Note on solar radiation in mountain regions at high altitude

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(Manuscript received January 18, 1966)

ABSTRACT

The following article gives a short survey over recent measurements of solar radiation at mountain stations of high altitude ($h > 3000$ m), namely from Silver Hut Glacier 1961, during the Mount Everest expedition led by Sir Edmund Hillary, and from the Mauna Loa Observatory, Hawaii, organized by the U.S. Weather Bureau in collaboration with the U.S. Army. The measurements are compared with previous measurements of C. G. Abbot on Mount Whitney in the years 1908–1910, of A. K. Ångström and E. H. Kennard on the same place in 1913, and also of Knut Ångström on Pico del Teide in 1896. The close agreement of the various results is due to the fact that the influence of variations of the composition of the atmosphere, evidently under ordinary conditions, plays a subordinate part at the altitudes and latitudes here concerned, where the influence of astronomical factors, solar height and distance between sun and earth are dominating.

This may be true as long as disturbances of cosmical origin or through volcanic outbreaks do not cause occasional deviations from the ordinary trend.

Through the comprehensive measurements of Abbot and his collaborators of the Astrophysical Observatory of the Smithsonian Institution, the basis has been given on which values of the "solar constant" have been derived. If we define, as is common, the solar constant as the value of the solar radiation on a surface normal to the sun's rays, at the limit of the atmosphere, reduced to the mean distance between sun and earth, this constant has according to the authorities of the Smithsonian Institution,[1] a value of 1.94 cal cm^{-2} min^{-1}, viz. 135 mw cm^{-2}. In this derivation of the solar constant the essential process consists in an extrapolation from *observed* values within a great number of spectral intervals (by means of bolometer and pyrheliometer) to the required integral value. The part A of the solar constant, thus obtained, amounts to about 90 to 95 per cent of the final solar constant, which is obtained by adding to A an amount B, derived on the basis of certain hypotheses (more correctly, perhaps, estimates) concerning the solar radiation within special regions where the radiation is not observed on account of its practically total absorption by the atmosphere. These regions are, especially, an ultraviolet interval, $\lambda < 280$ mμ, and an infrared one, $\lambda > 2400$ mμ. It seems appropriate to keep these partial solar constants, A and B, separated when we try to evaluate the accuracy, which ought to be ascribed to the present solar constant determinations. As regards part A, it may now (after an agreement has been reached on an International Pyrheliometric Scale) be given with an accuracy of about ± 1.0 per cent, and evaluated to 1.890 cal cm^{-2} min^{-1}, while part B has been given values which differ considerably from author to author. At present, a value of 0.09 can be suggested as an average, but the true value may be 0.04 lower or perhaps 0.10 cal cm^{-2} min^{-1} higher, dependent on conditions within the highest atmospheric layers, about which our knowledge is incomplete. For the integral solar constant Nicolet suggests a value of 1.98 cal cm^{-2} min^{-1} ± 5 per cent and Stair and Johnston 2.05 cal cm^{-2} min^{-1} ± 5 per cent.

For practical meteorology, this separation of the solar constant S into two parts, A and B, has a useful application. If we allow for a Rayleigh scattering within the stratosphere, amounting to 0.04 cal cm^{-2} min^{-1} for vertical incidence of the sun's rays, part A can be assumed to coincide rather well with the solar radiation

[1] Personal information by the late L. B. Aldrich to A. J. Drummond.

TABLE 1

$m = 0.25$	0.375	0.50	0.625	0.75	1.0
$\Delta = 0.040$	0.063	0.075	0.090	0.105	0.13 cal cm^{-2} min^{-1}
$h = 11$	7.8	5.5	3.8	2.3	0.0 km

reaching the tropopause when the solar height is 90°. The solar radiation measured on high mountains can consequently be expected, under all conditions, to be lower than 1.89–0.04 = 1.85 cal cm^{-2} min^{-1}. How much lower, is dependent on (1) an additional Rayleigh scattering by the air molecules, (2) scattering by liquid or solid particles within the atmosphere and (3) additional selective absorption especially by the water vapor within the layer located between the place of observation and the tropopause. The Rayleigh scattering can be regarded as known for a given altitude of the station. Table 1 gives its amount in cal cm^{-2} min^{-1}, referred to the integral radiation A, for different values of the absolute air mass m. The last horizontal column of Table 1 gives the altitude which corresponds to the vertical air mass of the first column.

The highest value for the solar radiation which can be reached in the case of the sun at zenith and in the case of no extinction from selective absorption or scattering within the troposphere, is consequently as presented in Fig. 1.

With these conditions in mind it is of interest to consider the solar radiation measurements which have been made at high altitudes ($h >$ 3000 m). Among the observations now available we may draw special attention to some of the most recent ones, namely those of Bishop at

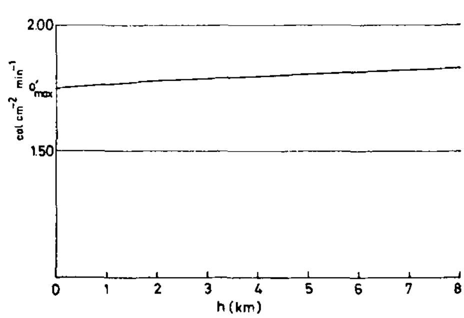

FIG. 1. Q'_{max} in the case of no extinction by selective absorption or dust scattering (only Rayleigh scattering).

