Atmospheric Attenuation of Solar Radiation[1]

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ABSTRACT

Eighteen years of clear day solar radiation data accumulated at Phoenix, Ariz., are analyzed to yield monthly averages of the transmittance of the atmosphere for solar radiation. These figures serve as a basis against which theoretical calculations of the atmospheric transmittance are compared. Calculations based upon the complete set of attenuation relations proposed by Houghton average 2% lower than the measurements. When Houghton's water vapor absorption curve is replaced by the McDonald water vapor absorption relation, however, the yearly averages of the measurements and calculations are essentially identical. A procedure for approximating the effects of dust variability is introduced which further improves even these calculations in terms of monthly comparisons.

1. Introduction

Atmospheric attenuation of solar radiation has attracted the attention of numerous physicists and meteorologists over the past 50 years. However, apart from the original measurements of Fowle, Abbott, and others (Fowle, 1912, 1915) at the Smithsonian Institution, most of the work conducted in this area has dealt with the re-evaluation of these original data; and disconcertingly, there have thereby been developed almost as many empirical descriptions of the several attenuation phenomena as there have been investigators of them.

A good case in point deals with the attenuation of solar radiation due to water vapor absorption. Kimball (1930), Mugge and Möller (1932), Yamamoto and Onishi (1952), Houghton (1954), and McDonald (1960) all derived different expressions for this phenomenon from the same reservoir of Smithsonian data. A series of communications between McDonald and Houghton during the preparation of the former's paper also revealed that there are apparently two different and irreconcilable sets of these data. Thus, McDonald could only conclude that a major observational program was needed to eliminate the confusion.

Acting in accord with this suggestion, Monteith (1962) initiated a study of solar radiation attenuation in the British Isles. Although he admitted to lacking sufficient precision in his data to discriminate between the different water vapor absorption curves of Houghton and McDonald, he did state that they "strongly support the internal consistency of the complete set of coefficients which Houghton presented."

Although the discrepancy between the Houghton and McDonald water vapor absorption curves is sufficient to introduce uncertainties of up to 30% in insolation absorption studies (McDonald), it is clear from the conclusion of Monteith (1962) that the uncertainties in total atmospheric transmittance will be much less. Thus, it is the purpose of this paper to investigate the utility of both of these absorption curves in conjunction with the remaining complement of the Houghton attenuation coefficients, in the hope that a semiempirical method for computing the clear sky solar radiation available at the surface may be achieved, and that the discrepancies due to uncertainities in water vapor absorption may be clarified.

2. Calculating the theoretical attenuation

Houghton calculated the transmittance of the atmosphere for solar radiation as the product of four component transmittances: that due 1) to absorption by water vapor, 2) to scattering by water vapor, 3) to absorption and scattering by dust, and 4) to scattering by dry, dust-free air. In doing this, he assumed as a computational convenience that attenuation by absorption occurs first and then attenuation by scattering. This procedure has been followed by both McDonald and Monteith and will also be followed here.

Of these four attenuating mechanisms, only Houghton's absorption curve for water vapor has been questioned by McDonald. Each of their descriptions of this phenomenon, plus those of three other sets of investigators mentioned in the introduction, are depicted in Fig. 1. For comparative purposes, calculations will be made here for the curves of Houghton and McDonald.

In using Fig. 1 to compute an average daily or monthly value for solar radiation absorption by water

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[1] Contribution from the Soil and Water Conservation Research Division, Agricultural Research Service, U. S. Department of Agriculture.

Table 1. Computation of weighted optical air mass for January at Phoenix.

Hour H	Solar zenith angle sec Z	Normalized intensities NI	Weighted optical air mass $(NI)(\sec Z)$
0.5	1.750	0.9885	1.7298
1.5	1.928	0.8850	1.7059
2.5	2.396	0.6781	1.6247
3.5	3.654	0.3908	1.4279
4.5	10.217	0.1034	1.0564
Totals		3.0458	7.5447
Average	2.477		

vapor, it is necessary to know the pertinent average optical air mass weighted for the intensity of solar radiation received and the average optical depth of the atmosphere's precipitable water.

