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Boundary Layer Turbulence and Urban Heat Variability in the Coastal City of Port Harcourt, Nigeria

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Abstract

This study examined the boundary layer turbulence pattern and the heat index in the lower atmosphere of the coastal city of Port Harcourt using Richardson number (Ri) technique and temperature-humidity index equation. Six years surface data (2011-2016) from Era-Interim Platform were used for this study. The study was conducted for the period of October-December 2016 when the black soot emission from illegal petroleum crude refining was noticed across the atmospheric boundary layer of Port Harcourt. Mean turbulence within the surface layer (10-50m) height was between 0.27-0.52. This indicates a weak mechanical turbulence since all the values were greater than the Richardson critical (R_{ic}) value of 0.25. Generally, Ri values for the study area at the surface layer were less than 1 while Ri values at the mid layer (50-100m) were greater than 1 indicating laminar condition. The heat index analysis shows that the extreme caution and danger levels constituted about 85% which could generate heat stroke for the city dwellers especially the elderly persons. Study results revealed that the heat island during the night is enhanced within the hours 00:00-03:00 hours. The weak Ri values of mechanical origin shows that the enhanced heat island mostly experienced during the night periods will not be diluted easily and faster. This enhanced heat island is due to the positive radiation forcing of the emitted black soot, the humid atmosphere as well as the very stable atmospheric condition of Port Harcourt. These lower atmospheric factors reduce the strength of the winds in modifying the heat island. In order to mitigate the increased heat island in the city mostly at night, policy makers should ensure that anthropogenic emission releases are reduced from sources to avoid air pollutants build-up. Also, the greater Port Harcourt plan that proposes the decongestion of the city's increasing population should be adopted to create opportunity for adequate expansion thereby reducing concentration of business hubs around the long-standing city center.

Keywords

Turbulence, Heat Index, Port Harcourt, Black Soot, Richardson Number, Atmosphere

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1. Introduction

Urban micro-climatic conditions are strongly modified by energy fluxes driven by different composite physical and chemical processes [1, 2]. The progression of urban expansion and the accompanied anthropogenic activities has a substantial impact on the atmospheric boundary layer [3-6]. The boundary layer turbulence of any urban center depends largely on the landscape, local climate features, size of the area, population and the activities that take place within and around the urban area [7]. These features either enhance or reduce the heat instabilities of the area. The energy that radiates from the urban boundary layer atmosphere is being driven by mechanical and thermal turbulence. Mechanical turbulence is mainly governed by wind shear due to the urban surface roughness which enhances surface drag while

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thermal turbulence is generated from the earth surface interactions with solar radiation [7, 8]. Both mechanical and thermal turbulence can influence surface layer comfort index. This is because the atmospheric surface layer is the active link between the atmosphere and the surface and plays a major role in the conveyance and interactions of surface layer activities such as suspended pollutants, water vapor and heat from the ground surface. Thus, turbulent fluctuations in this layer are of great importance towards a successful inhabitation of boundary layer dwellers.

With the continuous development of Port Harcourt city as well as its endless deteriorating boundary layer environment, the relationship between urban heat island (UHI) and air pollution is on the rising and gaining attention. Air pollution and the effect of urban heat are complementary as air pollutants could absorb solar heat and warm the lower surface layer [8]. Port Harcourt city in recent times has witnessed an unusual heat effect both during the day and night periods. This heat effect is largely due to the consistent and persistent black carbon emissions choking the lower tropospheric atmosphere of Port Harcourt city most especially during the night periods since late 2016 [9]. Black carbon emissions due to fossil fuel burnings are typically dense carbonaceous substance which when suspended in the lower atmosphere absorbs solar radiation during the day and re-radiates it into the surrounding air. Black carbon has a positive radiative forcing and this makes it a strong warming agent [10]. All anthropogenic sources of black carbon emissions releases hundreds of organic aerosols and gases and these aerosols absorbs solar radiation in the ultra-violent and visible wavelength thereby enhancing the warming capacity of black carbon [11]. The objective of this study is to determine the surface layer turbulence effect in reducing or enhancing the induced heat island in Port Harcourt due to the influence of black carbon emission.

