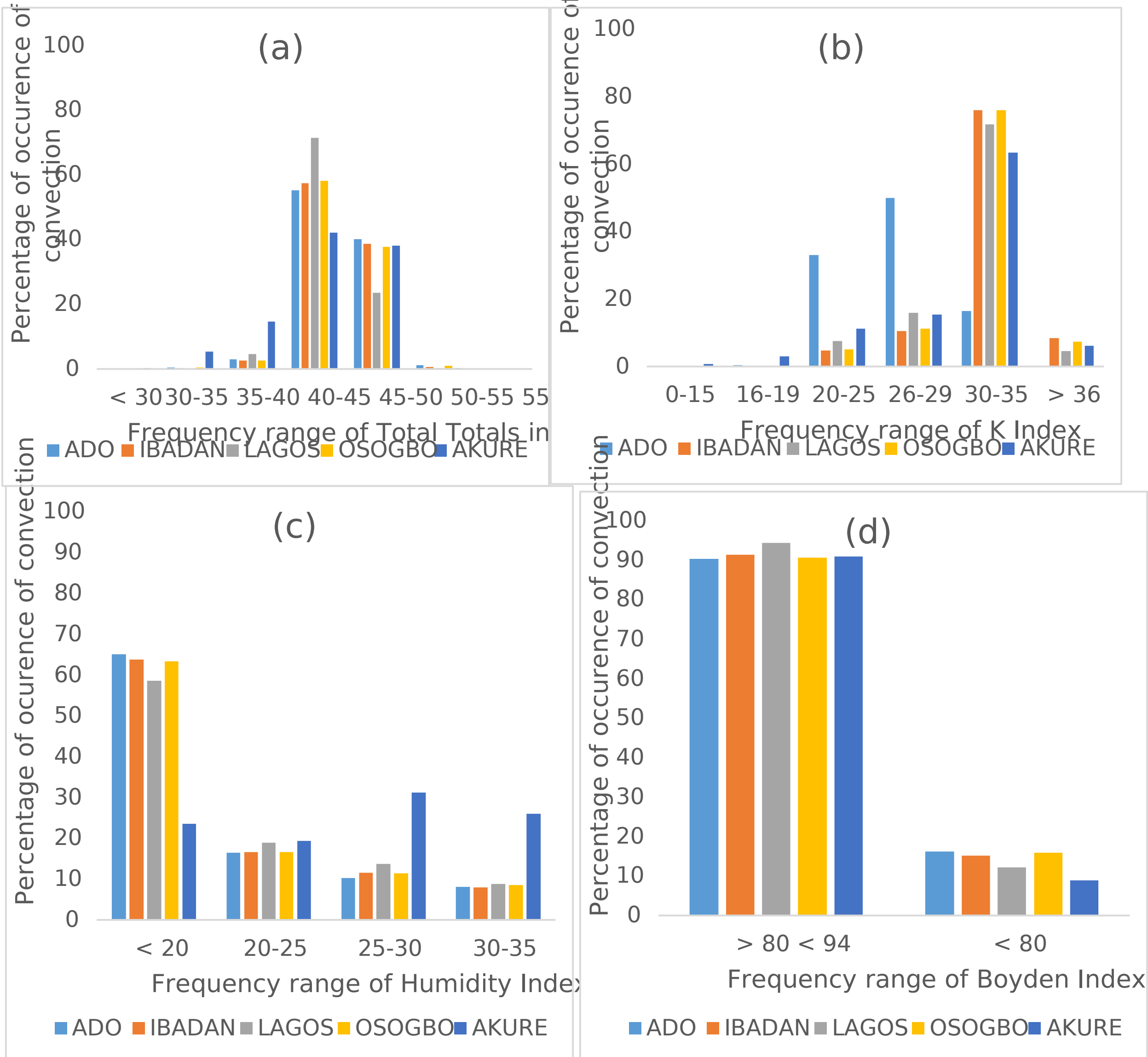


Figure 21: Percentage of occurrence of convection of the thermodynamic indices for (a) Total totals index (b) K-index (c) Humidity index(d) Boyden index.

