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VOLCANOES AND CLIMATE

BY

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During the summer of 1912 we were engaged, respectively, at Bassour, Algeria, and at Mount Wilson, California, in measuring with the pyrheliometer and spectrobolometer the intensity of the radiation of the sun. On June 19 Mr. Abbot began to notice in Bassour streaks resembling smoke lying along the horizon, as if there were a forest fire in the neighborhood of the station. These streaks continued all summer, and were very marked before sunrise and after sunset covering the sky then towards the sun nearly to the zenith. After a few days the sky became mottled, especially near the sun. The appearance was like that of the so-called mackerel sky, although there were absolutely no clouds. In the months of July, August, and so long as the expedition remained in September, the sky was very hazy, and it was found that the intensity of the radiation of the sun was greatly decreased by the uncommonly great haziness. Mr. Fowle noted similar appearances at Mount Wilson especially noting the streakiness beginning with June 21. Publications in European journals and elsewhere have indicated that this haziness was world-wide. We adopt the view expressed by Dr. Hellmann[1] that the haze in question was due to the eruption of the volcano of Mount Katmai in Alaska in June, 1912. In the present paper we give the effects of the haze on the quantity and quality of the solar radiation as determined by our measurements, and also the effect which the presence of the haze and that of similar occurrences in former years appear to have had on the climate of the earth.

Before passing to the numerical results it will be interesting to recall briefly the circumstances attending the eruption of Mount Katmai and of other extraordinary volcanic outbreaks which resulted in periods of prolonged haziness similar to that of the summer of 1912.

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[1] Zeitschrift für Meteorologie, January, 1913.

SOME GREAT VOLCANIC OUTBREAKS

Captain K. W. Perry, U. S. R. S., reported that on June 6, 1912, the Revenue Steamer "Manning" being moored at the wharf at St. Paul, Kodiak Island, he observed about 4 o'clock a peculiar looking cloud rising to the southward and westward. Ashes began to fall about 5 p. m., and after this thunder and lightning became very intense and the wireless apparatus refused to work. Volcanic matter continued to fall rapidly until 9 a. m., June 7, when five inches of ashes had fallen. About noon precipitation began again, and by 2 o'clock it was pitch dark. Although all ashes of the previous day had been removed, yet the decks, masts, and yards were again heavily laden, and the men stumbled about, colliding with one another in their efforts to free the decks with shovels and streams of water. It was not until 2 p. m., June 8, that the fall of ashes decreased, the sky assumed a reddish color, and finally objects became dimly visible. The average depth of the ashes at Kodiak Island, 100 miles from Mount Katmai, was nearly or quite 1 foot. It seems doubtful, however, if the fall of ashes in other directions from the volcano was as great as in the direction of Kodiak Island.

It is natural to compare this eruption of Mount Katmai with the extraordinary explosion of Krakatoa in the Strait of Sunda in the year 1883, which formed the subject of the exhaustive report of the Krakatoa Committee of the Royal Society of Great Britain. After a quiescent period of more than 200 years a sharp eruption on the Island of Krakatoa began in May, 1883, and a slight quantity of ash fell as far away as Batavia, Java. Parties landed several times on the island during the summer of 1883, and found much activity there, and destruction of the vegetation. Still nothing very extraordinary had occurred until on August 26, when a succession of frightful explosions began, lasting until the morning of the 28th. The most violent occurred on the morning of the 27th, when the northern and lower portion of the Island of Krakatoa was blown away, leaving a vertical cliff. Instead of a mountain 1,400 feet high, which previously existed, there was now left a submarine cavity reaching 1,000 feet below sea level.

The wave caused by this explosion was upwards of 50 feet deep when it reached the shores of Java and Sumatra, and a Dutch warship was carried about 2 miles inland, and left 30 feet above sea level. Nearly 40,000 people perished by the overwhelming of their villages. The wave was still several feet high when it reached the Cape of Good Hope, and was thought to be noted by the tide gauges of the English Channel. The noise of the explosion was heard as far as the Island of Rodriguez, 3,000 miles away, and it is believed that the noise was heard over an area of one-thirteenth the entire surface of the globe. The air-waves caused were noted by meteorological observers to have made seven complete passages of the globe, four going out from the volcano to the antipodes, and three in return. The cloud of dust sent up from the volcano was measured on the day before the greatest explosion to be 17 miles high. For many months thereafter a cloud of dust, which at the beginning was believed to have an elevation of about 20 miles, and which after a year had descended to 10 miles, surrounded the whole world. This dust caused extraordinary sunset glows, and the increased length of the twilight. Other effects from it will be noted later.

