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VARIATIONS OF ATMOSPHERIC BOUNDARY LAYER STABILITY CONDITIONS OVER CLIMATE BELTS IN NIGERIA

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ABSTRACT

This study examined the variation of atmospheric stability conditions in Nigeria's climate belts using the Pasquill-Gifford (PG) technique. Surface meteorological data (2010-2015) from Era-Interim platform were used. Results show that across climate belts in Nigeria unstable conditions increased from the coast of Port Harcourt (tropical wet climate) to Kano (tropical continental climate) in the northern part of Nigeria. There is a revered trend for the neutral conditions. It is also observed that stable atmospheric stability conditions are slightly higher in the tropical continental climate and the semi-arid zone than the coastal zone. However the climate of Nigeria is dominated by the unstable atmospheric conditions. Very stable atmospheric conditions (stability class F) prevailed during the hours of the dawn for most of the seasons in the coastal areas while less stable atmospheric conditions (stability class E) prevailed in the semi-arid region of Nigeria. During the day, the boundary layer atmosphere is slightly unstable in the coastal areas and moderately unstable in the semi-arid belt. However, it indicates otherwise during transition periods. The implication of these atmospheric conditions across the various locations especially for the coastal city of Port Harcourt is that uncontrolled emissions will be constrained at ground level during the night due to subsidence inversion triggered by the very stable condition of the boundary layer. This will create health problems for boundary-layer dwellers exposed to severe air pollution episodes. Policy makers should ensure that emission reduction techniques are engaged by potential emitters sited near sensitive receptors in cities such as Port Harcourt.

Contribution/Originality: This study contributes in the existing literature the pattern of stability conditions over the climate belts of Nigeria. This identifies the most prevalent stability category that could either enhance or suppress boundary layer emissions.

1. INTRODUCTION

The most prevalent process in the atmospheric boundary layer is the convective system induced by thermal, mechanical or mixed turbulence [1]. A vital aspect on the nature and level of convention is the temperature gradient as defined in the concept of atmospheric boundary layer stability. Atmospheric boundary layer (ABL) stability conditions have an important effect in local and regional atmospheric circulation. As atmospheric air flow over the earth surface an immediate alteration in wind shear which affect energy flux and a change in the availability of dampness and heat is initiated [2]. The stability of air defines the extent of altitudinal movement of air mass within the boundary layer and is evaluated by the vertical temperature gradient in the lower troposphere. It has been disclosed by Brandon [3] that vertical variations of air is either enhanced or suppressed by the stability situation of the boundary layer. Increased atmospheric stability conditions are usually sustained by the occurrence of insolation and dry weather, while low conditions are generally responsible for cloudy and moist weather conditions. It was acknowledged by Sandeep, et al. [4] and Ayoade [5] that stability play a direct part in the extent of turbulence present in the ABL and therefore directly impact atmospheric diffusion processes. According to Canepa, et al. [6] understanding the local atmospheric pattern of any locality is central for assessing the air quality forecast actions suitable for the ecosystems in the boundary layer. This is because in the boundary layer humans dwell there, heat and momentum fluxes interrelate and there are incessant deviations in diurnal weather configuration as well as the interference of air emissions from both anthropogenic and natural origins. Stability significantly affects the weather conditions of the ABL. Precipitation falling from a stable atmosphere usually affects a large expanse and fall with almost steady intensity (an all-day rain). However, confined showers in any locality and thunderstorms with promptly varying rainfall amounts show that the boundary layer atmosphere is unstable. Stability conditions occur at various heights in the atmosphere; however, this study has considered the conditions within the ABL which extends up to 1.5km in the lower troposphere depending on the time of the day across the distinct climate locations in Nigeria.

2. THE CLIMATE PATTERN OF NIGERIA

There are four major climatic belt across Nigeria based on the Köppen system of classification. According to Ogunsote and Prucnal-Ogunsote [7] this system of classification is generally accepted for the global evaluation of climatic belts. The major climatic belts in Nigeria include:

1. Hot semi-arid climate (or Köppen's *BSh* climatic classification)
2. Montane climate (recognized by another climatologist, Geiger)
3. Tropical continental climate (or Köppen's *Aw* climatic classification), and
4. Tropical wet climate (or Köppen's *Am* climatic classification)

The major climatic belts in Nigeria are shown in Figure 1 with the study locations.

