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THE REFLECTING POWER OF CLOUDS

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INTRODUCTION

In the spring of 1918, the War Department established an observation balloon school at Arcadia, California. On clear days the balloons of this school are in full view from the Smithsonian Observing Station on Mt. Wilson. The valley to the south and west of Mt. Wilson is often filled in the early morning with dense fog, and from the mountain-top one looks down upon a surface of white, billowy clouds remarkably level and unbroken as a whole. Usually after several hours the fog is dissipated, but on rare occasions it lasts until noon or later. From this combination of circumstances it appeared evident that one of these observation balloons sent up through such a fog sea offered an unusual opportunity for determining the reflecting power of a cloud surface practically filling a hemisphere of solid angle. The top of the mountain, to be sure, would cut off a portion of the horizon, but being in the quarter opposite the sun, several miles distant and with intervening haze itself supplying nearly as much radiation as the small solid angle of cloud it took the place of, no correction would be needed to allow for the presence of the mountain. Accordingly Dr. Abbot obtained from the Director of Military Aeronautics, General Kenly, permission to use a balloon and detail of officers and men for cloud reflection work on the first favorable day. Preliminary arrangements were made with the Commanding Officer at Arcadia, and a favorable day awaited.

On September 16, 1918, a very heavy fog filled the valley, persisting all day and its top level almost reaching the summit of Mt. Wilson. Prospects seemed excellent for a similar heavy fog at a lower level on September 17, and final arrangements for the experiments were made. The sky conditions of September 17 more than fulfilled expectations. A dense, homogeneous fog, unusually level and even on top, filled the valley. Its upper surface was about 800 meters (2,600 feet) from the ground. It was 500 meters (1,600 feet) thick at the start and 180 meters (600 feet) thick at the close of the work.[1]

The sky above was cloudless and very clear. Under these conditions the following experiments were made.

OBJECT AND METHOD OF THE EXPERIMENTS

It was desired to determine what proportion of the rays of the sun, including sun rays scattered by the sky, is reflected upward from a level layer of cloud of indefinite extent. For this purpose a pyranometer[2] having a glass hemispherical cover was to be exposed in one series of experiments in its inverted position to measure the rays coming up from fog in the hemisphere below, and on a similar day in the usual position to measure the rays from the sun and sky in the hemisphere above. The glass cover served as a screen to sift out for observation rays lying between 0.3 microns and 3.0 microns in wave length. These rays comprise practically all rays of relatively appreciable intensity in the solar spectrum. The glass excludes rays of more than 3.0 microns in wave length such as the earth, the clouds, and the atmosphere emit by virtue of their proper temperatures. In order to determine whether the reflecting power of a wide sheet of cloud differs much with the angle of incidence of the rays, it was desirable to begin the experiments at low sun and continue them till the sun reached high altitude above the horizon. Experiments reported in Volume II of the Annals of the Smithsonian Astrophysical Observatory[3] of course show that the reflection varies in azimuth and nadir distance greatly with the angle of incidence. But it was not shown certainly whether the total intensity of the reflected rays summed up over all azimuths and nadir distances within a hemisphere would change much with the angle of incidence of the rays upon the cloud layer.

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[1] In passing up and down through the layer of fog the observer reported as follows:

Pacific standard time	6 hr. 55 min.	9 hr. 00 min.	10 hr. 00 min.	10 hr. 55 min.
Level of bottom (feet)	1,000	1,800	....	2,000
Level of top (feet)	2,600	2,600	2,600	2,600

Such a thinning of the fog from the bottom without much change in its upper level seems curious and is probably unusual.

[2] See Smith. Misc. Coll., Vol. 66, Nos. 7 and 11, 1916.

[3] For further discussion of the theory of the method of observing see the figure and explanation given in Addenda to Annals Vol II, entitled, "Note on Reflecting Power of Clouds."

ARRANGEMENTS

Pyranometer A. P. O. No. 5, modified for use in the eclipse expedition of June 8, 1918,[1] was somewhat further modified for this work. It was proposed to suspend the pyranometer, inverted, below the basket of the balloon, thus exposing the pyranometer strip to the radiation from a practically infinite cloud surface. The sun shade was removed and the glass hemisphere securely fastened in place with shellac. The pyranometer was suspended about one-half meter below the bottom of the balloon basket, and a flexible shaft, operating the shutter through miter gears, extended to within easy reach of the officer in the basket. For stability the galvanometer was necessarily mounted on the ground and connected to the pyranometer through a reel of special telephone wire. (Insulated piano wire was employed such as is used in ordinary balloon work for telephone communication with the ascending officer. This introduced probably over 1,000 ohms resistance into the galvanometer circuit, but the pyranometer was sufficiently sensitive to give deflections ranging from 1.50 to 4.0 cms. and could be read to 0.01 cm.). The galvanometer, ammeter, and accessories were the same as used on the eclipse expedition of last June, 1918.[1]