It is obvious that the violence of the explosion of Krakatoa far exceeded that of Mount Katmai, for no such reports of the noise of the explosion have reached us in 1912. On the other hand the quantity of ash which fell at Kodiak Island, 100 miles from the volcano of Mount Katmai, exceeded by many fold the quantity which fell at similar distances from Krakatoa. According to Verbeek the depth of the ashes at 100 miles from Krakatoa averaged less than 1 centimeter.

In connection with their report of the extraordinary atmospheric conditions which followed the Krakatoa eruption, the Krakatoa Committee published accounts of various earlier periods of haziness associated with great volcanic action. From these we glean the following.

In the year 1783 occurred the eruption of Asamayama, Japan, stated to be the most frightful eruption on record. Immense rocks were hurled in all directions, and towns and villages buried. One stone said to be 264 feet by 120 feet fell into a river and looked like an island. The (if possible) still more extraordinary eruption of Skaptar Jökull in Iceland, also occurred in the same year beginning near the end of May, and with the most violent eruptions on June 8 and 18. Arago records that the dry fog of 1783 commenced about the same day, June 18, at places distant from each other, such as Paris and Avignon, Turin, and Padua. It extended from the north coast of Africa to Sweden, and lasted more than a month. The lower air did not seem to be its vehicle for at some places the fog came on with a south, at others with a north wind. Abundant rains and the strongest winds did not dissipate it. In Languedoc its density was such that the sun was not visible in the morning up to

17° altitude above the horizon. The rest of the day the sun was red and could be observed with the unprotected eye. At the time of new moon the nights were so bright that the light was compared to that of full moon, even at midnight.

In 1814 occurred the great eruption of the volcano of Mayon in the Philippine Islands, and on April 7 to 12, 1815 the extraordinary outbreak of Tomboro, Sumbawa, of which it is said this eruption was the greatest since that of Skaptar Jökull in 1783. For three days there was darkness for a distance of 300 miles. After these extraordinary volcanic outbreaks there were noted in Europe streaky skies, haziness, long twilights and red sunsets, so that the year 1815 is the most remarkable as regards sunset lights recorded up to that date.

Passing on to the year 1831 there occurred three moderate eruptions, and three more of the very first magnitude. Thus Graham's Island was thrown up, and eruptions took place in the Babujan Islands and at Pichincha. Arago says "the extraordinary dry fog of 1831 was observed in the four quarters of the world. It was remarked on the coast of Africa on August 3, at Odessa on August 9, in the south of France and at Paris on August 10, in the United States on August 15. The light of the sun was so much diminished that it was possible to observe its disk all day with the unprotected eye. On the coast of Africa the sun became visible only after passing an altitude of 15° or 20°. M. Rozet in Algeria and others in Annapolis, United States, and in the south of France, saw the solar disk of an azure, greenish, or emerald color. The sky was never dark at night, and even at midnight in August small print could be read in Siberia, Berlin, Genoa, etc. On August 3 at Berlin the sun must have been 13° below the horizon when small print was legible at midnight."

MOUNT KATMAI AND THE SOLAR RADIATION

In the following table we give the transmission of the atmosphere for the solar radiation as determined by the pyrheliometer, and for the separate wave-lengths by the spectrobolometer. In the first column we have the ratio of the mean values of the total intensity of the solar radiation (as determined by the pyrheliometer) compared with the intensity of the radiation which would be obtained outside the atmosphere, on the moon, for instance. The results are grouped with regard to time as indicated in the side headings. Pyrheliometer measurements of the different days have been reduced to the values which would have obtained if the sun had been at 48° from the zenith (air mass 1.5) and if the earth's distance from the sun had been at its mean value. The remaining columns of the table give the vertical transmission coefficients[1] at different wave-lengths in the spectrum. The values in the first line, corresponding to May and early June, are in close accordance with similar values obtained in former years when the atmosphere was of normal transparency. Accordingly the values in subsequent lines indicate by comparison with the first line the average effect of the volcanic dust in diminishing the transparency of the air.

TABLE 1. ATMOSPHERIC TRANSMISSION, 1912.

Time.	Total radiation.[1]	Wave-lengths in microns.[2]								
		0.34	0.36	0.40	0.50	0.60	0.80	1.00	1.50	2.00
		a. MOUNT WILSON, CALIFORNIA.								
Early June	0.77	...	.645	.741	.866	.890	.967	.974	.967	.960
Late June	0.77	...	.644	.733	.851	.887	.970	.974	.971	.955
July................	0.69	...	.549	.654	.782	.835	.919	.937	.956	.938
August..............	0.64	...	.536	.623	.738	.785	.872	.898	.931	.931
Haziest days	0.59	...	.467	.528	.639	.677	.774	.808	.883	.876
		b. BASSOUR, ALGERIA.								
Early June	0.72	.557	.606	.696	.832	.869	.951	.964	.956	.947
Late June	0.71	.558	.607	.696	.832	.872	.946	.962	.955	.955
July................	0.59	.487	.514	.598	.709	.747	.833	.856	.876	.904
August..............	0.59	.496	.527	.597	.707	.754	.830	.863	.842	.895
Haziest days	0.51	.406	.439	.495	.604	.656	.737	.767	.887	.872

[1] The values in this column give the ratios of the pyrheliometer readings at a solar zenith distance 48° (air mass 1.5), and reduced to mean solar distance, compared to the solar constant of radiation, taken as 1.93 calories per sq. cm. per minute.

