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Planetary Layer Lapse Rate Comparison of Tropical, Montane and Hot Semi-Arid Climates of Nigeria

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ARTICLE INFO*Article history*

Received: 15 June 2020

Accepted: 27 June 2020

Published Online: 30 June 2020

Keywords:

Lapse rates

Planetary layer

Climate belts

Nigeria, Emissions

ABSTRACT

This study assessed the pattern of planetary layer lapse rate across the major climate belts of Nigeria. Six years' data (2010-2015) for air temperature values between 1000 mbar and 850 mbar atmospheric pressure levels were acquired from Era-Interim Re-analysis data centre. The data was retrieved at 6-hourly synoptic hours: 0000H, 0600H, 1200H and 1800H at 0.125o grid resolution. Results showed that the lower tropospheric layers throughout the various climate belts has a positive lapse rate. Findings also revealed that the average annual lapse rate condition were: Tropical wet zone (Port Harcourt) -5.6 oC/km; Bi-modal Tropical continental zone (Enugu) 5.8 oC/km; Montane zone (Jos) -6.5 oC/km; Mono-modal Tropical continental zone (Kano) -6.6 oC/km; and Hot semi-arid zone (Maiduguri) -6.6 oC/km. This average values presents the lapse rates to be close to the Saturated Adiabatic Lapse Rate (SALR). Average diurnal results for the climate belts showed that lapse rate is higher during the afternoon and transition periods than the rest periods and increases from the coastal areas northward. The seasonal periods of highest lapse rates during the day time are from December - May (i.e. 5.8-9.5 oC/km) with slight decrease from June - November. The positive lapse rate of range -1.8 - -5.9 oC/km observed during the period of dawn across the entire region showed that infrared radiation was still being released and modified by less energetic mechanical turbulence that characterizes the surface layer across Nigeria. This also indicates that global warming is real and in substantial effect. The study findings imply that conditional instability prevailed over the entire region, therefore, the planetary layer environment will be of slow to moderate dispersive potential and will require forceful mechanism to lift emissions are introduced into it. It is recommended that industrial stacks are above 50 m to enhance the dispersion of emissions aloft.

1. Introduction

Lapse rate is the decrease of environmental air temperature in relation to vertical height. It is generated when the earth surface heated by solar radiation warms the overlaying air and the temperature of this am-

bient air reduces as it graduates upwards from the source of warming i.e. earth surface^[1]. The global average tropospheric lapse rate is -6.5 °C per km, however, this value varies with vertical height, latitude and season^[2]. The lapse rate principle is based on a heated parcel of air that rises and expands due to decreasing pressure with height.

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The air parcel's expansion reduces its temperature without exchanging heat with the surrounding environment. This is referred to as 'adiabatic lapse rate'. When dry air rises it cools at the dry adiabatic lapse rate of $-9.8\text{ }^{\circ}\text{C}$ per km. This rate in the atmosphere depicts a scenario where there might be water vapour in the atmosphere but has no liquid moisture in form of fog, droplets or cloud^[3]. When lapse rate reduces or increases with height, it is referred to as a 'positive' or 'negative' lapse rate respectively. The negative lapse rate also known as 'temperature inversion' occurs highly in the upper atmosphere (stratosphere). It also occurs within the planetary layer during the night when temperature increases with height. The decrease of environmental air temperature with altitude in the lower atmosphere (0-15km) is very vital to the stability and dynamics of climatic variables that characterizes the lower atmosphere. The stability of air is boosted by the distribution of temperature in the troposphere at different altitudes. Consequently, by observing the temperature variance at various heights between the surrounding environment and a rising air parcel, the stability conditions of the boundary layer atmosphere can be determined. Temperature stratification in the lower atmosphere is influenced majorly by these dynamics which includes dry and moist convection, heat exchanges, radiation flux, turbulence and wind shear. There is the balance of boundary layer climate through the effective altitudinal transmissions of heat and moisture. A sustainable mechanism that promotes the vertical displacement of an air parcel in the planetary layer is turbulence. Turbulence can either be thermal or mechanical and mechanical turbulence is the dominant pattern across the planetary layer in Nigeria^[4]. Vertical energy transfer in the troposphere is accomplished by the rate of turbulent motions and this enhances or reduces the energy exchange between the surface layer and lower atmosphere.