2. Material and Methods

2.1. Study Area

Port Harcourt is located within Latitudes $4^{o}\ 45^{l}$ – $4^{o}60^{l}$ N and Longitudes $6^{o}\ 55^{l}$ – $7^{o}56^{l}$E (Figure 1). The area is situated in the Nigeria's coastal zone classified under Koppen's '*Am*' tropical monsoon climate. The area which is roughly 40km from the ocean exposes it to the influence of continentality and this enhances both the effects of mechanical and thermal turbulence on the city boundary layer atmosphere. The humid northward maritime air mass from the Atlantic Ocean and the dry continental air mass from the Saharan desert control the area's climate regime during the wet and dry season. However, the predominant presence of the tropical maritime air mass ensures rainfall occurrence almost throughout the year. Unlike the northern part of Nigeria, where diurnal temperature variation is large, Port Harcourt experiences a low diurnal temperature variation due to the more humid atmosphere all through the year and this influences the cloud cover pattern of the area. The dispersal capacity of the boundary layer atmosphere to diffuse emissions is moderate and this encourages pollutants buildup in the lower atmosphere.

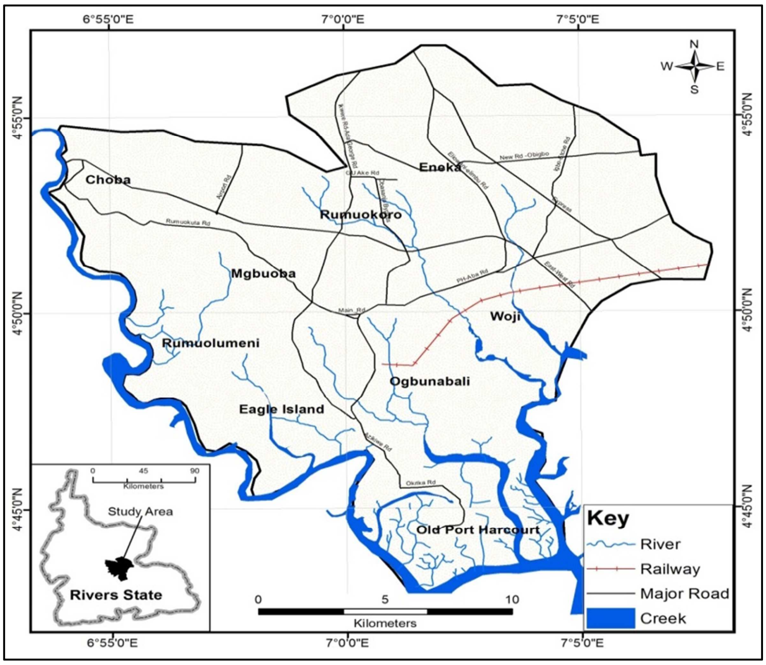

Figure 1. Map of Port Harcourt.

Source: [12]

2.2 Material Methods

A 6-year (2011-2016) diurnal surface meteorological data for temperature, cloud cover, wind speed and sunshine radiation was retrieved from the ERA-Interim plat form for the coastal city of Port Harcourt. The 6-hourly diurnal data was acquired at 0.125° spatial grid resolution. The Richardson (Ri) number technique as shown in equation 1 was used to determine the surface and mid layer turbulence characteristics of the study area. The Richardson number is a mathematical weather forecasting model pioneered by a British Meteorologist: Lewis Fry Richardson [13]. It is of practical significance in the analysis of the level of turbulence in the atmosphere. The atmospheric turbulence may be mechanical as well as thermal origin. The ratio of the two processes is called the Richardson number (R_i), which reflects the imbalance between thermal (convective), turbulence and mechanical turbulence. The numerator is associated to the destabilizing force that creates updrafts while the denominator is associated to the kinetic energy that terminates updrafts. The dimensionless parameter R_i is a function of the height z, given by:

$$R_i = \frac{\frac{g}{T}\left[\left(\frac{\partial T}{\partial z}\right)+\Gamma\right]}{\left(\frac{\partial U}{\partial z}\right)^2} \quad (1)$$

Where:

g -gravity constant in (m/s^2)

T -air temperature (°C)

Γ -adiabatic lapse rate (°C/m)

$\left(\frac{\partial u}{\partial z}\right)^2$ - is the mean wind speed (m/s^2)

z -altitudinal height (m)

Where,

$$\left(\frac{\partial u}{\partial z}\right)^2 = \frac{\Delta u}{Z_m \ln(Z_2 / Z_1)} \quad (2)$$

The notation 'Zm' is the mean vertical height considered.