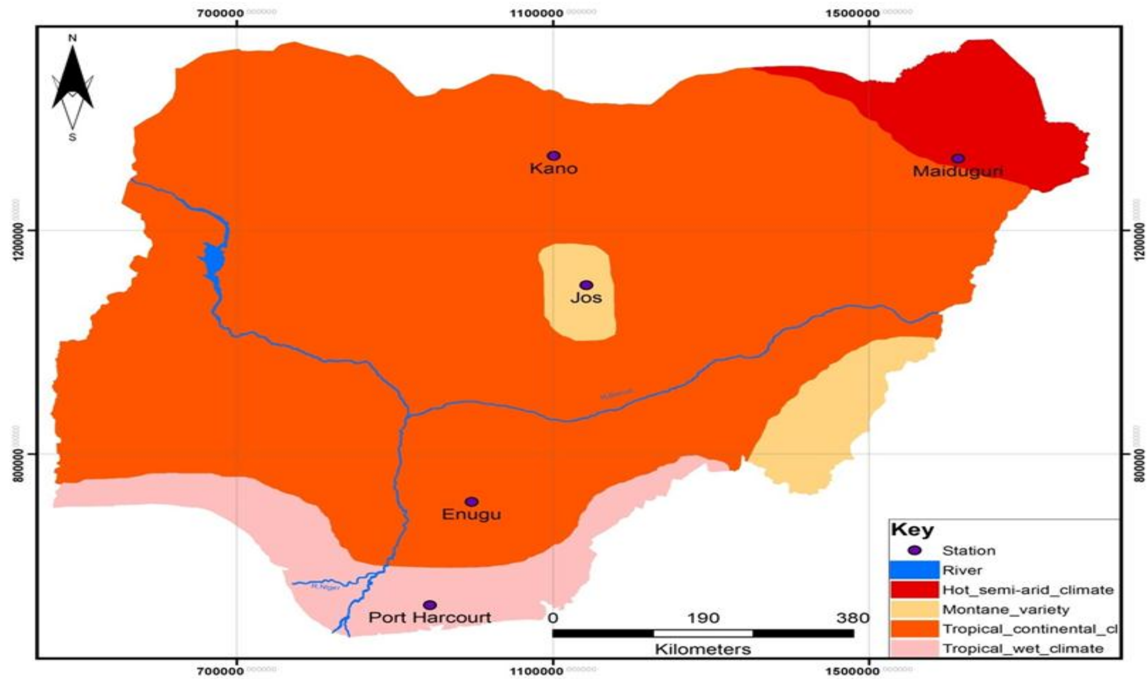

Fig-1. Climatic Belts of Nigeria Showing Study Areas.

Source Edokpa [8].

The Semi-arid Zone - This zone is characteristically of the dry tropical type with distinct wet and dry seasons. The region is found in the zone of subtropical highs where subsiding air masses prevail. The zone's position in the continental interiors denies 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 dry season is from October to early May, while the wet season is concentrated in a short period that runs from May to September [9]. The rainfall intensity is high between the months of July and August with peak in August. The rainfall peak in August is due to the presence of ITD which drive the maritime air mass across the zone.

Montane - This high altitude variety climate dominate on the Jos, Obudu, Adamawa and Mambilla plateaux [10]. Temperatures are very low both in the wet and dry seasons due to the highlands well over 1500m above sea level [11]. According to Sowunmi [12] the mean temperature range all through the year in this zone is within 20–23°C. Also, Borokini, et al. [11] noted that the mean annual rainfall in the areas such as the Mambilla plateau exceeds 1780mm with peaks in June/July and September while dry season last between November and February.