Various studies had shown that temperature decreases with altitude and that temperature lapse rate is one of the controlling factors governing the structure of any planetary atmosphere^{[5][6][1]}. However, it has been explained^[7] that studies on the vertical temperature structure of the lower tropospheric layer in many tropical locations of the earth, including areas where there are gaps in observational data, are completely insufficient. It was also admitted that the tropical region is principally characterised by more or less uniform decrease in temperature with height within the lower tropospheric layer. It was observed^[8] that the use of constant and regular atmosphere measuring instruments like radiosonde and rocket in tropical locations is still at its poor state.

An estimation of tropospheric lapse rate^[5] using the global monthly mean data of the NCEP/NCAP reanalysis

(1948-2001). The result shows that the average positive tropospheric lapse rate in the northern hemisphere as a whole and over the continents was between $6.1 - 6.2\text{ }^{\circ}\text{C}/\text{km}$. It was noted that at the sub-tropics temperature decreases up to 20 km and at polar latitudes, temperature decreases up to 10 km. The seasonal and synoptic variations in near-surface air temperature lapse rate in south-central Idaho was examined using maximum temperature data from 14 synoptic stations^[9]. The result showed that the average lapse rate from January to December ranged between -0.43 to $-0.70\text{ }^{\circ}\text{C}/100\text{m}$. It was noted that lapse rate during humid conditions approximated the saturated adiabatic lapse rate (SALR) i.e. -0.4 to $-0.5\text{ }^{\circ}\text{C}/100\text{m}$. Results also proposed that if observations are not available in the area of interest, then the environmental lapse rate (ELR) may be adequate for maximum air temperature computations.

Furthermore,^[10] determined the mean moist and dry adiabatic lapse rates for the lower troposphere in the northern hemisphere for January and July. For January, values for the dry adiabatic were about $4.95\text{ }^{\circ}\text{C}/\text{km}$ while in July it was $5.21\text{ }^{\circ}\text{C}/\text{km}$. Mean moist lapse rate was about $6.21\text{ }^{\circ}\text{C}/\text{km}$ in January and about $5.10\text{ }^{\circ}\text{C}/\text{km}$ in July. The mean annual lapse rate for both dry and moist conditions was $5.16\text{ }^{\circ}\text{C}/\text{km}$ and $5.67\text{ }^{\circ}\text{C}/\text{km}$ respectively. It was specified that a better choice for critical lapse rate would be a constant equal to $5.1\text{ }^{\circ}\text{C}/\text{km}$. Further emphasis revealed that hemispheric mean lapse rates in the mid and lower troposphere are within $0.4\text{ }^{\circ}\text{C}/\text{km}$ of the moist adiabatic lapse rate in July. It was stated that the latitudinal distribution of tropospheric mean lapse rates clearly delineates two regimes in the atmosphere: a high latitude regime which exhibits the critical lapse rates are and a low latitude regime where the lapse rates are principally moist adiabatic.

An assessment of the lapse rate values for China mainland by^[6] shows that it generally has a branded distribution from southeast to northwest and range from -0.3 to $-0.9\text{ }^{\circ}\text{C}/100\text{m}$ in all seasons. On the plateau, the lapse rates range from $-0.6\text{ }^{\circ}\text{C}/100\text{m}$ in summer to $-0.8\text{ }^{\circ}\text{C}/100\text{m}$ in spring/winter. In northeast China, they are within -0.7 to $-0.9\text{ }^{\circ}\text{C}/100\text{m}$. However, the stabilizing lapse rate value was around -0.6 to $-0.8\text{ }^{\circ}\text{C}/100\text{m}$. Harlow et al., (2004) conducted an analysis of temperature lapse rate in the semi-arid south-eastern Arizona for one year. The result reveals that the lapse rate predicted from mean and maximum daily temperature data taken at 2m height was similar to the ELR i.e. $-6\text{ }^{\circ}\text{C}/\text{km}$. The calculated values from radiosonde data were within -6 to $-8\text{ }^{\circ}\text{C}/\text{km}$. Using 4 to 60 years' data,^[11] estimated the mean positive lapse rate ($^{\circ}\text{C}/100\text{m}$) for the following regions such as US Rockies,

Eastern North America, Northern South America, Scandinavia, Western Europe, Europe and Asia to be 0.58, 0.78, 0.61, 0.90, 0.62, 0.47 and 0.67 respectively.