The Monin- Obukhov Length (L) which defines the height where thermal turbulence of an air mass replaces mechanical turbulence was estimated from the Richardson number relationship with mean vertical height. That is;

$$Ri = \frac{Z_m}{L} \quad (3)$$

Richardson number is a viable substitute and also widely accepted method for evaluating boundary layer turbulence characteristics [14]. The heat index was evaluated for October, November and December, 2016, i.e. the period when the black soot emission was enormously detected across the boundary layer environment of Port Harcourt. The heat index equation is given by [15]:

$$HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T*T - .05481717*RH*RH + .00122874*T*T*RH + .00085282*T*RH*RH - .00000199*T*T*RH*RH. \quad (4)$$

Where,

HI = heat index in degrees Fahrenheit,

R = Relative humidity,

T = Temperature in ∘F,

The essence of evaluating both the turbulence characteristics and the heat index is to determine the influence of the surface layer turbulence of the study area in diluting the heat island generated during the night as a result of the black soot concentration across the boundary layer atmosphere of Port Harcourt. A computer programme was written in excel spreadsheet to make the heat index equation a friendly user interface.

3. Results and Discussions

3.1. Boundary Layer Turbulence in Port Harcourt

The Table 1 shows the outcome of the Richardson number analysis for the surface and mid boundary layer atmosphere of Port Harcourt from October to December, 2016. Atmospheric researchers have noted that for any Richardson number less than the critical Richardson number (Ric) of 0.25 or not more than the Richardson Termination Level (R_{iT}) of 1, a level of turbulence that could generate instability exist. The critical value of 0.25 relates only at the surface layer gradient of not more than 50m and not across thick layers [16]. It has been noted that the acceptable range of Ric is between 0.2 and 1 [17]. It has been emphasized that low positive values of Ri indicates the influence of the denominator creating some level of turbulence [18]. Any flow above the Richardson Termination value of 1 becomes laminar and also that the level of turbulence due to wind shear is higher for small positive Richardson number than large positive numbers, i.e. rate of forced turbulence decreases with increases in positive Ri values. However, small negative Ri values has increased turbulence due to wind shear than any positive Ri values [19].

Table 1. Richardson Number (Ri) Analysis for Port Harcourt.

Hour	Surface Layer 0-50m	Mid Layer 50-100m	Obhukuv Length (L) (m)
00:00	0.38	3.09	31.9
06:00	0.52	9.38	19.2
12:00	0.27	5.09	32.2
18:00	0.44	3.59	24.9

The mean Ri values for Port Harcourt at the specified hours were slightly higher than 0.25, but far less than the Richardson Termination Level (R_{iT}) of 1. These trends show that the surface layer during this period across the study area is vulnerable to mechanical turbulence rather than thermally generated. The next layer above the surface (50-100m) indicated a more laminar pattern with Ri values greater than 1. This indicates a lesser level of turbulence with thermal interphase. The surface layer is the layer where humans, animals, and vegetation dwell and where most anthropogenic activities take place. The sharpest variations in meteorological variables with height occur within the surface layer and, consequently, the most significant exchanges of momentum, heat, and mass also occur in this layer. The pattern of turbulence in the study area at the surface layer shows that not much boundary layer heat will be dispersed or diluted by the weak turbulence in the area. Turbulence is the mechanism for effective transfer, mixing and exchange of mass, heat, and momentum throughout the ABL. Through the transfer of energy fluxes, boundary layer turbulence regulates the microclimate close to the earth surface and makes it habitable. The quality of the air we breathe is governed by the mixing capability of the boundary layer turbulence [20]. The average wind speed value for Port Harcourt is between 0-3m/s, with higher values during the day and lower values to calm periods during the night period [7]. This shows that the dispersive potential of air over the coastal city will be moderate during the day and worse at night. Also, the high humid environment of the study area all year round shows that the wind capacity to dilute pollutants faster will be low.

