OPACITY OF THE SKY AFTER JULY 1953

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1. INTRODUCTION

At 0500 MST, July 9, 1953, a subsidiary cone on the south flank of Mt. Spurr, about 80 miles west of Anchorage, Alaska, erupted a dark cloud of ash and vapor to a height of approximately 70,000 feet [1]. Vaucouleurs [2] has suggested that the spread of the volcanic dust be investigated by use of the pyrheliometric data in widely separated areas. A preliminary study by one of us [3] utilized data from three stations in the United States and evidence was given of a decrease in radiation for the 6-month period October 1953–March 1954. That investigation is described in greater detail here and is extended to Athens, Greece, Uccle, Belgium, and four stations in Japan.

2. DATA

The basic data at all stations are measurements of the intensity of the direct solar beam. At Lincoln, Nebr. and Blue Hill, Mass., the measurements are made with Eppley normal-incidence pyrheliometers. At Table Mountain, Calif., the more precise Smithsonian silver-disk and modified Ångström normal-incidence pyrheliometers are used. A silver-disk pyrheliometer is used frequently to check the Eppley instrument at Blue Hill. In Japan, silver-disk pyrheliometers constructed by the Japan Central Meteorological Observatory are used. A Kipp-Zonen pyrheliometer on a stand is used at Athens, while at Uccle two Linke-Feussner actinographs measure the solar radiation.

The average monthly values of the clear-sky radiation at a particular time of day or zenith distance were readily available at all stations except Uccle [4, 5, 6, 7]. The data for Uccle, kindly furnished us by Mr. R. Dogniaux, were the total amounts of radiation falling each half-hour regardless of sky condition. Values were extracted for those times when the percentage sunshine was 100. In order to determine the radiation at a particular airmass the times of observation were converted to airmass values. When this was done it became evident that more observations were available in the neighborhood of airmass 4.00 than at any other airmass value. On the large majority of days no observation was taken at exactly airmass 4.00, but some were made at higher airmass values and some at lower. A plot of log of radiation against airmass was made for each day. A smooth curve was drawn free-hand through these points and the value of radiation for airmass 4.00 was interpolated. It was apparent from the great variability within a single month that this procedure did not completely eliminate those days when high cirrus, smoke, haze, or fog affected the pyrheliometric measurements. Thus, monthly means computed from these values did not accurately estimate the clear-sky radiation. On the assumption that there should be at least one good observing day each month, the highest radiation value for the month was used as a measure of the monthly mean clear-sky radiation at Uccle.

At each station monthly "averages" were secured. The "average" is defined as the weighted arithmetic mean of the monthly radiation values for the period of record up through 1952, the weights being the number of observations in the month. An exception was made at Blue Hill. There the instructions are that observations should be taken only when clouds do not interfere with the measurements. This is a somewhat subjective matter and undoubtedly introduces some fluctuations into the data. At Blue Hill, a new observer reported for duty near the end of 1951, and has taken observations there since the beginning of 1952. He has chosen only the "clearest" skies, so that the "average" appropriate to his observations is apparently about 11 percent higher than the "average" for the period 1934–51. To adjust for this, the monthly radiation values after December 1951 were divided by 1.11 and these new values were used in all subsequent work. The "average" at Blue Hill was then computed by the method used at the other stations.

The departures of the average monthly radiation from the monthly "averages" were computed and expressed as percentages of the "average"; these are hereafter called "D values." The results for the entire period of record are listed in table 1 and the values from 1950–54 are shown in figure 1. The small numerals over the curves are the number of observations made during the month.

Since results from independent sources are more reliable, D values at some of the stations were tested for interdependence. Correlation coefficients between each two of the three United States stations and between each two of the four Japanese stations are shown in table 2. The period 1934 through 1952 was used in the United States and 1939 through 1952 in Japan. None of the

