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ON THE ATTENUATION OF SOLAR RADIATION BY ABSORBING GASES IN THE ATMOSPHERE

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ABSTRACT

An expression for assessing the attenuation characteristics of the atmospheric gases has been developed. The results from the application of the expression in assessing the attenuation of radiation due to the influence of the uniformly mixed atmospheric gases (O_2, CO_2, CH_4, N_2O and CO) and water vapour are found, on the average, to be in agreement with the findings of Bird and Hulstrom (1981, 1982). The proposed expression may be relevant to solar radiation models at different strata in the atmosphere for which the 'reduced height' has appropriate values.

1. INTRODUCTION

The intensity of the extraterrestrial solar radiation which traverses through the earth's atmosphere is attenuated by the various atmospheric constituents namely water vapour aerosols, ozone, clouds, air molecules and so on. Estimation of solar radiation at the surface of the earth therefore requires the knowledge of the transmission function for all the constituents of the atmosphere.

According to Psiloglou, et al. (1995), water vapour and ozone constitute the major absorbers of the incoming solar radiation so that the net global (direct and diffuse) solar radiation that eventually reaches the earth's surface is substantially reduced.

The distribution with height of the major atmospheric gases, nitrogen (N_2) and oxygen (O_2) are well documented (Rishbeth, 1988). Up to the height of about 100 km, the major gases are well mixed and their concentration ratio of 4:1 does not change with height. Above about 100 km, the major gases are diffusively separated by the action of gravity so that atomic oxygen (molecular mass, M = 16) progressively becomes more abundant than molecular nitrogen (M = 28) and molecular oxygen (M = 32). The relative concentration of the uniformly mixed gases, molecular oxygen (O_2), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and carbon monoxide (CO) do not vary with height unlike the unmixed gases, water vapour (H_2O), ozone (O_3) and nitric acid (HNO_3) whose concentrations are a function of height. The unmixed gases have strong absorption bands within the solar spectrum and exert a varying influence on the incoming solar radiation (Prasad, et al., 1987).

While water vapour accounts for about 10 % of the attenuation of solar radiation which corresponds to nearly 90 % of the absorption of the incoming solar beam (Bird and Hulstrom, 1982), the depletion and absorption due to uniformly mixed gases are often neglected.

Evaluation of the integral transmission function of the uniformly mixed gases and other atmospheric absorbers have been carried out by several workers (Hogt 1978; Bird and Hulstrom, 1982; Santamouris, et al., 1985; Psiloglou, et al., 1994, Louche, et al., 1987).

In this study, the attenuation of the incoming solar radiation at the earth's surface is considered along the lines used by Chapman (1931). A single expression is developed for the determination of the instantaneous solar radiation for all the five uniformly mixed gases and water vapour in the atmosphere. The depletion and absorption of the incident solar beam by these gases are comprehensively analyzed as function of the sun's zenith angle.

2. THEORETICAL BACKGROUND

The equation for the attenuation of solar radiation as it traverses downwards through the atmosphere is developed along the lines used by Chapman (1931) for photoionization in the atmosphere.

Considering the complex nature of the variations of the atmospheric parameters, Chapman made the following simplifying assumptions:

i. The radiation is monochromatic with a photon flux $S(h)$.
ii. The atmosphere is plane and horizontally stratified.
iii. The atmosphere consists of a single absorbing gas with number density $n(h)$.

Radiation enters the atmosphere at a zenith angle χ. Its intensity is S_∞ on the top of the atmosphere and S at a reference altitude h from the ground as shown in Figure 1.

The intensity of the radiation changes with distance as:

$$dS = qSec\chi\, dh \qquad (1)$$

where q denotes the number of electrons produced per second in a unit volume.

The number of electrons produced is proportional to the product of particle density and photon flux. Hence,

$$q = n\delta S \qquad (2)$$

where δ is the absorption cross-section of the radiation in the gas.

The law of gaseous equilibrium gives:

$$n = n_o \exp(-z) \qquad (3)$$

n is the number density at the reference level and z is the "reduced height".

Combining equations (1), (2) and (3), we have:

$$dS = n_0 \delta\, S \exp(-z) Sec\chi\, dh \tag{4}$$

where

$$z = h / H \tag{5}$$

and

$$H = \frac{KT}{mg} = \frac{RT}{Mg} \tag{6}$$

H is known as the scale height of the gas and z as the reduced height (measured in units of H). T is temperature, K is Boltzmann constant, m is particle mass, g is acceleration due to gravity, R is gas constant and M , the molar mass.

Equation (4) may thus be re-written as:

$$\frac{dS}{S} = n_0 \delta\, H\, Sec\chi \exp(-z) dz \tag{7}$$

The reference level in the atmosphere may be chosen for n or h, such that $n_0 \delta\, H = 1$.