3.2. The Heat Index Effect in Port Harcourt

The Table 2 shows the percentage summary heat index for Port Harcourt during the black soot incidence from October to December 2016. It is revealed that the heat event during the periods under review was 47.9% extreme caution and 37.1% danger region. Both the extreme caution and danger heat range constitute about 85%. Only about 8% of the heat index exhibited a stable pattern throughout the duration under consideration. This pattern of heat stress will impact on the comfort index of Port Harcourt boundary layer dwellers if there are no suitable measures to cushion the heat effect. Heat index is the extent of how warm an environment or body really feels when the relative humidity is incorporated with the actual environmental temperature. With respect to the human body, it usually cools itself by the evaporation of the sweats from the surface of the skin. Nevertheless, under a very humid environment such as Port Harcourt, the rate of evaporation from the body reduces. This leads to a lesser rate of heat loss, hence a reduced comfort index. An Increase in daytime air temperatures as well as higher air pollution concentration levels which reduces night time cooling can affect human health by contributing to discomfort, respiratory problems, heat cramps and exhaustion, heat stroke, and heat related mortality.

There have been several researches on the sources and impact of the heat effect including surface heat flux unevenness due to urban built-up structures, anthropogenic heat release, and the contributory micro-climatic conditions of the environment [21, 1-6]. The heat island experienced across Port Harcourt atmospheric environment mostly during the night time is strongly related to the black soot emissions which emanates from the illegal refining of petroleum crude [9]. The boundary layer atmosphere of Port Harcourt is very stable at night, slightly unstable during the day and moderately unstable during the transition periods [10]. The very stable microclimatic nature during the periods of the dawn discourages vertical ascent of air. Therefore the black soot emission across the area is able to trap outgoing terrestrial radiation and hence warm up the ambient environment. Black soot has a positive radiation forcing and this makes it a strong warming agent. The weak-laminar surface layer mechanical turbulence analysis of Port Harcourt boundary layer is incapable of diluting the built heat island.

Anthropogenic heat is one of the primary factors that create heat island [22]. It was noted that when there is an increased heat occasions, the energy demand on power infrastructures to act as palliative measures will be very high. It was emphasized that there would be 2% rise in a city's electricity demand at 1^{o}C rise in temperature due to the required additional cooling space for optimal comfort. This additional energy demand will lead to the enhancement of stratospheric greenhouse gases [22].

Table 2. Percentage Summary of Heat Index (HI) for Port Harcourt from October to December 2016.

Key Index	Percentage HI (%)	Health Impact
Stable	8.1	Less fatigue with prolonged exposure
Caution	3.5	Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramp
Extreme Caution	47.9	Heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke
Danger	37.1	Heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity
Extreme Danger	3.4	Heat stroke is imminent

The Figure 2-8 shows the heat index chart for Port Harcourt area during the night/early hours of dawn i.e. 00:00-06:00 hours for the periods under review. The black soot emission across the boundary layer atmosphere of Port Harcourt is noticeable during these periods. It is revealed that the effect of the heat index is more between 00:00-03:00 hours and reduces from 04:00-06:00 hours. It has been highlighted that black soot emission spread is dominant during 00:00-03:00 hours across the boundary layer atmosphere of Port Harcourt [9]. This authenticates the reason for the higher heat index during the early hours of the night.

