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Determination of the vertical variations in temperature and longwave radiation within the gray Earth's troposphere using radiative equilibrium profile model

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This study estimated the vertical variation in mean temperatures within the tropospheric layer using the radiative equilibrium profile model and longwave radiation with Stefan-Boltzmann equation at a tropical meteorological station located besides Physics Building (7.55°N:4.56°E), Obafemi Awolowo University, Ile-Ife, Nigeria. In the model, the height of the troposphere was assumed to be 16.0 x 10^0 km and the standard effective mean temperature (255K) in the tropics was used in estimating the tropospheric mean temperatures for two layers: the ground surface (1.6 x 10^{-3} km) and the top of the troposphere (16.0 x 10^0 km). Arithmetic progression expression was then used to obtain the temperatures and longwave radiations for 16 equal sub-layers within the vertical height of the Earth's troposphere. Our results showed that the estimated ground layer temperature (33.3°C) and longwave radiation (499.1 Wm^{-2}) for the meteorological station were comparable with the observed (31.9°C; 490.0 Wm^{-2}). Both the temperature and radiation were found to decrease with altitude within the tropospheric layers. The study concluded that the model performed reasonably in estimating the vertical profile of temperatures and longwave radiation over the study area.

Key words: Radiative equilibrium profile, temperature, longwave radiation, troposphere.

INTRODUCTION

The Earth's atmosphere is defined as an envelope of gases mixed up in remarkable proportion with varying percentage compositions (Olajire, 2008). For example, the percentage composition of Nitrogen (N_2) by volume is approximately 78.08%; Oxygen (O_2), 20.95%; Argon (Ar), 0.93%; Carbon dioxide(O_2), 0.03%; Neon (Ne), 0.002%; Helium (He), 0.005%; Methane (CH_4), 0.0002%; Krypton (Kr), 0.00001% and Hydrogen (H_2), 0.00005% while N_2O, Xe, CO, O_3 in traces of water vapor are 0.0001% (Roger and Richards, 1995).

Literature illustrated that the atmosphere can be divided into four layers or regions using the characteristic temperature lapse rates (that is, troposphere, stratosphere, mesosphere and thermosphere). The first layer, troposphere, is a friction layer where many atmospheric activities take place. This layer was found to vary in height and extends to a height of approximately 8 km in the polar region and 16 -19 km over the tropical regions (Cole, 1980). Figure 1 illustrates the vertical variations in temperature within the different layers of the atmosphere as reported by Scisat-1 (2010). The figure showed that, within the troposphere, the temperature decreases from about 18°C on the earth's surface to about -47°C at the top (12 km) of the troposphere. The tropical region is principally characterized by more or less uniform decrease in temperature with height within this

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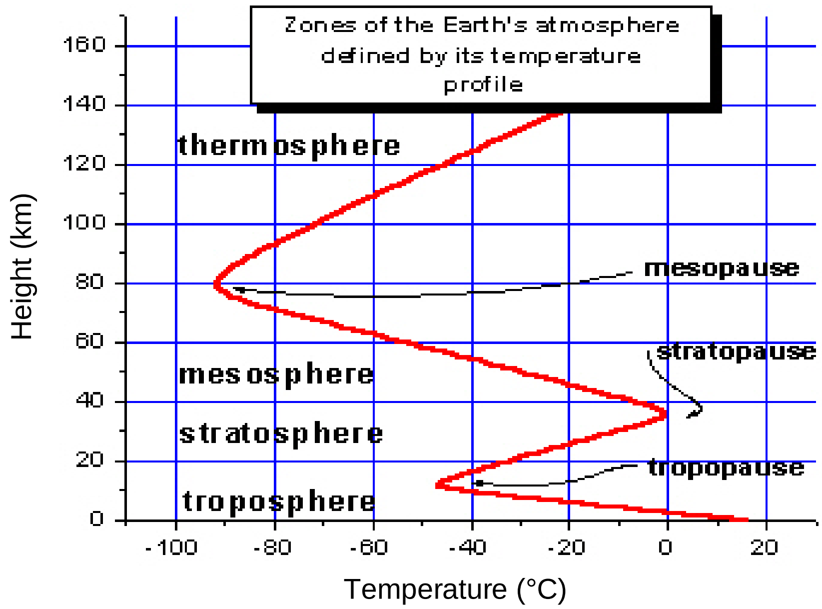

Figure 1. Variation in temperature with altitude (After Scisat-1, 2010).