Observation Balloon No. 7, with its complement of officers and men, was assigned to aid in the work. The writer wishes to express his appreciation for their assistance, and particularly for the interest and efficient help of Lieut. E. W. Raeder, the ascending officer. Lieut. Raeder reported the sky conditions and manipulated the pyranometer shutter from the balloon basket, being in constant telephone communication with the ground through a second reel of telephone wire. His great zeal and gallantry are shown by the fact that, being alone in the basket, he tied his ankle by a bit of rope to the balloon and hung head downward for about 5 minutes to fix a defect in the exposing apparatus which developed near the end of the experiments, then climbed back and continued the observations.

OBSERVATIONS

The observations of cloud, sun, and sky, and of electric current for calibration of the pyranometer, are given in Table I. As the balloon was brought to earth between observations of groups 7 and 8 (see

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[1] See Smithsonian Misc. Coll., Vol. 69, No. 9.

TABLE I

Group No.	Hour angle of sun (East)		Air mass of sun (Sec. Z)	Brightness of sky alone on horizontal surface (Calories)	Sun alone per sq. cm. normal to beam (Calories)	Sky and sun per sq. cm. of horizontal surface (Calories)	Calories per sq. cm. reflected from cloud	Altitude of instrument above cloud surface (Meters)	Wind velocity at balloon basket (Meters per sec.)	No. of individual determinations	Current calibration values of $\frac{C^2}{Dc}$	Mean deflections of galvanometer (cm.)	Per cent reflected from cloud surface	Probable error per cent	Maximum range of galv. zero drift (cm.)	Estimated grade based on zero drift
	H.	*Min.*														
1	4	29	2.84	.064	1.250	.504	.401	30.	0.	10	.01085	1.532	79.6	1.2	0.16	Ex.
2		15	2.47	.070	1.303	.598	.460	120.	4.	10	.01089	1.752	76.9	0.5	0.54	V. G.
3		01	2.26	.073	1.337	.665	.530	210.	9.	11	.01093	2.014	79.7	1.4	2.56	P.
4	3	48	2.07	.077	1.367	.737	.567	120.	3.	10	.01097	2.144	77.0	0.8	0.57	V.G.
5		35	1.92	.080	1.390	.804	.615	25.	0.	11	.01100	2.317	76.5	0.7	0.22	Ex.
6		12	1.71	.083	1.424	.916	.824	25.	0.	11	.01104	3.098	90.0	1.5	1.25	Fair.
7	2	56	1.59	.086	1.442	.994	.868	105.	2.	10	.01108	3.251	87.4	0.8	0.67	G.
8	1	34	1.26	.092	1.493	1.278	1.019	60.	5.	9	.01114	3.787	79.8	2.2	1.19	Fair.
9		18	1.24	.093	1.497	1.300	1.145	60.	5.	10	.01115	4.265	88.1	3.0	2.80	V. P.
10		09	1.22	.094	1.500	1.324	1.051	50.	3.5	6	.01118	3.897	79.4	0.8	0.42	V. G.
11	0	59	1.20	.094	1.503	1.346	.945	50.	3.5	8	.01118	3.514	70.2	1.1	0.81	G.

Mean of all = 80.4 per cent. Mean of first five = 77.9 per cent. Mean of all with probable error 1.2 per cent or less (7 values) = 78.1 per cent. Adopted best value = 78.0 per cent ± 1.1 per cent.

table) three current calibrations[1] were made—just before the first ascension, between the first and second, and after the second ascension. The galvanometer circuit was unchanged throughout the observations, so that the calibrations were made under the same conditions as the cloud observations, save that the balloon was near the ground for the former and above the fog for the latter.

Column 5 in the table (total solar radiation per sq. cm. normal to the beam) was obtained as follows: On the morning of September 16, the usual solar constant observations, which include pyrheliometer measurements of the total solar radiation on normal surface, were made on Mt. Wilson. Then on September 17, simultaneously with the cloud reflection observations, Mr. H. Benioff of the Mt. Wilson Solar Observatory staff very kindly made pyrheliometer readings on Mt. Wilson with Pyrheliometers IV and VII. He made eight determinations, the mean of which gave for an air mass 1.5 the value 1.46 calories, total solar radiation received per square centimeter of normal surface. The plotted values of September 16 give for the same air mass the practically identical value, 1.452 calories. Furthermore the solar constants determined at the recently established Smithsonian station in Chile are:

September 16, 1918	1.960
September 17, 1918	1.951

As far as visual observations of the sky could indicate the two days were identical. Thus, since the two days show nearly identical solar constant values and nearly identical pyrheliometer values at a given air mass, it is to be assumed that the pyrheliometer values for the whole range of air masses would have been nearly identical. Values of column 5 are therefore taken from the pyrheliometer curve of September 16.

