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Determination of Linke's Turbidity Factors from Model and Measure Solar Radiations in the Tropics Over Highland of South-East Ethiopia

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Abstract

Linke's turbidity factors T_L and perceptible water vapor in the atmosphere are essential for evaluating pollution trends in the area. The rise of T_L is directly related to deforestation, industrialization, urbanization and influx of dusts and particulate matters from closer and far distance to the region. In this study, there is a computation of T_L from three methods global solar radiation (GSR) data. These are model, ground and satellite recorded GSR. The model codes of mathematical equations in determining model GSR and T_L were handled by MATLAB tool. The T_L from model GSR were compared with ground and satellite GSR in terms of statistical evaluation indicators: The coefficient of determination (R2), root mean squared error (RMSE), Nash-Sutcliffe efficiency (E), its relative efficiency criteria (Er), index agreement (d) and its relative efficiency criteria (dr). All T_Ls from the model, ground and satellite GSR are approximately varied between 4 and 8. The rising levels have been approximately found in the range between 20% and 37.5% as compared to T_L of tropical warm air (continental) since 1947. Atmospheric turbidity is an important procedure for early warning on monitoring air, water, soil quality for stability of healthy ecosystem.

Keywords: Aerosols; Africa rising; Global solar radiation; Links turbidity factors; Perceptible water vapor

Introduction

The attenuation of solar radiation through a real atmosphere *versus* that through a clean, dry atmosphere gives an indication of the atmospheric turbidity. It is a very suitable approximation to model the atmospheric absorption and scattering of the extraterrestrial radiation relative to dry and clean atmosphere [1]. Its study is important for monitoring atmospheric pollution trough the presence of dust aerosols in the meteorology and climatology. Atmospheric turbidity associated with aerosols from dust loads, water vapor and anthropogenic source is also an important parameter for assessing pollution trends [2].

As other published literatures, atmospheric aerosol has increased enormously over the last two decades. It can either have non-anthropogenic or anthropogenic sources and are either emitted as primary particles (i.e. They are directly emitted to the atmosphere) or formed by secondary processes (i.e. By transformation of emitted precursor gases). It has been rising from low concentration over the preserved forest of Amazonian because of land-use change from natural begins to biomass burning [3] may bring T_L to the pollution level. According to Engelbrecht and Derbyshire [4] the pollution level of dust aerosols through the determination of T_L being closer to 8.

The global source regions of dust have covered the Northern Hemisphere, including North Africa, the Middle East, the Northwest Indian subcontinent, central Asia, and Northwest China [4]. Ethiopia is not immune from the large influx of dust because of its proximity, particularly in the Sahel and Arabia Peninsula. Influx dust from these regions, particulate matter from nearby industries, and smokes from deforestations for agriculture and fuel wood combined with maritime (Red Sea and Indian Ocean) moisture may contribute the rise of a turbidity factor in the area. The study area for this purpose is an Illusanbitu District located in tropical highland of South-East Ethiopia at about 7° latitude, 40° longitudes and 2500 m altitude. The determination of Linke's turbidity factor T_L was carried out from three method data.

- The meteorological data on Global Solar Radiation (GSR) were obtained from a non-government organization called Africa Rising [5] settled there.
- The model GSR data were extracted through integrating of mathematical equations from four atmospheric parameters by MATLAB tool.
- The satellite GSR data at the location was freely logged down from a website called Atmospheric Science Data Center controlled by the National Aeronautics and Space Administration NASA.

Materials and Methods

Mathematical formulations for global solar radiation modeling

The mathematical formulations were largely reviewed from the book written by Iqbal [6], and some published journals listed in the reference. The modeling in determining GSR entirely depends upon integrating the four major classifications of atmospheric parameters discussed below:

a. Geographical Parameters: The altitude and latitude in combining solar geometry climatic and optical parameters are essential in determining the amount of solar insolation reaching the earth's surface.