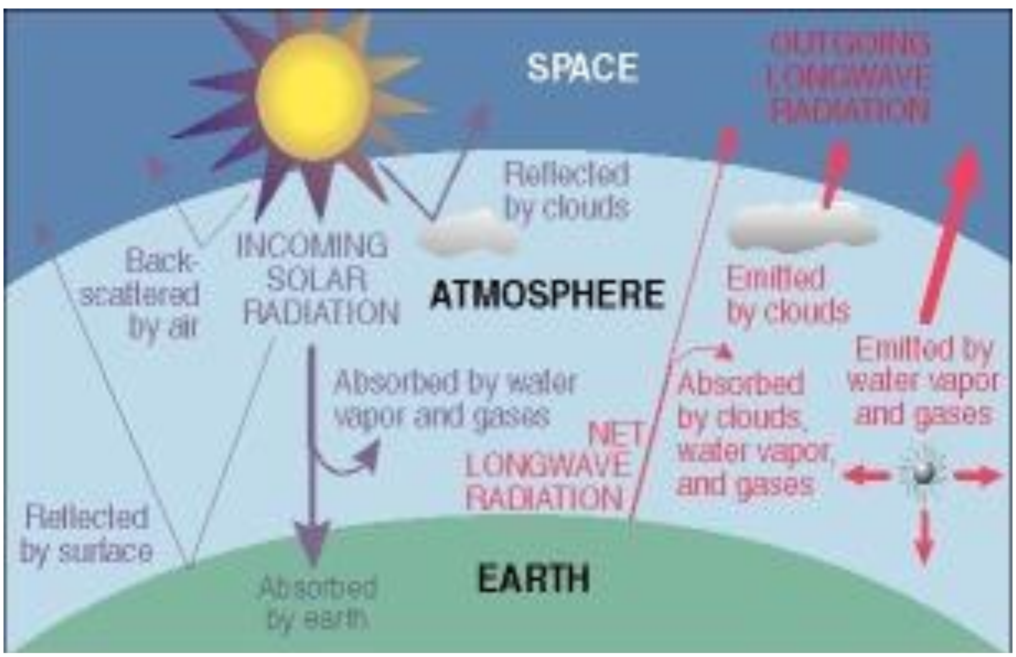

Figure 2. Radiation balance at the Earth's surface (Source: Ritter, 2009).

layer. Just above the troposphere, the temperature remains constant for further 1 or 2 km (called the tropopause) before it increase again from about -47°C (at a height 14 km; top of the tropopause) to about 0°C (at a height 35 km; top of the stratosphere). Within the stratosphere (36-80 km), the temperature decreases to about -92°C. The vertical temperatures increase within the thermosphere to reach about -20°C at the top of this layer (140 km).

About fifty-one percent (51%) of the solar or short wave radiation (0.2- 4.0 µm) at the top of the atmosphere were found to reach the earth's surface (Ritter, 2009). This is so because of the atmospheric radiation absorption, reflection and scattering (Figure 2). The atmospheric

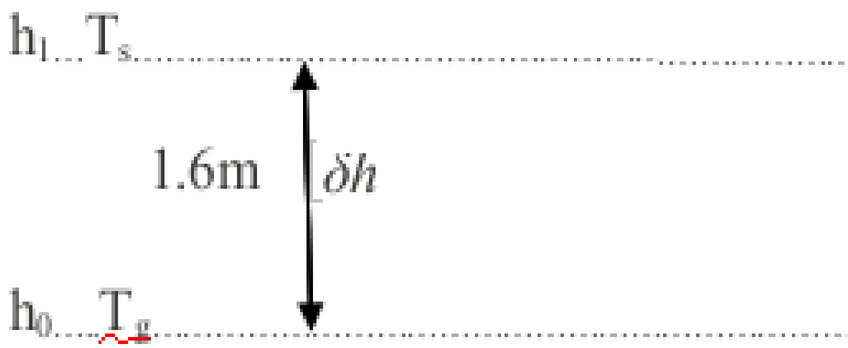

Figure 3. Stephenson screen height above the ground surface at Meteorological station located besides Physics Building, Obafemi Awolowo University Campus, Ile-Ife, Nigeria.