[2] The values in these columns give the transmission coefficients for the wave-lengths named for celestial bodies in the zenith (air mass 1.0).

In further illustration of the effect of the haze we give Table 2, which is computed to represent the condition of the solar radiation transmitted obliquely through the atmosphere, at a solar zenith distance of about 48° (corresponding to air mass 1.5). In the first column are given the mean values of the total radiation per square centimeter per minute. In the second and third columns respectively, are the fractions transmitted and the fractional decrease in the intensity of the total solar radiation in passing from the outside of the atmosphere to the surface of the earth. The remaining columns give the

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[1] By vertical transmission coefficient we mean the fraction of the intensity of a beam of rays from a celestial body in the zenith which reaches the ground.

fractional decrease in the intensities of different wave-lengths found by comparing them with the values which were found for them during May and early June.

Some results of the haziness are plainly shown by the accompanying illustrations, Fig. 1 and Fig. 2. Fig. 1 gives the march of the pyrheliometry and of the transmission of green light (at wave length 0.5 μ) from June until September. It is computed for the solar zenith distance of 48° corresponding to air mass 1.5. The values are given for both Mount Wilson and Bassour. In Fig. 2 are given the vertical transmission coefficients of the haze itself for various times and wave-lengths. Curves representing this are shown corresponding to the latter part of June, to July, to August, and to some days when the transparency was especially low. These data are also given for both Mount Wilson and Bassour.

TABLE 2. ILLUSTRATING OPACITY DUE TO VOLCANIC MATTER.

Time.	Total radiation.[1]			Percentage depletion.[2]						
				Wave-lengths in microns.						
	Values in calories.	Ratio to early June.	Percentage depletion.	0.34	0.36	0.40	0.50	0.60	1.00	2.00
a. MOUNT WILSON, CALIFORNIA.										
Early June	1.49	1.00	0	...	0.0	0.0	0.0	0.0	0.0	0.0
Late June	1.48	0.99	1	...	0.2	1.6	2.7	0.5	0.0	0.7
July	1.33	0.89	11	...	21.6	16.9	14.5	9.0	5.8	3.4
August	1.24	0.83	17	...	24.3	23.0	21.4	17.3	11.7	4.3
Haziest days	1.13	0.76	24	...	38.5	39.7	36.5	33.7	24.9	13.0
b. BASSOUR, ALGERIA.										
Early June	1.39	1.00	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Late June	1.37	0.99	1	—0.2	—0.2	0.0	0.0	—0.5	0.4	—1.4
July	1.14	0.82	18	18.3	21.9	20.3	21.3	20.1	16.4	6.6
August	1.14	0.82	18	15.9	18.7	20.7	21.7	19.0	15.2	7.9
Haziest days	0.99	0.71	29	38.0	38.4	40.1	38.1	34.2	28.9	11.6

[1] These values relate to pyrheliometer measurements at a solar zenith distance of 48° (air mass 1.5) and mean solar distance.

[2] These values relate to atmospheric transmission for solar zenith distance of 48° (air mass 1.5) and depend on spectro-bolometric measurements at the wave-lengths named. The percentage depletion indicates the loss of direct radiation attributable to the volcanic haze, assuming none was present in early June.

From these results we may draw the following conclusions:

(1) The haze produced by the volcano of Mount Katmai began to affect measurements in Algeria on or about June 19, and those of Mount Wilson on or about June 21.

