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(Publication 3678)

CITY OF WASHINGTON
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The late F. E. Fowle published several papers descriptive of the establishment and applications of a spectrobolometric method to determine how thick a stratum of liquid water would be produced if all the water vapor in the atmosphere could be instantaneously precipitated.[1] As we practice it, the method employs the quantity ρ/ρ sc. By this symbol we designate the ratio between the ordinate at the bottom of the great water-vapor band ρ, seen as a depression in a bolograph of the upper infrared spectrum, and the ordinate of the smooth curve drawn across the top of the band and measured at the same place in abscissae. At each of our solar-constant stations we have worked out an empirical relationship of the same sort as explained by Fowle[1] between ρ/ρ sc and the quantity of precipitable water vapor (termed, for short, "precipitable water"). He at first used ϕ/ϕ sc and ψ'/ψ' sc, but later himself frequently employed ρ/ρ sc as we do. The precipitable water thus determined includes all of the water vapor in a column of atmosphere from the station outward to the limit of the atmosphere in the direction of the sun. The length of such a column, as compared to a vertical one, is given by the "air mass." For solar-zenith distances less than 70° where the value is approximately 3.0, the air mass is approximately secant Z, where Z is the angular distance of the sun from the zenith. Hence if w_m is the precipitable water measured at air mass m, the value w_1 corresponding to zenith sun, and representing the thickness of liquid water which would fall uniformly upon the earth at the given locality, is $\frac{w_m}{m}$.

The quantity of precipitable water in the atmosphere is a value of great meteorological significance, but one for which at present there are no means generally available to measure. Accordingly it seemed useful to assemble the results from the numerous spectrobolometric determinations of the solar constant of radiation, as measured at several stations of the Smithsonian Institution during the last 30 years. It will be understood that though these determinations of precipitable water have been made at all seasons of the year, at stations

[1] Astrophys. Journ., vol. 35, p. 149, 1912; vol. 37, p. 359, 1913.

ranging from 5,000 to 9,000 feet altitude, and in days of different meteorological conditions of the atmosphere, they must nevertheless have been made only on days when the sun shone, and the sky was fairly free of clouds. It will be difficultly comprehensible to some that the precipitable-water values given below are generally so low when compared with the actual depths of rain which fall on many occasions. Our stations have been located in far-separated regions of the earth, so that the results given here must fairly well represent fair-weather conditions of the atmosphere above 5,000 feet the world over. How, then, it will be asked, can rainfalls many times as deep as the precipitable water occur?

This is partly accounted for by the consideration that the values to be given here generally relate to stations above 5,000 feet in altitude. It is well known that the lower atmosphere is comparatively rich in water vapor. Our Washington observations, practically at sea level, were all made before Fowle worked out this precipitable-water method. We cannot now obtain precipitable-water values corresponding to all of the Washington observations given in table 14, volume 2 of the Annals of the Astrophysical Observatory. However, to give at least a rough idea of what these Washington observations might have disclosed, my colleague, Mr. Aldrich, has kindly reduced for me, as well as can be done after many years, the indications from measurements he has made on 59 Washington bolographic curves still preserved at the Astrophysical Observatory. These results, given below, indicate roughly the average precipitable water at sea level for the four seasons at latitude 39° N.

Another consideration tending to reconcile rainfall with precipitable water values is that during a rainfall or snowfall, atmospheric circulation may sweep into the path of the storm a considerable part of the atmospheric-water load from much larger areas, outside the region of actual precipitation. Thus by the partial denudation of water vapor from large surrounding areas, smaller areas of the atmosphere may be provided with quantities of precipitable water several, or even many, times as great as they normally contain. When a storm advances over paths many hundreds of miles long, as for instance from the Gulf of Mexico to Washington, we are not, of course, to imagine that water gathered in the Gulf of Mexico during the earlier part of the storm is carried by clouds to Washington to fall there later on. It is rather a state of atmospheric disturbance which travels, producing clouds along the way and precipitating local supplies of moisture for local rains all along the path. It is not at all, in other words, as if one dipped a bucket in the Gulf of Mexico and, carrying it to Washington, emptied it there.

Hoping that meteorologists will welcome these precipitable-water data, as of a kind perhaps attainable only from Smithsonian solar radiation observations, I now give, in addition to the Washington results referred to above, numerical data computed by Miss N. M. McCandlish from the tabular results of various solar-constant investigations published in volumes 3, 4, 5, and 6 (now in press) of the Annals of the Astrophysical Observatory. It will be understood that the term "precipitable water" and the symbol w_1 as used below, refer in every case to the quantity of precipitable water found in a vertical column of atmosphere above the station stated.