Silver Hut Glacier during the Mount Everest expedition 1961 (because of the high altitude), and those of the U.S. Weather Bureau at the Mauna Loa Observatory (because of the very great number of observations from which the maximum values have been selected).

The former measurements (those of Bishop) are treated in more detail in a paper by B. C. BISHOP, A. K. ÅNGSTRÖM, A. J. DRUMMOND & J. J. ROCHE (1966). The observations on Mauna Loa have been partly treated by the present authors, as a U.S. Army contract study (1965). Acknowledgment is made for the inclusion here of an extract.

Some further comments may be added to those given in the remarks below Table 2. The early measurements of K. Ångström on Pico de Teyde were made with his first model of the electrical compensation pyrheliometer, where the strips of the receiver were not of manganin, as in later specimens, but from platinum. As the resistance of platinum is markedly influenced by temperature, this construction made a correction for temperature necessary, which was derived, by K. Ångström, on the basis of an ingenious procedure. When we now refer to these observations, we have added a second correction for reduction to mean distance between sun and earth, but we have not applied the internationally accepted correction of +1.5 per cent from the Ångström scale to the international one of 1956. This correction is neglected here, because it seems from the drawings given by Ångström in his paper treating the Tenerife observations, that the "edge effect" adherent in the later standard instrument did not affect measurements made with this first model.

The instrument Å 158, used by A. K. Ångström and E. H. Kennard for their measurements on Mount Whitney, in 1913, was found from comparisons on several occasions to read 4.57 per cent lower than the Smithsonian scale, instead of the traditional 3.5 per cent. It could therefore be reasonable to assume that an extra +1.0 per cent ought to be added to these

TABLE 2

Observer	Place	Latitude (°N)	Altitude (m)	Q_{max}	Q'_{max}	m	Local apparent time	Day/ Month	Year	Pyrheliometer
K. Ångström	Pico de Teyde, Tenerife	16°38′	3683	1.62	1.67	0.65	12.02	27.6	1896	K. Ångström
C. G. Abbot	Mt. Whitney	36°6	4420	1.63	1.66	0.73	13.47	25.8	1908	Silver disk
C. G. Abbot	Mt. Whitney	36°6	4420	1.65	1.68	0.69	12.54	3.9	1909	Silver disk
C. G. Abbot	Mt. Whitney	36°6	4420	1.69* (1.66)	1.73* (1.70)	0.65	12.12	17.8	1910	Silver disk
A. K. Ångström & E. H. Kennard	Mt. Whitney	36°6	4420	1.58	1.62	0.66	10.44	12.8	1913	K. Ångström
U.S. Weather Bureau	Mauna Loa	19°5	3380	1.75	1.70	0.84	12.00	1.2	1959	Eppley
U.S. Weather Bureau	Mauna Loa	19°5	3380	1.74	1.69	0.82	12.00	8.2	1960	Eppley
U.S. Weather Bureau	Mauna Loa	19°5	3380	1.70	1.65	0.89	12.00	12.1	1961	Eppley
U.S. Weather Bureau	Mauna Loa	19°5	3380	1.68	1.68	0.69	12.00	3.4	1962	Eppley
B. C. Bishop	Silver Hut Glacier	27°8	5710	1.65	1.68	0.54	10.44	30.4	1961	Eppley
				Mean δ	1.673	0.72				

Remarks

1. Q_{max} represents the highest measured radiation, with correction where necessary to the International Pyrheliometric Scale (1956). After correction to mean earth distance from the sun, we obtain Q'_{max}.
2. m is the absolute air mass (i.e. corrected for station altitude).
3. The intensities marked with an asterisk were considered doubtful by Abbot. The bracketed values were derived from an alternative instrument constant.
4. The Hawaii record has been continued to date, but the measurements since March 1963 show reduced values, believed to be due to a layer of atmospheric dust resulting from the eruption of Mt. Agung, Bali, during that month.
5. The Mount Whitney values of 1913 probably influenced to some extent by the Mount Katmai eruption June 1912.

Mount Whitney values. Such a correction is however not applied in the present table. If applied, it would raise the corresponding Q'_{max} value from 1.62 to 1.64.

There is remarkably good agreement between the values from the different localities, spread as they are over an extensive area of the N. Hemisphere. The mean deviation from the mean value is only ± 0.018 cal cm^{-2} min^{-1}. If we compute the mean deviation from the mean value (referred to the mean distance between sun and earth) for the 56 Mauna Loa noon values, during the period May–September 1961 (relative air mass practically 1.0), we get a value of ± 0.016 cal cm^{-2} min^{-1}. It would therefore appear reasonable to conclude that deviations from the means apparent in the table do not necessarily involve any systematic characteristics of the place in question.