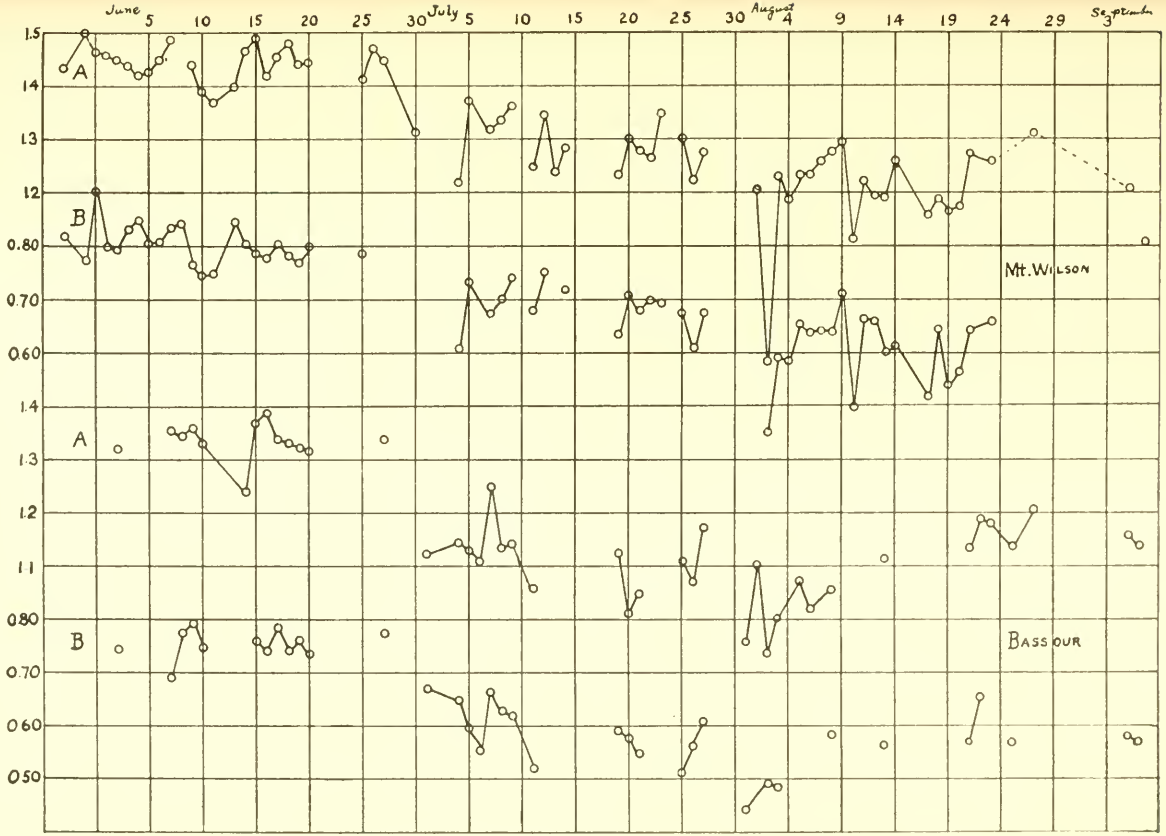

Fig. 1.—Effect of dust on solar radiation and atmospheric transmission at Mount Wilson, Cal. and Bassour, Algeria.
AA Pyrheliometer results at solar zenith distance 48° (air mass 1.5).
BB Atmospheric transmission for green light ($\lambda = 0.5\,\mu$) at zenith distance 48°.

(2) The effect increased during July, and had reached its maximum for Bassour by the middle of August, but seemed still increasing at Mount Wilson to the end of August.

(3) The maximum decrease of the total solar radiation attributable to the haze seems to have reached nearly or quite 20 per cent at each station.

(4) It would appear from inspection of the transmission coefficients for different wave-lengths that the peculiarities of the sky in the latter part of June produced no marked decrease of the transparency of the air.

(5) As regards the different wave-lengths of the spectrum, the effect of the haziness is greater for visible rays than for infra-red ones, but the difference of transmission does not increase so greatly towards the violet as one would expect. Indeed for the Bassour results there was nearly uniform effect throughout the whole visible and ultra-violet spectrum. The Mount Wilson results, however, show somewhat increasing effects towards the shortest wave-lengths. This circumstance is very noteworthy and indicates to us that the size of the particles which produced the scattering of light was on the whole much greater than the size of the particles which produced the ordinary blue light of the sky. Lord Rayleigh has shown that for particles small as compared with the wave-length of light the scattering effect is inversely proportional to the fourth power of the wave-length. It is from this extraordinarily rapid increase of the scattering towards the shorter wave-lengths that we owe the very blue character of the sky. The haze, on the other hand, produced a whitish appearance on account of the larger size of the particles concerned.

As Bassour is at a lower altitude (1,160 meters) than Mount Wilson (1,730 meters), it may be that the atmosphere above Bassour included on the average grosser particles than the atmosphere above Mount Wilson. This may account for the fact that the haze effect for Bassour did not increase toward short wave-lengths as rapidly as that for Mount Wilson. There is even a tendency toward smaller effects at Bassour for the extreme ultra-violet than for the visible rays. If this be real we think it may be due to a selective action of the dust due to its composition of volcanic glass and sulphur.