TABLE 1.—*Departure of monthly solar radiation intensity from monthly "average" expressed as a percentage of "average"*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
BLUE HILL OBSERVATORY, MILTON, MASS.												
1934	−13	1	−10	−3	−7	10	17	−1	0	3	0	8
1935	6	1	2	17	0	11	22	14	3	1	−6	4
1936	5	1	−16	10	3	−3	−15	23	−11	1	8	7
1937	−3	5	7	11	0	23	6	1	5	7	5	−1
1938	−8	6	−1	17	32	14	41	------	11	−14	−18	−10
1939	−9	4	0	−6	−2	−3	0	−5	−9	1	−5	6
1940	−3	−4	6	7	−6	5	−16	26	−6	2	−2	8
1941	7	4	10	−6	−4	−26	−8	−5	11	4	−3	4
1942	−7	−3	−2	−20	−16	−19	−22	−1	−18	−3	7	−10
1943	6	−4	4	5	−1	−27	5	−12	10	−2	0	−3
1944	−9	−4	10	6	−23	−6	−9	5	3	7	−2	−2
1945	8	0	26	3	2	8	−8	−1	−2	7	−5	3
1946	2	−6	−17	−2	−1	−7	−1	6	−9	−5	5	3
1947	−6	1	−3	7	8	−6	3	−17	4	−7	9	6
1948	9	2	5	11	6	−7	6	−13	−10	−8	6	0
1949	8	−1	10	−11	−18	12	6	−6	10	5	−2	4
1950	0	6	12	7	11	0	7	9	11	−8	−13	−5
1951	0	3	2	−4	6	−6	−5	7	−1	−7	15	−22
1952	−2	−5	−6	−1	−1	3	1	22	0	−4	−4	−7
1953	−3	−5	6	−4	------	−1	10	−14	−5	−11	−24	−8
1954	−9	−16	−11	5	−5	−2	−3	13	−7	−4	−11	−3
TABLE MOUNTAIN, CALIF.												
1926	0	3	−2	−2	−1	−2	0	1	1	0	−1	0
1927	−1	0	−1	1	1	−1	0	−1	1	−1	0	1
1928	1	−1	−1	1	------	1	1	0	1	−1	1	1
1929	0	2	0	0	−1	0	−5	−4	−1	−3	−1	−1
1930	−4	−1	−2	1	0	1	0	0	−1	1	0	1
1931	1	−3	0	−1	1	−1	−5	−5	1	0	0	1
1932	0	−1	0	0	0	−1	−1	−2	−5	0	−1	−1
1933	−1	0	0	−1	−1	0	0	0	1	−1	0	−1
1934	0	0	−2	2	0	−1	−1	−5	0	−1	0	3
1935	0	0	2	−1	−2	0	2	1	−3	2	2	1
1936	0	2	0	2	2	1	−3	0	1	0	0	0
1937	0	3	1	1	−3	−1	0	−2	0	0	−1	1
1938	0	1	−1	0	0	−3	−2	−2	−1	0	2	1
1939	1	1	1	0	0	0	0	−1	1	2	0	0
1940	4	0	2	1	0	−1	1	−2	0	0	2	0
1941	2	0	−1	1	1	−1	−1	0	0	2	0	1
1942	0	1	1	1	2	1	1	−3	1	−1	−2	−1
1943	−1	1	0	−1	2	1	0	1	−2	1	0	−1
1944	0	1	1	1	0	1	2	3	2	0	0	1
1945	−1	0	------	------	2	0	2	5	1	0	0	−1
1946	0	−1	0	0	0	1	0	0	1	2	0	3
1947	0	0	0	−1	−1	−1	1	3	0	0	0	1
1948	0	2	1	2	2	1	2	3	1	0	0	−1
1949	2	1	1	2	−1	1	0	3	3	0	0	1
1950	2	−2	2	−1	1	1	−2	−2	0	1	−1	0
1951	0	−1	−1	1	−3	1	0	2	1	1	0	1
1952	0	−2	0	−9	−1	0	−2	−2	−3	0	0	−1
1953	−1	0	0	−1	1	1	−4	−1	−2	−3	−2	−1
1954	−3	−2	−3	−3	0	0	−4	−1	1	0	−1	0
LINCOLN, NEBR.												
1917	------	------	12	−18	------	13	7	15	−8	−3	−5	−3
1918	------	0	−4	9	−1	2	−2	7	7	6	3	------
1919	0	3	3	12	7	−3	−13	14	0	1	8	6
1920	−5	−9	3	−13	------	8	3	−5	12	6	9	3
1921	6	6	−2	0	8	9	0	−1	−2	6	4	3
1922	−10	−1	4	3	13	−9	−4	−3	0	−1	3	−1
1923	0	−2	4	−21	13	3	4	10	7	12	2	11
1924	3	−8	0	6	------	−8	------	7	7	9	1	6
1925	3	−8	3	------	0	8	−4	−7	4	17	3	6
1926	3	3	12	0	−6	4	−6	0	11	7	−3	------
1927	1	−2	12	15	8	6	7	2	1	5	1	−3
1928	5	6	2	6	2	18	1	14	1	−4	4	−10
1929	2	−11	5	7	6	7	−8	−13	−19	−1	−2	------
1930	0	−7	5	−4	8	10	−8	−22	2	------	−2	4
1931	−3	−3	6	2	−7	−4	−2	6	−8	7	4	6
1932	3	−1	2	------	2	1	10	14	5	6	4	−4
1933	−3	−1	2	−1	−4	0	3	8	4	3	0	3
1934	0	−7	10	−13	−3	3	2	−1	8	−5	1	3
1935	6	−3	4	4	16	7	−4	7	7	9	8	7
1936	6	−1	2	1	4	13	12	3	1	13	−3	− 3
1937	0	−16	16	62	−3	2	−1	15	1	3	10	8
1938	6	3	−6	14	12	1	------	−27	0	8	5	14
1939	11	6	7	9	3	−10	−2	12	3	−4	−1	−3
1940	5	1	------	15	------	−6	------	14	------	5	------	------
1941	------	------	------	------	------	−15	2	−7	6	15	0	3
1942	3	−2	12	−1	−10	------	------	−44	−3	−7	−10	1
1943	−2	−7	−9	−1	6	1	3	−5	4	0	------	------
1944	------	−7	9	5	2	1	2	−2	−7	17	3	3
1945	3	------	−5	2	0	−6	−1	−2	1	2	−1	1
1946	−5	−8	0	−9	------	−6	−7	5	15	−1	−11	0
1947	1	−3	−3	−6	−4	12	−3	−10	−13	−3	5	1
1948	−2	−1	−2	10	2	−4	−4	−12	−5	−11	−3	3
1949	−2	−6	------	0	−3	−10	−13	−1	−6	−5	−9	−5
1950	−2	−8	11	1	−11	−10	2	1	−16	−8	0	0
1951	−5	−15	−3	21	3	−13	3	5	0	−5	−2	3
1952	−8	−6	−8	−6	10	−10	0	−7	−15	−15	−8	0
1953	−9	------	−5	------	−3	0	−7	−2	−6	−13	−9	−3
1954	−6	−10	−26	−2	8	−9	−15	13	−8	2	−5	0
ATHENS, GREECE												
1952	−2	2	−7	−3	4	3	2	0	−3	4	2	4
1953	7	0	6	0	−5	2	4	0	3	−6	3	−10
1954	−1	0	−2	4	2	−4	−3	1	0	−4	−5	5
1955	−1	−3	−1	1	−2	−1	−4	−2	0	7	------	------