It was mentioned that lapse rate is mostly steeper during day period than at night time as well as during hotter season than in colder periods [12]. It was also declared [13] that lapse rates are significantly controlled by synoptic airflow with shallower lapse rates associated with southerly air flows and northern flows associated with steeper lapse rates.

2. The Nigeria Climate Pattern

The study areas are situated in various climate belts of Nigeria. These are the tropical wet zone (Port Harcourt with coordinates: Longitudes 6° 57' - 7°59' E and Latitudes 4° 41' - 4°56' N); the bi-modal tropical continental zone (Enugu with coordinates: Longitude 07° 54' E and Latitude 06° 48' N); the montane climate (Jos with coordinates: 08° 53' E and Latitude 09° 51' N); the mono-modal tropical continental zone (Kano with coordinates: Longitudes 7° 47' - 9° 30' E and Latitudes 10° 32' - 12°24' N) and hot semi-arid zone (Maiduguri with coordinates: 13° 03' E to 13° 08' E and Latitude 11° 26' N to 11° 34' N). The Figure 1 shows the Nigeria climate belts and study areas.

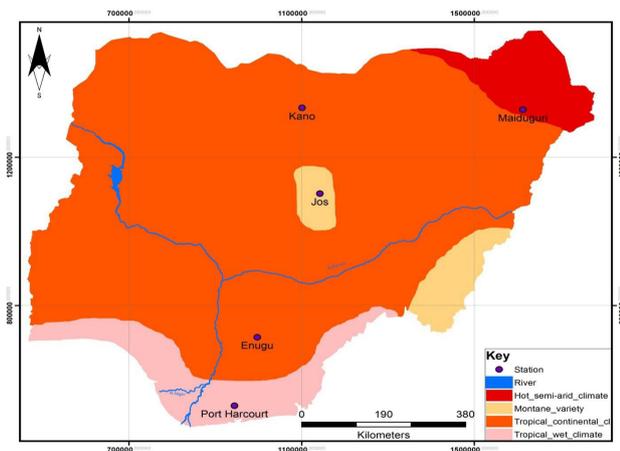


Figure 1. Climatic Belts of Nigeria Showing Study Areas

Source: [4]

2.1 Tropical Wet Climate

This climate zone is found around the coastal areas, up to 150 km inland. This climate pattern is closely linked with the tropical monsoon climate influenced by the moisture laden air from the Atlantic Ocean. The weather producing system in the zone is the monsoon i.e. the south-westerly winds coming from across the Atlantic and blowing towards the thermal low-pressure system created by solar heating in the interior of the continent [14]. Average annual

maximum temperature values vary between 27 °C to 32 °C most of the year. Average relative humidity is in the zone range from 80 % with over 2400 mm of annual rainfall for places like Port Harcourt [15]. This climatic belt (representative of the Niger Delta area) which is influenced by the humid and warm tropical maritime air mass (mT) almost throughout the year has the bi-modal rainfall regime. The rainfall is usually conventional in nature due to the region's closeness to the equatorial belt. The peak bi-modal rainfall period in July and September is dominant in the region.

2.2 Tropical Continental Climate

This climate belt is found inland, and covers over 80% of the area of the country [4]. It is demarcated by the bi-modal rainfall line (a moderate tropical continental type south of the line and an extreme mono-modal tropical continental type north of it). The southern end has subdued temperature ranges with higher annual and bi-modal rainfall with a shorter dry season of about four months e.g. Enugu. The northern end has higher temperature ranges with lower annual and mono-modal rainfall but a longer dry season of six to eight months e.g. Kano. Rainfall decreases from the southern part as one move towards the northern part of the line. It was disclosed that this northern end [15] is mostly influenced by the tropical continental air mass (cT) from across the Sahara Desert for most of the year. The climate zone has a wide range of relative humidity. Average annual rainfall and temperature vary from over 1700 mm and 26.3 °C in places like Enugu to below 800 mm and 26.1 °C in places like Kano respectively [4].