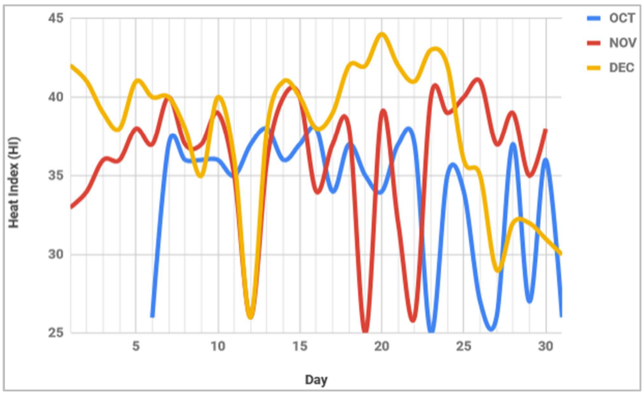

Figure 2. 00:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

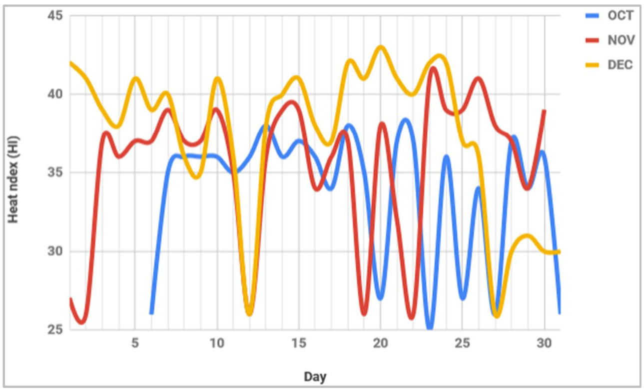

Figure 3. 01:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

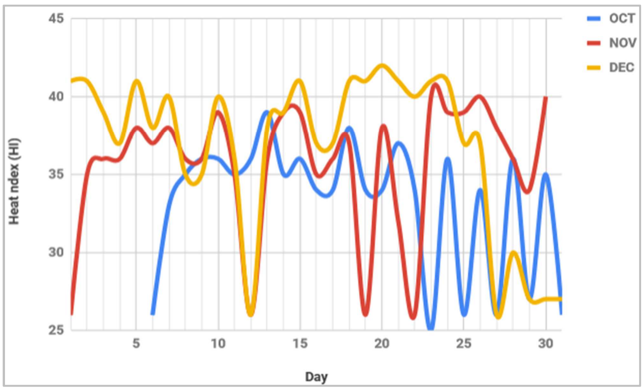

Figure 4. 02:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

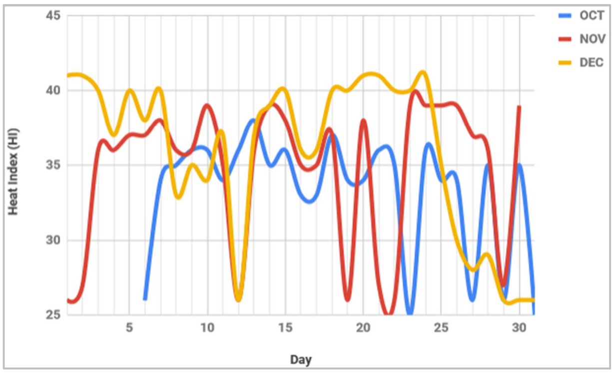

Figure 5. 03:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

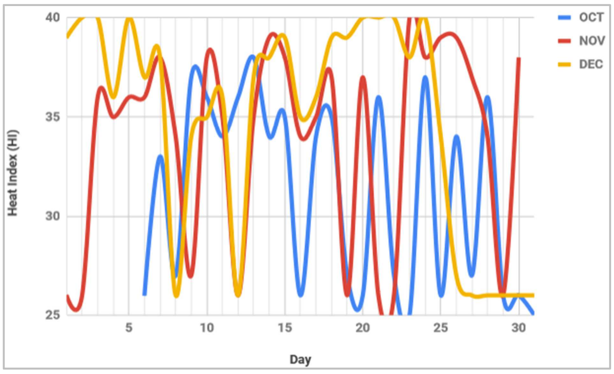

Figure 6. 04:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

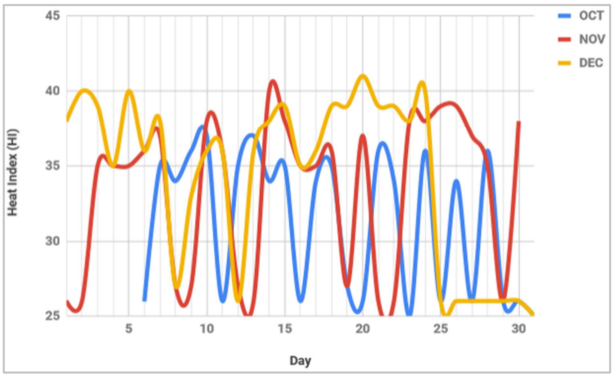

Figure 7. 05:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

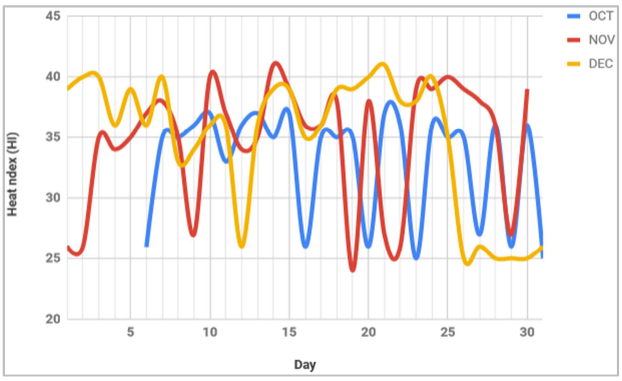

Figure 8. 06:00Hr Heat Index Chart for Port Harcourt from October-December, 2016.

3.3. The Port Harcourt Heat Index and Air Pollution

Due to the increasing population of the coastal city of Port Harcourt arising from the city's vast potentials for business opportunities, there is a corresponding deteriorating effect on the urban environment. One of the most impactful of this urban deterioration is its air quality. Airborne pollutants such as black soot influence the heat island of any locality due to its large capacity to absorb, scatter and reflect radiation process. The low to moderate dominant mechanical turbulent pattern that characterizes the Port Harcourt boundary layer limits the mixing potential of ambient air across the area's lower atmosphere. This enables the airborne pollutants to be dispersed at a minimal rate with the pollutants having a long residence time in the lower atmosphere. When the local atmosphere of a city is strongly enhanced with anthropogenic emissions, the higher will be the pollutant concentrations. With the consolidated emission concentrations within the boundary layer atmosphere, there could be a reduced amount of radiation reaching the lower boundary atmosphere. However, with the absorption of heat energy from anthropogenic sources at the surface layer, the heat releases downwards could exceed the reflection of radiation effect from the upper atmosphere.

Based on these circumstances, the heat island would intensify creating a warmer lower atmospheric environment. Tougher and durable heat island concentration could enhance a more energetic lower boundary layer circulation and this could restructure the lateral and horizontal spread as well as dilution of pollutants from emission sources across sensitive receptors. The black soot event which is prominent during the night periods in Port Harcourt chokes the