SOME SOLAR RADIATION RATIOS AND THEIR INTERPRETATIONS WITH REGARDS TO RADIATION TRANSFER IN THE ATMOSPHERE

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Abstracts: Ratios of some radiation fluxes such as global (total) solar radiation, H, direct solar radiation, H_b, diffuse solar radiation, H_d, and extraterrestrial radiation, H_o were proposed to define radiation coefficients related to radiation transfer in the atmosphere and solar radiation measurement on the ground surface. The irradiative transfer interpretations and applications in radiation measurement of the ratios were explained. Examples of such ratios are H/H_o and H_d/H. These are used to define the "clearness index" and "cloudiness index" of the atmosphere respectively, and are already in common knowledge and use. H/H_o and H_d/H for example, were found, from experimentation, to add up practically to unity, i.e. $H/H_o + H_d/H = 1$. Based on this result, an empirical expression for predicting the direct solar radiation was developed in a previous work. Other ratios are H_b/H, H_b/H_o, H_d/H_o, H_r/H_o and H_a/H_o. They were proposed to define relevant radiation coefficients, and were used to develop equations for estimating the reflection of the earth's surface and the absorption of the earth's atmosphere.

Keywords: solar radiation, radiation transfer, clearness index.

Nomenclature: *H=Total solar irradiance, H_o=Extraterrestrial Radiation, H_d=Diffuse solar irradiance, H_b=Direct solar irradiance, H/H_o=Clearness index, H_b/H_o=Transmitting coefficient, H_d/H_o=Scattering coefficient, H_r/H_o=Reflection coefficient, H_a/H_o=Absorption coefficient, H_b/H=Cleanness index, H_d/H=Cloudiness index*

1. INTRODUCTION

Solar radiation fluxes measured on the earth's surface, and used in this work are:

(i) sw - Global (Total) radiation, H
(ii) sw - Direct solar radiation, H_b, and
(iii) sw - Diffuse solar radiation, H_d

Extraterrestrial radiation, H_o, also used in this study, is the solar irradiance reaching the top or edge of the earth's atmosphere at normal incidence from the sun. Its daily values were computed using equation (1) after [1].

$$H_o = (24/\pi) I_{sc} E_o \cos\delta \cos\phi (\sin\omega_s - \pi/180)(\omega_s \cos\omega_s) \quad (1)$$

where

I_{sc} is the solar constant. Its value used in this work is 4921 $kJm^{-2}h^{-1}$
E_o is the eccentricity correction
δ is the declination angle
ϕ is latitude of site and
ω_s is sunset hour angle

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2. THE PROPOSED RADIATION RATIOS

From the radiation fluxes above, the following ratios were computed, studied and explained:

H/H_o, H_d/H, H_b/H, H_b/H_o, H_d/H_o, H_r/H_o, H_a/H_o.

Since solar radiation, through its spectrum, interact with the various constituents of the atmosphere as it passes through it to the ground surface, the ratios above will be found useful in defining and determining some atmospheric parameters related to the irradiative transfer in the atmosphere. As it is known, the atmosphere contains, at variable quantities, clouds, solid particles (called aerosols), air molecules and water vapour, each dominating the atmosphere at different season of the year. The main effects of these variables on solar radiation are absorption, scattering and reflection; consequently causing radiation extinction or depletion in the atmosphere [2]. These ratios are, therefore, expected to be related to, or be a measure of the optical effects of the atmospheric constituents on the radiation interacting with them.

Definition and Characteristics of the Ratios

H/H_o (Clearness index)

It is the ratio of the total solar radiation, H, obtained on a horizontal surface on the ground surface, to the extraterrestrial radiation, H_o, the maximum solar radiation available for the earth at the edge of the atmosphere. The value of the global solar radiation measured on the ground surface depends on the clarity or transparency of the atmosphere to the incident radiation; hence the value of the ratio, H/H_o, will depend on the clearness of the atmosphere, and therefore can suitably be used to measure or define the clearness of the atmosphere. Biga and Rosa [3] called the ratio, "clearness index"; further more, according to them, the ratio can be used to measure the "transmission coefficient" of the atmosphere. However, the ratio is worldwide referred to as, "clearness index" of the atmosphere ([3], [4], [5], [6]) to mention a few.

It can be inferred from the ratio that the maximum value attainable by the ratio is unity. That is, $H/H_o = 1$. If $H/H_o = 1$, then $H = H_o$. This will suggest that there is no absorption, no backward scattering nor reflection of radiation in the atmosphere as the radiation passes through the atmosphere. This will therefore imply that, that atmosphere is devoid of clouds, scattering agents like dust, or even air molecules or any agent of depletion and extinction of radiation. Such an atmosphere hardly exists nor experienced, therefore the value of the ratio can only approach unity but never unity.

