SOME NORMAL-INCIDENCE SOLAR RADIATION OBSERVATIONS DURING THE IGY[1]

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ABSTRACT

Normal-incidence solar radiation values were measured during the IGY at the South Pole and Little America (Antarctica), at Mauna Loa (Hawaii), Tucson (Arizona), and Blue Hill Observatory (Massachusetts); some results are given in tables and graphs. Essential differences among them are discussed. The radiation data at Tucson and Blue Hill are appreciably lower than at the other stations. The radiation, corrected for solar distance, is similar at the Antarctic stations to the radiation measured at Mauna Loa. However, the actual measured values in summer are higher at the South Pole than at Mauna Loa, because the sun is closer to the earth in the Southern Hemisphere summer. The "extrapolated turbidity factor" is over 2.5 at Tucson and Blue Hill, but averages 2.0 or less at the other stations with the lowest values of about 1.5 at the South Pole.

During the International Geophysical Year many new solar radiation observations were taken at many places. In particular, new stations were installed in Antarctica and one was installed at the Mauna Loa Observatory in Hawaii. Some of the normal-incidence solar radiation data which have so far been evaluated are presented in this paper.

The measurements were made with Eppley Normal-Incidence Pyrheliometers and some tests were made which indicated that the temperature coefficient of this instrument was too small to influence the main results. In taking normal-incidence observations, the observers are instructed to point the instrument to the sun in those cases only when no clouds appear in front of the sun. If we now intercompare the *mean* value of radiation at one station with that at another for the same optical air mass then a certain subjectivity is introduced into the results, because many times the sky is covered with a very thin milky veil. Some observers consider that the sky is then covered by a thin cirrus cloud and they do not take normal-incidence observations under those conditions. Therefore, at those stations, the "clear" days with the lowest transmission are not included in the mean data so that the mean transmission is relatively high. On the other hand, some observers consider the "milky" sky as a clear sky and do take normal-incidence observations; consequently, at such stations the *mean* values are relatively low. Thus, in comparing the *mean* normal-incidence solar radiation data at one station with those at another, some uncertainty is introduced.

We may attempt to get around this uncertainty by plotting all the radiation values that have been observed at the station; and then taking the very clearest days as samples of the clear-day values. However, some subjectivity arises in this case too; a single extreme value is often incorrect because of slight errors of recorder settings or for other reasons. Therefore in choosing the highest few measurements as representative of the clearest days, subjectivity arises in the selection of those few measurements.

This difficulty is indicated in figure 1. The measurements at the various stations are taken at specified zenith distances, Z, of the sun. These correspond to integral optical air mass, m_0, at sea level pressure, p_0 (taken as 1000 mb.). At elevated stations, the air mass has been computed from the formula $m=m_0\ (p/p_0)$ where p is the mean station pressure.

Thus in figure 1, the observations taken at four specific values of Z have been plotted above those values of Z indicated at the bottom of each diagram; the points have been spread horizontally for ease in plotting. At Mauna Loa, the skies selected appear to be of relatively uniform character and the points are clustered in a narrow range of radiation values. But at Blue Hill the "clear" skies appear to be much less uniform, and the points are considerably spread out in radiation values at a given air mass.

The lines drawn through the topmost points are subjective and represent high values of radiation. These lines should *not* be taken to represent a typical diurnal variation during a *single day* with high radiation, since the slope may be changed appreciably by a slightly different selection of the "top" points. This is especially true at Blue Hill.

[1] Paper delivered by S. Fritz to International Radiation Commission of IUGG, 1959, Oxford, England.