Monthly averages of the first of these parameters were calculated as the weighted daily values on the 15th day of each month at Phoenix, Ariz. The data required for these calculations were obtained from the *American Ephemeris and Nautical Almanac* for the year 1962 and from pyranometric records of the U. S. Water Conservation Laboratory at Phoenix. The average optical air mass numbers were computed by calculating the secant of the sun's zenith angle (sec Z) at the mid-point H of each hour that there was potential insolation for half-day periods on the dates in question, multiplying these values by the normalized intensities NI of solar radiation received at Phoenix at these times and dates, summing the respective half-day totals, and dividing by the similarly totaled normalized solar radiation intensities. An example of the procedure is given in Table 1 for the month of January (daylength on 15 January being 10.02 hr); and results for the entire year are included in Table 2 (line 1) after being amended to mean sea level conditions by a square-root pressure law correction.

Since the optical depth of precipitable water in the atmosphere is not a determination regularly made at Phoenix, it is necessary to arrive at monthly values of this parameter by means of some other measurement. Monteith (1962) used the results of an earlier study of his (Monteith, 1961), wherein he had found a fairly good linear relation between the logarithm of the precipitable water and the square root of the surface vapor pressure at Kew. It was thus decided to derive a similar relation for use at Phoenix. A report by Reitan (1957) was found to contain precipitable water data for three

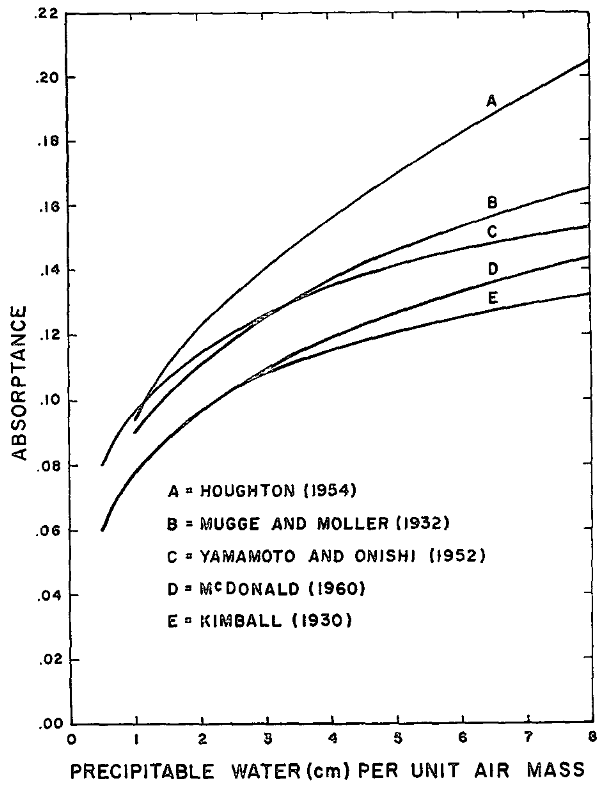

Fig. 1. Water vapor absorption curves for solar radiation, constructed by various investigators from the data of the Smithsonian Institution (after McDonald, 1960).

Table 2. Computations of average monthly atmospheric transmittances for solar radiation at Phoenix, calculated for the complete set of Houghton coefficients. See text for definitions of line entries.

Line	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
1	2.44	2.03	1.75	1.59	1.48	1.44	1.45	1.47	1.57	1.79	2.29	2.52	1.82
2	0.918	0.901	0.901	0.926	0.926	1.122	2.176	2.414	1.666	1.182	0.969	0.910	1.251
3	0.1253	0.1163	0.1102	0.1072	0.1045	0.1112	0.1424	0.1486	0.1328	0.1228	0.1249	0.1264	0.1227
4	0.8747	0.8837	0.8898	0.8928	0.8955	0.8888	0.8576	0.8514	0.8672	0.8772	0.8751	0.8736	0.8772
5	0.1176	0.0989	0.0859	0.0783	0.0731	0.0712	0.0717	0.0726	0.0774	0.0877	0.1108	0.1213	0.0888
6	0.1028	0.0873	0.0764	0.0699	0.0654	0.0632	0.0614	0.0618	0.0671	0.0769	0.0969	0.1059	0.0779
7	0.0514	0.0436	0.0382	0.0349	0.0327	0.0316	0.0307	0.0309	0.0335	0.0384	0.0484	0.0529	0.0389
8	0.7719	0.7964	0.8134	0.8229	0.8301	0.8256	0.7962	0.7896	0.8001	0.8003	0.7782	0.7677	0.7993
9	0.9465	0.9563	0.9628	0.9655	0.9679	0.9619	0.9248	0.9158	0.9379	0.9498	0.9473	0.9458	0.9485
10	0.8040	0.8288	0.8470	0.8580	0.8658	0.8682	0.8678	0.8660	0.8595	0.8441	0.8122	0.7992	0.8433
11	0.7609	0.7925	0.8154	0.8283	0.8380	0.8351	0.8025	0.7930	0.8061	0.8017	0.7693	0.7558	0.7998
12	0.5873	0.6311	0.6632	0.6816	0.6956	0.6894	0.6389	0.6261	0.6449	0.6416	0.5986	0.5802	0.6398
13	0.0923	0.0826	0.0751	0.0706	0.0672	0.0681	0.0786	0.0817	0.0776	0.0793	0.0898	0.0937	0.0797
14	0.7310	0.7573	0.7765	0.7871	0.7955	0.7891	0.7482	0.7387	0.7560	0.7593	0.7368	0.7268	0.7585

