Mausam, (1988), **39**, 4, 415-420

551.521.14 : 551.571.1

Effect of variations in water vapour and albedo on diffuse sky radiation

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(*Received 22 November 1985*)

सार — नियत काशानुपात पर गुप्ता एवं अग्रवाल (1984) ने क्षैतिज तल पर विसरित आकाशीय विकिरण (D_r) के लिये, वायु द्रव्यमान व गंदलापन गुणांक B के पदों में तर्कसंगत एवं विश्वसनीय समीकरण की व्युत्पत्ति की। प्रस्तुत लेख में संघनीय जल वाष्प के लिये संशोधन का सूत्र सुझाया गया है। वायु द्रव्यमान एवं जल वाष्प के विभिन्न मानों के लिये D_r को विभिन्न काशानुपात पर प्राप्त करने हेतु परिवर्तन सूत्र निकाला गया है। यह दर्शाया गया है कि जल वाष्प व गंदलापन गुणांक के प्रभाव को एक दूसरे से विलगित नहीं किया जा सकता।

ABSTRACT. A reasonably reliable equation was derived (Gupta and Agarwal 1984), relating diffuse sky radiation (D_r) on a horizontal surface to air mass (m_r) and Schüepp turbidity coefficient B in dry atmosphere with constant albedo ($A=0.25$) of the terrain. The expression for D_r has been corrected for different values of precipitable water w. Also a reasonable equation giving conversion factor for finding D_r (A) from D_r ($A=0.25$), for different values of air mass m_r and water vapour content w has been developed. It has been shown that due to interaction between B and w, within the absorption bands of water vapour, the effect of B and w cannot be individually separated.

1. Introduction

The diffuse sky radiation (D_r) arrives at the earth's surface as a result of simple and multiple scattering. A reasonably reliable equation relating diffuse sky radiation D_r on a horizontal surface to air mass (m_r) and Schüepp turbidity coefficient B in a dry atmosphere with constant albedo ($A = 0.25$) of the terrain was proposed by Gupta and Agarwal (1984), as :

$$D_r(m_r)=D_r(1)(0.06)+[0.94\times 10^{-m(B)}(m_r^{0.57}-1)] \quad (1)$$

where,

$$D_r(1)=646.7-556.7\ e^{-2.324B} \quad (2)$$

$$\text{and } m(B)=(0.684-0.364\ e^{-2.467B}) \quad (3)$$

This radiation is increasingly attenuated with increasing water vapour content. Based on elaborate computations, Schüepp developed a table for estimating corrections due to water vapour contents (Robinson 1966) as a function of B. By shifting the origin at $w=0$, the Schüepp correction table has been modified in Table 1.

The intensity of direct solar radiation incident on a given surface depends on the depletion along its path through atmosphere. The depletion is small in pure air but increases with the amount of pollution or turbidity associated with variable components such as water vapour, dust, smoke and haze which are generally known as aerosol particles. To assess atmospheric turbidity, Linke's turbidity factor T was found to be theoretically valid, although its quantitative formulation suffers from the defect of "virtual variation". Schüepp turbidity coefficient B gives most valuable information about turbidity. Majumdar *et al.* (1978) defined rational turbidity factor which removes various difficulties. The variation of albedo produces a considerable effect on D_r radiation due to multiple scattering and absorption. For a more opaque atmosphere the amount of energy scattered is, of course, greater both backward and forward directions. But the intensity scattered in the backward direction is somewhat greater than the forward scattered intensity. This is due to multiple scattering (Robinson 1966). So the scattered intensity and specially the backward scattered intensity is a varying function of the surface albedo, because the backward intensity includes the energy reflected by the surface. This effect of albedo of the surface is effective only up to a certain atmospheric thickness. Then the effect diminishes due to a marked increase in attenuation of radiation (absorption in particular). For wavelengths greater than 0.4 μ, the increase in forward scattered intensity may be due to large "Mie particles". For wavelengths below 0.4 μ the observed energy is smaller mainly due to the absorption by ozone. Therefore, mainly backward scattered (the negative Mie effect) intensity is obtained.