Mr. Fowle collected on Mount Wilson some dust which fell upon the mirror of the coelostat, and this dust has been very kindly

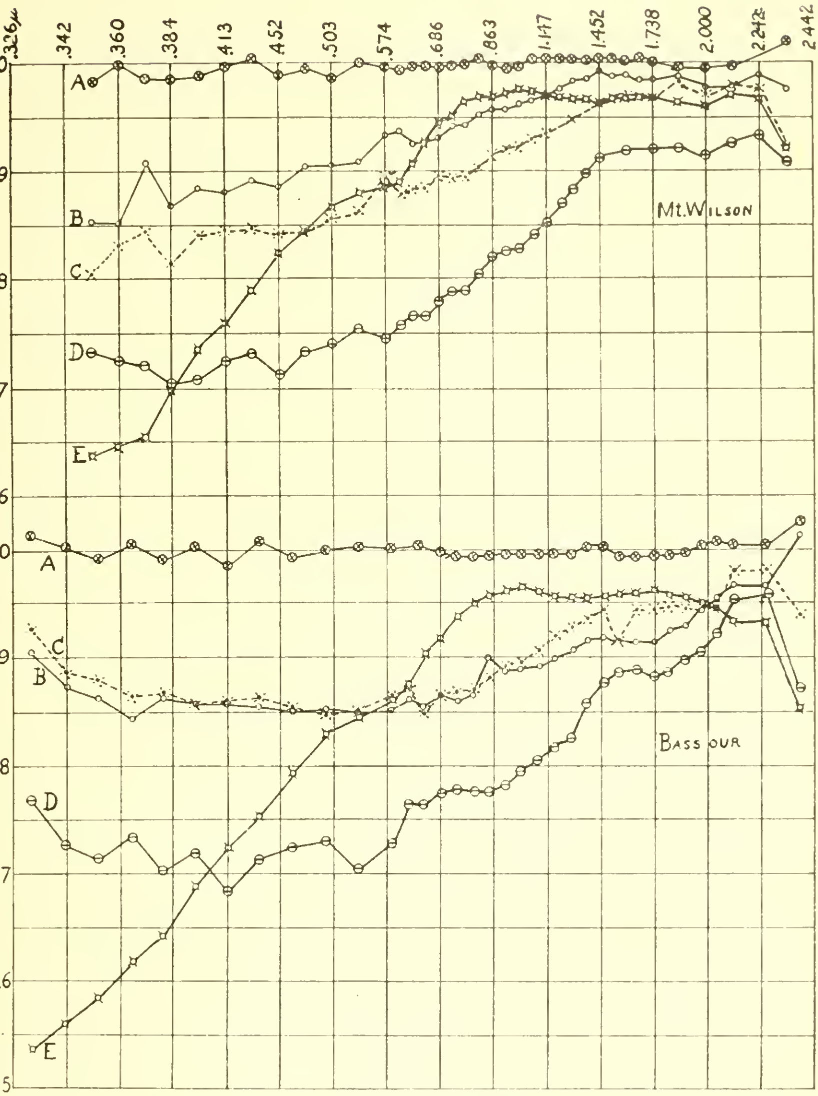

FIG. 2.—Effect of dust on atmospheric transmission at Mt. Wilson, Cal., and Bassour, Algeria.

EE Vertical transmission of atmosphere early June, 1912.
AA Transmission ratio: late June to early June.
BB " " all July to early June.
CC " " all August to early June.
DD " " haziest days to early June.

analyzed for us by Dr. Merrill of the United States National Museum, who writes:

> Dr. Pogue has reported on the dust left by you this morning as being composed of fragments of volcanic glass, quartz, feldspar and kaolin. Volcanic glass is a common constituent of volcanic dust, as is also feldspar. Quartz would occur only rarely, and kaolin scarcely at all. On account of the decomposed condition of much of the glass, and the presence of kaolin, we are both of us inclined to regard the dust as probably from the plains, and not as derived directly from the volcano, although the glass would suggest an ultimate volcanic origin.

DECREASE OF HEAT AVAILABLE TO WARM THE EARTH

In the passage of the beam of sunlight from the outer limit of the atmosphere to the soil, losses of energy occur in the direct beam as follows: (1) Absorption by the gases and vapors of the atmosphere, principally in the infra-red water-vapor bands. (2) Scattering of light towards the ground from the direct solar beam by the molecules and dust particles of the atmosphere, thus producing the light of the sky. This loss in the direct solar beam is made up to us by the sky-light. (3) A fraction of the solar beam is scattered by the molecules and dust particles of the air in such a direction as to go out to space, and thus be lost to the earth for heating purposes. To this may be added the quantity of radiation (if any) which is absorbed in the higher atmosphere.