Likewise, the minimum value of the ratio is not possible to be zero during the day light hours; otherwise, it will imply that no radiation penetrates the atmosphere to neither the ground surface nor any radiation available to be scattered. This is also not experienced. Thus it can be said that H/H_o would have values between 0 and 1, i.e.

$$0 \angle H / H_o \angle 1.$$

The value of the ratio anytime therefore indicates the sky condition of the site [6].

H_d/H (Cloudiness Index)

The ratio is the fraction of the diffuse radiation, H_d, in the global (total) radiation, H, measured at the surface of the earth. Diffuse radiation originates in the atmosphere as a result, mainly, of scattering and reflection of radiation passing through the atmosphere [2]. The value of the diffuse radiation measured depends on the prevailing constituents of the atmosphere responsible for the scattering.

It is possible, however, that the maximum value of the ratio be unity, i.e. $H_d/H = 1$ or $H_d = H$. In such situation, all the radiation measured is diffuse radiation. This would suggest that all the radiation entering the atmosphere from the edge of the atmosphere is converted to diffuse radiation, partly scattered and reflected towards the ground, and partly scattered and reflected back to space. Consequently no single solar ray, directly undeviated, from the sun, reaches the ground surface. Such situation will imply that the atmosphere would mostly be dominated by the scattering agents such as dust and clouds, or mainly dust, or mainly clouds. If the atmosphere is mostly cloudy, particularly with occluding clouds, the radiation received will likely and completely be diffuse. It can therefore be inferred that the amount of diffuse radiation received at the ground surface, and its ratio as above, is a parameter by which the condition and the constituent of the atmosphere in particular, could probably be determined ([6]; [7]).

Thus for instance, if the total radiation received is large and the ratio H_d/H is large, it suggests that the diffuse radiation received is also large. The large amount of the diffuse radiation is then likely due mostly to scattering of radiation by dust or reflection of radiation by broken clouds. The contemporary atmosphere would, in the case of scattering, be full of dust particles and other solid particles and very little or no clouds as is the case in the dry season, and in the case of reflection, the atmosphere would be mainly scattered clouds as is the case during the cloudy months. But if the total radiation received is small and yet the ratio H_d/H is large, the global radiation recorded would be mostly diffuse. The small diffuse radiation in this case would be mostly due to scattering and reflection by clouds, and some scattering by water droplets in the atmosphere. Most of the radiation then passing through the atmosphere must have been reflected back to space, with some absorbed in the atmosphere by clouds and water vapour molecules, as it is experienced during the rainy season months. Such atmosphere would be characterized by heavy occluding clouds. Thus the ratio H_d/H aptly defines the cloudiness and turbidity of the atmosphere, as done by [6], [1], [8], [9]) to mention a few.

The minimum value of the ratio is rare to be zero, for it is rare to have no diffuse radiation being incident. If by some means, the diffuse radiation measured is zero, it suggests that the sky is cloudless, devoid of dust and even of dry air molecules. Such situation in the earth's atmosphere is not experienced. If large amount of global radiation is recorded and very little diffuse radiation is recorded, it suggests that the sky may be clear and clean. In such situation most of the incoming radiation got transmitted through the atmosphere to the ground surface undeviated, that is, transmission of the radiation by the atmosphere in such situation will be high. In summary, we can put the possible values of H_d/H to be

$$0 \langle H_d / H \leq 1$$

and it can be inferred from this discussion that as
$H / H_o \rightarrow 1, H_d / H \rightarrow 0$ *and*
$H / H_o \rightarrow 0, H_d / H \rightarrow 1$
H_d/H is a parameter, like H/H_o, extensively studied by many workers [10].

H_b/H (clearness and clearness index)

This is the ratio of the amount of the undeviated radiation from the sun, that is, direct solar beam, H_b, in the total radiation, H, measured on the ground surface. The amount of the direct solar radiation received on the ground surface depends on the clearness and cleanness of the atmosphere. Clearness of the sky implies little or no occluding clouds in the sky, and cleanness of the atmosphere implies very little amount of dust and solid particles or none in the atmosphere. In the absence of these, solar rays coming from the sun, passing through the atmosphere, suffer little or no scattering, absorption and reflection. Therefore this ratio will be a suitable parameter to measure the clearness and cleanness of the atmosphere.