city's local atmosphere due to the more reduced boundary layer height. The boundary layer height for Port Harcourt during the night averages between 10-182m [7]. This height ensures that pollutants are spread below 182m or lower. When pollutants acquire heat under this condition, the heat island circulation is strengthened and when there is continuous enrichment of the pollutants within the boundary layer atmosphere, the heat island becomes severe, thereby enhancing boundary layer discomfort.

4. Conclusion and Recommendation

The interaction between boundary layer turbulence, urban heat island and air pollution is a critical one that either enhances surface layer comfort or discomfort. Since the last quarter of 2016, black soot emissions have been choking the city of Port Harcourt and these episodes have ample negative impacts. This study has shown that the urban heat island which is peculiar to the buildup of heat during the period solar activity in conjunction with urban modifications during the period of the day could be enhanced by the concentrations of airborne pollutants during the periods of the night. Terrestrial radiation is being released during transition and night periods. However, with the peculiar nature of black soot which has a positive radiation forcing, its emissions as observed in Port Harcourt within the past 2 years are capable of increasing the heat island effect of the city thereby impacting on the boundary layer dwellers. Surface layer mechanical turbulence, a vital microclimatic component of the lower atmosphere for any locality which helps in modifying surface layer heat flux is in the weak-laminar range in Port Harcourt. This minimal turbulence pattern is been enhanced by the moderate wind speeds and humid atmospheric conditions of the lower atmosphere in Port Harcourt where air pollutants dissipation will be weak and not responsive most especially during the night periods. This will ensure the buildup of pollutants and subsequent absorption of radiation heat thereby warming the boundary layer atmosphere. In order to mitigate the increased heat island in the city mostly at night, policy makers should ensure that anthropogenic emission releases are reduced from sources to avoid air pollutants build-up. Also, the greater Port Harcourt plan that proposes the decongestion of the city's increasing population should be adopted to create opportunity for adequate expansion thereby reducing concentration of business hubs around the long-standing city center.

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