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
UCCLE, BELGIUM												
1949	19	13	0	−3	8	18	29	10	2	−1	4	5
1950	17	6	−4	−15	−3	0	6	13	5	−4	−16	−28
1951	−40	0	−15	22	−4	3	6	−15	−3	20	19	4
1952	−8	−6	20	14	4	4	−4	5	−11	−5	6	0
1953	3	−7	22	−7	−3	−11	19	−12	−2	−1	−19	−18
1954	18	−6	−23	−11	−4	−15	−55	−21	13	−8	−11	10
FUKUOKA, JAPAN												
1939	2	0	−5	2	3	−2	−2	−4	1	−3	−3	2
1940	6	4	------	5	------	2	0	0	2	0	−2	−4
1941	------	3	0	4	4	6	−3	−10	4	4	5	4
1942	7	−5	−7	−3	−2	−2	1	------	−1	−1	3	−13
1943	2	8	6	2	−1	−5	------	1	−4	−5	−1	0
1944	−15	2	2	1	−9	−4	12	3	−2	10	2	------
1945	−14	3	0	−10	5	−3	7	1	0	4	2	------
1946	7	1	6	1	8	12	5	------	−11	−2	11	11
1947	------	8	11	5	−8	2	------	−6	10	8	−4	15
1948	8	−1	3	5	0	3	------	1	−1	−2	−5	0
1949	0	2	−1	11	5	−8	4	−3	1	−11	4	−13
1950	−5	7	2	−11	2	−8	−6	5	9	−1	0	------
1951	1	−19	−7	3	−1	−3	8	3	------	−2	−3	2
1952	4	------	−5	3	0	6	−13	−1	1	1	−3	−8
1953	−5	------	4	−1	−1	13	−6	------	−3	1	4	−9
1954	------	−11	−1	1	0	8	------	−6	−7	1	−9	−2
MATSUMOTO, JAPAN												
1939	4	7	2	−4	6	−5	−2	7	3	2	−4	3
1940	−2	2	------	3	------	1	7	0	−1	2	5	2
1941	−1	1	−2	3	3	−2	5	−4	------	−1	−2	−1
1942	3	−4	−1	3	−8	4	−2	------	−3	−4	5	1
1943	3	3	−4	2	−3	−2	3	−2	−13	5	1	7
1944	2	1	5	------	−11	−3	−2	3	0	3	−2	−1
1945	−2	1	2	−2	4	2	13	−3	2	6	7	2
1946	0	1	3	−1	−1	2	3	4	2	4	1	5
1947	2	1	1	0	−1	4	−4	0	5	4	4	2
1948	6	2	1	−3	3	1	7	4	−1	−3	4	3
1949	−4	------	------	4	4	5	4	2	2	3	1	6
1950	−5	2	1	0	5	0	−1	−8	−2	−1	−6	0
1951	−1	1	−1	1	−3	1	2	−7	1	−3	−2	−7
1952	4	−5	−5	−4	6	2	−6	0	−3	1	0	−4
1953	−4	−4	2	−2	0	−3	−3	−6	−3	−4	−5	−8
1954	1	−7	−4	−4	−6	−2	2	−2	−2	−2	−5	−5
SHIMIZU, JAPAN												
1939	2	3	3	1	−1	0	−1	−2	0	3	−2	2
1940	−4	2	------	5	------	3	−9	6	1	2	2	8
1941	−1	0	−6	−4	−8	−8	2	5	5	6	0	0
1942	5	−1	------	0	0	------	−2	------	−3	1	−7	−1
1943	2	1	3	5	−4	−13	0	−4	−3	−4	3	−3
1944	9	------	2	3	------	------	−1	5	−11	−2	------	−6
1945	−2	1	0	−3	------	------	------	------	------	------	------	------
1946	------	------	------	------	------	------	------	------	------	−5	7	3