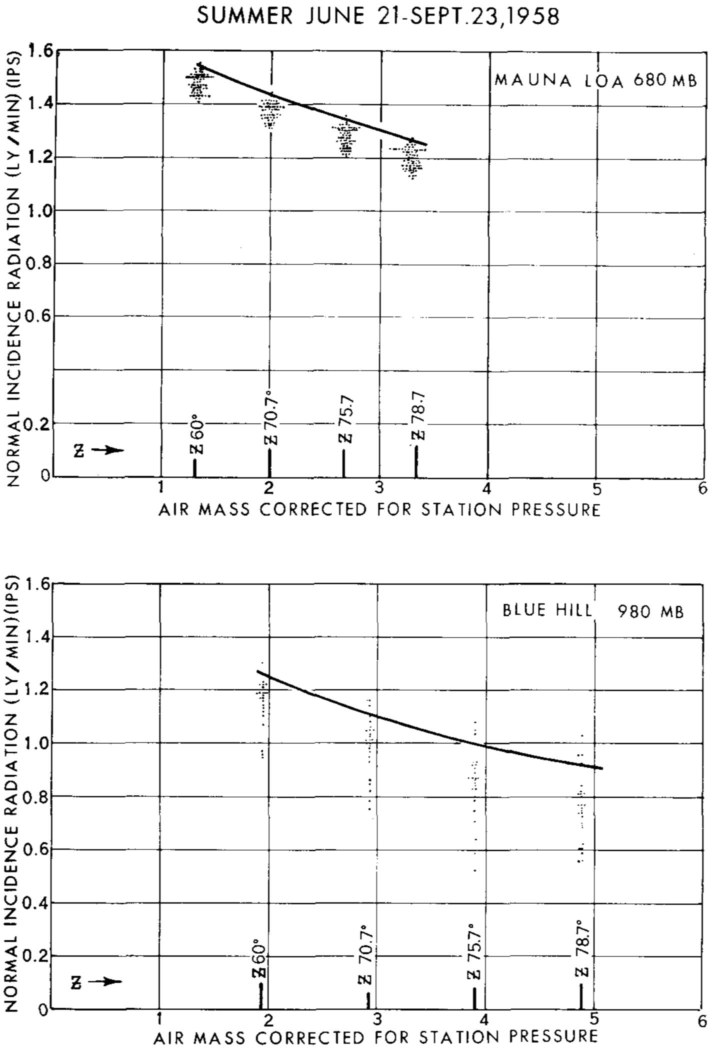

FIGURE 1.—Normal-incidence solar radiation observations for Mauna Loa, Hawaii and Blue Hill, Mass., taken at the specified zenith distances, *Z*, of the sun, are plotted for comparison. Note spread in values at a given air mass, especially at Blue Hill, indicating the subjectivity inherent in the choice of "clear" skies.

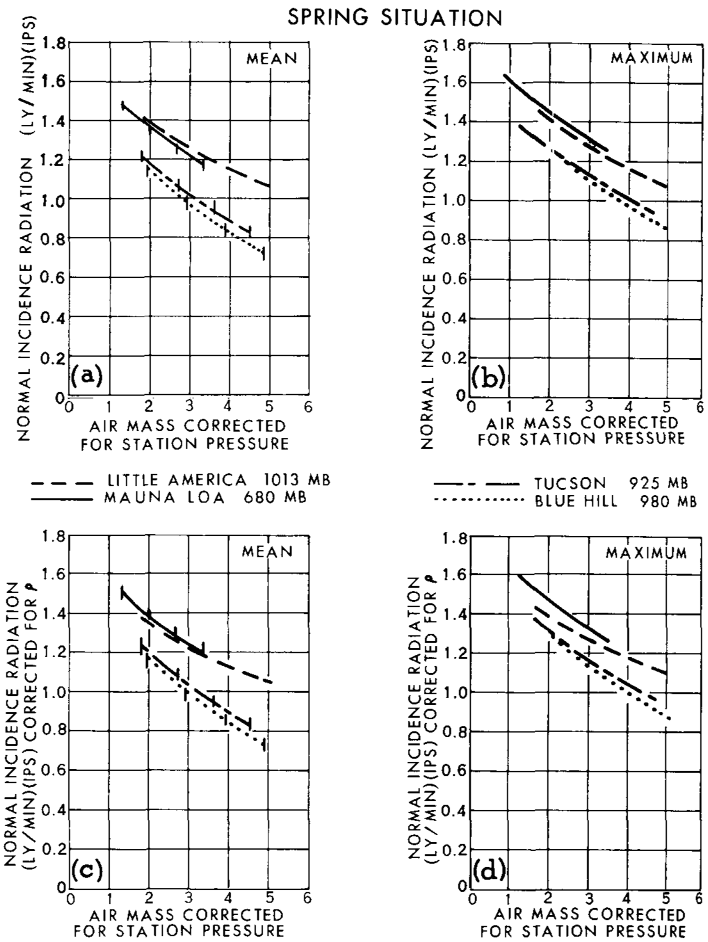

FIGURE 2.—Spring season mean and maximum normal-incidence solar radiation values; (c) and (d) corrected for ρ, (a) and (b) uncorrected.

From figure 1 it is also evident that the "mean" value of radiation, which can readily be computed from the radiation observations tabulated by the observer, is also ambiguous; the much wider spread of points in the Blue Hill diagram suggests that the criteria for selecting "clear" days were not the same for the two stations.