It is not possible however for its maximum value to be unity as this will imply that there is no cloud, the atmosphere is void of any solid particles including air molecules to scatter radiation and no water vapour to absorb radiation. Its value, however, is possible to be very small, almost zero; suggesting that the sky is completely covered with very thick clouds and no ray directly from the sun penetrates the atmosphere to the ground surface. All the rays were absorbed, scattered and reflected. It can be said that such atmosphere will rather be cloudy than dusty, as it is the case in the rainy season when the value of the ratio is very low. It can therefore be inferred that low values of the ratio will indicate cloudiness of the atmosphere, and corresponding high value of H_d/H. This ratio is not yet studied extensively like its counterparts are, but it was found useful in providing an expression for estimating the direct radiation measured on the ground surface ([11]; [12]).

H_b/H_o (Transmitting Coefficient)

This ratio is the fraction of the direct solar beam, H_b, measured on the ground surface in the extraterrestrial radiation, H_o. In other words, it is the amount of the solar rays, in H_o, coming directly from the sun, and transmitted by the atmosphere to the ground surface undeviated. Therefore the ratio can suitably measure the transmitting ability of the contemporary atmosphere, that is, the "transmittance" or "transmitting coefficient" of the atmosphere. In this case, however, total wavelengths transmittance or transmitting coefficient of the atmosphere is suggested and not monochromatic transmittance. Total wavelengths imply all the short wavelengths are included in the incident radiation. A high value of the ratio would suggest that a high proportion of the radiation, H_o, available for the earth at the top of the atmosphere, got through to the ground surface as the direct solar beam, H_b, with little scattering, absorption and reflection. This suggests that the atmosphere has very little or no clouds, dust particles and very little or no water vapour. The ratio is not commonly studied, but will be a very useful parameter in the study and measurement of the cleanness of the atmosphere. Cleanness and clearness of the atmosphere enhance transmission of radiation in the atmosphere, consequently enhance the amount of the direct solar irradiance incident on the ground surface. This work therefore considers the ratio H_b/H_o a more appropriate parameter to define or measure the total wavelengths transmittance of the atmosphere.

H_d/H_o (Scattering coefficient):

This ratio is the fraction of the measured diffuse solar radiation, H_d, in the extraterrestrial radiation, H_o. That is, the fraction of the extraterrestrial radiation H_o reaching the ground surface in form of scattered and reflected radiation. If the value of the ratio is high, it suggests that a large proportion of the radiation passing through the atmosphere got scattered and reflected towards the grounds surface, hence the ratio will suitably measure or define the scattering ability or efficiency of the contemporary atmosphere, that is, the "total wavelengths scattering coefficient" of the atmosphere. This ratio is not commonly studied just like its counterpart, H_b/H_o. However [9] called the ratio, "diffuse coefficient" and [6] considered the ratio as "index of effectiveness" of the sky in scattering the in coming radiation. In other words these researchers agree with the concept to use the ratio to define or determine the "scattering coefficient" of the atmosphere. The two ratios, H_b/H_o and H_d/H_o, are obviously very important and relevant in the study of atmospheric radiation transfer. H_d/H_o will be particularly useful in studying the scattering efficiency of any particular solid particle prevailing in the atmosphere and the reflectance of any type of clouds covering the sky, while H_b/H_o will be useful in the study of the transmitting efficiency of the atmosphere.

H_r/H_o (Reflectance):

The ratio is the fraction of H_o, the extraterrestrial radiation at the top of the atmosphere, reflected and scattered back to space. H_r is composed of the sw – radiation reflected back to space partly by the ground surface and partly by clouds, and backward scatter by dust and any solid particles in the atmosphere. H_r is dependent on the nature of the ground surface [1]. Therefore this ratio can be used to define or determine the albedo or the "reflection coefficient" of the earth's surface and the atmosphere. Its value cannot in practice be unity but it may tend to zero depending on the nature of the surface of the ground and the clearness of the atmosphere. Therefore it will have values expressed by

$$0 < H_r/H_o < 1.$$

Consider the ratio H/H_o to be the fraction of H_o incident on the ground surface, and H_r/H_o the fraction of H_o reflected and scattered back to space, and H_a/H_o, the absorbed fraction in the atmosphere. Considering the fraction, H_a/H_o, being very small compared with the others: incidence, reflection and scattering, as observed in table 1, and therefore can be safely neglected, hence

$$H/H_o + H_r/H_o = 1 \quad (2)$$

From this, the ratio H_r/H_o is given by

$$H_r/H_o = 1 - H/H_o \quad (3)$$

and gives H_r as

$$H_r = (1 - H/H_o)H_o \quad (4)$$

This gives a very convenient and simple way of estimating a very important and rarely measured radiation flux, reflected irradiance.