1947	−2	------	4	1	1	−3	2	−1	0	3	0	1
1948	1	−4	3	7	1	4	------	------	4	−1	2	−1
1949	5	−4	1	−1	7	−6	9	−2	5	0	3	2
1950	−3	2	7	−6	1	2	7	−6	−3	−6	−1	0
1951	0	−1	−6	−2	−1	2	1	0	4	1	−3	−1
1952	0	−5	3	3	−1	2	3	2	3	1	−8	−3
1953	−2	−1	−2	−10	−6	−6	------	−8	−8	−5	−5	−5
1954	−5	−9	−4	−6	3	−1	−1	−8	−3	−2	−5	−11
TOKYO, JAPAN												
1939	2	6	11	4	------	1	−6	14	3	−1	12	11
1940	4	15	------	5	------	−8	4	26	10	10	−4	4
1941	1	11	4	2	3	9	8	−9	11	2	−4	−19
1942	−1	−2	−3	2	1	5	−8	------	−2	−5	4	3
1943	11	0	3	10	−2	−8	2	6	3	1	−4	5
1944	5	11	12	5	7	−4	−1	−4	0	12	−8	4
1945	4	2	3	------	------	------	------	------	------	------	------	------
1946	------	------	------	------	------	10	−8	0	4	8	6	5
1947	−2	3	2	−3	11	------	7	−1	5	10	−2	0
1948	1	2	−1	2	12	2	1	14	8	−2	6	7
1949	6	−1	1	0	8	4	1	------	−14	5	3	17
1950	7	7	8	−14	26	------	3	------	−1	−12	0	−1
1951	−4	−5	−13	6	3	6	------	−13	−9	1	4	−1
1952	−11	−8	−2	−3	2	5	−11	−9	−4	−2	−2	−13
1953	−1	−8	−3	−6	−9	------	------	3	14	−8	2	−3
1954	−5	−14	−4	−3	2	------	------	------	3	−10	−7	7
JAPAN (Mean of the four stations above)												
1939	2.5	4.0	2.8	0.8	2.7	−1.5	−3.0	4.8	1.8	0.3	0.8	4.5
1940	1.0	5.8	------	4.5	------	−.5	.5	8.0	3.0	3.5	.3	2.5
1941	−.3	2.3	−1.0	1.3	.5	1.3	3.0	−4.5	6.7	2.8	−.2	−4.0
1942	3.5	−3.0	−3.7	.5	−2.2	2.3	−2.7	------	−2.2	−2.2	1.3	−2.5
1943	4.5	3.0	2.0	4.8	−2.5	−7.0	1.7	.3	−4.2	−.7	−.2	2.3
1944	.3	4.7	5.3	3.0	−4.3	−3.7	2.0	1.8	−3.2	5.8	−2.7	−1.0
1945	−3.5	1.8	1.3	−3.0	4.5	−.5	10.0	−1.0	1.0	5.0	4.5	2.0
1946	3.5	1.0	4.5	0.0	3.5	8.0	0.0	2.0	−1.7	1.3	6.3	6.0
1947	−.7	4.0	4.5	.8	.8	1.0	1.7	−2.0	5.0	6.3	−.5	4.5
1948	4.0	−.2	1.5	2.8	4.0	2.5	4.0	6.3	2.5	−2.0	1.8	2.3
1949	1.8	−1.0	.3	3.5	6.0	−1.2	4.5	−1.0	−1.5	−.7	2.8	3.0
1950	−1.5	4.5	4.5	−7.7	8.5	−2.0	.8	−3.0	.8	−5.0	−1.7	−.3
1951	−1.0	−6.0	−6.7	2.0	−.5	1.5	3.7	−4.2	−1.3	−.7	−1.0	−1.7
1952	−.7	−6.0	−2.2	−.2	1.8	3.8	−6.7	−2.0	−.7	.3	−3.2	−7.0
1953	−3.0	−4.3	.3	−4.7	−4.0	1.3	−4.5	−3.7	0.0	−4.0	−1.0	−6.2
1954	−3.0	−10.2	−3.2	−3.0	−.2	1.7	.5	−5.3	−2.2	−3.2	−6.5	−2.7