Column 4, the sky brightness, was not so easily obtained. Unfortunately, owing both to delay in the return of instruments and to an unprecedented amount of cloudy weather, sky brightness values on a day with sky conditions similar to September 17 were not available.[2] The pyranometer data of previous years was examined and

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[1] The first-swing method was used. See Smith. Misc. Coll., Vol. 66, No. 11, p. 8.

[2] It will be possible to obtain such values at some future time, however.

two days chosen, one of greater haziness and one of greater clearness than September 17, as follows:

Place	Date	Sky brightness at air mass		Kind of sky
		1.2	2.8	
Mt. Wilson, California.	Aug. 7, 1916 (A. M.)	.105 cal.	.065 cal.	Very hazy. Pyrheliometer 5% lower than Sept. 17, 1918.
Hump Mountain, N. C.	Nov. 17, 1917 (A. M.)	.085 "	.061 "	Very clear. Pyrheliometer values not obtained, but on neighboring days were several per cent above Mt. Wilson values of Sept. 17, 1918.

A mean between the values of sky brightness for these two days was adopted as the sky brightness for September 17, 1918. It is certain that on the first of these days the sky was brighter than on September 17, and on the second it was less bright than on September 17. If we were to adopt the values of either of these two days, the resulting values of total sky and sun brightness of September 17 would not be altered by so much as one per cent from those given in the table.

Comparisons of the pyranometer with Pyrheliometer IV on the sun alone were made before this work,[1] and again after the work on October 8 and October 9. A mean of 10 values on these last two days gave a constant 2½ per cent higher than the earlier comparisons. Taking a mean of all comparisons, the constant of the pyranometer was regarded as 24.1 instead of 23.8 as used for the eclipse reductions. The computed values originally obtained from measurements of dimensions, electrical resistances and assumed absorbing power of the pyranometer strips is 25.9. That recent observed values are so much lower is doubtless due to rough usage of the blackened surface necessary in fastening in new thermo-couples.

It is to be noted that a very considerable irregular galvanometer drift was present throughout the cloud observations. This seemed due mainly to the changing air currents as the balloon basket swung in the wind. Table I shows that in general the higher the wind velocity, the greater the range of zero drift. Inadequate protection of the galvanometer from vibrations caused by passing trains and auto trucks also contributed to the drift. However, since each individual determination required but five seconds and in each group

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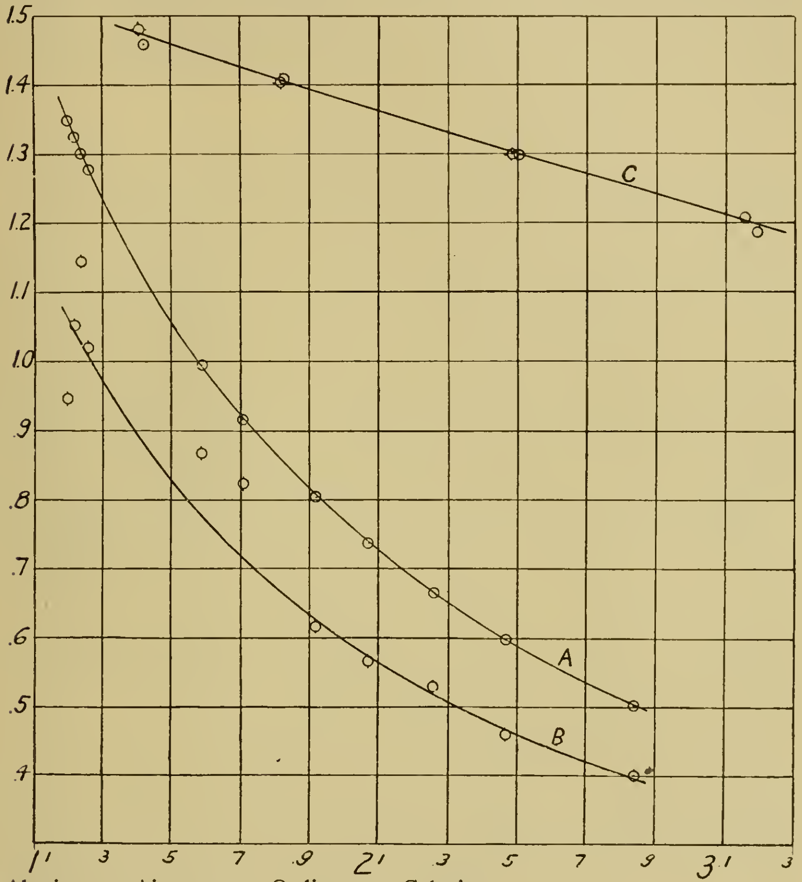
[1] See Report of Eclipse Expedition, Smith. Misc. Coll., Vol. 69, No. 9, p. 6.