Schüepp (Robinson 1966) developed a graphical method to evaluate D_r for different values of albedo ($A=0.1$ to $A=0.9$) with m_r (from $m_r=1$ to $m_r=10$) and turbidity coefficient B. A correction table for different

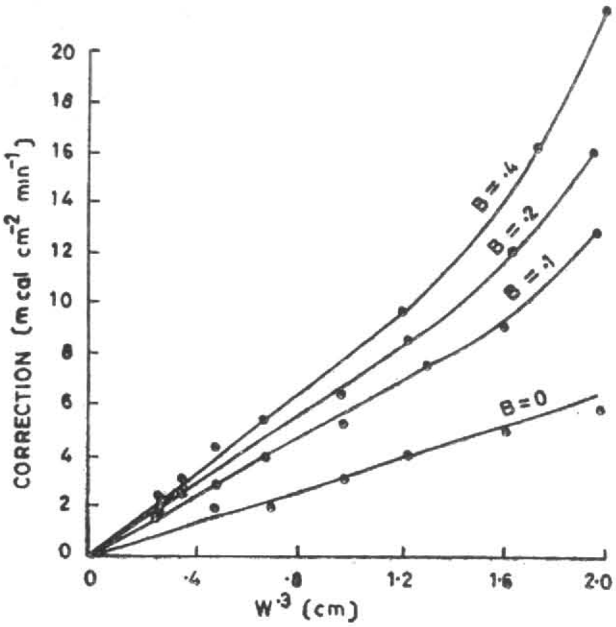


Fig. 1. Relation between $w^{\cdot 3}$ (cm) and correction (cal cm^{-2} minute)