correlations between stations in the United States is significant at the 5 percent level, while all the correlations between Japanese stations are significant beyond the 1 percent level.

The results indicate that the D values at the three stations in the United States are usually independent but that there may be some slight interdependence between the stations in Japan. The United States stations are more than 1,000 miles from each other, whereas the distance between Japanese stations ranges from approximately 100 to 600 miles. Therefore, the D values at the four Japanese stations were averaged to secure one value, which can be considered as an estimate of the amount of clear sky radiation over Japan. These averages are listed in table 1 and plotted in figure 1.

Although no correlations were made involving Athens, Greece or Uccle, Belgium it appears reasonable to assume, especially in view of the low correlations in table 2, that the D values at these two stations are independent of each other as well as of the stations in Japan and the United States. Thus there are six relatively independent series of radiation values: Blue Hill, Lincoln, Table Mountain, Japan, Athens, and Uccle.

TABLE 2.—*Correlation coefficients between departures from "average" radiation.*

	Lincoln	Table Mountain	Matsumoto	Shimizu	Tokyo
Blue Hill	0.10	0.12			
Lincoln		−.03			
Fukuoka			0.30	0.39	−0.24
Matsumoto				.35	.34
Shimizu					.39

Because of the rather large variability of the D values, 6-month running means were computed for all consecutive 6-month periods for which data are available. There is nothing especially significant about the choice of a 6-month period, it simply appeared to be a reasonable length to use to reduce the variability of the monthly D values. The 6-month running means for 1950 to 1954 are shown in figure 2; the points are plotted at the fourth month of the 6-month period. The dashed portions of the curves cover periods when less than six consecutive months of data were available. In these cases linear interpolation was used to estimate the values for the missing months and 6-month