In spite of these difficulties, the major differences between stations still appear. For example, stations at high latitudes and high elevations have systematically higher mean and maximum "clear day" transmissions than those in middle latitudes, near sea level. These results are indicated in figures 2 and 3 and in tables 1 and 2. In table 1, normal-incidence solar radiation values, on the International Pyrheliometric Scale, are shown for the spring months. The air-masses have been reduced to sea level pressure and the radiation, I, has been adjusted for the mean distance of the Earth from the sun by the relation $I=I'\rho^2$, where ρ is the radius vector of the earth in units of its mean value and I' is the measured radiation. The mean values of radiation, and also the maximum values (estimated from curves such as those of fig. 1) are shown in the table. We see immediately that the radiation values for Little America and for Mauna Loa are both definitely

TABLE 1.—*Normal-incidence solar radiation values, I, (ly./min.) reduced to mean distance from sun. Spring (March 21–June 21, 1958) (At Little America, Sept. 23–Dec. 22, 1957)*

Station	Assumed station pressure (mb.)	Air mass (reduced to sea level pressure)					
		2		3		4	
		I (mean)	I (max.)	I (mean)	I (max.)	I (mean)	I (max.)
Little America, Antarctica	987	1.35	1.38	1.22	1.26	1.13	1.18
Mauna Loa, Hawaii	680	1.39	1.46	1.24	1.32	-------	-------
Blue Hill, Mass.	980	1.18	1.29	0.99	1.12	0.85	0.99
Tucson, Ariz.	925	1.20	1.30	1.04	1.16	0.90	1.04
South Pole, Antarctica	687	-------	-------	-------	-------	-------	-------

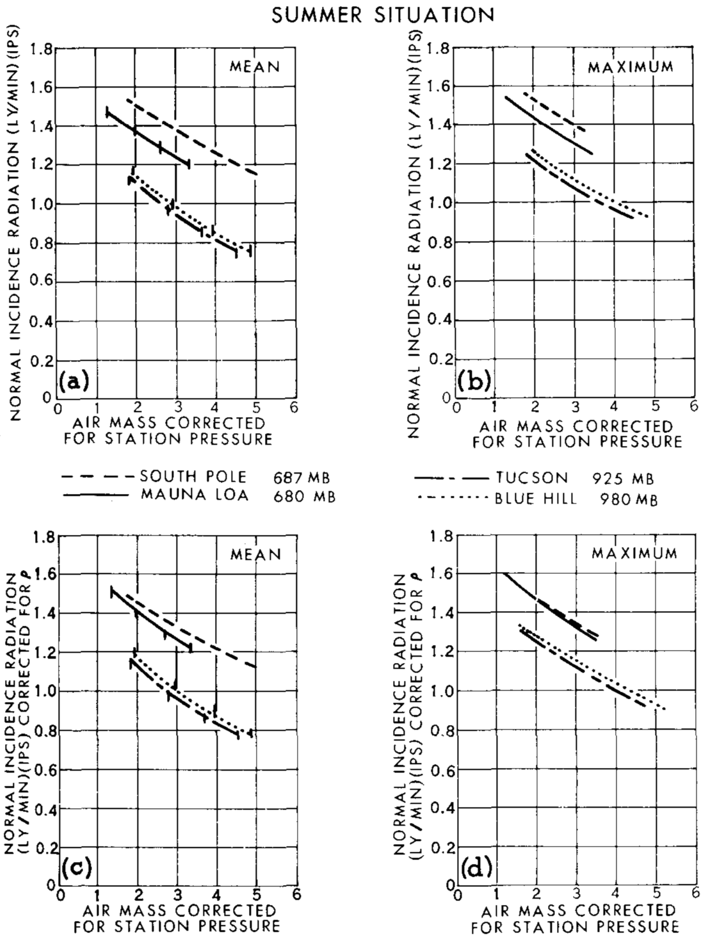

FIGURE 3.—Summer season mean and maximum normal-incidence solar radiation values; (c) and (d) corrected for ρ, (a) and (b) uncorrected.

higher than the values for Blue Hill and for Tucson. Mauna Loa has an elevation of about 11,000 feet, while the other stations are nearer sea level. Little America is at a much higher latitude than the other stations and presumably has a less polluted atmosphere with smaller amounts of water vapor. The values at Mauna Loa seem to be slightly higher than those at Little America. This is true for both the mean and the maximum values. However, the values are close enough together so that the reality of the difference is in doubt. The same thing may be said for Blue Hill and Tucson. Their values are in general so close together that the difference may not be real.

In table 2, and in figure 3, similar data are presented for the summer situation. Here, data for the South Pole were available while those for Little America were not yet evaluated (in 1959). Again the radiation values for the South Pole and for Mauna Loa are greater than for the two continental United States stations. In this case, the values for the South Pole seem to be slightly higher than those for Mauna Loa. The difference appears small, in view of the fact that both stations are at high elevations, as indicated by the station pressures in table 1, and that one might expect the water vapor content over Mauna Loa to be appreciably higher than it is over the South Pole. Of course, at high enough elevations, the influence of water vapor must eventually become small at all stations. Figure 3 indicates that the difference between the two stations is small and it may not even be real. Blue Hill and Tucson again have similar radiation values, and of course in both cases the radiation received is appreciably smaller than that at Mauna Loa.