Tropical Continental Climate. This climate zone is found inland, and covers over 80% of the area of the country. It is demarcated by the double maxima rainfall line (a moderate tropical continental type south of the line and an extreme tropical continental type north of it). The southern end has subdued temperature ranges with higher annual and double maximum rainfall with a shorter dry season of about four months e.g. Enugu. The northern end has higher temperature ranges with lower annual and single maximum 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 [8]. This northern end which is mostly influenced by the tropical continental air mass (cT) for most of the year has a wide range of relative humidity. Mean annual rainfall and temperature vary from over 1700mm and 26.3°C in places like Enugu to between 800-900mm and 26.1°C in places like Kano [13].

Tropical Maritime Climate - This type of climate is found around the coast, up to 150km inland [10] and influenced by the moist air from the Atlantic Ocean. According to Ayoade [14] in West Africa, the weather producing system is the monsoon, 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. Mean annual maximum temperature values vary between 27°C to 32°C most of the year. Relative humidity is in the region of 80-85% with over 2300mm of annual rainfall for places like Port Harcourt [8]. This climatic belt has the double maxima rainfall regime with peaks in June and September. The rainfall is usually conventional in nature due to the region's closeness to the equatorial belt.

3. MATERIALS AND METHOD

A 6-year diurnal surface data for temperature, cloud cover, wind speed and sunshine radiation on synoptic hour were acquired from the ERA-Interim platform for the following areas, namely: Port Harcourt, Enugu, Jos, Kano and Maiduguri. The 6-hourly surface data for the specified period was obtained at 0.125° spatial grid resolution. This low resolution was chosen to achieve a reliable spatial scale across sample areas. The atmospheric boundary layer stability condition for the various domains across the climate zones in Nigeria was determined by the Pasquill-Gifford (PG) stability classification technique. This method of analysis incorporates both mechanical and thermal turbulence proposed by Pasquill in 1961 and later modified by Gifford the same year [15]. The Pasquill method uses surface meteorological data such as wind speed, solar radiation and cloud amount for the assessment of stability conditions from A (extremely unstable) to F (very stable) classifications. Table 1 shows the PG approach to determining the stability pattern of any location [16]. A vital benefit of this method of analysis is its simplicity of usage. The PG technique is the most efficient scheme over a widespread area as its takes into consideration the average overall cloud cover of a locality. Another significant advantage of this approach is the non-applicability of ground heat fluxes as required by the Monin-Obukhuv Length method for boundary layer stability determination.

Table-1. Pasquill-Gifford (PG) Stability Classification

Pasquill-Gifford Stability Classification Technique (PG)								
Surface wind (m/s)	**Insolation**					**Cloud Cover (Night-time)**		
Height at 10m	>600W/m^2	300-600	< 300	Radiation Overcast	1Hr Before Sunset or After Sunrise	0 -3 Oktas	4 – 7 Oktas	8 Oktas
<2	A	B	B	C	D	F or G	F	D
2-3	B	B	C	C	D	F	E	D
3-5	B	C	C	C	D	E	D	D
5-6	C	C	D	D	D	D	D	D
>6	C	D	D	D	D	D	D	D
G Category Introduced later for exceedingly stable situations								

Source: Essa, et al. [16].

4. RESULTS AND DISCUSSION

4.1. Analysis of Pasquill-Gifford Classification Scheme across Climate Belts

Tables 2-5 show the percentage occurrence as well as the trend of stability conditions for the study locations from 2010 to 2015 during the night, day and transition periods. The analysis was for peak dry season; December-February (DJF), early wet season; March-May (MAM), peak wet season; June-August (JJA) and early dry season; September-November (SON).

Night Period

During the DJF, MAM, and SON seasons, very stable atmospheric condition (PG class F) dominated the coastal area of Port Harcourt i.e. 77.9% 68.6% and 55.6% respectively. However, neutral condition (PG class D) dominated the coastal city during the JJA season (53.3%). Very stable conditions prevailed throughout the seasons in the montane region of Jos while it was slightly dominant in Enugu (DJF; 41.9%) and Kano (DJF and SON; 51.7% & 61.3%). Stable conditions (stability class E) prevailed over Maiduguri during DJF, MAM and SON seasons i.e. 62.3%, 48.6% and 40.0% except for JJA season when neutral condition prevailed (i.e. 52.7%). Apart from Kano and Jos which had the prevalence of stable and very stable conditions during the peak of rainfall in Nigeria i.e. in JJA, neutral condition dominated the rest areas.