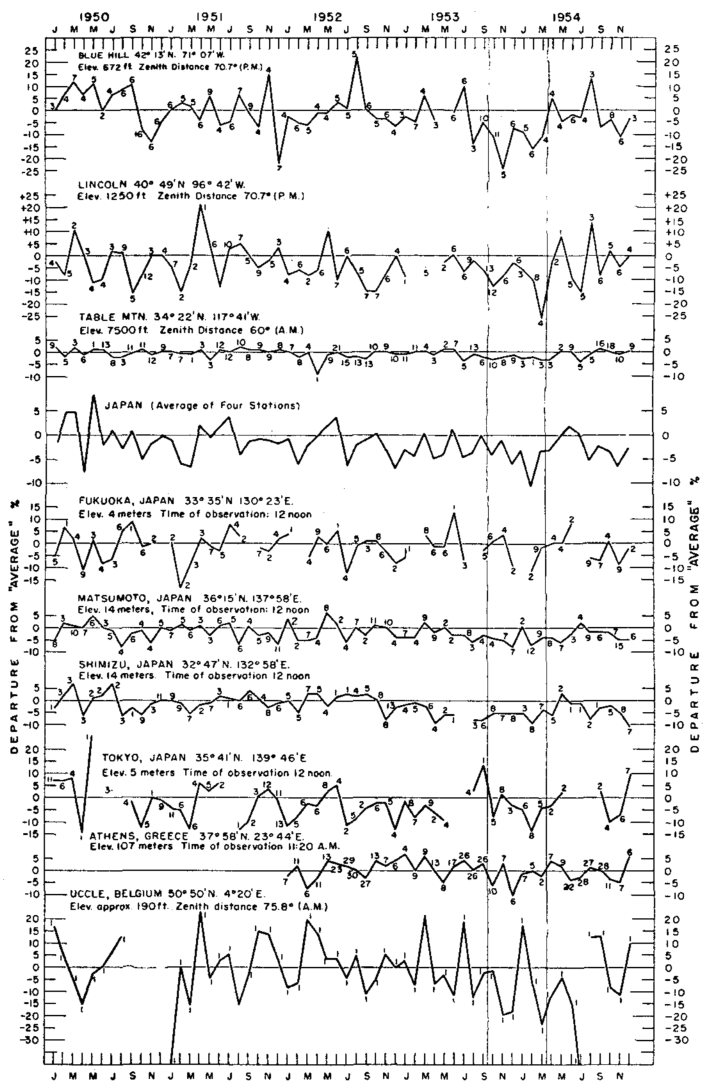

FIGURE 1.—Solar radiation intensity—departure from "average". (The small numerals over curves are the number of observations.)

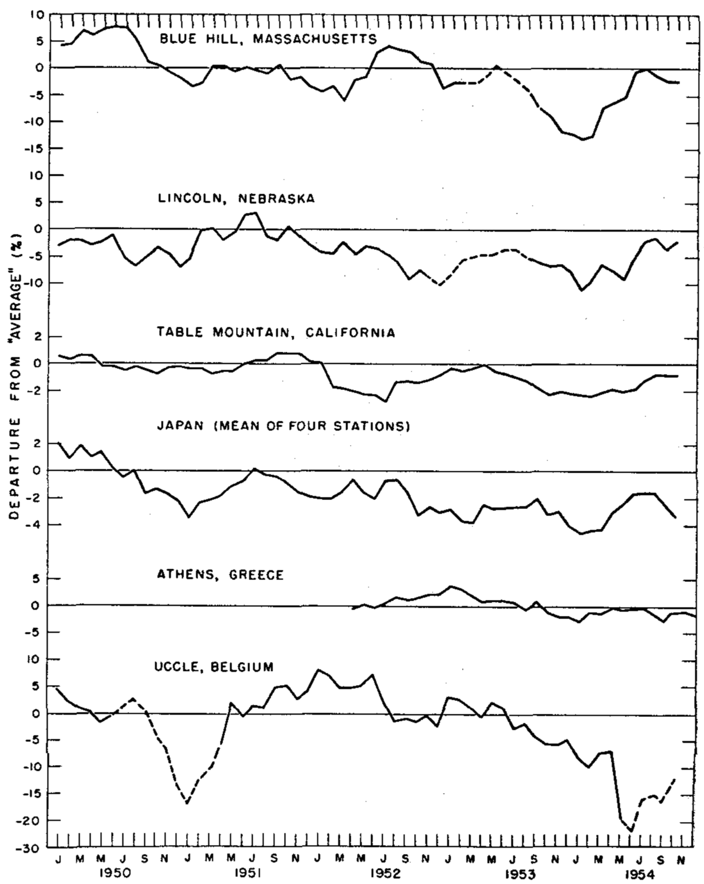

FIGURE 2.—Six-month running means of solar radiation intensity. Dashed portions are based, in part, on interpolated values. (Note different scales for Table Mountain and Japan.)

averages were then computed. Interpolated values and 6-month averages computed by using one or more interpolated values are excluded from the analysis to be described below.