2.3 The Montane Variety Climate

This high altitude variety climate dominates on the Jos, Obudu, Adamawa and Mambilla plateaux. Temperatures are very low both in the wet and dry seasons due to the highlands well over 1500 m above sea level [4][16]. The average temperature ranges all through the year in this zone is within 20 - 23 °C [4][17]. The mean annual rainfall in the areas such as the Mambilla plateau exceeds 1780 mm with peaks in June/July and September while dry season last between November and February [16].

2.4 Hot Semi-Arid Climate

The climate of the semi-arid zone in Nigeria is characteristically of the dry tropical type with distinct wet and dry seasons. The zone is found in the region of subtropical highs where subsiding air masses prevails [4]. The zone's position in the continental interiors obstructs it of continuous influence of the tropical maritime air masses from

across the ocean. Hence, the cool and dry tropical continental air mass from across the Sahara Desert dominates the region for most of the year. The average annual and diurnal range of temperature is large and between 20 °C to 25 °C. Average minimum temperature ranges vary from 12 °C in December/January to 23 °C in May. Average maximum temperature range from 31 °C in December/January to 40 °C in April. The warmest months are March and April when daytime temperature exceeds 40 °C [4]. According to [18], rainfall in the zone is highly variable and the onset of rain is erratic. The dry season is from October to early May, while the wet season is concentrated in a short period that runs from May to September [4] [19]. The rainfall intensity is high between the months of July and August with peak in August and average range between 215 - 250 mm [4][14]. The rainfall peak in August is due to the presence of ITD which drives the maritime air mass across the zone. Typical average annual rainfall values range between 150 mm to less than 1000 mm [4][14] [18]. It was stated that the zone is ravaged [20] with prolonged increasing evapotranspiration, drought and desertification due to low rainfall amount. During the dry season, the atmosphere is strongly dominated by the dry dusty wind referred to as 'Harmattan' which transports dust over land from the Sahara Desert. Relative humidity is relatively low throughout the year ranging between 18 - 63 % with low and high peaks during the dry and wet seasons respectively. Due to the massive landmass void of much vegetation to retard wind velocity, average amount range from 1.5 - 12 m/s with average annual sunshine duration ranging between 8 - 11 hours [4].

3. Methodology

The data for this study was sourced from the Era-Interim Re-analysis data for the period of six years (2010-2015). The data was acquired for 6-hourly interval at 0000, 0600, 1200 and 1800 synoptic hours. According to [14], meteorological observations are made at fixed observing hours. The main synoptic hours internationally agreed upon are 0000 (midnight), 0600 (6am), 1200 (noon) and 1800 (6pm) Greenwich Mean Time. Upper air temperature values at pressure level 850mbar and 1000mbar for an approximate surface level was obtained. The Era-Interim Reanalysis data is the newest universal atmospheric data generated by the European Centre for Medium-Range Weather Forecast. The gridded products comprise a large variety of data for surface and upper air. Furthermore, its application has surpassed expectations and speaks volume about the outstanding successes obtained in recent years [4]. It was highlighted that the Era-Interim global data provides meteorological parameters the required

understanding for enhanced knowledge of the circulatory system across West Africa [21]. The Era-Interim data for the specified years is obtained at 0.125° spatial resolution. This low resolution was chosen to obtain a reliable spatial scale across sample areas.

The vertical temperature profile for the lower atmosphere is given by:

$$T(z) = T_0 - \Gamma \cdot z \tag{equation 1}$$

Where T_z and T_0 are temperature at the varying heights, Γ is the environmental lapse rate at 6.5 °C/km and z represents any vertical height. An important aspect of environmental air temperature is that it decreases with height above the surface within the troposphere up to 15km. The rate of decline is defined by:

$$\Gamma = -\frac{\partial T}{\partial z} \tag{equation 2}$$

The environmental lapse rate for the area was determined using the following equation [22].

$$\Gamma = \frac{T_{850\text{mbar}} - T_{1000\text{mbar}}}{\partial z} \tag{equation 3}$$

Where:

$T_{850\text{mbar}}$ = air temperature at reference height (between 1-1.4 km)

$T_{1000\text{mbar}}$ = air temperature at surface level (approximately 0.01 km)

∂z = the difference in elevation between the two heights.