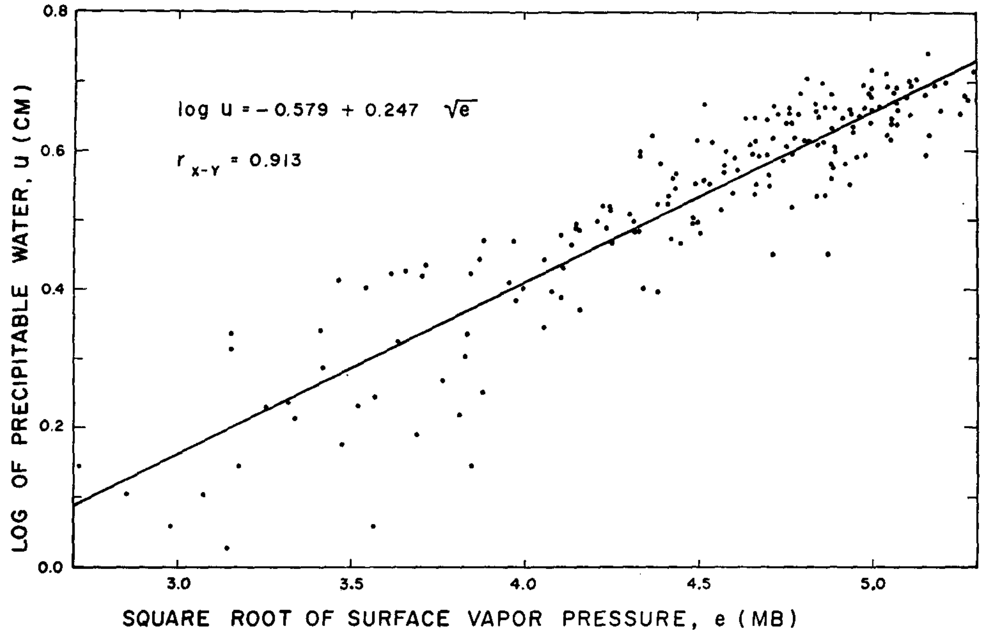

FIG. 2. The relation between precipitable water and surface vapor pressure as determined for Phoenix, Ariz.

summers at Phoenix, including 190 days. Average temperatures and relative humidities were obtained for these same days from U. S. Weather Bureau data, and the corresponding average surface vapor pressures were determined. The logarithms of the precipitable water, expressed in centimeters, were then plotted as functions of the square roots of the surface vapor pressures, expressed in millibars, with the results as shown in Fig. 2. From this graph, and from average monthly vapor pressures computed for the years 1950–1967, the average monthly precipitable water contents at Phoenix were determined. Then, since Fritz (1949) has indicated that the precipitable water on clear days is about 85% of the mean for all days, these figures were accordingly amended to clear sky conditions and recorded in Table 2 (line 2).