### 3.2 Thermodynamic Structure of the Atmosphere On 22nd April, 2020.

A heavy downpour of rain that comes with widespread of thunderstorm was reported over Lagos, Akure and Osogbo on the 22nd of April, 2020. Figure 2(a-d) gives the spatial distribution of the stability indices over the South-western Nigeria.

In the region of formation of thunderstorm, the K-Index value as shown in Figure (2a) range between 30-31 for Ado and Akure and 32-33 for Lagos, Ibadan and Osogbo which show high percentage of convective activity.

The TT-index values as shown in Figure (2b) ranges between 44-48 $^{0}$C which shows the possibility for convective activity. Due to the high convective nature of the day, the Humidity Index values as shown in Figure (2c) ranges between 26-28 which are well below the threshold of +30$^{0}$C as recorded by [10]. The spatial analysis for the Boyden-index is described in Figure (2d). The values ranges show that there is possibility for the occurrence of thunderstorm, as the values ranges between 80-81.

Convective clouds emerged over Ibadan, Osogbo, Akure, Lagos, and Ado as a result of the instability observed over south-western Nigeria, according to the maps of instability indices. On the other hand, convective clouds have not been seen in other places. The legitimacy of the satellite method for estimating instability is not called into doubt by this disparity because instability indices can only be viewed as markers of a conducive environment for convection to occur.