The question arises how much the third loss, by diffuse reflection and scattering to space and higher atmospheric absorption, was increased owing to the presence of the dust cloud of 1912. It is not possible to determine this loss by direct measurements. However, knowing the solar constant of radiation, the intensity of the direct solar beam at the earth's surface, the intensity of the sky radiation, and the quantity of absorption by atmospheric vapors, the loss by high atmospheric absorption and by reflection of the atmosphere to space may be approximately computed. We obtain the value of the solar constant of radiation, the intensity of the direct solar beam at the earth's surface, and the loss of radiation by absorption in the vapors of the lower atmosphere, on each day of observation. In order to determine the total intensity of the sky radiation Mr. Abbot devised and constructed at Bassour two pieces of apparatus, and made measurements for this purpose.

The first contrivance was a bolometer with a somewhat wide receiving strip. This bolometer was made with a wooden case, and rough interior construction, but it was found to answer the purposes for which it was designed fairly well. It had an alt-azimuth mounting, and measurements were made with it of the intensity of the sky radiation at all parts of the sky as compared with the intensity of the direct beam of the sun. In this comparison the direct solar beam was reduced in intensity by means of a rotating sector diaphragm, and a series resistance was inserted for diminishing the sensitiveness of the galvanometer when the sun was observed. Measurements were made with this bolometer on the brightness of the sky on September 5, 6 and 7, 1912.

The other apparatus used was a device originally intended for measuring the nocturnal radiation, and was similar in principle to the Ångström Compensation Pyrheliometer. The two blackened metal strips, instead of being side by side, were placed one above and the other beneath a thin horizontal plate of brass, and were so protected by strips of horn that the metal strips could not give off radiation except from their outward surfaces. The radiation from the outward surface of each strip was free to go in any direction within a hemisphere. In the use of this instrument a blackened screen was placed beneath it so that the lower strip was exchanging radiation only with this screen, which subtended a whole hemisphere. The upper strip was exchanging radiation with the whole sky.

In the use of the bolometer mentioned above, the instrument was protected from exchanges of radiation of great wave-length by means of a plate of glass. The nocturnal radiation instrument, on the other hand, had no plate of glass in front of it. Accordingly while the bolometer measured only the radiation of the sky transmissible by glass (that is to say, the radiation coming indirectly from the sun), the nocturnal instrument, on the other hand, measured the combined effect of rays of all wave-lengths. Accordingly a correction had to be applied in the latter measurements for the radiation which the instrument would have sent out if the sun had been in eclipse. Of course this correction could not really be measured, but Mr. A. K. Ångström had made measurements at Bassour of the nocturnal radiation on the morning and evening of each of the days in question and these he has kindly permitted us to use. Assuming that the nocturnal radiation would have had the mean of these morning and evening values at mid-day if the sun had been eclipsed, we may thus estimate and correct the results for the exchange of long-wave rays between the blackened strip and the sky. Thus we determine the solar radiation scattered from the sky to the observer as indicated by the nocturnal radiation apparatus. The experiments of all three days with this instrument indicated that the scattered solar radiation received from the sky was in excess of the long-wave radiation lost to the sky.

The bolometric observations at different parts of the sky were reduced by graphical methods so as to give the mean brightness of the various zones, and these were summed up with regard to their relative areas, so as to give the total effect of the sky on a horizontal surface. The values given are for noon observations, and are stated in calories per square centimeter per minute. In the daylight observations with the nocturnal radiation apparatus the sun was screened away by a broom held at about 2 meters distance. The results represent therefore the whole sky except a part very close to the sun. The results of both kinds of observations are collected below:

Table 3. Radiation of the Sky. Bassour, 1912.

	Intensity.			
	Date.			Mean.
	Sept. 5.	Sept. 6.	ept. 7.	
a. BOLOMETRY OF SKY RADIATION.				
Direct solar beam in calories	1.24	1.25	1.25	1.25
Fraction added by the sky	0.267	0.126	0.129	0.174
Sky radiation in calories	0.331	0.158	0.161	0.217
b. MEASUREMENTS OF SKY RADIATION BY NOCTURNAL APPARATUS.				
	calories.	*calories.*	*calories.*	*calories.*
Before sun-rise	—0.169	—0.205	—0.208	—0.194
Noon	+0.062	+0.092	+0.047	+0.067
After sun-set	—0.208	—0.225	—0.220	—0.218
Total sky radiation in calories	0.250	0.307	0.261	0.273

Although the results show a large divergence in percentage, it is not great in calories; and the mean result of all experiments, namely 0.245 calories per square centimeter per minute, probably represents the total sky radiation to within 0.05 calories.

We will now give, as a mean for the three days, noon measurements of the three quantities of radiation: (1) That which reaches the earth in the direct beam of the sun. (2) That which reaches a horizontal surface by scattering from the whole sky. (3) That which is absorbed from the direct beam of the sun and from the sky radiation by the vapors of the atmosphere.