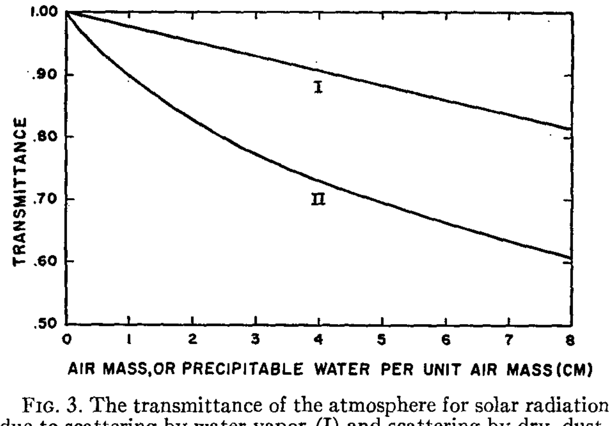

FIG. 3. The transmittance of the atmosphere for solar radiation due to scattering by water vapor (I) and scattering by dry, dust-free air (II) (after Houghton, 1954).

With this information at hand, the computation of the atmospheric attenuation of solar radiation may be begun. Table 2 includes these calculations for the complete set of Houghton coefficients. By entering the abscissa of Fig. 1 with the products of optical air mass and precipitable water obtained from the first two lines of Table 2, the monthly values for water vapor absorption are determined from the Houghton absorption curve and entered on line 3. These absorptances are subtracted from unity and the remaining fractional energy fluxes are recorded on line 4.

The optical air mass m is now used again in the equation Houghton proposed for describing depletion DD of the solar beam by dust, i.e.,

$$DD = 1.00 - 0.95^m. \qquad (1)$$

The resulting coefficients are entered on line 5 of Table 2 and multiplied by the remaining fractional energy fluxes of line 4 to give, in line 6, the fractional amount of the original solar beam depleted by dust.

Originally, Houghton assumed that half of the dust depletion was by absorption and half by scattering, and further that half of the scattered radiation was transmitted in a forward direction and half backward. According to the theory of Mie particle scattering, however, and the measurements of several investigators cited by Middleton (1957), an often significantly larger portion of the scattered radiation is transmitted in the forward direction. Thus, since it is also possible that less than half of the dust depletion could be due to absorption, I have considered half of the energy depleted by dust to reach the earth as diffuse radiation. Whether or not this is precisely correct will be seen later to be im-

Table 3. Computations of average monthly atmospheric transmittances for solar radiation at Phoenix using the McDonald water vapor absorption curve. See text for definition of line entries.

Line	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
1	2.44	2.03	1.75	1.59	1.48	1.44	1.45	1.47	1.57	1.79	2.29	2.52	1.82
2	0.918	0.901	0.901	0.926	0.926	1.122	2.176	2.414	1.666	1.182	0.969	0.910	1.251
3	0.0981	0.0923	0.0883	0.0864	0.0846	0.0890	0.1087	0.1126	0.1028	0.0965	0.0978	0.0987	0.0963
4	0.9019	0.9077	0.9117	0.9136	0.9154	0.9110	0.8913	0.8874	0.8972	0.9035	0.9022	0.9013	0.9036
5	0.1176	0.0989	0.0859	0.0783	0.0731	0.0712	0.0717	0.0726	0.0774	0.0877	0.1108	0.1213	0.0888
6	0.1060	0.0897	0.0783	0.0715	0.0669	0.0648	0.0639	0.0644	0.0694	0.0792	0.0999	0.1093	0.0802
7	0.0530	0.0448	0.0391	0.0357	0.0334	0.0324	0.0319	0.0322	0.0347	0.0396	0.0499	0.546	0.0401
8	0.7959	0.8180	0.8334	0.8421	0.8485	0.8462	0.8274	0.8230	0.8278	0.8243	0.8023	0.7920	0.8234
9	0.9465	0.9563	0.9628	0.9655	0.9679	0.9619	0.9248	0.9158	0.9379	0.9498	0.9473	0.9458	0.9485
10	0.8040	0.8288	0.8470	0.8580	0.8658	0.8682	0.8678	0.8660	0.8595	0.8441	0.8122	0.7992	0.8433
11	0.7609	0.7925	0.8154	0.8283	0.8380	0.8351	0.8025	0.7930	0.8061	0.8017	0.7693	0.7558	0.7998
12	0.6056	0.6482	0.6795	0.6975	0.7110	0.7066	0.6639	0.6526	0.6672	0.6608	0.6172	0.5985	0.6590
13	0.0951	0.0849	0.0769	0.0723	0.0687	0.0698	0.0817	0.0852	0.0803	0.0817	0.0925	0.0967	0.0821
14	0.7537	0.7779	0.7955	0.8055	0.8131	0.8088	0.7775	0.7700	0.7822	0.7821	0.7596	0.7498	0.7813

material. The figures on line 7 of Table 2, being 50% of those in line 6, should thus give an end result that is an upper limit in terms of light transmission.