Another way of comparing the clarity of the atmosphere in various places is to compute the "turbidity factors." Linke [1] has presented two different definitions of the turbidity factor [2]. The turbidity factor for total radiation is the number of "reference" atmospheres which would transmit the same amount of energy as the actual moist, turbid atmosphere transmits. In the older turbidity factor, T, the reference atmosphere is the pure dry molecular atmosphere, scattering in accordance with Rayleigh's law. In the new[2] turbidity factor, θ, the reference atmosphere is a dustless atmosphere containing one centimeter of precipitable water vapor.

However, Fuessner and Dubois [3, 4] have pointed out that for high stations it is necessary to use an "extrapolated turbidity factor," T_p. Table 3 shows values of T_p computed for each of the values shown in tables 1 and

TABLE 2.—*Normal-incidence solar radiation values, I, (ly./min.) reduced to mean distance from sun. Summer (June 21–Sept. 23, 1958) (At South Pole, Dec. 22, 1957–March 21, 1958)*

Station	Air mass (reduced to sea level pressure)					
	2		3		4	
	I (mean)	I (max.)	I (mean)	I (max.)	I (mean)	I (max.)
South Pole, Antarctica	1.46	1.48	1.34	1.35	1.22	
Mauna Loa, Hawaii	1.41	1.46	1.26	1.32		
Blue Hill, Mass	1.17	1.28	0.99	1.16	0.87	1.04
Tucson, Ariz	1.13	1.25	0.96	1.12	0.84	1.00

TABLE 3.—*"Extrapolated Turbidity Factor" T_p*

Season	Station	Air mass (reduced to sea level pressure)					
		2		3		4	
		I (mean)	I (max.)	I (mean)	I (max.)	I (mean)	I (max.)
Spring	Little America	2.1	2.0	2.0	1.8	1.8	1.7
	Mauna Loa	1.7	1.5	1.7	1.5		
	Blue Hill	2.9	2.4	2.8	2.3	2.8	2.3
	Tucson	2.7	2.3	2.5	2.1	2.5	2.0
Summer	South Pole	1.5	1.5	1.5	1.4	1.5	
	Mauna Loa	1.7	1.5	1.6	1.5		
	Blue Hill	2.9	2.4	2.8	2.2	2.7	2.1
	Tucson	3.0	2.5	2.8	2.2	2.7	2.2

[2] In reference [2], equation 22, the logarithm should be used to the base 10.

2. It should be realized that the turbidity coefficient is merely a convenient index. To get more precise optical information requires spectral measurements, which are in general not available.

The values in table 3 show that Blue Hill and Tucson with a mean T_p of over 2.5, are much more "turbid" than the other stations, where T_p is mainly less than 2.0 and is only 1.5 at the South Pole. The table suggests that Mauna Loa is somewhat less turbid than Little America but has turbidity rather similar to the South Pole station.

The values shown in table 1 and 2 have been adjusted for the mean distance of the sun from the earth. There is interest also, for practical application, in the actual values as received at the earth's surface. The mean and "maximum" values of actual observations are shown in figures 2 a and b for spring and in figures 3 a and b for summer. The variations of these actual observed data, from the values shown in tables 1 and 2, occur because the sun is nearer to the earth in the Southern Hemisphere summer. As a consequence the measurements of radiation at the South Pole for the summer are appreciably higher than those at Mauna Loa in summer. In the spring the differences are not so great, but there still is a small excess in the mean radiation at Little America relative to the stations in the north. Thus, by comparison of figure 2a with 2c the mean value of radiation uncorrected for ρ at Little America is actually somewhat higher than that for Mauna Loa, although the difference is very small. For the maximum values of radiation, that is on the clearest days, Mauna Loa apparently has higher values of radiation than Little America even in values uncorrected for ρ which are not much different from those in table 1. But this depends somewhat on whether the observations used to determine maximum values occurred near September or December.

REFERENCES

1. F. Linke, *Handbuch der Geophysik*, bd. 8, Lief 1 and 2, Gebr. Borntraeger, Berlin, 1942, 1943.
2. S. Fritz, "Solar Radiant Energy and its Modification by the Earth and its Atmosphere," in *Compendium of Meteorology*, T. F. Malone, ed., American Meteorological Society, Boston, Mass., 1951, pp. 13–33.
3. K. Feussner and P. Dubois, "Trübungsfaktor, Precipitable Water, Staub," *Beiträge zur Geophysik*, vol. 27, 1930, pp. 132–175.
4. Radiation Commission of IAMAP (IUGG), "Radiation Measurements and Instruments," *Annals of the IGY*, Part VI. (Undated) pp. 367–466. (See p. 404.)