b. Solar Geometric Parameters: Under this category, the amount of solar irradiance reaching the study area are influenced by solar geometry parameters such the solar zenith angle θ_z, declination angle δ solar altitude angle η and solar hour angles ω. The solar geometry called declination angle δ is computed as:

$$\delta = 23.45 \sin\left(\frac{360}{365}(n+284)\right) \quad (1)$$

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The orientation of a horizontally placed solar receiver towards the incident radiation related to the declination angle δ, solar zenith θ_z, latitude ϕ, solar altitude angle η and solar hour angle ω in degree related as:

$$\sin\eta = \cos\theta_z = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega \quad (2)$$

$$\omega = -15(LT-12) \quad (3)$$

Where L_T is the local time from the midnight. On the other hand, it is well known that atmospheric turbidities linked with the presence of aerosols, water vapor, and ozone are the most important extinction components affecting the direct and diffuse components of solar radiation under clear skies [7]. As a matter of fact, the effect of moist or water vapor is taken by considering the w in centimeter in terms, relative humidity H_r, ambient temperature T and partial pressure in Kelvin are expressed in Equations 4 and 5.

a. Climatic parameters: These classifications involve the measurement of ambient temperature, relative humidity, horizontal climate visibility and partial air pressure. The ambient temperature and relative humidity are also served for computing perceptible water vapor w using Equations 4 and 5. As a matter of fact, the effect of moist or water vapor is taken by considering the w in centimeter in terms, relative humidity, H_r ambient temperature T and partial pressure in Kelvin are expressed in these equations.

$$w = 0.49\frac{H_r P_s}{T} \quad (4)$$

$$P_s = \exp\left(26.23 - \frac{5416}{T}\right) \quad (5)$$

The horizontal visibility V is also a significant climate factor in computing optical air transmittance in Equation (6). The horizontal Vis of the area lies within the range of 17 km up to 22 km during winter when there are low rainfall and cloud coverage.

b. Atmospheric optical parameters: It is the most complex atmospheric phenomena in determining the energy budget at a given location. The amount of solar energy reaching the surface is affected by optical properties of water vapor, air, ozone layer and aerosol masses. Their effects on solar irradiance are sensed by computing their optical transmittance, reflectance, absorbance, Rayleigh centeredness and turbidity coefficients that attenuate the solar irradiance reaching the surface. The ground albedo is also taken into consideration for modeling purposes. The computed value of relative optical masses of aerosol τ_a, air mass m_a, water vapor m_w and ozone m_o at a given location are given under Equations (6), (7) (10) and (11) respectively. Their values are almost in closer ranges as stated by Iqbal [6]. However, an optical mass of aerosols m_o is the most uncertain parameters in calculating solar radiation on the ground [6]. They are highly variable in size, distribution, composition, and optical properties. For lack of required information, the value of computing optical air mass m_a can be used as a substitute for optical mass of aerosol m_o in Equation (7). Therefore, the optical transmittance τ_a written in Eq. (6) as the presence of aerosols is calculated as

$$\tau_a = \left(0.97 - 1.265(Vis)^{-0.66}\right)^{m_a^{0.9}} \quad (6)$$

Where m_a is in the Equation (6) is the relative optical dry air mass for local conditions computed through Equations 7, 8, and 9.

$$m_a = m_r\frac{P}{P_o} \quad (7)$$

Where P and P_o are the local pressure and sea level pressures in millibars respectively. The local atmospheric pressure above sea level at altitude z is evaluated as:

$$\frac{P}{P_o} = \exp(-0.0001184z) \quad (8)$$

The altitude of the study location z is around 2480 m. The relative optical air mass m_r in Equation (7) may be approximated by relating to zenith angle θ_z:

$$m_r = \left(\cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}\right)^{-1} \quad (9)$$

On the other hand, the corresponding expressions for relative optical water vapor mass m_w and relative optical ozone mass m_o are expressed in the following two expressions by Iqbal.

$$m_w = \left(\cos\theta_z + 0.0584(92.650 - \theta_z)^{-1.452}\right)^{-1} \quad (10)$$

$$m_o = \frac{1+\frac{Z_3}{R_e}}{\left(\cos^2\theta_z + 2\left(\frac{Z_3}{R_e}\right)\right)^{\frac{1}{2}}} \quad (11)$$

Where Z_3 measures the concentrated ozone at around 22 km and R_e is the radius of the earth approximated as 6370 km. Overall spectrally integrated transmittance computation for each atmospheric constituent is necessary steps for solar radiation parameterization in modeling [7]. The total transmittance τ as a function of the ozone layer thickness ℓ in cm, perceptible water vapor w in cm, turbidity coefficient β and α, and the relative mass is evaluated by Iqbal [6]:

$$\tau = f(\ell, w, \beta, \alpha, m) \quad (12)$$

The transmittance quantities τ_a, τ_o and τ_a' for some major atmospheric constitutes such as water vapors, ozone layers and aerosols are expressed as respectively in Equations (13), (16) and (28).