constituents such as oxygen (O_2), water vapour (H_2O) and carbon dioxide (CO_2) re-emit the absorbed shortwave radiation back to the earth's surface within the longwave band (12.0 - 150.0 μm). Similarly, at the Earth's surface, solar radiation is partially reflected, absorbed and then re-radiated back to the space as terrestrial or longwave radiation. The atmosphere is much more absorbent to longwave radiation than to short wave radiation. Most absorption of the longwave radiation by water vapour takes place in the lowest layer of the atmosphere thereby making the clouds very effective absorbers (Ritter, 2009). Under clear skies, radiation is emitted by the surface but little is received by the atmospheric constituents in the atmosphere and therefore the temperature falls rapidly, (Olajire, 2012). Longwave radiation varies directly as the fourth power of the surface's absolute temperatures. Its value thus depends largely on the land-cover, atmospheric constituents (such as gases in the atmosphere and aerosols) and clouds cover, types and drift (Briggs and Smithson, 1995).

Various observations had shown that temperature varies with altitude and that temperature lapse rate is one of the controlling factors governing the structure of any planetary atmosphere (Roger and Richard, 1995). However, studies on the vertical temperature structure of the tropospheric layer in many tropical locations of the world, including those areas where there are wide gaps in observational data, are grossly inadequate. More so that the use of common atmospheric measuring instruments like radio sonde, rocket, etc (Roger and Richard, 1995) in these locations is still rare. Thus, the primary objective of this study was to estimate the tropospheric layer temperature over Obafemi Awolowo University (OAU) Campus, Ile-Ife, Nigeria using the principle of radiative equilibrium profile model and longwave radiation using the Stefan-Boltzman equation. The paper evaluated the performance of the radiative equilibrium profile model in estimating the vertical variation in mean temperatures and Stefan-Boltzmann equation in estimating longwave radiation within the troposphere. The results enhanced our scientific understanding of the vertical profile of the troposphere.

MATERIALS AND METHODS

A Stephenson screen of about 1.6 x10^{-3} km (Figure 3) above the ground surface containing a dry bulb thermometer was sited at the meteorological station located besides Physics Building, Obafemi Awolowo University, Ile-Ife (7.55°N: 4.56°E), Nigeria (Figure 4) for continuous measurements of micrometeorological parameters (such as temperature, rainfall, wind speed, relative humidity, solar radiation and surface heat fluxes) at 10 min time interval.

The radiative equilibrium profile model is a multi-layer model. Within each layer, both the temperature and longwave radiation were assumed to be uniform but vary across the layers. In this study, however, a 2-layer radiative equilibrium profile model was assumed. An arithmetical progression expression was then used to further sub-divide the two layers into 16 equal sub-layers. In the model, the standard effective mean temperature (T_e = 255K) in the tropics was used to obtain the mean temperatures at different layers within the tropospheric height which was assumed to be 16.0 x 10^0 km at the study area (Cole, 1980).

Radiative Equilibrium Profile Model's descriptions

Radiative Equilibrium Profile Model, fully described by Henderson-Sellers and McGuffey (2007) is a multi-layer model (Figure 5). The model assumes that the solar radiation goes straight to the surface (not absorbed by any layer) and that the longwave radiation given out by each layer will go to next adjacent layer (that is, no one crosses next adjacent layer). This agreed with the submission of Swinbank (1963) in that most of the atmospheric longwave radiation reaching the earth's surface originates from within a few hundred meters from the ground. The model also assumed that the layers are neither too thick nor too thin and that the longwave radiation is emitted to the last surface from the ground. The surface temperature T_g (K) is presumed to be approximately equal to the air temperature T_a (K) measured by the dry bulb thermometer in the Stephenson screen. With this, the earth surface behaves like a perfect black body where the energy absorbed is approximately equal to the energy emitted and emissivity, ε, is approximately unity (ε = 1).