Hence, equation (7) becomes:

$$\frac{dS}{S} = Sec\chi \exp(-z) dz \tag{8}$$

Integrating equation (8), we have:

$$\ln \frac{S}{S_\infty} = Sec\chi \int_\infty^z \exp(-z) dz \tag{9}$$

$$\ln \frac{S}{S_\infty} = -Sec\chi \left[\exp(-z)\right] \tag{10}$$

The instantaneous attenuated solar radiation S for all wavelengths is then given by the expression:

$$S = S_\infty \exp\left[-\exp(-z) Sec\chi\right] \tag{11}$$

where $S_\infty = 1.38 KWm^{-2}$ (Ohvril, et al., 1999) is the solar constant (the unattenuated solar radiation at the top of the atmosphere).

3. CHOICE OF VALUES FOR THE PARAMETER 'z'.

The attenuation of the solar beam as it traverses from the top of the atmosphere and arrives at the ground varies with the mass of the gases it encounters in its path. In the analysis that follows, altitudes between 100 and 600 km will represent the upper atmosphere while those below 100 km will be regarded as the lower atmosphere.

The principal layers in the upper atmosphere are produced by extreme ultraviolet and X-rays emitted from the sun as spectral lines and continuous radiation. In these regions, oxygen becomes dissociated into atoms by the action of solar uv radiation.

Each gas in the upper atmosphere has its own scale height corresponding to its molar mass. The principles governing the dynamics of the upper atmosphere may be extended to the lower region where ozone is formed through dissociating oxygen molecules. Various definitions are found in the literature for z (e.g., Rishbeth, 1988), but generally, z is defined by equation (5). Uncertainty, however, surrounds the determination and relevance of the parameters in the lower atmosphere. Estimations of z are rendered difficult because of the scanty knowledge of the effects of the parameter in the lower atmosphere. For want of an appropriate definition to aid the analysis which follows, z would be taken as the ratio of the scale height of each of the uniformly mixed gases to the scale height of the oxygen atom.

In this vein, the z values for the five uniformly mixed gases O_2, CO_2, CH_4, N_2O and CO would be 2.00, 2.75, 1.00, 2.75 and 1.75 respectively.

4. RESULTS AND DISCUSSION

Based on the analysis in Section 3, values of instantaneous "attenuated" solar radiation for all the five uniformly mixed gases were computed using equation (11). The results are presented in Fig. 2. The transmittances, T_L, of the uniformly mixed gases is estimated from the expression:

$$T_L = \frac{S}{S_x} = \exp[-\exp(-z)Sec\chi] \qquad (12)$$

Two attenuation properties associated with atmospheric gases are 'absorption' and 'depletion' of the incoming solar beam.

The absorption of the incoming solar beam is defined as the difference between S_χ and T_L, while the depletion of the incoming solar flux is taken as the difference between S_x and S.

Estimations of absorption and depletion due to the influences of the uniformly mixed gases and water vapour are limited to χ values between 0 and 70^0, corresponding to day-time period when solar radiation in the tropics is on the rise towards its peak value normally attained around noon when the sun is overhead.

The depletion of solar radiation from this study shows that the uniformly mixed gases is found to be approximately 1 %, corresponding to 13 % of the absorption of the incoming solar beam.

The results are in agreement with the findings of Bird and Hulstrom (1981) that only 1-3 % of the solar radiation attenuation is due to the absorption of the minor atmospheric gases which often corresponds to 10-15 % of the absorption of the incoming solar beam.

To test the efficacy of the proposed expression and the validity of results obtained, the procedure was applied to evaluate the depletion and absorption characteristics due to the influence of water vapour ($z = 1.13$) in the atmosphere on solar radiation. It is found from the test that water vapour accounts for 9 % depletion of solar radiation which corresponds to 38 % of the absorption of the incoming solar beam. Bird and Hulstrom (1982) report in their findings that water vapour typically accounts for about 10 % of the solar radiation depletion which corresponds very close to 90 % of the absorption of the incoming solar beam. The difference in the absorption results may not be unconnected with the methodology used and possibly from adopted values of the different parameters in the two studies.

It is established however that the proposed expression can be used to estimate the attenuation characteristics of atmospheric absorbers of solar radiation and may be relevant to solar radiation models at different strata in the atmosphere for which z has appropriate values.

4. CONCLUSION

A new expression for estimating the attenuation characteristics of the uniformly mixed gases and other atmospheric absorbers has been developed. The proposed expression is derived along the lines used by Chapman (1931) for photoionization in the upper atmosphere. The results show that the uniformly mixed gases accounted for 1 % depletion of the solar radiation corresponding to 13 % of the absorption of the incoming solar beam. It is also shown that water vapour accounted for 9 % of the depletion of solar radiation, which corresponds to 38 % of the absorption of the incoming solar beam. The results are on the average, in agreement with the reports on the findings of Bird and Hulstrom (1981, 1982).

The proposed expression may be relevant to solar radiation models at different strata in the atmosphere for which the 'reduced height' parameter has appropriate values.