The unit for precipitable water, w_1 in the following tables is 1/10 of 1 millimeter of liquid water. The average deviation from the mean, Δw_1, is given in the same units. In addition, I give the probable error of w_1 in percentage. It is computed as $\frac{0.84}{\sqrt{n}} \times \frac{\Delta w_1}{w_1} \times 100$, where n is the number of years included in the mean monthly values.

Station: Montezuma, Chile

Lat. 22°40′ S., long. 68°56′ W., alt. 8,895 ft.

Interval covered, September 1923 to September 1939

Fair days only

Monthly mean values of precipitable water, average deviation, and percentage probable error

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	92	99	85	42	34	25	22	22	27	30	35	52
Δw_1	20	24	17	7	6	3	4	5	6	7	8	12
P.e.%	4.5	5.1	4.1	3.4	3.8	2.4	3.9	4.7	4.7	4.8	4.5	4.9

From Montezuma, for the interval stated above, I give also the numbers of days during months of the year when precipitable water, w_1 of 0.5 millimeter or less was observed, and also the months when precipitable water of 15.0 millimeters or more was observed. The maximum value found at Montezuma during fair days was 19.4 millimeters. In the following table, the unit is still 1/10 of 1 millimeter.

Numbers of fair days, 1923-39, when precipitable water had certain values

w_1	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
5	...	...	1	1	3	5	4	4	7	...	1	...
4	...	...	...	...	2	3	4	5	4	1	...	...
3	...	...	...	...	...	5	1	2	4	...	...	...
2	...	...	...	...	...	2	2	2	...	...	...	...
1	...	...	...	...	...	1	...	...	...	...	...	...
>15.0	12	14	10	...	...	...	...	...	...	...	...	...

Station: Table Mountain, Calif.

Lat. 34°22′ N., long. 117°41′ W., alt. 7,500 ft.

Interval covered, January 1926 to September 1939

Fair days only

Monthly mean values of precipitable water, average deviation, and percentage probable error

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	30	26	37	37	46	54	68	77	54	50	39	31
Δw_1	4	5	8	7	7	9	16	17	12	6	8	4
P.e.%	3.2	4.7	4.8	4.6	3.4	3.6	5.2	5.1	5.0	3.0	4.6	2.8

Station: St. Katherine, Egypt

Lat. 28°31′ N., long. 33°56′ E., alt. 8,500 ft.

Interval covered, January 1934 to November 1937

Fair days only

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	14	16	18	17	28	28	31	34	27	35	30	22
Δw_1	2.5	3.5	1.7	1.2	5.0	4.2	3.2	6.5	3.2	4.7	4.0	1.7
P.e.% [a]	7.5	9.2	3.9	3.0	7.6	6.3	4.3	8.0	5.0	5.6	5.6	3.2

[a] The larger % probable errors, compared to Montezuma and Table Mountain, are due to the shorter interval.

Station: Harqua Hala, Ariz.

Lat. 33°48′ N., long. 113°20′ W., alt. 5,646 ft.

Interval covered, October 1920 to October 1925

Fair days only

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	27	34	31	41	55	76	162	158	84	52	42	38
Δw_1	3.8	4.2	4.2	4.4	6.2	12.2	15.0	8.0	22.2	10.3	2.8	4.6
P.e.% [a]	5.3	4.7	5.1	4.0	4.2	6.0	3.5	1.9	9.8	6.8	2.5	4.5

[a] The larger % probable errors, compared to Montezuma and Table Mountain, are due to the shorter interval.

Station: Mount Wilson, Calif.

Lat. 34°13′ N., long. 118°04′ W., alt. 5,665 ft.

Interval covered, spring, summer, and autumn months, 1910 to 1920

Fair days only

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	...	...	...	28 [a]	70	82	117	111	92	84	51	...
Δw_1	...	...	...	...	4 [b]	21	19	10	17	11	4 [b]	...
P.e.%	...	...	...	...	...	7.6	4.2	2.3	4.8	3.7	...	...

[a] One day only.
[b] Few years observed

Station: Mount Brukkaros, S.W. Africa
Lat. 25°52′ S., long. 17°48′ E., alt. 5,202 ft.