$$\tau_w = 1 - \alpha_w \quad (13)$$

Where α_w is the attenuation coefficient of water vapor given as:

$$\alpha_w = \frac{2.9U_1}{(1+141.54)^{0.635} + 5.925U_1} \quad (14)$$

Where U_1 is the pressure-corrected relative optical path length written in terms of m_r and w as:

$$U_1 = wm_r \quad (15)$$

The transmittance τ_o due to the ozone layer is given as:

$$\tau_o = 1 - \alpha_o \quad (16)$$

Where α_o is the attenuation coefficient due to direct irradiance transmission through the ozone layer. Its expression is written as:

$$\alpha_o = \frac{0.02118U_3}{1.0042U_3 + 3.23\times10^{-3}U_3^2} + \frac{1.082U_3}{(1+138.6U_3)^{0.805}} + \frac{0.0658U_3}{1+(103.6U_3)^3} \quad (17)$$

The U_3 is the ozone relative optical path given by:

$$U_3 = \ell m_r \quad (18)$$

For broad spectral range, the integrated transmittance for Rayleigh scattering τ_r over the wavelength interval $\Delta\lambda$ is defined as (Iqbal, 2012)

$$\tau_r = \frac{\left(\sum_{\lambda=0}^{\infty} I_{on} \exp\left(-0.008735\lambda^{-4.08} m_a\right)\Delta\lambda\right)}{I_{sc}} \quad (19)$$

I_{on} is the direct irradiance on horizontal surface normal to the sun's rays (also called direct normal radiation) and I_{sc} is the solar constant whose value is 1367 W/m^2. A regression-type correlation that fits Equation (19) is given as:

$$\tau_r = 0.972 - 0.08262 m_a + 0.0093 m_a^2 - 0.00095 m_a^3 + 0.000437 m_a^4 \quad (20)$$

During parameterization of the solar radiation, the direct normal irradiance I_{on} on a horizontal surface at a zenith angle θ_z at mean sun-earth distance by including the correction factor called eccentricity ε can be given by Iqbal [6]:

$$I_{on} = \varepsilon I_{sc} \left(\tau_o \tau_r - \alpha_w\right) \tau_a \cos\theta_z \quad (21)$$

Where the eccentricity ε correction factor related to the number n of days in the year is given by:

$$\varepsilon = 1 + 0.033 \cos\left(\frac{360n}{365}\right) \quad (22)$$

Therefore, the total global irradiance I_T on a horizontal surface from direct irradiance and diffused irradiance I_d from surrounding environment can be written as follows:

$$I_T = I_{on} + I_d \quad (23)$$

The I_d can be further written as:

$$I_T = I_{dr} + I_{da} + I_{dm} \quad (24)$$

The broadband diffuse irradiance I_{dr} under a cloudless sky as the effect of Rayleigh scattering is given as

$$I_{dr} = I_{sc} \cos(\theta_z) \tau_o \left(0.5\left(1 - \tau_r\right)\right) \tau_a \quad (25)$$

On the other hand, the diffuse irradiance scattering because of aerosol-scattered diffuse radiation I_{da} reaching the ground after the first pass through the atmosphere is given as

$$I_{da} = I_{sc} \cos(\theta_z)\left(\tau_o \tau_r - \alpha_w\right)\left(F_c \omega_o \left(1 - \tau_o\right)\right) \quad (26)$$

Where F_c is symbolized for forward scattering, ω_o is symbolized for the single scattering albedo by Iqbal, which is the ratio of energy scattered by aerosol to the total attenuation under primarily incident by the direct radiation. In this paper a value of $F_c = 0.5$ [6] was taken for the computation. The determination of ω_o is experimentally a troublesome, according to Iqbal [6]. However, a few amount of aerosol particles in rural environment usually scattered than those found in the urban-industrial area [6,8]. During solar irradiance modeling $\omega_o = 0.6$, by Iqbal [6] is used for urban-industrial region where as $\omega_o = 0.9$ [6,8] is used for agricultural region. Since the study location is widely known as the rural and agricultural center, so $\omega_o = 0.9$ was applied in the solar radiation modeling. The horizontal visibility (Vis) for greater than 5 km, Ångström turbidity factor β, and wavelength exponent α are related as:

$$\beta = 0.5^{\alpha}\left(3.912/Vis - 0.01162\right) \times \left(0.02472\left(Vis - 5\right) + 1.132\right) \quad (27)$$