Line 8 of Table 2 represents the portion of the direct solar beam not affected by water vapor absorption and dust depletion. It is available for scattering by water vapor and the dry, dust-free atmosphere. Fig. 3, as constructed by Houghton from the Smithsonian data, is now used to obtain the two component transmittances due to these phenomena. Line 9 contains the transmittances determined by entering the abscissa of Fig. 3 with the product of optical air mass and precipitable water to obtain the transmittances due to water vapor scattering; and line 10 contains the transmittances due to dry, dust-free scattering similarly obtained with the optical air mass. In line 11 the products of these two sets of transmittances are obtained, and in line 12 the actual values of transmitted direct solar radiation are calculated as the products of these combined transmittance functions and the radiation available for scattering in line 8. Subtracting these values from those in line 8 then gives the amount of radiation scattered by this process, and dividing by 2 gives that scattered to the earth, recorded in Table 2 on line 13. Then, adding the contributions of lines 7, 12 and 13, the total transmittance of the atmosphere is obtained at line 14. Table 3 contains the results of a similar process carried out for the McDonald water vapor absorption curve.

3. Obtaining the actual attenuation

The solar radiation data used to obtain the actual attenuation were taken from records of the U. S. Weather Bureau station at Sky Harbor Airport, Phoenix. These data covered all clear days for the 18-year period 1950–1967, where the clear day criterion used was 100% of possible sunshine plus zero tenths sky cover. The sensing devices used were Eppley pyranometers.

For each day of the year, the total potential insolation on a horizontal surface in the absence of an atmosphere was calculated from zenith angle, daylength, and solar distance considerations. The solar constant employed in these calculations was 1.94 cal cm^{-2} min^{-1}. This same value was also used by Houghton and McDonald.

With these unattenuated values for total solar radiation reception, the measured values were converted into transmittances. The 18 years' results were then pooled into monthly groups and averaged to give the values in line 1 of Table 4.

These figures require some slight modification, however, before serving as a basis for comparison with the theoretical calculations. First of all, the Eppley pyranometer is temperature dependent, its calibration factor changing, according to Robinson (1966), by 0.05–0.10% (°C)$^{-1}$ over the ambient temperature range −50 to +40C. Tests carried out by J. M. Norman and D. G.

Table 4. Calculations of actual monthly atmospheric transmittances for solar radiation at Phoenix. See text for definition of line entries.

Line	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
1	0.7751	0.8057	0.8119	0.8040	0.7950	0.7837	0.7489	0.7491	0.7652	0.7709	0.7684	0.7584	0.7780
2	1.028	1.025	1.021	1.014	1.007	1.000	0.995	0.997	1.001	1.009	1.020	1.026	1.012
3	0.982	0.985	0.988	0.991	0.993	0.993	0.993	0.993	0.991	0.988	0.983	0.982	0.988
4	0.7681	0.7977	0.8046	0.8000	0.7950	0.7892	0.7579	0.7566	0.7713	0.7732	0.7661	0.7523	0.7776

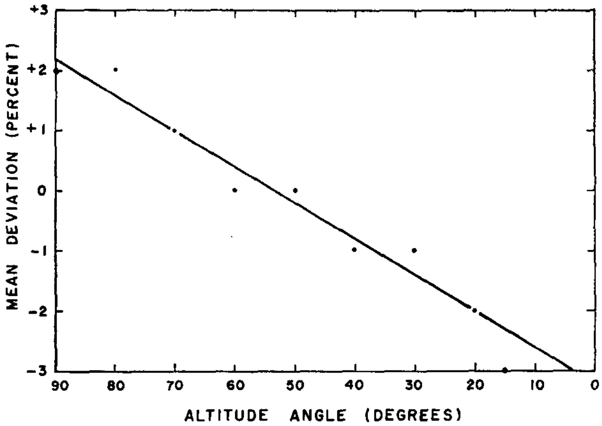

FIG. 4. The percentage error in Eppley pyranometer readings from measurements reported by Robinson (1966) for clear sky conditions in South Africa and Newport, R. I., as a function of sun altitude angle.