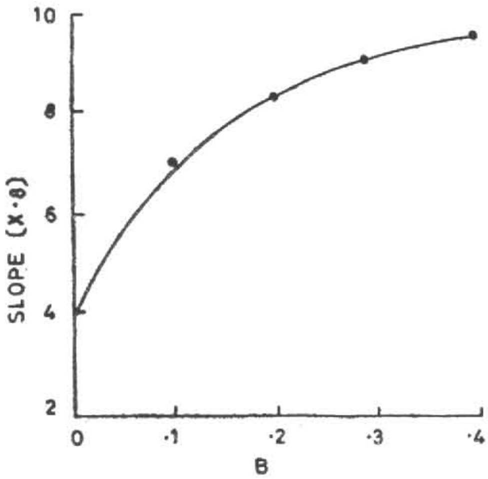


Fig. 2. A graph between B and slope of lines of Fig. 1

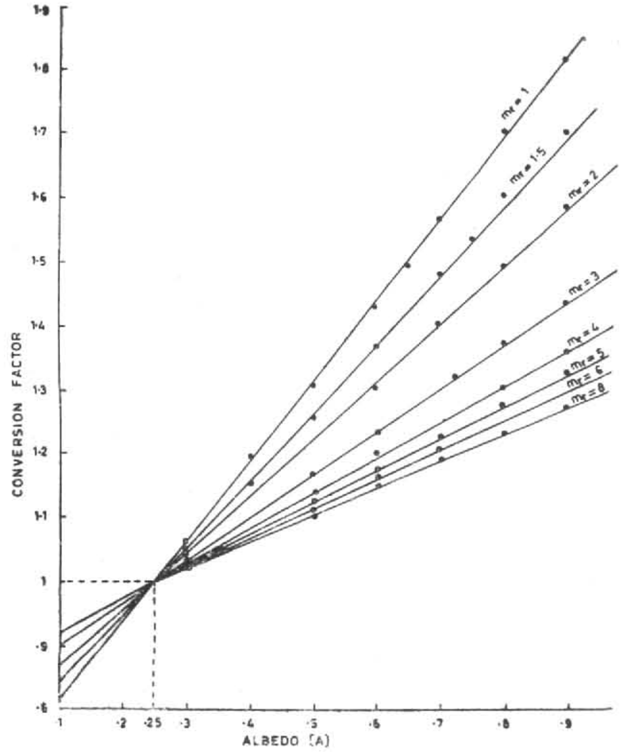


Fig. 3. Relation between albedo and conversion factor, $(R+1)$

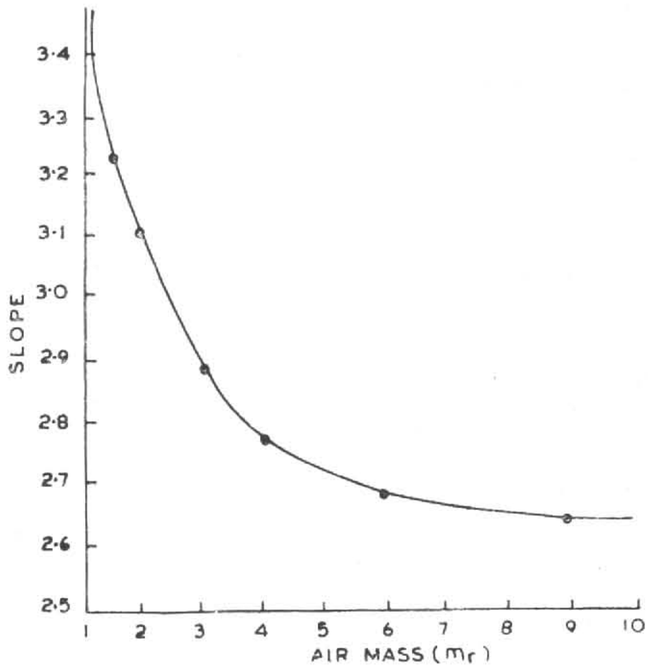


Fig. 4. A graph between slope of lines of Fig. 3 and air mass m_r

TABLE 1

Corrections (in m cal cm^{-2} mm^{-1}) **for** D_r **values**

B	w (cm) 0	.01	0.03	0.1	0.3	1	2	5	10
0	0	—1	—1	—2	—2	—3	—4	—5	—6
.10	0	—1	—2	—3	—4	—5	—7	—9	—13
.20	0	—1.4	—2.4	—4.4	—5.4	—6.4	—8.4	—12.4	—16.4
.40	0	—1.7	—2.7	—4.7	—5.7	—6.7	—9.7	—15.7	—21.7

values of w ranging from 0 to 10 cm was also provided. Due to nature of various complicated steps involved in the computation, the practical use of this method has been very limited.

In the present communication, an attempt has been made to find an equation giving the attenuation due to water vapour content. Also a simple formula giving a conversion factor, to find D_r (A) when $A \neq 0.25$ from D_r $(A=0.25)$ has been suggested.

2. Effect of water vapour content

Kondrtyev (1969) and Majumdar *et al.* (1979), have shown that attenuation of solar radiation due to water vapour varies almost practically as $w^{0.3}$. This is exemplified in Fig. 1, in which attenuation has been plotted against $w^{0.3}$ for different values of B from Table 1. It is clear that up to $w=2$ cm almost straight lines are obtained. For w greater than 2 cm, it is seen that the attenuation increases more rapidly. The curvature further increases as B increases.

First considering the variation as $w^{0.3}$ (restricting ourselves up to $w=2$ cm), the slope of the various lines have been calculated. The slope has been plotted against B in Fig. 2, which is an exponential curve. So we conclude that attenuation may be of the form :

$$\triangle D_r\,(w) = [\,Y_\infty - (Y_\infty - Y_0\,)\,e^{-\lambda B}\,]\,w^{0.3} \quad (4)$$

where, Y_0, Y_∞ and λ are constants of the equation, which can be determined from Fig. 2. Putting values of the constants in Eqn. (4), we get :