The wavelength exponent α = 1.3 in Equations (27) and (28) was used in the computation according to Iqbal [6]. The aerosol transmittance τ'_a computed using air-mass m'_a, Ångström turbidity factor β, and wavelength exponent α is:

$$\tau'_a = \left(0.1245\alpha - 0.01162\right) + \left(1.003 - 0.125\alpha\right)\exp\left(-\beta m'_a \left(1.089\alpha + 0.5123\right)\right) \quad (28)$$

Where m'_a is the relative aerosol mass at the local station calculated as:

$$m'_a = \frac{1.66P}{P_o} \quad (29)$$

The downward irradiance I_{dm} because of multiple reflections between the ground and the atmosphere is computed as:

$$I_{dm} = \left(I_{on} + I_{dr} + I_{da}\left(\frac{\rho_g \rho'_a}{1 - \rho_g \rho'_a}\right)\right) \quad (30)$$

Where ρ_g is the ground albedo and ρ'_g is cloudless sky albedo. The value of ground albedo for variation of multiply reflected irradiance lies between 0.2 and 0.7 according to Iqbal [6]. On another reference, the ground albedo varied between 0.1 and 0.25 for agricultural and grassland is written in Encyclopedia of Soil Science. In this paper $\rho_g = 0.25$ was used for computing the downward irradiance I_{dm} due to multiple reflections between the ground and the atmosphere. The cloudless sky albedo ρ'_a is computed as Figures 1 and 2

$$\rho'_a = 0.0685 + 17\left(1 - \tau'_a\right)\omega_o \quad (31)$$

Results and Discussion

Determination of linked turbidity factor T_L

The influence of T_L on GSR at site were evaluated by Inman and Becker [9,10]:

$$T_L = \left(\delta_r m_a\right)^{-1} \ln\left(\frac{I_{sc}}{I_{on}}\right) \quad (32)$$

Where δ_r is the Rayleigh optical thickness. It was employed in evaluating T_L were referenced by Inman [9]:

Its equation is represented as:

$$\delta_r = \frac{1}{9.4 + 0.94 m_a} \quad (33)$$

$$T_L = \frac{\ln\left(\frac{I_{sc}\varepsilon \sin\eta}{I_{on}}\right)}{0.8662\delta_r m_a} \quad (34)$$

The δ_r is computed according the condition set by Wang, Chen, Niu, Salazar [11]. According to them η is to be greater than 10^0, I_{on} is to be greater than 200 W/m^2 and the δ_r is to be less than 20.

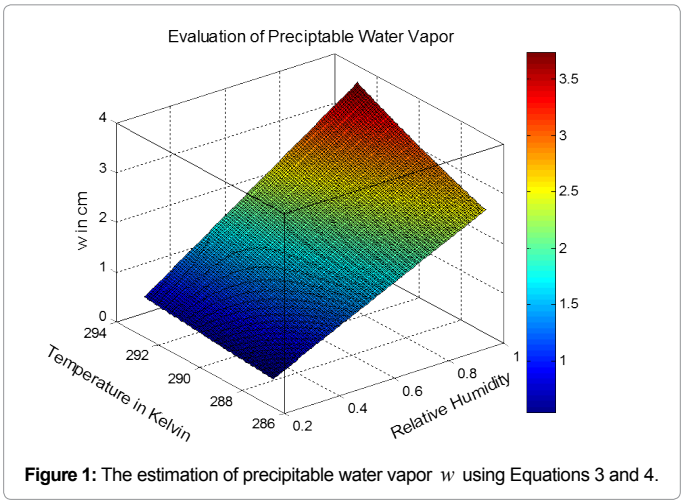

Figure 1: The estimation of precipitable water vapor w using Equations 3 and 4.

$$\delta_r = \frac{1}{6.577 + 1.1753m_a - 0.12002m_a^2 + 0.0665m_a^3 + 0.0013m_a^4} \quad (35)$$

The T_L illustrated on Figures 3-7 is from modeled GSR oscillated between 4.2 and 8.2 with its mean value about 6.2. The T_L from GSR of ground measurement is oscillated between 3.6 and 8.4 with mean value 6.16.