Long wave radiation, L_w was determined using the Stefan-

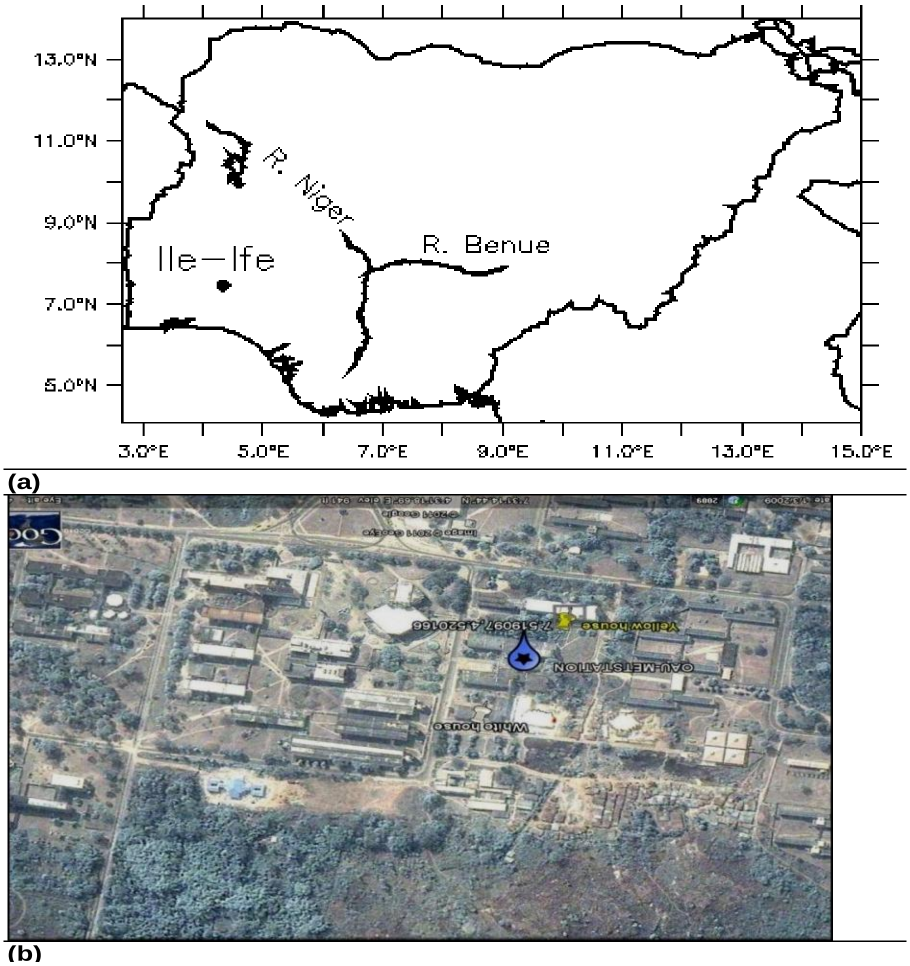

Figure 4. A Map of Nigeria showing (a) the location of Obafemi Awolowo University (OAU) Campus, Ile-Ife, Southwest Nigeria and (b) the position of the meteorological station beside Physics Building at OAU, Ile-Ife.