$$\triangle D_r\,(w) = [8.33 - e^{-6.1B} \times 5.082]\,w^{0.3} \quad (5)$$

In the region $w \gg 2$ cm, the attenuation increases more rapidly. Further, attenuation also increases with B, showing that interaction between B and w becomes more strong and the effect of B and w cannot be individually isolated. Water vapour and dust (haze) are the most important sources of turbidity. The absorption of radiation by water becomes more important at higher turbidities, because the absorption is limited to the infrared part of the solar spectrum. With a high atmospheric water content the far infrared radiation is also completely absorbed. To account for this variation, attenuation may be of the form $[1+f(B,\ w)]\ w^{0.3}$ instead of $w^{0.3}$, where $f(B,\ w)$ is a function depending upon both B and w. Its value can be estimated from Fig. 1. The slope of lines increase regularly with both B and w, so $f\,(B,\ w)$ may be taken proportional to both, B and w. Majumdar *et al.* (1979), however, showed that the effect of B and w are inseparable, $f\,(B,\ w)$ may be taken as $f(B,\ w) = K\ Bw \simeq 0.1\ Bw$, where, K is a constant of proportionality.

Thus the formula for calculating attenuation for different values of B and w then becomes :

$$\triangle D_r(w) = [8.33 - 5.082\,e^{-6.1B}]\,[1+0.1\,Bw]\,w^{0.3} \quad (6)$$

3. Effect of albedo and air mass

The value of diffuse sky radiation on a horizontal surface reaches its peak value at unit air mass ($m_r=1$) and decreases as m_r increases. It also increases almost linearly with albedo (Schüepp graph, Robinson). We can represent $D_r(A)$ for $w=2$ cm and $B=0$ in terms of D_r $(A=0.25)$ by introducing a conversion factor R as :

$$D_r\,(A) = D_r\,(A = 0.25) + D_r(A = 0.25)\ R(A) \quad (7)$$

As the value of D_r decreases exponentially as m_r increases and assuming that the value of R also decreases exponentially with increasing m_r, the value of R can be written as :