These quantities are as follows:

Direct solar beam	1.250	cal. per sq. cm. per min.
Total sky radiation	0.245	" " " " " "
Absorbed radiation	0.175	" " " " " "
Sum	1.67	" " " " " "
Solar constant	1.95	" " " " " "
Difference	0.28	" " " " " "

The difference between the solar constant and the sum of the three parts of the solar radiation, received at the earth's surface or absorbed in the lower atmosphere, gives approximately the combined loss by diffuse reflection from the atmosphere to space and by absorption in the higher atmosphere. This quantity is about 0.28 calories per square centimeter per minute. Experiments of similar nature have been made at Mount Wilson and Mount Whitney in former years, and their result has always indicated that the combined higher atmospheric absorption and the reflection of the atmosphere to space was not more than about 0.05 calories per square centimeter per minute. Accordingly the difference of 0.20 calories in round numbers seems to be attributable to the uncommon haziness which prevailed in the higher atmosphere during the summer of 1912. This difference is about 10 per cent of the solar constant of radiation.

It might be expected that if so great a decrease as this in the heat available to warm the earth's surface should continue indefinitely, the mean temperatures recorded at meteorological stations would thereby be lowered by about 7° centigrade. But it is not certain that the effect of this considerable diminution of heat was not counteracted by some change in the average cloudiness, or in the nocturnal radiation of the earth to space. It is conceivable that the cloud of haze prevented the escape of radiation of the earth to space in the same manner that it prevented the incoming of radiation from the sun to the earth, so that the decrease of heat available to warm the earth may have been in part or in whole compensated by a decrease in the rate of escape of heat from the earth, owing to the presence of the haze.

Mr. Ångström has kindly communicated to us some measurements of the nocturnal radiation which he made at Bassour in the summer of 1912. Unfortunately these measurements were not begun until after the haze from the volcano had reached a considerable density, but Mr. Ångström has arranged his values with reference to the degree of haziness which prevailed, as indicated by pyrheliometric measurements of the direct beam of the sun during the successive days. In this way be has divided his measurements of nocturnal radiation into two groups, one group being taken on the nights of the days in which the transparency of the atmosphere had been above the average, and the other group taken on the nights of the days in which the transparency of the atmosphere had been below the average. The number of days in each group is 17. He finds that the average nocturnal radiation was about 0.15 calorie per square centimeter per minute, and that the nights corresponding to days of more than usual transparency of the atmosphere gave a nocturnal radiation 0.001 calorie above the normal, while those nights corresponding to days of less than usual transparency gave a nocturnal radiation 0.001 calorie below the normal. This difference, 0.002 calorie, between the hazy days and the clearer ones is so small that Mr. Ångström is doubtful if it be a real effect, or only an accidental error of measurement.

However, it would not be expected that the effect due to a difference of haziness between the two groups of days would be so great as the effect due to the haziness produced by the volcano; and it can also be shown that the effect which might be expected from the volcano itself would not be very great, measured by thousandths of a calorie.

It is shown by us[1] that the direct radiation of the earth to space is not, perhaps, greater than 10 per cent of the total radiation of a body at the temperature of the earth. Mr. Angström's measurements incline him to think that the transmission of direct radiation to space is somewhat greater than this, perhaps 15 or 18 per cent. Suppose that we should assume it to be the latter. A perfect radiator at the temperature of the earth emits about 0.5 calorie per sq. cm. per minute. Taking 18 per cent of this we have 0.09 calorie. Then we assume that of the 0.15 calorie representing the nocturnal radiation, 0.09 calorie would be transmitted from the earth's surface to space and the remaining 0.06 calorie would be the counter-radiation of the cooler atmosphere towards the earth. Let us further suppose that the volcanic haze (which produced a decrease, as we have found, of 10 per cent in the incoming energy) produced a decrease of 5 per cent in the transmission of the higher atmosphere to the radiation sent out by the earth. This effect of course will influence Mr. Ångström's results only on the 0.09 calorie supposed to be transmitted from the soil through the atmosphere to space. Five per cent of 0.09 calorie is 0.0045 calorie; so that if it should be found that the nocturnal radiation experienced a decrease of 0.0045 calorie

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[1] Annals Astrophysical Observatory, Vol. 2, pp. 167-172.

per square centimeter per minute owing to the volcanic haze of 1912, the 10 per cent loss of heat incoming from the sun, due to the reflection of this haze to space, would be half compensated. The value 0.0045 calorie is so near the difference, 0.002 calorie, found by Mr. Angström to exist between his clear and hazy days, that it seems impossible to say as yet whether the decrease of heat available to warm the earth was not in considerable measure compensated as we have described.