H_a/H_o (absorption coefficient):

This ratio is intended to define or determine "total wavelengths absorption coefficient" in the atmosphere. It is the fraction of sw-radiation absorbed in the atmosphere. The absorption H_a itself can be obtained from the radiation arithmetic, in terms of the radiation ratios proposed, at the top of the earth's atmosphere, given by

$$H_b/H_o + H_d/H_o + H_r/H_o + H_a/H_o = 1 \quad (5)$$

Where

H_b is the direct solar radiation transmitted
H_d is the diffuse solar radiation
H_r is the radiation reflected back to space
H_a is the radiation absorbed
H_o is the extraterrestrial radiation at the top of the atmosphere.

3. SOME APPLICATIONS OF THE RATIOS IN RADIATION MEASUREMENT

(i) Relationship between H/H_o and H_d/H

One major outstanding result in the application of the ratios above to radiation measurement is in the sum of H_d/H and H/H_o, which was found to be approximately unity [4]. It was found that, on the monthly average, the sum of H_d/H and H/H_o was practically unity.

That is,

$$H/H_o + H_d/H = 1 \quad (6)$$

In combining equation 6 with the fact that

$$H_d/H + H_b/H = 1 \quad (7)$$

an expression for estimating the direct solar beam was obtained. That is, combining equations 6 and 7, the following expression is obtained, which has already been obtained in a previous work.

$$H_b = H^2/H_o \quad (8)$$

Equation 8, developed by [11], was a result of the combination of some of the ratios. The equation is very important to solar radiation measurement for the following reasons

(i) it is independent of the diffuse radiation component which is unavoidably in accurately measured
(ii) The equation is not theoretical base, but empirical
(iii) The direct solar radiation data is not readily available because of its being constantly difficult to measure at many radiation measurement stations.

Thus a very reliable estimation of it is required to provide data of the radiation, H_b. which is provided for in equation 8

The radiation data of year 2000 were used in year 2002 to verify the claims of equation 6 and to establish the validity of equation 8. The monthly averages of the sum are presented in table 2 and published [12]. It was found as expected that the daily values of the sum and their monthly averages upheld the result of 1995 [4]. Equation 8 was then tested on the data of year 2000 in predicting the obtained direct solar radiation H_b during the year. The predictions were in good agreement with the measured ones and even better in some cases.

(ii) H_b/H and H/H_o

Equation 8 can be re-written as

$$H_b/H = H/H_o \quad (9)$$

The ratios in equation 9 are two of the ratios proposed. In the analysis of the radiation data of year 2000, the ratio, H_b/H was found not to be exactly equal to H/H_o according to equation 9. H_b/H was then plotted against H/H_o to obtain some regression equations for computing H_b/H and thereby computed the needed data of the direct solar radiation H_b [12]. The values obtained from the computation were compared with those obtained with equation 8, and the measured ones. Their results were in good agreement for all various atmospheric conditions obtainable.

(iii) H/H_o and H_r/H_o:

Equation 2 was obtained by considering that the sum of the fractions of the incident radiation on the ground surface and the reflected radiation back to space must be unity. From this, equations 3 and 4 were obtained. Now using the data of year 2000, the monthly averages of the radiation ratios were computed and their values were substituted in equation 4 and 5 to verify the claims of the equations. Using these equations the reflected radiation and absorption were estimated and are presented in table 3.

4. CONCLUSION

Some of the radiation ratios proposed, particularly H/H_o and H_d/H are already being studied and in use. The others, H_b/H, H_b/H_o, H_d/H_o, H_r/H_o and Ha/H_o are under study, but their radiative interpretations and implications were explained. They were found useful in defining or determining relevant atmospheric parameters related to radiation transfer in the atmosphere, such as cleanness index, total wavelengths transmission coefficient total wavelengths scattering coefficients, total wavelengths reflection coefficient and absorption coefficient.

The sum of H/H_o and H_d/H was confirmed to be practically unity, and hence the expression for estimating the direct solar radiation H_b was upheld.

Similarly from the other ratios, the expressions for estimating or quantifying reflected sw-solar radiation from the earth's surface and absorption of sw-radiation in the atmosphere were developed as given in equation 4 and 5 respectively.

The ratios, satisfying equation 5, confirms the validity of the ratios as suitably representing the atmospheric parameters they were proposed to define.

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