$$R = R_0 + (R_0 - R_\infty)\,e^{-\lambda m_r} \quad (8)$$

where, $R_0 =$ Max. value of R

$R_\infty =$ Minimum value of R

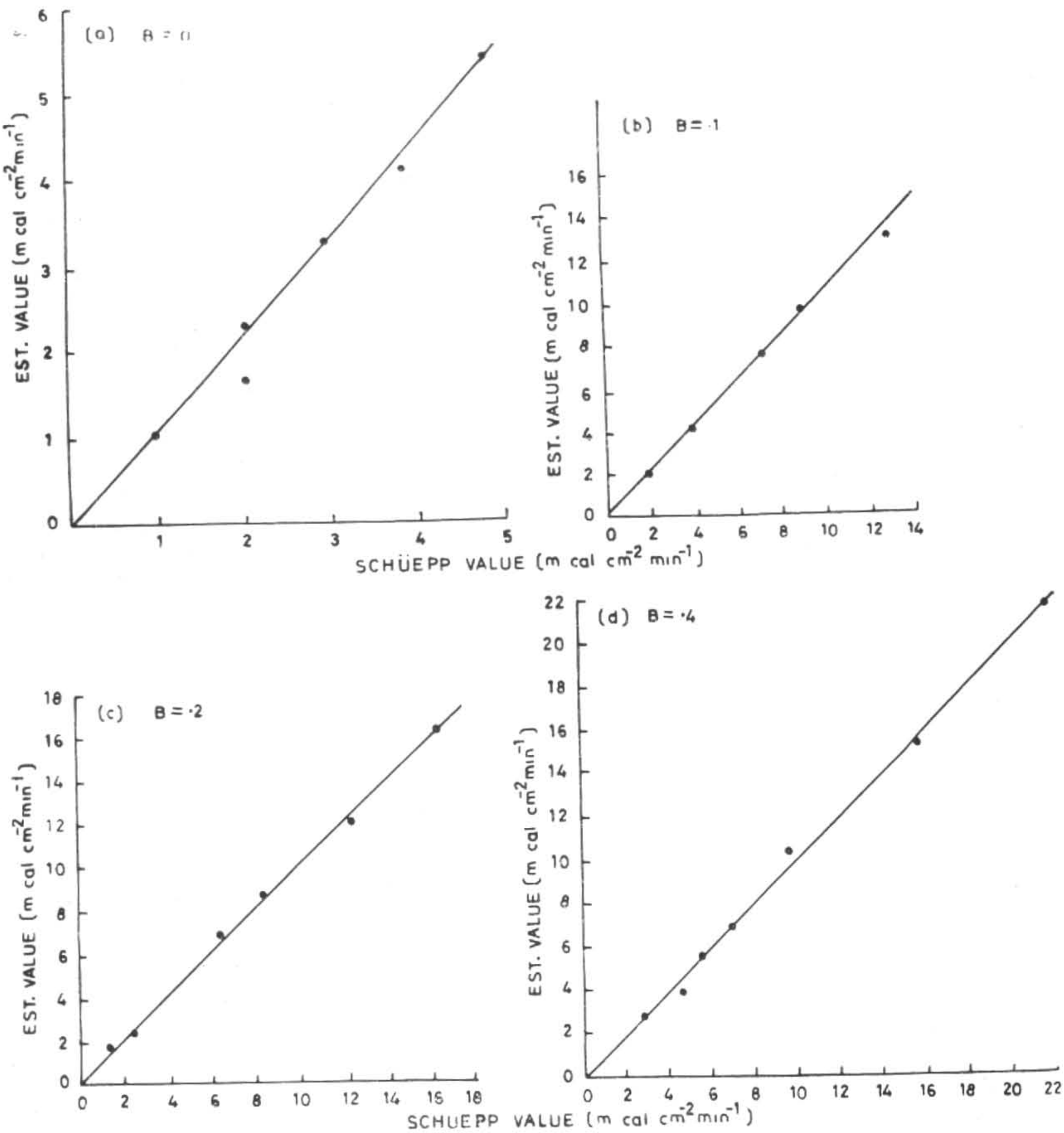
$\lambda =$ Some constant to be determined.

As assumed earlier, that $D_r(A)$ is linearly related to albedo, it will be more reasonable to plot $D_r(A)$ against albedo. It should then yield a straight line for each value of m_r and each line should pass through (0.25, 1). The slope of each line decreases as m_r increases for different values of albedo and approaches zero as $m_r \rightarrow \infty$, for all values of albedo. The relationship can then be represented as :