Day Period

The lower atmosphere over the coastal city of Port Harcourt was very unstable (PG class A) i.e. 54% than the other areas during the DJF season and slightly unstable (PG class C) for the rest of the seasons than the other areas. Both the very unstable and moderately unstable (PG class B) conditions were almost at the same level in Enugu during the DJF and SON seasons i.e. 47%/46.8% and 40.1%/39.2% respectively. Stability class A dominated slightly over class B in Jos during the MAM season (48.4%) while class B was prevalent in the high terrain area for the rest seasons. In Kano and Maiduguri, stability class B was prevalent throughout the seasons.

Transition Period

Stability class B prevailed over the coastal city of Port Harcourt during the transition periods for the entire seasons i.e. DJF (68.6%), MAM (60.9%), JJA (53.1%) and SON (57%). Stability class B also prevailed in Jos (JJA and SON), Kano (JJA) and Enugu (SON) during the stated period. However, the boundary layer atmosphere over Maiduguri was slightly unstable (PG class C) throughout the seasons.

Table-2. Percentage Occurrence for Peak Dry Season Stability Conditions

Location	December-February Stability Categories (%)									
	Night Period				Day Period			Transition Period		
	D	E	F	G	A	B	C	B	C	D
Port Harcourt	20.3	0.2	77.9	1.6	54.0	9.8	36.2	68.6	1.7	29.8
Enugu	22.7	30.1	41.9	0.3	47.0	46.8	6.3	33.3	49.2	17.6
Jos	9.0	33.7	56.7	0.6	20.1	72.5	7.4	20.0	72.3	7.8
Kano	9.1	39.3	51.7	0.0	5.5	85.4	9.1	0.2	97.4	2.4
Maiduguri	16.4	62.3	21.3	0.1	2.8	66.0	31.2	0.2	95.7	4.1

Source: Edokpa [8]

Table-3. Percentage Occurrence for Early Wet Season Stability Conditions

Location	March-May Stability Categories (%)									
	Night Period				Day Period			Transition Period		
	D	E	F	G	A	B	C	B	C	D
Port Harcourt	31.2	0.1	68.6	0.1	12.1	30.6	57.2	60.9	0.4	38.8
Enugu	47.7	36.5	15.8	0.0	26.1	56.0	17.9	29.5	45.7	24.8
Jos	22.6	33.9	43.2	0.3	48.4	40.8	10.9	34.8	51.4	13.8
Kano	26.4	44.3	29.3	0.0	29.3	60.7	10.0	18.8	75.7	5.4
Maiduguri	32.7	48.6	18.6	0.1	23.4	48.4	28.3	16.1	75.4	8.5

Source: Edokpa [8]

Table-4. Percentage Occurrence for Peak Wet Season Stability Conditions

Location	June-August Stability Categories (%)									
	Night Period				Day Period			Transition Period		
	D	E	F	G	A	B	C	B	C	D
Port Harcourt	53.3	0.5	44.0	0.3	0.0	23.4	76.6	53.1	2.2	44.7
Enugu	53.9	28.8	17.3	0.0	3.6	50.2	46.2	35.9	42.8	21.4
Jos	37.0	20.7	42.1	0.1	32.1	47.1	20.8	66.2	17.9	15.9
Kano	33.9	41.3	24.8	0.0	35.9	57.4	6.7	52.9	37.7	9.4
Maiduguri	52.7	36.6	10.7	0.0	20.9	64.6	14.5	30.3	57.8	12.0

Source: Edokpa [8]

Table-5. Percentage Occurrence for Early Dry Season Stability Conditions

Location	September-November Stability Categories (%)									
	Night Period				Day Period			Transition Period		
	D	E	F	G	A	B	C	B	C	D
Port Harcourt	43.5	0.4	55.6	0.6	1.3	30.6	68.1	57.0	1.6	41.4
Enugu	37.9	25.4	36.7	0.0	40.1	39.2	20.7	51.1	28.6	20.3
Jos	13.4	13.3	72.3	1.1	29.9	62.6	7.5	61.0	30.2	8.8
Kano	12.2	26.6	61.3	0.0	37.5	57.9	4.6	35.4	61.7	2.9
Maiduguri	22.1	40.0	37.6	0.3	29.9	56.8	13.4	28.8	65.4	5.9