Boltzmann equation:

$$L_W = \varepsilon \sigma T^4 \quad (1)$$

Where ε is the emissivity of atmospheric parameters (dust samples, gases, water vapour and clouds), σ is Stefan-Boltzmann constant and T the absolute temperature. In this study, the atmospheric parameters such as water vapour and clouds were considered as grey body with emissivity, ε approximately equal to 1. Thus Equation 1 becomes:

$$L_W = \sigma T^4 \quad (2)$$

Hence, the radiation leaving the top of the atmosphere is equal to incoming radiation. That is,

$$\sigma T_e^4 \downarrow = \sigma T_1^4 \uparrow \quad (3)$$

$$T_1^4 = T_e^4 \quad (4)$$

Layer 1 has temperature T_1 and radiates out at the rate σT_1^4 to layer 4 below and to the outer space. Therefore,

$$\sigma T_1^4 \downarrow + \sigma T_1^4 \uparrow = \sigma T_2^4 \uparrow$$
$$2\sigma T_1^4 = \sigma T_2^4 \uparrow \quad (5)$$

From Equations 4 and 5 we have,

$$T_2^4 = 2T_e^4 \quad (6)$$

For layer 2,

$$\sigma T_2^4 \downarrow + \sigma T_2^4 \uparrow = \sigma T_1^4 \downarrow + \sigma T_3^4 \uparrow$$
$$2\sigma T_2^4 = \sigma T_1^4 \downarrow + \sigma T_3^4 \uparrow \quad (7)$$

For layer 3,

$$\sigma T_3^4 \downarrow + \sigma T_3^4 \uparrow = \sigma T_2^4 \downarrow + \sigma T_4^4 \uparrow$$
$$2\sigma T_3^4 = \sigma T_2^4 \downarrow + \sigma T_4^4 \uparrow \quad (8)$$

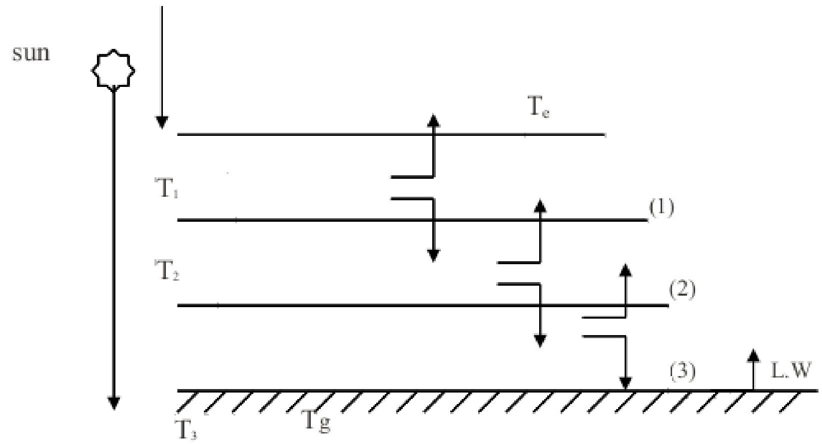

Figure 5. Radiative Equilibrium Profile Model used in this study (after Henderson-Sellers and McGuffey, 2007).

Table 1. Observed and estimated vertical mean temperatures and longwave radiations over Obafemi Awolowo University Campus, Ile-Ife, Southwestern Nigeria.

Altitude (km)	Temperatures (°C)			Longwave radiation (Wm^{-2})		
	Observed	Estimated	Bias	Observed	Estimated	Bias
1.6 $x10^{-3}$	31.9	33.3	1.4	490.0	499.1	9.1
16.0 $x10^{0}$	-	-18.0		-	239.8	

Using Equations 3 and 5 in Equation 7, we obtain

$$T_3^4 = 3T_e^4 \quad (9a)$$

Similarly,

$$T_4^4 = 4T_e^4 \quad (9b)$$

$$T_5^4 = 5T_e^4 \quad (9c)$$

Thus, at the surface, total energy absorbed is given as:

$$\sigma T_e^4 + 4\sigma T_e^4 = 5\sigma T_e^4 \quad (10)$$

If σT_g^4 is the energy lost from the earth's surface and going by the assumption that the earth surface behaves like a perfect black body where the energy absorbed is approximately equal to the energy emitted and emissivity, $\varepsilon \approx 1$ (approximately) then,

$$\sigma T_g^4 = 5\sigma T_e^4 \quad (11)$$

Therefore,

$$T_g^4 = (n+1)T_e^4 \quad (12)$$

Where n is the number of layers considered or optical thickness of the atmosphere, Temperatures at layer 1 (T_1), layer 2, (T_2) and ground surface (T_g) were obtained using Equations 4, 6 and 12, respectively. The temperatures of other layers within the temperatures of the two determined layers were calculated using arithmetic progression expression,

$$L = a + (n-1)d \quad (13)$$

Where $a = T_2$ = first term, $L = T_1 = T_e$ is the last term, $n = 16,$ is the number of layers and d is the common division between the two determined layers 1 and 2.