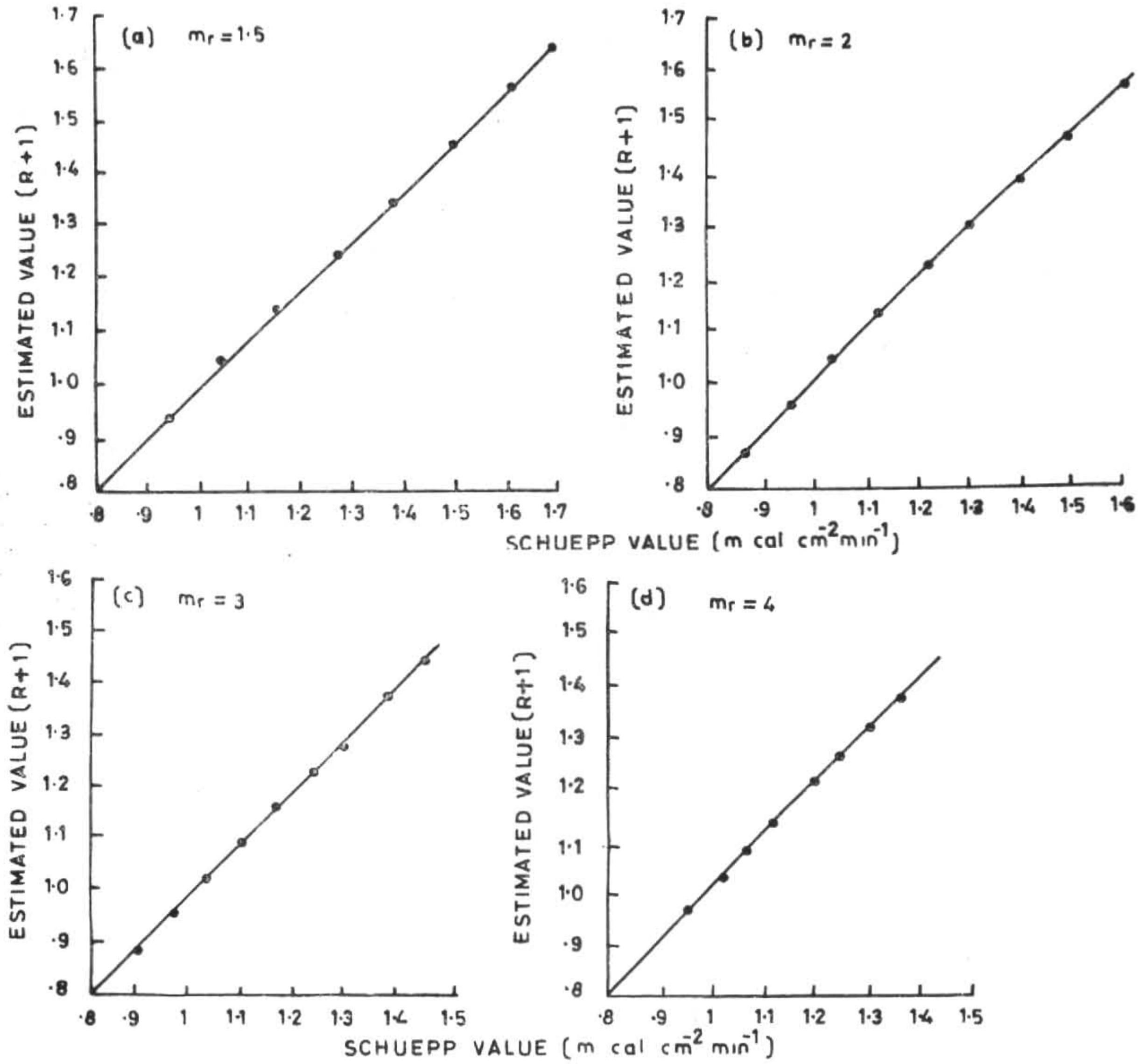
$$\frac{D_r\,(A)}{D_r\,(A=0.25)} = 1 + R_0 + [(R_0 - R_\infty)\ e^{-\lambda m_r}]\ (A - 0.25) \quad (9)$$

4. Present approach

The values of conversion factor R (for different air mass m_r and albedo A) were extracted from Schüepp graph, though for a fixed water vapour content ($w=$ 2 cm) of the atmosphere and Schüepp turbidity coefficient $B=0$. Schüepp has also provided a correction table for $w \neq 2$ cm also. We first consider the value of R for $w=2$ cm. Later we shall introduce effect of w (water vapour content) on R for different values of w also. By plotting the conversion factor found (by using Schüepp graph) against albedo for different values of m_r, straight lines were fitted to the points. Each line passes through (0.25, 1) [Fig. 3]. The slope of each line was calculated and a graph between slope and m_r was also plotted (Fig. 4).