Source: Edokpa [8]

4.2. Discussion

Results of the study showed that the night/early atmospheric conditions across sampled stations remain entirely in stable-neutral conditions. However, the degree of stability conditions differs across the various climate belts. For instance, the prevalent stability class F in Port Harcourt (tropical wet climate) for most of the seasons indicates the moderating effect of moist air from the ocean over the area which tends to lubricate the lower atmosphere. However, during JJA season, the slight dominance of class D over F in Port Harcourt portrayed the period of rainy season which generate cool conditions during the nights periods. This trend is advantageous for the prevalence of class D [17]. Although Jos (montane region) not closer to the ocean as Port Harcourt, the dominance of class F depicts the high altitude of the area where unique topographic effects could breed cool air at night. The prevalence of class E in Maiduguri (hot semi-arid climate) shows the dry nature of the continental air void of moisture for most of the year. However, the prevalence of classes D and F at peak rainy season during the early hours in Kano (mono-modal tropical continental climate region) and Maiduguri indicates the moist air that dominate the areas during the season. Notably, the dominance of class F at the northern part of Nigeria during the night/early periods shows the rapidly lost long-wave radiation that generates radiation fog and conveys cool air across the boundary layer environment.

It is observed that during the DJF season, PG class A is intense during the day period in Port Harcourt and Enugu (bi-modal tropical continental climate region) than the northern areas. This is because during this period, the sun is overhead at the southern end of Nigeria after retreating with the ITD back to its origin across the Atlantic Ocean. However, PG class C dominates in Port Harcourt during MAM season due to emerging cloud cover that prevent much solar intensity including the moderating effect of closer massive water bodies [17]. The much prevalence of stability class B at the northern fringes during the DJF season is due to the lesser solar radiation received by the zone due to the layer of Harmattan dust haze that restrain more solar radiation reaching the ground surface [8]. This reduces the effect of the ground surface heating the overlaying air. Also, the prevalence of class B within these northern margins than class 'A' during JJA and SON indicate the drier nature of the soil surface and the ambient air not damp enough to retain much heat including the higher wind speed trend that modifies ground surface thermals.

It was emphasised by Ahrens [18] that during periods of higher wind speed, turbulent swirls are capable of weakening hot thermals from the ground surface with cooler air above. This forced blending helps to dilute thermals away from the ground surface faster and effectively. The prevalent stability class C observed in Port Harcourt during JJA and SON than in MAM indicates the bi-modal pattern of rainfall season combined with substantial cloud cover. The massive cloud cover coupled with the humid atmosphere in Port Harcourt impede the buoyant effect of solar radiation on the ground surface [8]. This reduces the effect of the sensible heat flux that emanates from the ground surface on the overlaying air, hence a lower degree of unstable condition. This trend in Port Harcourt was not the case in Enugu as stability Class B slightly dominated the peak rainy season. This shows a lesser interference of cloud cover and a drier atmosphere as one move away from the coast [8]. It also indicates the difference in latitudinal and altitudinal positions of Port Harcourt and Enugu.

The deviations of stability pattern during the day period for the areas across the season depend on the prevailing circumstances that enhance temperature changes. Ground surface temperature is a controlling factor of many environmental processes. Therefore, it is important to many field of research including atmospheric stability. According to Ahrens [18] there is excess of heat created during the time lag between peak solar intensity during the day and the period when terrestrial radiation from the ground surface exceeds shortwave radiation. This excess of heat holds between two to four hours in the afternoon and largely regulates the time of maximum air temperature some meters over the ground surface. It is noted that the modification of this trend depends on notable features prevalent at any location. In locations with less cloud cover during the afternoon, maximum air temperature will occur from 3-5 hours after 1200 noon while in locations with much cloud cover, maximum air temperature occurs one or two hours after noon. Areas of close proximity to massive water bodies, exchanges between the water body and land may regulate air temperature pattern and cause maximum temperature to occur before or exactly at noon.