RESULTS AND DISCUSSION

Table 1 compares the observed and estimated temperatures and longwave radiation at the surface (1.6 x 10^{-3} km) and the top of the troposphere (16.0 x 10^{0} km). The results indicated that the model adequately estimated the temperatures and longwave radiation at different layers within the troposphere. For example, the difference between the observed (31.9°C) and estimated (33.3°C) temperature (that is, bias) was about 1°C at 1.6 x 10^{-3} km (Table 1). There was no observation for the temperature to the top of the troposphere (16.0 x 10^{0} km). However, the model estimated the temperature at this

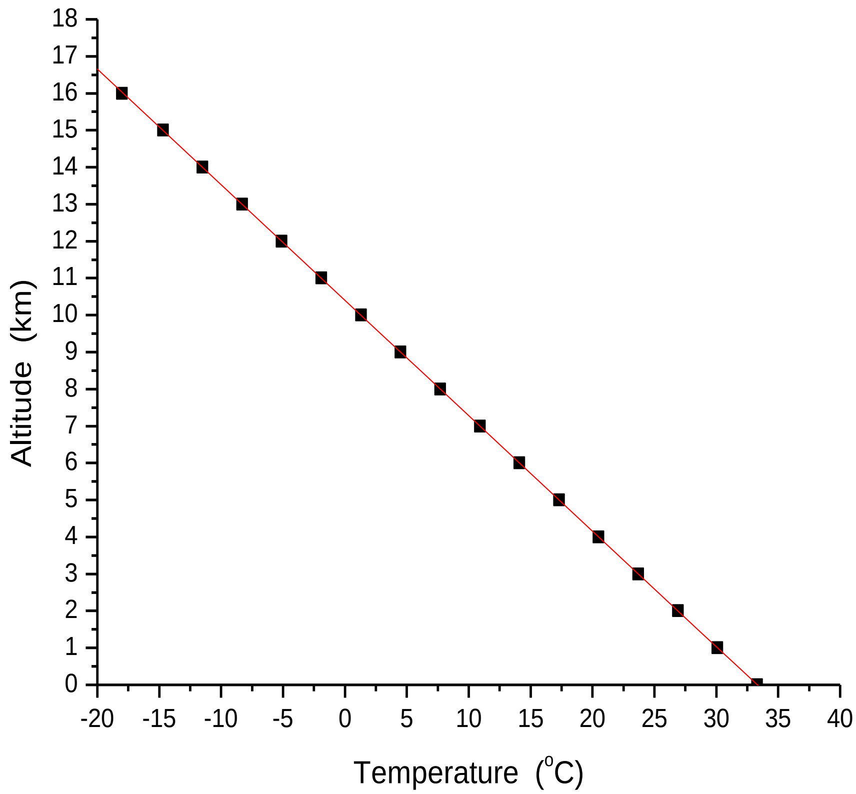

Figure 6. Vertical variation in temperature with altitude over Obafemi Awolowo University Campus, Ile-Ife, Southwestern Nigeria.

height to be -18.0°C. Similarly, the difference between the observed (490 Wm^{-2}) and estimated (499.1 Wm^{-2}) longwave radiation was less than 10.0 Wm^{-2} at 1.6 x 10^{-3} km and the estimated radiation was 239.8 Wm^{-2} at the top of the troposphere.