Figs. 5(a)-(d). The graphs between Schüepp values and estimated values of corrections for B=0, 0.1, 0.2 and 0.4



Figs. 6(a)-(d). The graphs between Schüepp values and estimated values of conversion factor for m_r=1.5, 2, 3 and 4

Since the conversion factor R decreases exponentially with m_r the relationship for R should be of the form:

$$Y = Y_0 + (Y_0 - Y_\infty)\, e^{-\lambda x} \tag{10}$$

Taking the equidistant points on the curve corresponding to m_r=1, 5 and 9 respectively, the values of various constants are obtained as follows :

$\lambda = 0.5555$ $\qquad R_0 = 0.4096$

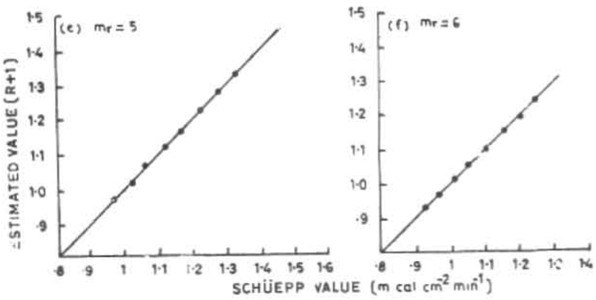
$R_0 - R_\infty = 1.4536$

So the expression for R is then given by :

$R = 0.4096 + 1.4536 \times e^{-0.5555 m_r}$ and

$$\frac{D_r\,(A)\;(A \neq 0.25,\, m_r,\, w)}{D_r(A=0.25,\, w=2\text{ cm},\, B=0)} = 1 + [\,0.4096 + 1.4536\, e^{-0.5555 m_r}] \times (A - 0.25) \tag{11}$$

The values of R have been calculated by using above equation for different values of A and m_r. Figs. 6 (a)-(f) show that calculated values are in close agreement with Schüepp values.



Figs. 6 (e)&(f). The graphs between schüepp values and estimated values of conversions factor for m_r = 5 and 6

5. Effect of water vapour

Attenuation of solar radiation due to water vapour varies as $w^{0.3}$ (Majumdar *et al.* 1979). D_r also may be assumed to vary with water vapour content in the same way. The value of D_r (A, w) can then be written as :

$$\frac{D_r\,(A, w)}{D_r\,(A=0.25,\ w=2\ \text{cm})} = 1 + [\,R\,(A-0.25)\,]\,f(w) \quad (12)$$

where, $f(w)$ is a function of w. It can be expressed as

$$f\,(w) = C_1 + C_2\,(w)^{.3} \quad (13)$$

where, C_1 and C_2 are constants.

For evaluation of the constants C_1 and C_2 various values of f(w) for different values of w were extracted from Schüepp chart. The least square method has been used to fit the data in the Eqn. (13). The values of C_1 and C_2 are obtained.

$$\text{So,} \quad f(w) = 1.21 - 0.185\,w^{0.3} \quad (14)$$

So for $B=0$, the conversion equation becomes :

$$\frac{D_r\,(A, w)}{D_r\,(A=0.25,\ w=2\ \text{cm})} = 1 + [R\,(A-0.25)]\,f(w) \quad (15)$$

where, $R = 0.4096 + 1.4536\ e^{-0.5555 m_r}$
and $f(w) = 1.21 - 0.185\ w^{0.3}$

6. Conclusion

A reasonably reliable equation, relating diffuse sky radiation D_r on a horizontal surface to air mass m_r, water vapour content ($w=0$ to 10 cm) and albedo ($A=0.1$ to 0.9) for $B=0$ has been derived. The Eqn. (6) gives attenuation for different values of B and w at constant albedo. This equation shows that attenuation increases almost linearly as $w^{0.3}$ up to $w=2$ cm. Beyond this value the interaction between B and w becomes more strong and the effect of B and w cannot be separated from each other. In this region the scattering of radiation by aerosol particles and absorption of the same by water vapour take place simultaneously, so that the attenuation increases more rapidly. The attenuation is small for pure air but increases with the turbidity. The turbidity B acts principally in the visible region and water vapour almost exclusively in the infrared region. The effect of absorption by water vapour becomes more and more important at higher turbidities. Using Eqn. (15) D_r can be calculated for any value of albedo A and w. A suitable expression to account for the effect of B can be applied to it. It has been found that D_r decreases as m_r increases but increases as albedo increases. This happens due to increasing multiple scattering of radiation as albedo increases. The absorption of radiation increases as w increases, and hence D_r decreases.

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