The dominance of stability class B in Port Harcourt during the transition periods throughout the season is due to the all year humid atmosphere capable of obtaining heat thereby making the air unstable. This humid environment is largely due to the robust influence on the area by the prevailing moist and warm tropical maritime air mass. Also, according to Ayoade [14] the continentality effect that influence the coastal environment due to land-water atmospheric interactions also stimulate periods of warmness thus making coastal environment most times unstable. Unlike Port Harcourt, the slight dominance of stability class C in Enugu for most of the season reveals its distance from the ocean and the minimal influence of continentality effect on the area. Enugu is about 150km distance from Port Harcourt. The prevalence of stability class C in the far north during DJF and MAM season showed the dominance of severe Harmattan especially during DJF period. This severe Harmattan impedes much of solar radiation. Also the dry nature of the prevailing tropical continental air mass including the drier/loose soil nature of the area is incapable of retaining heat. Hence, heat is easily let off creating a large diurnal temperature range during the day and night time [8]. The dominance of stability class B in Jos and Kano during JJA season is due to the incursion of the rain bearing warm tropical maritime moist air that retains heat and traverses across the areas. Also, according to Ayoade [14] during the JJA period, the northern zone is warmer because it receives more solar heat than the southern part.

Figure 2 show the cumulative pattern of PG stability classes as well as the major stability group with unstable category (A+B+C), neutral category (D) and stable category (E+F+G). This indicates the cumulative pattern of atmospheric stability conditions across study areas. It can be observed that the percentage cumulative PG stability classes over study areas across Nigeria showed this trend: Unstable>Stable>Neutral atmospheric conditions. Figure 2 also show that unstable conditions increased from the coast of Port Harcourt towards the far northern fringes while stable periods are higher in Jos, Kano and Maiduguri than in Port Harcourt and Enugu. Neutral condition is more prominent in the southern coast than the northern domain.

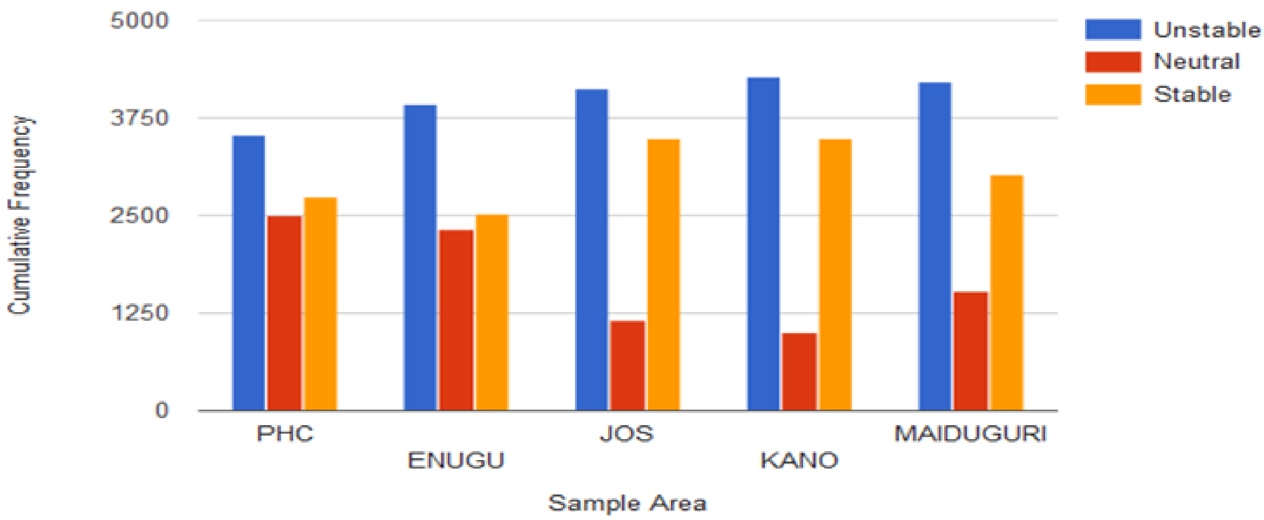

Figure-2. Cumulative Pattern of Atmospheric Stability Conditions across Study Areas