Baker[2] at St. Paul, Minn., and Madison, Wis., however, indicate a dependency as great as 0.20% $(°\mathrm{C})^{-1}$ may exist. Thus, I have assumed that the instruments responsible for the data I used had a temperature dependency of 0.15% $(°\mathrm{C})^{-1}$.

To apply this temperature correction, the average monthly temperatures were determined for the site of the radiation readings for the 18-year period. The differences between these monthly averages and the temperature at which the pyranometers were calibrated (85F for all instruments, as indicated by records supplied by the manufacturer) were then determined and multiplied by 0.15% $(°\mathrm{C})^{-1}$ and added to or subtracted from unity to give the correction factors listed in line 2 of Table 4. Dividing by these factors makes the temperature correction.

A second correction required was for the weighted mean altitude angle of the sun. From a table in Robinson giving the mean deviation in per cent of an Eppley pyranometer calibrated in sunlight at a mean altitude angle of 50°, the points of Fig. 4 were obtained. The straight line fitted by sight to these points was used, together with the mean monthly weighted zenith angles previously determined, to obtain the correction factors for this effect entered at line 3 of Table 4. Dividing the unadjusted transmittances of line 1 by the proper products of lines 2 and 3 then gives the final supposed actual transmittances of line 4.

4. Comparing the theoretical with the actual attenuation

Considering first the average transmittance for the entire 18-year period, the complete set of Houghton coefficients yields a value of 0.758. Exchanging Houghton's water vapor absorption curve for that proposed by McDonald alters this figure to 0.781. Since these values differ from each other by only 2%, it is obvious that the data herein presented cannot be used to judge with finality between the two water vapor absorption curves. However, since the theoretical calculations were carried out to give, if anything, a *maximum* transmittance, and since the supposed actual transmittance of 0.778 is only very slightly lower than the McDonald result, but fully 2% greater than the Houghton result, it may be concluded, for the semi-empirical estimation of solar radiation available at the earth's surface, that the McDonald water vapor absorption relation should be used in conjunction with the remaining Houghton coefficients.

This conclusion appears to contradict the findings of Monteith (1962), wherein he felt the complete set of Houghton coefficients were justified by his research. However, in his calculations he used a solar constant of 1.98 cal cm^{-2} min^{-1}, whereas I used 1.94. Thus, his supposed actual transmittances should be less than mine by the factor 1.94/1.98 or 0.98, which would alter my supposed actual transmittance to 0.762, in fair agreement with the Houghton result also. Thus, our two sets of data are compatible; and our differing conclusions are due solely to our different values for the solar constant.

The final resolution of the issue from our perspective, then, must rest with the solar constant. What is its correct value? Various observers have recorded values ranging from 1.89–2.05 cal cm^{-2} min^{-1}. I originally chose 1.94 to work with as this was the value used by both Houghton and McDonald, whereas Monteith chose 1.98 upon recommendation of the *I.G.Y. Instruction Manual* (C.S.A.G.I., 1957). Recent discussions by Johnson (1965), Drummond (1965), Gast (1966), and Robinson (1966), however, have emphasized the lack of close agreement among most of the early workers in this area and have called for more accurate measurements to be made anew. Three recent investigations will thus be mentioned here.

Stair and Ellis (1968) measured the solar spectral irradiance at an altitude of 11,150 ft on Mauna Loa, Hawaii, with recently developed instrumentation of the National Bureau of Standards and obtained a value of 1.95 cal cm^{-2} min^{-1} for the solar constant. A similar value was also obtained by Drummond *et al.* (1968) as a result of radiometric measurements from high-flying aircraft. Finally, Murcray *et al.* (1968) obtained a value of 1.91 cal cm^{-2} min^{-1} from measurements made with normal incidence Eppley pyrheliometers carried in balloons flying at 31 km. Thus, even though these recent determinations are not all similar, the weight of evidence does appear to be in favor of 1.94 over 1.98 cal cm^{-2} min^{-1}; and in light of this evidence the conclusion that McDonald's water vapor absorption curve

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[2] Personal communication.