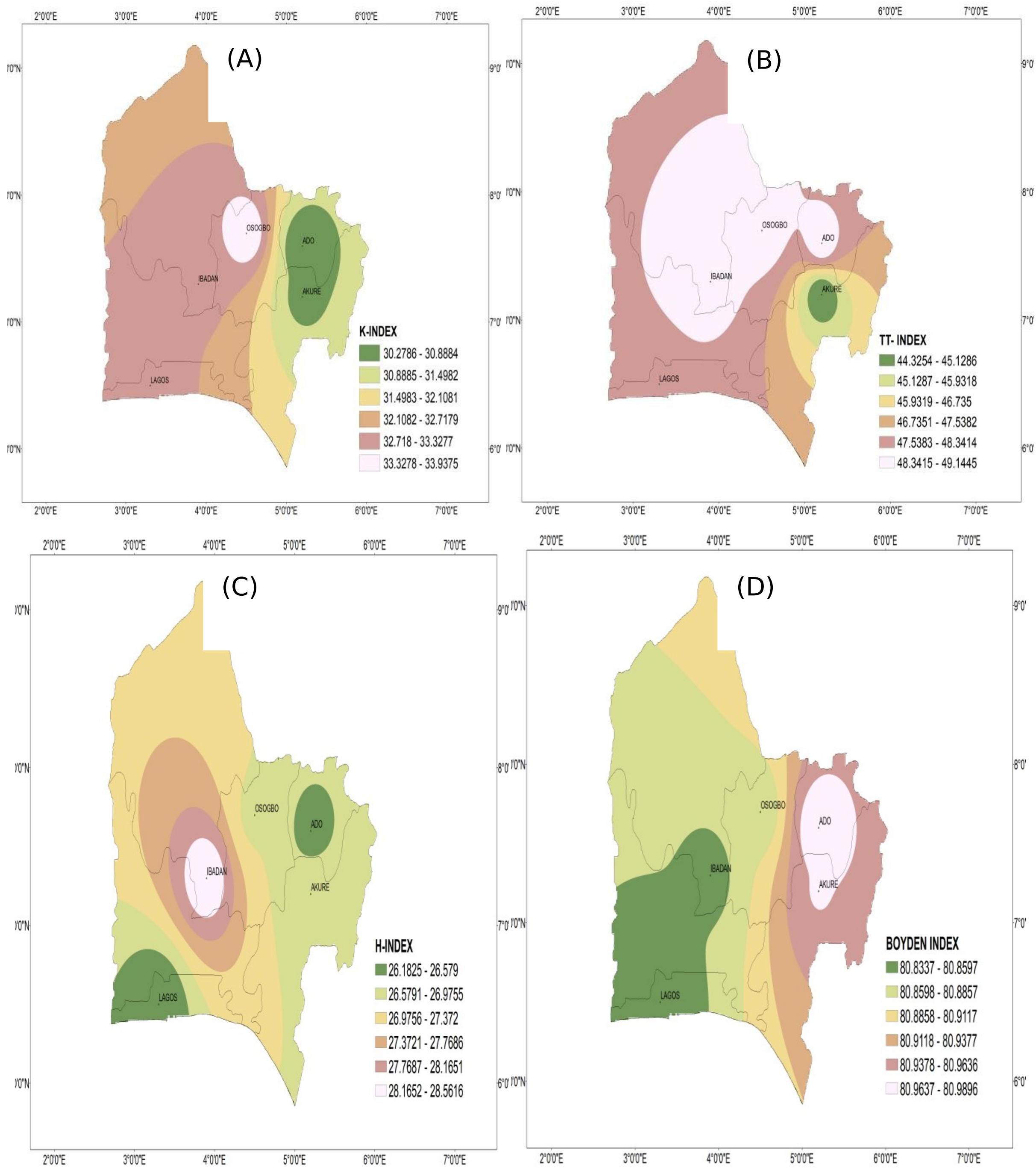


Figure 2.0: Spatial distribution of thermodynamics indices on 22 April 2020 for (a) K-index (b) TT-index (c) H-index (d) Boyden-index.

### 3.3 Monthly Variation of the thermodynamic indices

The monthly means of the thermodynamic indices is presented in Figure3 (a-d). The analysis of the Total totals-index as presented in Figure (3a) show that the index value observed during the dry month (November-February) is lower and higher during the rainy season month (March-October).

The monthly means of the Humidity index is presented in Figure (3b). As reported from previous literature, the probability of thunderstorm occurrence increases as the humidity index value decreases. Low values are observed in the rainy season month, while high values are recorded in the dry season months [4,14-16].

The monthly variation of the Boyden index is presented in Figure (3c). The values observed in all the month are below the threshold of +94, but there is tendency for thunderstorm to occur as the values observed are within the range of prediction (80 above).

The monthly means of the K-index presented in Figure (3d) shows that the probability of occurrence of Thunderstorm is high in most of the station observed throughout the year except for Lagos and Ibadan where the probability of thunderstorm occurrence is unlikely.