Source: Edokpa [8]

5. POLICY IMPLICATIONS

The significance of atmospheric boundary layer stability conditions in influencing the dynamics of the atmospheric boundary layer is becoming progressively known [8]. This is because the atmospheric boundary layer is an energetic structure that enhances the survival of dwellers. Atmospheric boundary layer events such as the dispersion, mixing, transformation and deposition of emissions released as a result of human's quest for survival and technological development strongly depend on the stability conditions of the lower troposphere [8]. Since emissions results from vast sphere of human activities such as the aviation sector, industrial sector, marine sector, domestic sector as well as illegal industrial activities etc. it is very important for policy makers to be abreast of which atmospheric conditions will worsen or degrade emission concentrations across sensitive receptors. This is to ensure a viable framework for air quality monitoring and control. The prevalence of black carbon observed across the lower atmosphere of Port Harcourt city in late 2016 and till date triggered an environmental disaster in the area and as a challenge, citizens raised alarm across the metropolis due to the gravitational deposits of the particulates on sensitive surfaces mainly during the hours of the dawn [19]. The primary reason for this settling was due to the very stable nature of the boundary layer where released pollutants from the emission sources were below inversion level and hence the resistance of ambient air to dispersed the particulates. Government's efforts to arrest the unpleasant situation proved abortive as the issue persisted. It is therefore crucial that government must initiate adoptable policies that will curtail the threat and therefore avoid fatalities over time. The World Health Organization in 2016 revealed that developing countries are being ravaged by poor air quality pattern and as a result, continuous loss of lives due to acute respiratory diseases [8]. While emission releases into the immediate atmosphere can be controlled and mitigated, the dynamic natural forcing of atmospheric stability cannot be truncated. The Bhopal gas disaster of 1984 in India that led to the death of many people was due to the very stable nature of the lower troposphere at night hence constrained emitted toxins found ways into the respiratory organs of local inhabitants [8]. It is based on this perspective that all stakeholders presume that alleviating air emissions within any sensitive part of Nigeria will become more apprehensive any moment if the existent attitude lingers. It is therefore vital that active actions and practicable resolutions be advanced by policy makers to protect the sensitive boundary layer expanse.

6. CONCLUSION

Generally in Port Harcourt and Jos stability class F (very stable condition) dominated the periods of the night/early hours except during JJA (peak rainy season) when stability class D (neutral condition) dominated Port Harcourt. Kano and Maiduguri were dominated mostly by stability class E (stable condition) during the same period while Enugu had a combination of Classes D, E and F. The reason for class F dominance in Port Harcourt and Jos is due to moderating effects of the ocean and mountains in the respective areas. Kano and Maiduguri indicated a dry stable atmospheric environment while the prevalence of stability class D in Enugu fall in-between the extremes moist and dry effects of Nigeria's atmospheric environment. Unstable conditions dominated the study areas during day periods with moderate stability from Enugu to Maiduguri at class A-B range and weaker stability in Port Harcourt at class A-C range. There is a reverse trend during the transition periods as Port Harcourt maintained a moderate stability class B range throughout the seasons and Enugu to Kano influenced by class B-C range while Maiduguri was in class C range throughout the seasons. This study have shown that across climate belts in Nigeria, unstable conditions increased from the coast of Port Harcourt (tropical wet climate) to Kano (tropical continental climate) in the northern part of Nigeria. It is also observed that stable atmospheric stability conditions are slightly higher in the tropical continental climate and the semi-arid zone than the coastal areas. However the climate of Nigeria is dominated by the unstable atmospheric conditions. The implication of these atmospheric conditions across the study areas most especially for the coastal city of Port Harcourt is that emissions will be constrained at the ground surface during the night due to subsidence inversion triggered by the very stable condition of the atmospheric boundary layer. This will create health problems for boundary layer dwellers exposed to severe air pollution. Policy makers in Nigeria should ensure that emission reduction techniques are engaged by potential emitters located near sensitive receptors.

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