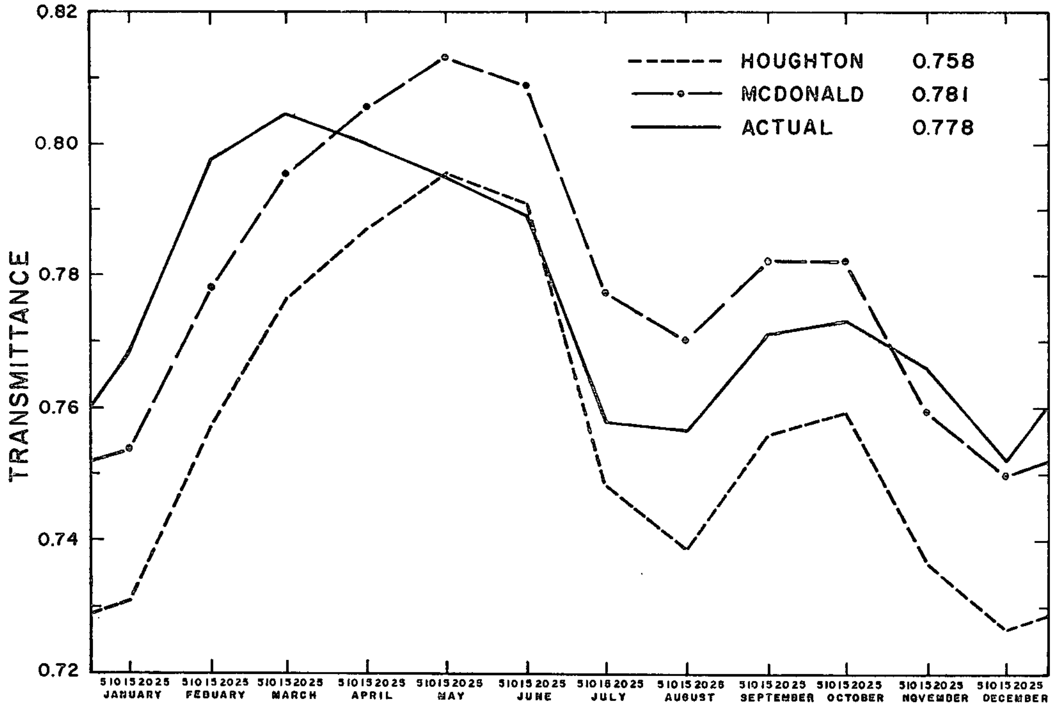

FIG. 5. Calculated and measured transmittances of the atmosphere for solar radiation on cloudless days at Phoenix, Ariz.

should be used in the estimation of total atmospheric transmittance must still stand.

A month-by-month comparison of the calculations is best portrayed graphically, as in Fig. 5. The general form of the actual transmittance curve is followed by both of the calculated curves, with the McDonald curve giving the better yearly average as discussed above. A rather curious discrepancy between the McDonald curve and the actual curve, however, is the almost symmetrical manner in which the former overpredicts the actual transmittance in the summer and underpredicts it in the winter. The question naturally raised by this observation is whether dust variations may be responsible for this discrepancy, for Houghton himself said that the dust content of the atmosphere was "extremely variable," proposing his dust depletion relation (1) for only average or mean conditions.

To test this idea, the average monthly wind speeds for the Phoenix site were determined for the 18-year period. Being located in a general sandy desert area, it was felt that the dust content of the atmosphere may be related to this parameter. Thus, line 2 of Table 5 represents the average wind speeds for this period.

As for the nature of the wind effect, Bagnold (1943) found the rates of sand flow in a wind tunnel to be proportional to the $\frac{3}{2}$ power of the average shear or drag of the wind on the surface. A similar result has also been obtained by Zingg (1953). Thus, since the wind speed at any height is proportional to the $\frac{1}{2}$ power of the shear, this would mean that the weight or amount of sand moved should be proportional to the cube of the wind speed.

Proceeding upon this assumption, line 2 of Table 5 contains the ratios of the wind averages of line 1 to the

TABLE 5. Abbreviated computations of average monthly atmospheric transmittances for solar radiation at Phoenix using the McDonald water vapor absorption curve and the postulated dust variability correction. See text for definition of line entries.