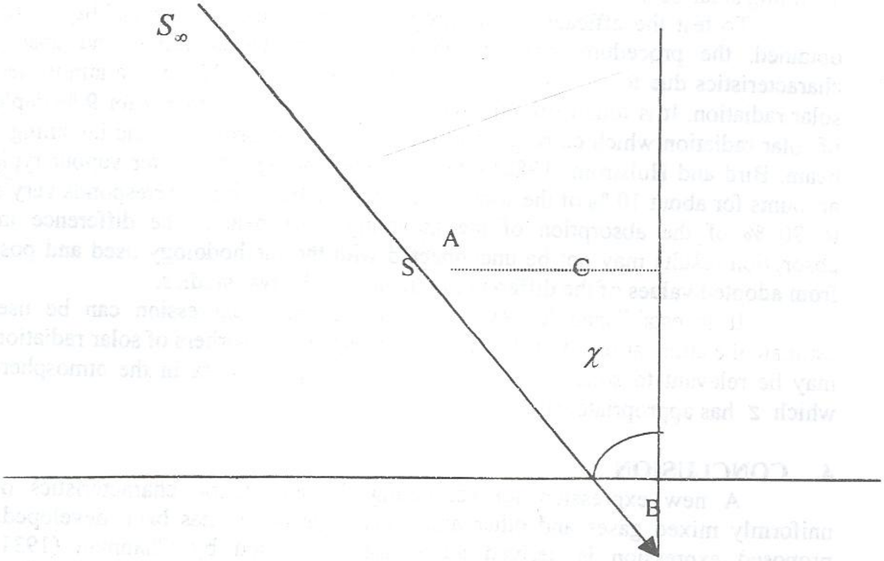

Figure 1: Flow of radiation in the atmosphere

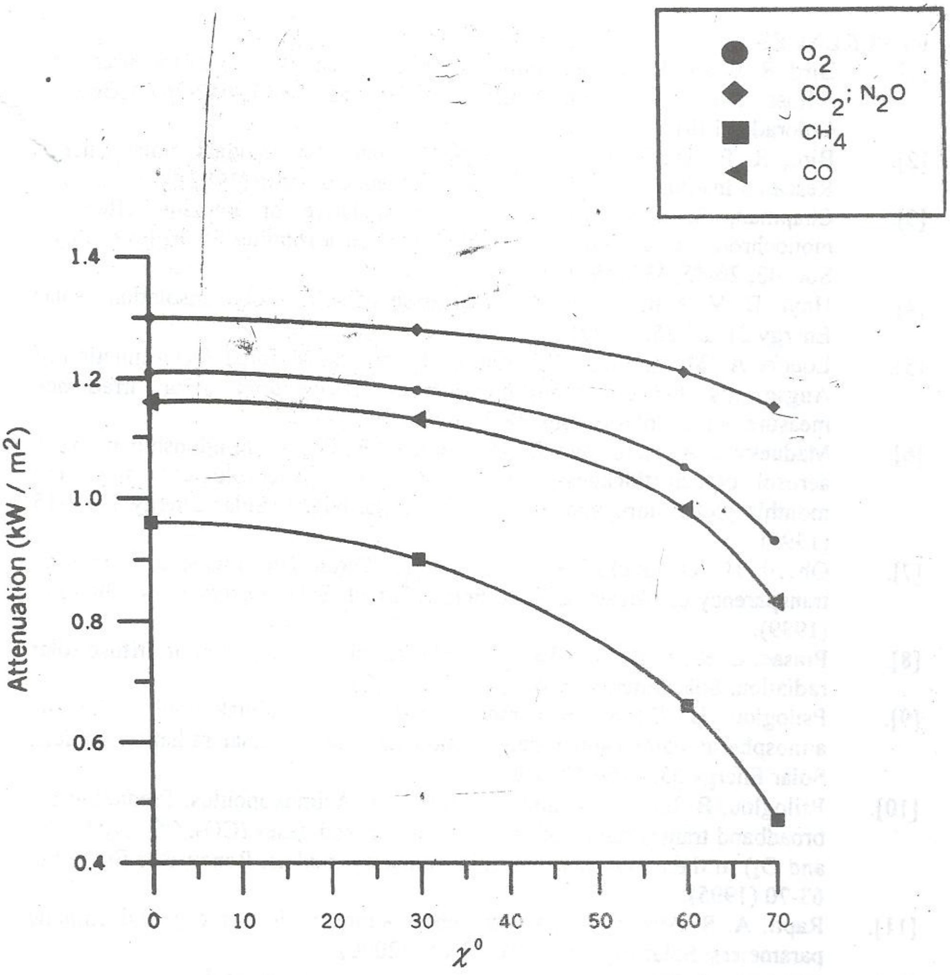

Fig 2: Variation of the proposed molecular oxygen (O_2), nitrous oxide (N_2O), ethane (CH_4), carbon dioxide (CO $_2$), carbon monoxide (CO) attenuations as a function of χ.

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