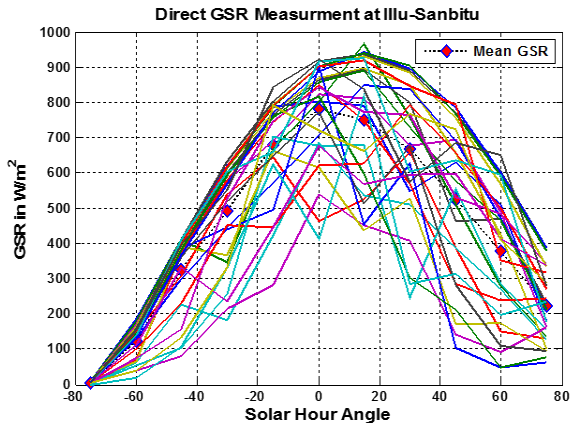

Figure 2: Ground measurement of GSR.

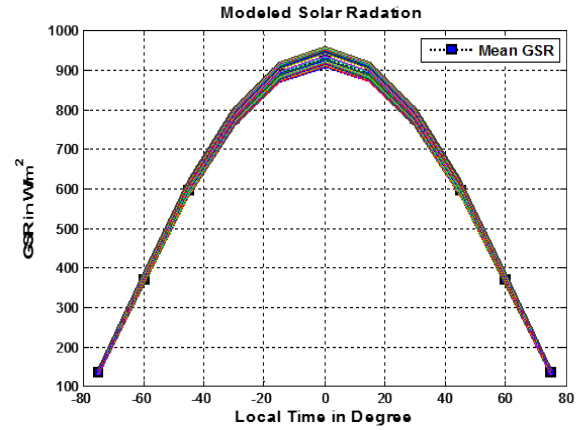

Figure 3: Model GSR.

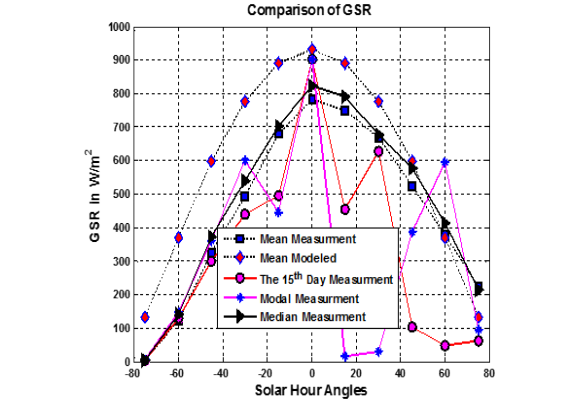

Figure 4: Comparison of mean, modal, median, and 15th day (January 2016) of ground measurement with model GSR.

The statistical tools for evaluating hydrological model assessment widely discussed by Krause, Boyle, Bäse [12], where applicable for evaluating the model efficiency in determining T_L. These are: Root Means Squared Error RMSE, Nash-Sutcliffe efficiency E and its relative efficiency criteria E_r, index agreement d and its relative efficiency criteria d_r and coefficient of determination R^2.

An efficiency of 0 indicates that the model predictions are as

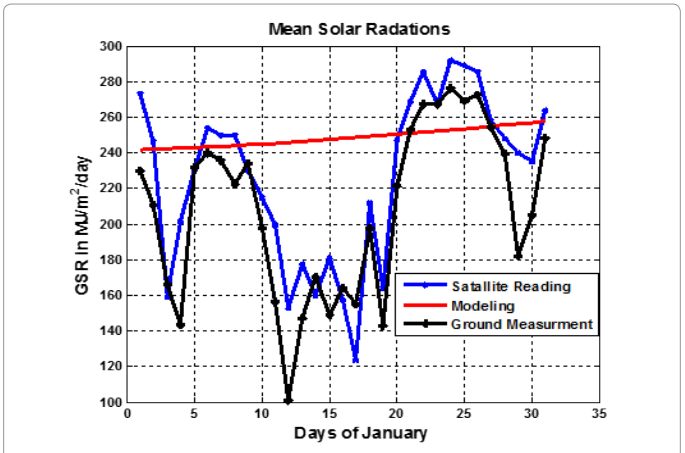

Figure 5: Mean daily GSR from modelling, ground measurement and satellite reading.