Interval covered, December 1926 to November 1928

Fair days only

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	146	181	197	142	104	75	60	62	70	82	104	142
Δw_1	8	28	11	6	16	13	5	7	9	12	11	16
P.e.%	Years too few for probable error.											

Station: Hump Mountain, N. C.
Lat. 36°08′ N., long. 82°00′ W., alt. 4,921 ft.

Interval covered, June 1917 to March 1918

Fair days only

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
w_1	19	38	22	...	...	52	131	92	72	71	48	57

Station: Washington, D. C.
Lat. 38°53′ N., long. 77°02′ W., alt. 30 ft.

Interval covered, July 1904 to April 1906

Averages of a few fair days only [a]

	Winter	Spring	Summer	Autumn
w_1	61	190	215	167

[a] On each of these days, however, several bolographs were taken at different air masses, each yielding independently a value of w_1. These independent observations on the same day agreed very well, and their mean values were used in computing the results given here.

Comparing the five stations, Montezuma, Table Mountain, Mount St. Katherine, Harqua Hala, and Mount Wilson, for all of which a considerable number of years of observation are available, we note certain interesting features.

The atmosphere above Mount St. Katherine, lying in the great desert belt of the Northern Hemisphere, between Arabia and the Sahara, is dryer than any of the others, and shows much less percentage range of precipitable water as between summer and winter than the other stations. Were it not for the war, and for the excessive isolation and the tendency to intestinal sickness there, Mount St. Katherine would be exceptionally well suited to solar-constant measurements.

Although a little higher than Mount St. Katherine, Montezuma, lying 6° nearer the Equator, is under an atmosphere considerably richer in water vapor. There is also a wide range of humidity as between summer and winter. Our experience has indicated that the moist summer months there are a little disappointing as regards both number and quality of solar-constant observations. It is thought, however, that meteorologists will note with surprise and interest how many days have been found there in winter when the entire superincumbent atmosphere contains less than $\frac{1}{2}$ of 1 millimeter of precipitable water.

Table Mountain shows much less range of humidity as between summer and winter than Harqua Hala, where summer thunderstorms prevail. Mount Wilson, also, shows a considerably less summer humidity than Harqua Hala, though much more than Table Mountain, which is both 900 feet higher and lies nearer the Mojave Desert.

Washington, at sea level, shows, of course, the great concentration of water vapor in the lower atmosphere. Lying, however, in latitude 39° N., Washington does not give a full indication of the precipitable water which would be found at sea level within the Tropics. It would, indeed, be very interesting if a series of spectroscopic measurements of the quantity could be made at the Canal Zone or in tropical South America. The United States Weather Bureau has an instrument designed and constructed for such measurements by the Smithsonian Institution.[2] One may hope that it may be practicable for them to conduct a series of precipitable-water measurements with it at the Canal Zone.

THE MARCH OF PRECIPITABLE WATER AT TIMES OF RAINFALL

It might be supposed that rains would be presaged by decided increase of atmospheric humidity for several days, and that such changes of humidity, being readily measured by spectrobolometric observations, could serve as a means of predicting the approach and the probable amount of rainfall, for several days in advance.

To investigate this probability I have examined the run of precipitable water and of rainfall at Harqua Hala and at Hump Mountain. For Harqua Hala I made a comparison with the rainfall at Phoenix, Ariz., and for Hump Mountain with Asheville, N. C. At Harqua Hala I noted the variations of precipitable water near the dates of every rainfall which at Phoenix exceeded 0.05 inch from October 1920 to October 1924, and at Hump Mountain I compared precipitable-water data for the 10 months June 1917 to March 1918 with Asheville rainfall.

These studies led to a negative conclusion. There was found no general relationship or certain connection between the march of pre-

[2] See U. S. Monthly Weather Rev., vol. 68, p. 95, April 1940.

cipitable water from day to day and the fall of rain. It appeared that if notable changes of precipitable water preceded and followed rains, such changes must generally have taken place only within a few hours of rainfall, when the sky was probably too cloudy for spectrobolometric observations. Certainly there was no definite change of precipitable water considerably antedating rainfalls which could serve for forecasting their times and amounts.

This tends to support the view advanced earlier in this paper, namely, that the approach of a rainstorm is not accompanied by any considerable transport of water from the direction whence the storm comes. What occurs is a traveling disturbance of the atmosphere, which, as it reaches successive localities, draws together from short distances aqueous vapor already suspended within the atmosphere in those regions. This view is supported by the observation which I made that on the day next following a rainfall the precipitable water is apt to be less than that which usually prevails at that time of the year.