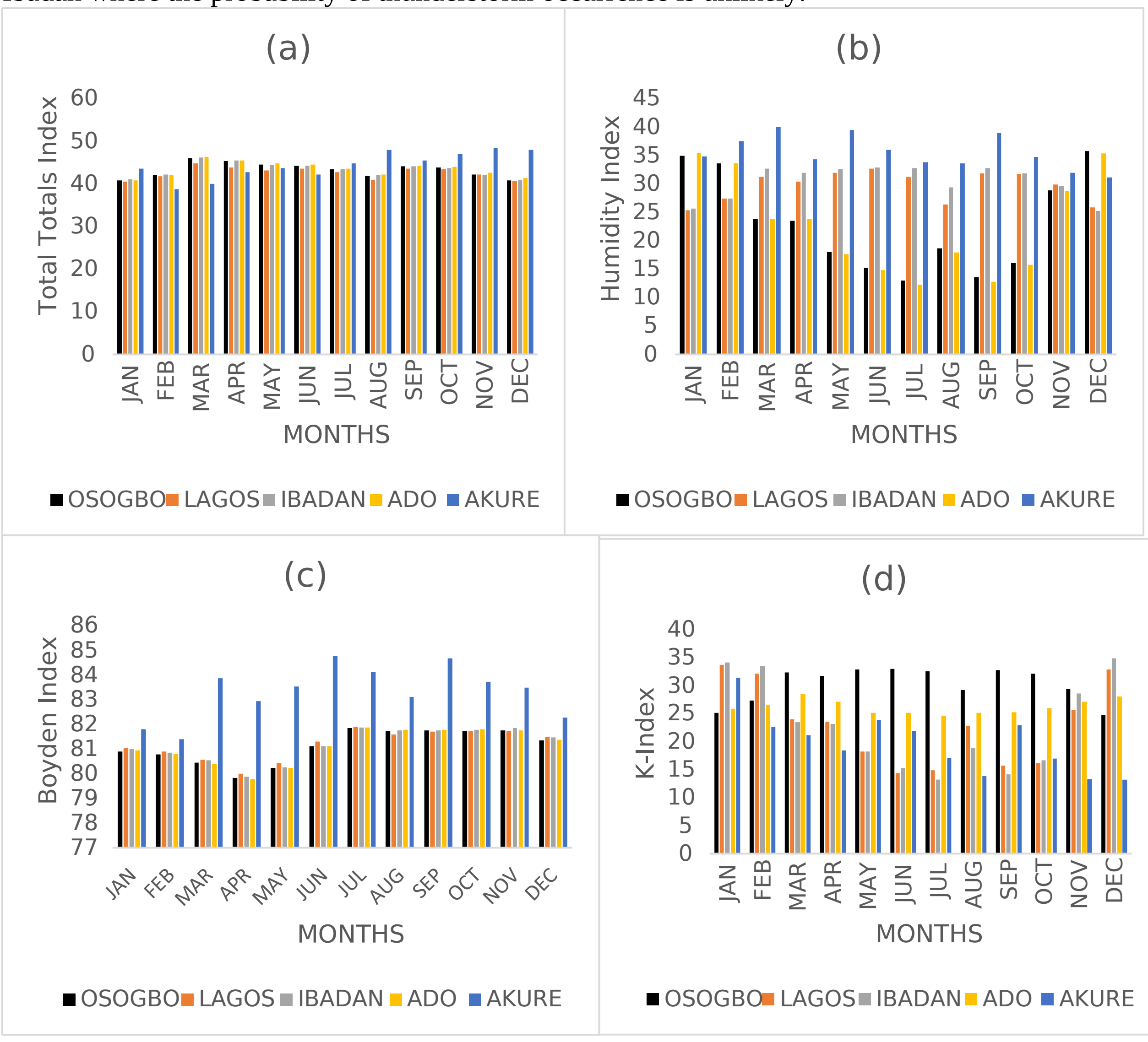


Figure 3: Monthly variation of thermodynamics indices (a) Total Totals Index (b) Humidity-index (c) Boyden-index (d) K-index

## 3.4 Time series plots

The time-series plot of Humidity Index for each of the station under consideration is presented in Figure 4.0. The Periodic Nature of the HI is vivid from the annual cyclic trend, which underscores its dependence on atmospheric variability. Similar trends were observed in all the locations. This shows that HI is a comparatively good predictor for convective activities, and explains why thunderstorm activities increase as the value of HI decreases.