The relationship between the ELR and the air parcel lapse rates i.e. dry and moist adiabatic lapse rates (DALR & MALR) was used in this study to determine the major domain of the atmospheric stability conditions as it relate to the lapse rate pattern of the study region. The following criteria were adopted for stability classification [4,23].

- (1) ELR = -6.5 °C/km
- (2) DALR = -9.8 °C/km
- (3) SALR = -5.0 °C/km

When:

- (1) ELR < SALR < DALR = Stable Atmospheric Conditions
- (2) SALR < DALR < ELR = Unstable Atmospheric Conditions
- (3) SALR < ELR < DALR = Conditional Instability
- (4) ELR = DALR = Neutral Atmospheric Conditions (Unsaturated Air)
- (5) ELR = SALR = Neutral Atmospheric Conditions (Saturated Air)

MATLAB software was used in resolving the mathe-

mathematical procedures and the occurrence of lapse rate distribution.

4. Results

The Figures 2 - 7 presents the average diurnal, seasonal and annual lapse rate trend for the study areas for the specified synoptic hours (0000Hr, 0600Hr, 1200Hr and 1800Hr). From the study, it is shown that the lower tropospheric layers throughout the various climate belts has a positive lapse rate. Results showed that the average annual lapse rate condition for the climate belts in Nigeria are: Tropical wet zone (Port Harcourt) -5.6 °C/km; Bi-modal Tropical continental zone (Enugu) 5.8 °C/km; Montane zone (Jos) -6.5 °C/km; Mono-modal Tropical continental zone (Kano) -6.6 °C/km; and Hot semi-arid zone (Maiduguri) -6.6 °C/km (Figure 2). This specified that lapse rate increased from the coastal area of Port Harcourt towards the semi-arid interiors of Maiduguri. The average annual lapse rate indicated that Jos, Kano and Maiduguri followed the standard environmental lapse rate (ELR) of -6.5 °C/km while Port Harcourt and Enugu followed the moist or saturated adiabatic lapse rate pattern. However, the average annual lapse rate for the entire region is the moist adiabatic range. The position of Nigeria is principally within the lowland moist tropics north of the equator and branded by a high temperature system [4]. It was noted that Nigeria's latitudinal position within the tropics and the mostly low relief enhances the high-temperature all the year round [24]. The high surface temperature creates a dynamic system where energy fluxes are transferred from the surface to the upper layers of the troposphere [4].



Figure 2. Mean Annual Lapse Rate Pattern for the Study Areas

Average diurnal results for the climate belts showed that lapse rate is steep during the afternoon and transition periods (i.e. 1200 and 1800 hours) for the entire areas than the rest periods (Figure 3). There is an average increase of -6.3 °C/km in the coastal wet zone to -9.0 °C/km respectively in the hot semi-arid areas of Nigeria. The Figure 6 shows that the seasonal period of March - May (MAM)

for Kano and Maiduguri during the afternoon period had a lapse rate value of 9.5 °C/km and 9.4 °C/km respectively. These values are close to the dry adiabatic lapse rate of 9.8 °C/km and this indicates the very dry nature of the lower atmosphere within these climate belts. It is noted that MAM is the hottest period in the climate zones as air temperature exceeds 40 °C. The higher values (7.1 and 8.1 °C/km) noted at the southern bi-modal tip of Nigeria's Port Harcourt and Enugu in January indicates the period of peak dry season in the areas where the dry north-easterly wind covers the areas pushing back the moist south-westerly wind over the Ocean.