Generally, our results suggested good agreement between the observation and the model. However, there were slight over-estimations in both the mean temperatures and longwave radiation. Furthermore, the vertical variations in the estimated tropospheric mean temperature over the study area were presented in Figure 6. Results suggested that temperature decreases with height within the troposphere. For example, temperatures at heights 1.6 x 10^{-3} km, 1.0 x 10^{0} km, 2.0 x 10^{0} km, 10.0 x 10^{0} km and 16.0 x 10^{0} km were 33.3, 30.1, 26.9, 1.3 and -18.0°C respectively (Figure 6). This implies that the temperature decreases steadily by -3.2°C/km (dry adiabatic lapse rate) within the troposphere. These results agreed with previous studies (Roger and Richard, 1995; Briggs and Smithson, 1995; Russell, 2009; Scisat-1, 2010) in that temperatures decrease (get cooler) with increasing altitude in the troposphere.

Results of this study also showed that the longwave radiation decreases with height within the troposphere. For example, temperatures at heights 1.6 x 10^{-3} km, 1.0 x 10° km, 2.0 x 10° km, 10.0 x 10° km and 16.0 x 10° km were 499.1, 478.6, 458.7, 321.0 and 239.8 Wm^{-2}, respectively (Figure 7). These were indications that the longwave radiation decreased steadily by -16.2 Wm^{-2}/km within the troposphere. Then, going by the submission of Briggs and Smithson (1995) that longwave radiation is a function of surface's temperature and Roger and Richard (1995) that temperature decreases with height within the troposphere, it could be deduced that steady decrease in longwave radiation within the troposphere as found in this study was reasonable.

Conclusion

This study used the radiative equilibrium profile model in estimating the vertical variation in the Earth's tropospheric temperatures and Stefan-Boltzmann equation for longwave radiation over a tropical meteorological station located besides Physics Building (7.55°N:4.56°E), Obafemi Awolowo University (OAU) Ile-Ife, Nigeria. The study showed that the model adequately replicated the vertical profile of the tropospheric layer temperature and longwave radiation over the study area. The results of this study were fairly good data resources particularly over the remote areas of the tropics where there are dearth of meteorological measurements.

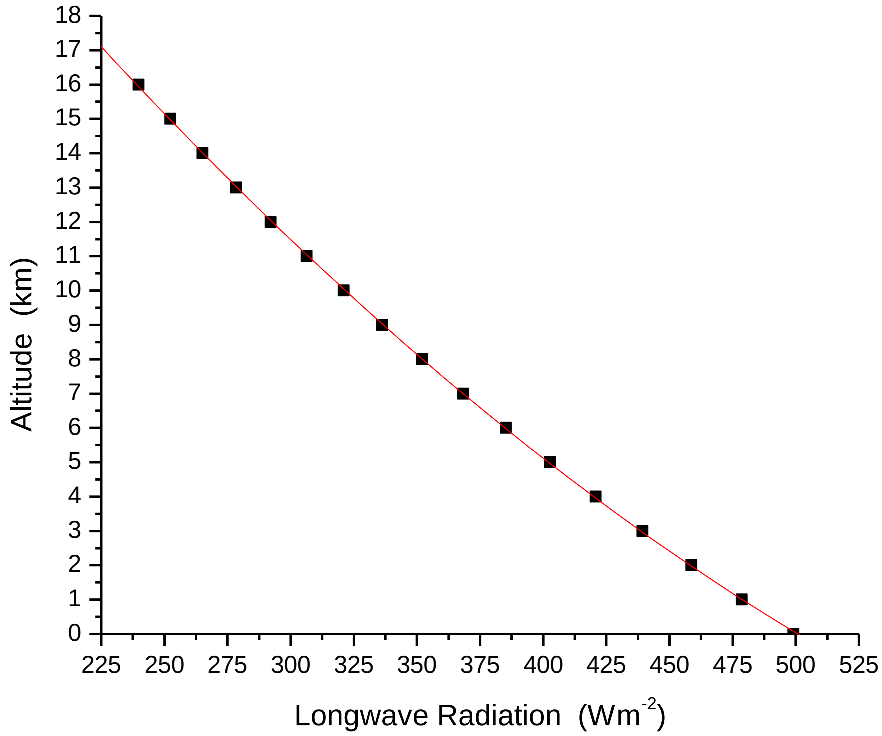

Figure 7. Vertical variation in longwave radiation with altitude over Obafemi Awolowo University Campus, Ile-Ife, Southwestern Nigeria.

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