the mean of a number is used, the error from irregular drift is minimized. The writer is inclined to place more weight in the observations of the first half of the morning, for the fog then was thicker and its top surface more level. As the sun rose higher there was not only more boiling of the fog surface but the increased temperature differences tended to increase possible thermo-electric disturbances.



Abscissae = Air masses. Ordinates = Calories.
Curve *A* = Total sky and sun per sq. cm. of horizontal surface.
Curve *B* = Calories reflected from cloud per sq. cm. of horizontal surface.
Curve *C* = Pyrheliometry of September 16, 1918. Total calories from sun alone per sq. cm. normal to beam.

RESULTS

The mean value is 78 per cent. No evidence of a change of reflecting power with a change in solar altitude is evident for the range of air masses in Table I. This is of importance in deducing a value of the albedo of the earth from these results, for it tends to show not only that fog layers near the boundaries of the earth's surface differ little in reflecting power from those directly under the sun, but also that rough clouds do not differ very much from smooth ones in reflecting power. This latter point of course should not be urged too far, for it is obvious that clouds with very deep holes and furrows must reflect less than smooth ones.

Referring to the discussion of cloud reflecting power in Volume II, Annals of the Smithsonian Astrophysical Observatory, page 145, we find that using 65 per cent as the reflecting power of a cloud surface a value of 33.7 per cent is obtained as the total amount of the incoming solar radiation over the whole earth reflected to space by clouds. Substituting 78 per cent for 65 per cent this value becomes 40.4 per cent. It seems probable that the low cloud reflection value of the early Mt. Wilson work (65 per cent for cloud reflecting power) can be attributed largely to the uncertainty of the extrapolations necessary, since the observations were limited to a small range of nadir distance. Moreover, the contribution from the very bright area near the angle of specular reflection was perhaps minimized.

Following the method of pages 162 and 163 (Annals, Vol. II), a new value of the albedo of the earth is derived. Using 78 per cent as the cloud reflecting power, the albedo of the earth (as defined by Bond, see article by Russell, Astrophysical Journal, 43, p. 175) becomes 43 per cent. Russell (Astrophysical Journal, 43, p. 190) derives for it a value of 45 per cent from a consideration of Very's visual observations on Venus and the moon.

It will be clear that the method here adopted to get the cloud reflecting power (i. e., taking the ratio of the total radiation received by the pyranometer per square centimeter of horizontal surface from the cloud, to the total radiation received from sky and sun by a square centimeter of horizontal cloud surface) may give different results from measurements by visual or photographic methods as employed in photometry. Although even in the present work part of the solar rays is missing, owing to water vapor absorption, the results are more clearly applicable to considerations of the earth's temperature than photometric results would be. Still it is probable that the difference is small.

The planet Venus according to Russell's discussion of Müller's observations, has a Bond albedo of 59 per cent for visual rays. Because of its high reflecting power and the absence of telescopic markings Venus is usually regarded as altogether cloudy. If this is the case, unless the clouds are very deeply broken up by pits and billows an albedo for total radiation of 78 per cent (or even a little more considering the specular reflection near the edges of the sunlit surface) would be expected. Young notes that the limb of the planet is always much brighter than the central parts. This may indicate that the clouds while general are not thick enough to give full cloud reflection except for rays received obliquely.

SUMMARY

A pyranometer suspended below the basket of an army observation balloon was used to measure the reflecting power of a level cloud surface practically filling a hemisphere of solid angle. Over one hundred determinations were made. The solar air masses ranged from 2.8 to 1.2, and the sky above was cloudless and very clear. A mean value of 78 per cent is obtained. No change of total reflection depending on solar zenith distance is apparent within a range of zenith distance from 33° to 69°. A value of 43 per cent for the albedo of the earth is obtained by revision of the earlier value of Abbot and Fowle (Annals, Vol. II, p. 162) which depended on a lower value of cloud reflection based on observations over but a small part of a hemisphere.