Solar radiation measurements are important mainly from two points of view. The first concerns radiation as a *climatological factor*. An interesting result of the comprehensive records of the global radiation at the Mauna Loa Observatory was that the intensity of this radiation for a clear sky was dependent mainly on geometrical factors like solar height and mean distance between sun and earth, and only to a small degree on variations in the composition of the atmosphere. Further, if we divide the spectrum in two parts, one consisting of wavelengths shorter than 700 mμ and the other of wavelengths above this limit, they were both represented to almost the same relative amount in the global radiation, the intensity of the longer wavelength group being very close to 51 per cent of the total, under quite different conditions of solar height and turbidity.

The other interest connected with meteorological solar radiation measurements, concerns their usefulness for determining the *composition of the atmosphere as regards turbidity and vapor content.*

Also in this field, the fundamental observations of the Astrophysical Observatory have furnished a basis for meteorological evaluations. The transmission values derived by Abbot for various wavelengths have given us the possibility to derive, from integral pyrheliometric measurements behind appropriate filters, turbidity coefficients of general applicability. The laboratory measurements, by Fowle, combined with bolometric field measurements, have formed the basis for the derivation of practical formulas relating water vapor absorption and "precipitable water" in the path of the sun's rays. With proper use of Fowle's results, the total water vapor absorption can be derived from filtered pyrheliometric measurements combined with those of the intergral direct solar radiation.

At Mauna Loa and also during the Everest expedition, radiation measurements of the kind necessary for the determination of the water vapor absorption as well as the turbidity were made. At the Silver Hut Glacier, we find for the absorption an extreme low value of 0.04 cal cm^{-2} min^{-1} (referred to the vertical air mass above the station), whereas the turbidity coefficient was as high as 0.045–0.050, which implies that about 0.12 cal, with the sun in the zenith, was scattered by solid and liquid particles within the atmospheric layers above the station. The absorption agrees rather well with the value 0.035 derived, by Abbot, from his bolometric observations, on Mount Whitney, on August 17, 1910. The Mauna Loa observations, during 1961 and 1962, give values of the turbidity generally falling between the limits 0.010 and 0.020, with a mean value of 0.017, which implies that about 0.04 is scattered by the aerosol (vertical incidence of solar radiation). The average absorption was rather high compared with the more continental stations, Silver Hut and Mount Whitney, namely 0.13 cal. From this value the average amount of precipitable water above the station at noon is computed to be 5.0 mm, an amount which comes close to the noon value 4.1 mm, which can be derived from observations and diagrams (four cases) published by STAIR & JOHNSTON (1958). The values for turbidity as well as water vapor absorption come very near to those derived by Liljequist, for the station Maudheim in the Antarctic.

It must be borne in mind that the derivation of turbidity and water vapor absorption, in the cases treated above, is closely connected with assumptions which may be valid only with some approximation. The molecular scattering is assumed to follow the law of Rayleigh, supplemented by a depolarization factor for which we have taken the value 1.061 of Penndorf. An error of ± 1 per cent may be possible, in this instance, which could affect the low β-values determined here by ± 20 per cent or so. Another assumption concerns the spectral variation of the scattering. The basic law, derived chiefly from Abbot's transmission data, seems to be valid with good approximation for mean values at high altitudes ($h > 1200$ m) but, in individual cases, may introduce considerable errors, perhaps, amounting also to ± 20 per cent in the β-values.

On the other hand, the conclusions drawn here concerning turbidity and water vapor absorption within the higher air layers of the troposphere are independent of our assumptions with regard to the partial solar constant B (see above) and dependent only on the value derived for A, which can be given with good accuracy.

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ЗАМЕЧАНИЕ О СОЛНЕЧНОЙ РАДИАЦИИ В ГОРНЫХ ОБЛАСТЯХ НА БОЛЬШОЙ ВЫСОТЕ

В настоящей статье дается краткий обзор недавних измерений солнечной радиации на горных станциях, расположенных на большой высоте (h > 3000 м). Рассматриваются измерения на леднике Силвер Хат, проведенные в 1961 году во время экспедиции на Эверест, руководимой сэром Эдмундом Хиллари, и на обсерватории Маунта Лоа на Гавайях, организованной Бюро Погоды США совместно с Армией США. Эти измерения сравниваются с предыдущими измерениями К. Г. Аббота на Маунт Уитни в период 1908–1910 гг, А. К. Ангстрема и Е. Х. Кеннарда, проведенными там же в 1913 г., и Кнута Ангстрема на Пико дель Тейде в 1896 г. Хорошее согласие различных результатов объясняется тем, что, очевидно, при обычных условиях, влияние вариаций состава атмосферы играет на этих высотах и рассматриваемых широтах подчиненную роль, а доминирующим является влияние астрономических факторов: высоты Солнца и расстояния между Землей и Солнцем.

Это может быть справедливым до тех пор, пока возмущения космического происхождения или извержения вулканов не вызовут случайных отклонений от обычного хода процесса.