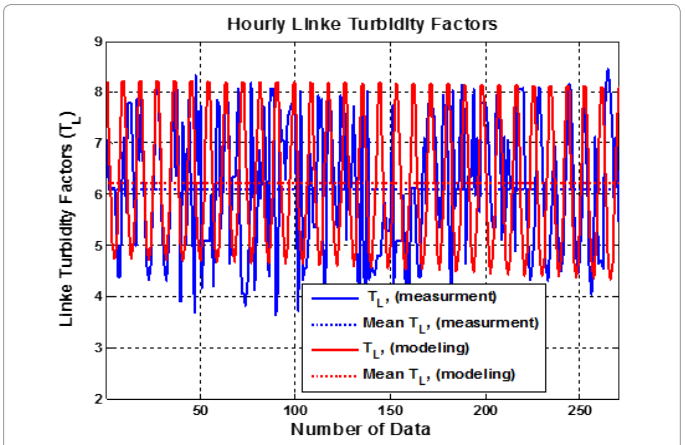

Figure 6: The T_L from GSR modelling and ground measurement.

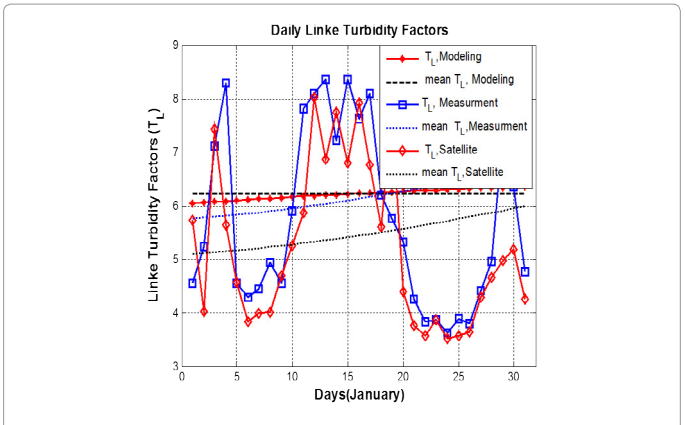

Figure 7: Daily determination of T_L's with their means (model, measurement and satellite).

accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < E < 0$) occurs when the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1; the model is becoming more accurate. On the other statistical explanation on modeling, the coefficient of determination R^2 ranging between 0.33 and 0.66 would have moderate explanatory power [13].

As it is seen in Figure 7 the daily T_L from model GSR is smoothly varied between 6.02 and 6.34 with mean 6.22. However, the daily T_L from ground GSR is considerably varied between 3.62 and 8.36 with the daily mean ranging between 5.77 and 6.71. The daily T_L from satellite GSR is also dramatically varied between 3.51 and 8.02 with daily mean lies between 5.12 and 6.01.

Conclusion

The model GSR for the study is computed from integrated atmospheric parameters such as optical thickness, optical air mass, and ozone layer, the amount of aerosol effect, perceptible water vapor, climate data, solar geometry and geographical positions. This rise of Like's turbidity factor is an outcome of the suspension of particulate matters, smokes and water droplet in the atmosphere. The area's proximity to Sahel and Arabia Peninsula, large influx of dusts can stream in to it. Maritime moisture from Red Sea and Indian Ocean combined with the dusts, particulate matters from local industries, smokes from traditional energy consumption patterns may bring the turbidity factors to the pollution level assisted through local and global wind system transport. These would have consistent pressure on the sustainability of water, air, and soil quality in the area. The T_L from the model, ground and satellite GSR is approximately in a close agreement varied between 4 and 8 with the daily average 6 point. This rise of T_L is approximately laid in the range between 20% to 37.5% as compared to T_L of tropical warm air (continental) in 1947 as discussed by Becker [10]. The result is almost in closer agreement with the analysis made in other continent (Asia) by Wang, Chen, Niu and Salazar [11], Computing the Like's atmospheric turbidity is an important procedure for early warning on monitoring air, water, soil quality for stability of healthy ecosystem.

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