3. RESULTS

Figure 1 shows that the radiation at the three stations in the United States was low after July 1953. All three stations were below "average" on August 1953 and continued so through March 1954. A study of table 1 shows that below "average" radiation for a period of eight months is rather unusual at any one station. It is highly unlikely that the simultaneous occurrence of low radiation at three independent stations for such a long period can be due to random fluctuations. Examination of the curves of the other stations plotted in figure 1 reveals no such readily apparent low radiation values although there is some tendency in that direction.

However, the smoothed values in figure 2 do show low radiation sometime after July 1953 at all six places. The value plotted at January 1954, which is the mean for the period October 1953 through March 1954, appears to be low on all six curves. To test this, a comparison was made between this 6-month mean and means prior to July 1953. The results are shown in table 3. In the third column is listed the number of consecutive 6-month periods for which means were available prior to July 1953, while column four shows how many of these were equal to or lower than the October 1953–March 1954 radiation. At Table Mountain there were 312 overlapping 6-month means in the period 1926 through June 1953. Two of these were lower than the October–March mean, while three were equal to it. At the other five places the October 1953–March 1954 radiation was less than that in any 6-month period prior to July 1953. Thus, at each of six relatively independent stations the radiation in the period October 1953–March 1954 was quite low. Using Fisher's method of combining probabilities it can be shown that the probability that such low radiation could have occurred simultaneously at six relatively independent stations simply by chance is less than one in ten thousand.

TABLE 3.—*Comparison of 6-month means of radiation in period prior to July 1953 with average for October 1953–March 1954 period*

	Period of record	Number of 6-month means	Number ≤October 1953–March 1954
Blue Hill, Mass	1934 to June 1953	203	0
Lincoln, Nebr	1917 to June 1953	307	0
Table Mountain, Calif	1926 to June 1953	312	5
Japan	1939 to June 1953	165	0
Athens, Greece	1952 to June 1953	13	0
Uccle, Belgium	1949 to June 1953	54	0

Comparison of the October 1953–March 1954 mean with 6-month means after July 1953 can be made by examination of figure 2. The October 1953–March 1954 mean (plotted at January 1954) is lower than any 6-month mean after July 1953 on four of the six curves; at Table Mountain it is lower than all except the November 1953–April 1954 mean; while at Uccle it is lower than all except the November 1953–April 1954 and February–July 1954 means. It may be noted that some of the dashed portions of the Uccle curve are considerably lower than the October 1953–March 1954 value. However, the dashed portions are based on less than six monthly values and are not strictly comparable with the 6-month means.

The cause of the low radiation is speculative. Arakawa and Tsutsumi [8] also noted a decrease in radiation in Japan. They hypothesize that thermonuclear tests may be responsible for the observed decreases in radiation but also state that these tests can not be said to be the unique cause of the radiation decrease. There is no conclusive evidence that nuclear tests decrease solar radiation on a worldwide basis. For example, no definite decrease occurred at all three stations in the United States following the November 1952 tests. Explosive volcanoes, on the other hand, have unquestionably reduced solar radiation markedly on occasions in the past. The decreases in radiation following the Krakatoa (1883) and Katmai (1912) volcanic eruptions are well known and cannot be ascribed to nuclear bursts. The Mt. Spurr eruption, although smaller than either of these, seems to be a more likely cause of the observed worldwide decrease in radiation after October 1953 than the thermonuclear experiments.

Whatever the cause, it is clear that there is strong evidence for a reduction in radiation in the period October 1953 through March 1954, at widely separated areas in the Northern Hemisphere. Data from the Southern Hemisphere should be examined to see if a decrease in solar radiation occurred there also.

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