Line	Month												Year
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	
1	4.96	5.63	6.26	6.65	6.88	6.78	7.04	6.60	6.31	5.50	5.07	4.89	6.05
2	0.820	0.931	1.035	1.100	1.138	1.121	1.164	1.091	1.043	0.909	0.838	0.808	1.000
3	0.551	0.807	1.109	1.331	1.474	1.409	1.577	1.298	1.134	0.751	0.588	0.527	1.000
4	0.7727	0.7844	0.7914	0.7953	0.7986	0.7977	0.7607	0.7616	0.7768	0.7886	0.7735	0.7669	0.7807

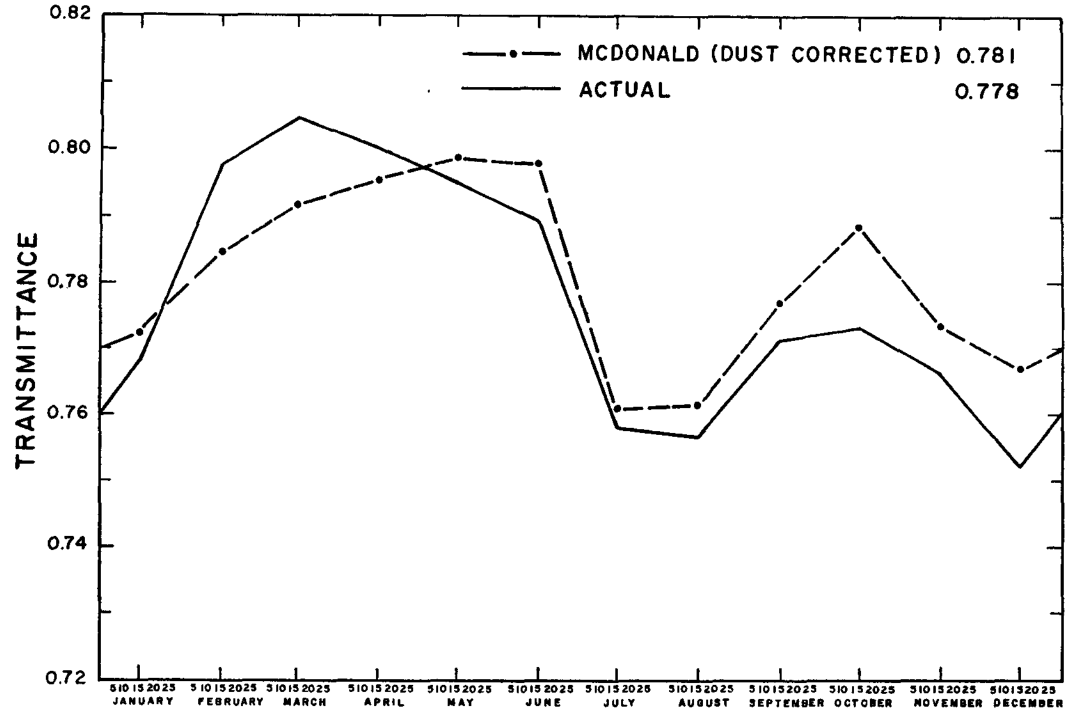

FIG. 6. Comparison with the actual transmittance of that calculated with the McDonald water vapor absorption curve and the remaining Houghton coefficients corrected for postulated dust variability.

average wind speed for the year. In line 3 these values are cubed. The results are then used to modify by multiplication the dust depletion values determined by Eq. (1) in an otherwise identical analysis to that portrayed in Table 3. The final transmittances thereby obtained are recorded at line 4 and plotted in Fig. 6 along with the actual transmittance. It is there observed that indeed the postulated dust variations do improve somewhat the monthly calculations.

Acknowledgments. I wish to express my appreciation to Mr. R. S. Ingram, Weather Bureau, ESSA, Meteorologist in Charge, Sky. Harbor Airport, Phoenix, for making available to me the pertinent meterological records there obtained over the past 20 years. I also wish to thank Prof. J. E. McDonald, Inst. of Atmospheric Physics, Univ. of Arizona, and Dr. D. G. Baker, Soil Science Dept., Univ. of Minnesota, for critically reviewing the manuscript.

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