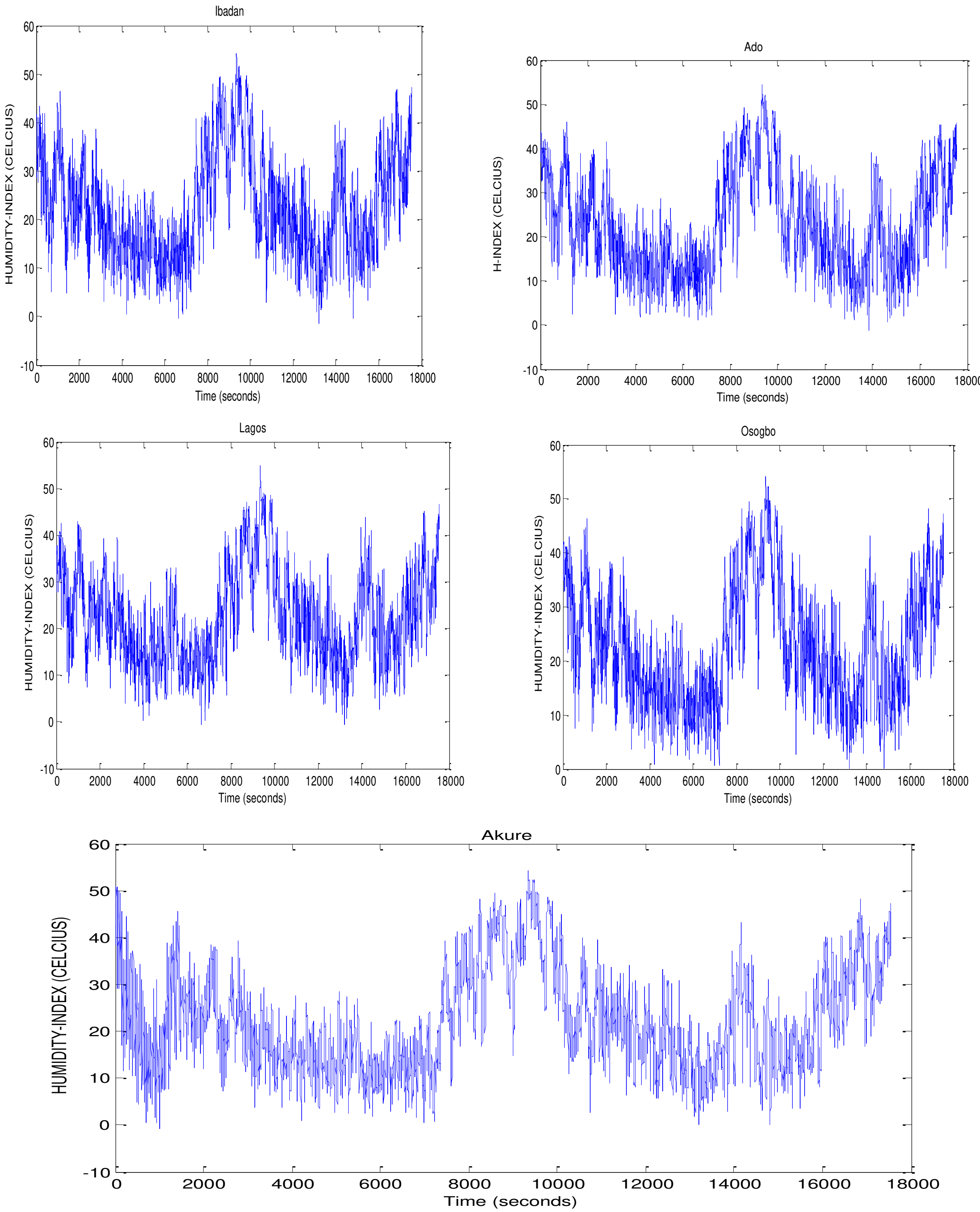


Figure 4: Time series plot of thermodynamic indices (Humidity Index)

## Conclusion

The occurrence of convective activities has been studied over South-western Nigeria, using satellite derived data. The convective activity of the atmosphere over south-western Nigeria responds to the value of the thermodynamic indices and parameters during pre-monsoon. The skill scores of different stability indices during convective activity are brought out. The value of the K-Index is in the range of 30-35 over the unstable region. The TT-Index value are in the range of 40-55 over the unstable region and very low values over the stable region. Among the observed indices, the Humidity index tends to be a comparatively good predictor of convective activities. The results are in tandem with the report of Matthew et al., [6] and Falodun et al., [9], which discovered that the ranges of values given by the stability indices were rather accurate in predicting the circumstances of atmospheric convection and instability across various climatic zones. Their depiction of seasonal fluctuations in atmospheric instability conditions, as well as the movement and oscillation of the north-easterly and south-westerly wind systems, was sufficient. The work also reported that decreased precipitation corresponds to declining trends of stability indices during the period of investigation, and this has implications for better convection system and precipitation forecasting in West Africa.

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