The early hours of the day (00:00-06:00 hours) exhibited a lower average positive lapse rate across the entire region, however, while there was a near uniform trend at 00:00 hour of range -5.1 to -5.9 °C/km, there were variations during the 06:00 hour of range -3.5 to -5.1 °C/km (Figure 3). The lower lapse rate trend of -3.5 °C/km (Figure 3) at the continental interiors during the period of dawn (06:00 hour) indicates the large diurnal temperature difference that is prominent in the areas due to the dryer air than at the coastal zone with moist air. The average seasonal values for the periods of dawn exhibited a lapse rate of range 4.4 - 6.2 °C/km and 1.8 - 5.4 °C/km across the entire region for 00:00 and 06:00 hours respectively (Figures 4 and 5). The lower values observed at 06:00 hour across the entire region portrays the much released longwave radiation that took place between the hours.



Figure 3. Mean Diurnal Lapse Rate Pattern for the Study Areas

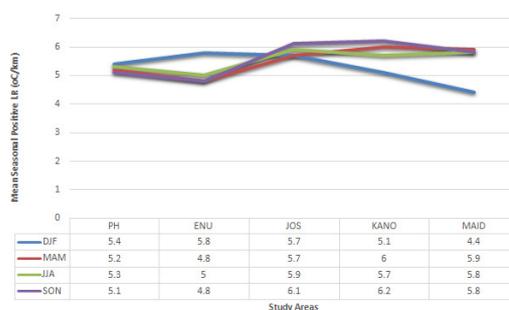


Figure 4. Mean Seasonal Lapse Rate Pattern for the Study Areas (00:00 Hour)

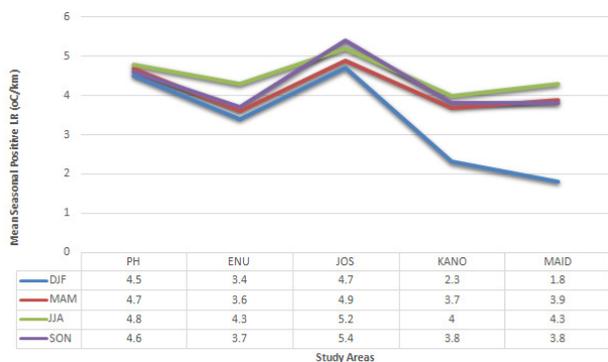


Figure 5. Mean Seasonal Lapse Rate Pattern for the Study Areas (06:00 Hour)

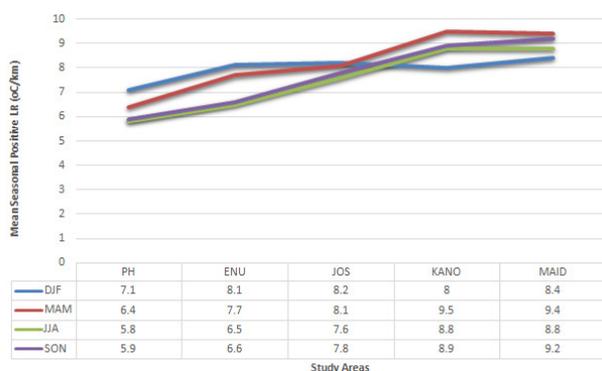


Figure 6. Mean Seasonal Lapse Rate Pattern for the Study Areas (12:00 Hour)

The positive lapse rates observed during the night and dawn across the entire region showed that infrared radiation was still being released even during the periods of dawn. Solar insolation peaks at noon because at that time incoming solar radiation exceeds heat loss from the earth's surface. Therefore, surface temperature is still increasing. Maximum temperature occurs when the rate of heat loss from the earth's surface is the same as rate of heat gained from solar insolation. This occurs later in the afternoon usually (1400-1600 hours). At 1800 hour, infrared exceeds insolation and this can continue till the periods of dawn [4].

Also, the effect of greenhouse gas build-ups such as increased carbon dioxide (CO₂) concentration in the atmosphere and the essence of global warming enhances the occurrence of positive lapse rates during the dawn. This is due to the heat exchanges that takes place between the earth surface and lower atmosphere i.e. 'the surface energy releases and the atmospheres energy returns'. This creates a mechanism whereby an upward heat transfer still occurs across the boundary layers that maintains the specified lapse rates. The notable factors that also enhance positive lapse rate values during the period includes the availability of less energetic surface mechanical turbulence at night across Nigeria [4], the heat capacity of the

surfaces and the energy stored at the surfaces.

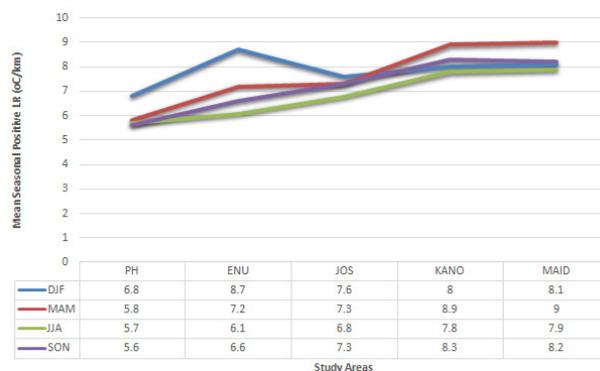


Figure 7. Mean Seasonal Lapse Rate Pattern for the Study Areas (18:00 Hour)

5. Discussion

The lapse rate is a vital factor that impacts the atmospheric stability conditions of any area. It affects the stability of air masses across the lower troposphere through the relationships between the ELR, DALR and the SALR.

According to [25], there are two aspects of instability, i.e. absolute instability (where ELR is higher than both the DALR and SALR) and the conditional instability (where the ELR is within the range of the SALR i.e. -1 to -6.5 °C/km but lower than the DALR i.e. -9.8 °C/km). A significant extract of lapse rate analysis is the conditional instability arrangement of the lower troposphere. The term 'conditional' is utilised since air is required to be pushed aloft before it gets to a point where free ascent takes over. The lapse rate is the only source to determine this aspect of atmospheric stability. This study showed that the average lapse rate values for the entire region is close to the ELR and the SALR and lesser than the DALR. During this conditions, stable air is forced to rise to certain height where condensation occur, and, on releasing latent heat continues ascension freely. It should be noted that the ELR represents an average condition where heating, mixing and wet adiabatic process are also taking place [3]. The relationship between the ELR and the DALR regulate the stability of air and the rate with which emissions will be dispersed and diluted in the atmosphere. When the ELR is the same as the DALR, neutral condition exists in the atmosphere. It was disclosed that the ELR [9] is exclusively relevant to maximum temperature as it commonly overestimates minimum temperature and mean temperature lapse rates. From the lapse rate analysis, conditional instability exists across the lower troposphere of the sample areas. This stability condition implies that there will require a force to lift emissions dispersed at ground level either by mechanical or thermal turbulence. Mechanical turbulence

dominates the surface layer of Nigeria (10-50 m), while thermal turbulence is prominent aloft^[4]. This means that ground level emission sources will require moderate to stronger wind velocity to lift pollutants to a height where further transportation and dispersion is effected by thermal turbulence. Where mechanical turbulence is weak at the surface layer, stacks for stationary emission sources must be above 50 m in any location in Nigeria to have a better dispersion rate.

6. Conclusion

This study has analysed the lapse rate pattern of major climate belts across Nigeria. The lapse rate which is the variation or change in air temperature with vertical height in the troposphere significantly influence how released emissions are conveyed and diluted in the lower atmosphere. Findings from this study revealed that positive lapse rate conditions exist throughout the entire region within the periods of study. Results showed that the average annual lapse rate for boundary layer conditions in Nigeria is within the environmental/moist adiabatic lapse rate range (i.e. 5.6-6.6 °C/km) thereby allowing a state of conditional instability to persist. In this atmospheric condition, an air parcel will be forced to rise by either mechanical or thermal turbulence at any given time or location under a stable atmospheric state. Findings from this study also showed that lapse rate is higher and increases from the coastal areas to the northern fringes of Nigeria most especially during the day and lower during the periods of dawn. The positive lapse rate indicated during periods of dawn emphasises the continuously releases of infrared radiation from the ground surface as well as the reality of global warming due to the build-up of greenhouse gases in the atmosphere.

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