INFLUENCE OF FORMER HAZY PERIODS ON THE SOLAR RADIATION

It is only since just before the Krakatoa eruption of 1883 that we have had measurements of the intensity of solar radiation comparable to those that were available in 1912. From a paper of Prof. H. H. Kimball[1] we copy the data for the top line of the accompanying Fig. 3, which shows the departures of the annual solar radiation received at the earth's surface, as measured at Montpelier and other stations. The smoothed curve (A) of the figure is formed from the combination of these results by adding to twice the value for the year in question the value for the year next preceding and the value for the year next following, and dividing the sum by 4. It is apparent that very great departures from the usual intensity of solar radiation occurred from 1883 to 1887, from 1888 to 1893, and from 1902 to 1904 respectively. The departure which followed the Krakatoa eruption is only what we should have expected, but it is interesting to find, if we can, the causes of the diminished solar radiation having minima in 1891 and 1903 respectively.

Considering first the period 1888 to 1893; undoubtedly the greatest eruption of this period occurred in northern Japan. Bandai-San is a mountain about 5,800 feet high which had shown no sign of activity for about 1,100 years. A subordinate peak called "Little Bandai-San" arose on its northeastern side. On the morning of July 15, 1888, with only a few minutes earthquake as a preliminary warning, Little Bandai-San was blown completely into the air and obliterated. The debris buried and devastated an area of at least 30 square miles. An estimate based on the depth of the material in this area indicated that the quantity of earth, rocks and volcanic material reached 700,000,000 tons, and that doubtless the true figure would be much greater still. About 600 people perished horribly, and many more were reduced to destitution. It was with one possi-

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[1] Bulletin of the Mount Weather Observatory, Volume 3, Part 2.

ble exception the most terrible volcanic disaster which had occurred in Japan since the famous explosion of Asamayama in 1783. The force of an explosion capable of tearing a mountain to bits and distributing it over an area of 30 square miles may well have been sufficient to blow the column of ashes high enough into the air to have been carried over the earth like those ejected from the crater of Krakatoa in 1883.

An eruption took place of the volcano Mayon in the Philippine Islands, December 15, 1888. Vast columns of ashes ascended from the crater, and in a short time the darkness was so intense that, though it was mid-day, lights had to be used in every house in Manila. Violent eruptions were also reported from other volcanoes in the Philippine Islands.

The activity of the Island of Vulcano, near the coast of Sicily, lasted 20 months from August 3, 1888 to March 22, 1890. The most violent explosions occurred on August 4, 1888, December 26, 1889 and March 15, 1890. An eruption on January 6, 1889, was observed by Prof. A. Ricco from the Observatory of Palermo to be sending a column of smoke to the height of 10½ kilometers.

In February, 1890, there was the volcanic eruption at the island of Bogoslof in the Bering Sea. Three small islands were created in the immediate vicinity, and the island was raised 1,000 feet. Ashes were collected in Unalaska, about 40 miles distant.

On June 7, 1892, by a great outbreak of a volcano near the capital of the island of Great Sangir, South of the Philippines, some thousands of people were killed and immense quantities of ashes fell all over the island. The noise of the explosion was heard at Sandakan, 500 miles from Great Sangir.

An eruption of Mount Etna began on the night of July 8 and 9, 1892, and continued with more or less intensity all the month, and occasional outbreaks occurred afterwards. The eruption was notable for the enormous quantities of smoke and sand emitted.

Passing now to the period 1902 to 1904, the question whether the frightfully destructive eruption of Mt. Pelée, Martinique, May 8 and 20, 1902, and the simultaneous great activity of Soufriere, St. Vincent, produced a widely distributed haze in the earth's atmosphere cannot be certainly answered. On the one hand the measurements made at the Astrophysical Observatory of the Smithsonian Institution on the transmission of the earth's atmosphere in 1901, 1902 and 1903 show that during the latter part of 1902 and the whole of 1903 the transparency of the atmosphere was very decidedly below the normal. On the other hand, a measurement of the total intensity of the solar radiation made at this Observatory in Washington on October 15, 1902, gives a value of the intensity of 1.40 calories per square centimeter per minute, which is among the very highest observations of this kind which have been made at this station. It is of course possible, though unlikely, that the haze due to the eruption of Mount Pelée was not so quickly distributed towards the more northern latitudes as that of Mount Katmai in Alaska was this year towards more southerly ones, so that perhaps the effect reached Washington later than October 15, 1902. However, there were other volcanoes active about this time.

On October 24, 1902, there occurred the eruption of Santa Maria in Guatemala. The ashes from this volcano covered an area of more than 125,000 square miles. Pumice stone and ashes fell to a depth of eight inches or more in a region extending over about 2,000 square miles, within which the houses and farm buildings were crushed under the weight of the ejected material, and in some cases totally destroyed. Six thousand persons are believed to have been killed. The cloud from the volcano reached 18 miles in height and the sound of the explosion was heard at Costa Rica, 500 miles away. The whole side of the mountain was blown away, exposing a cliff, nearly perpendicular, 7,000 feet in height, and forming a crater three-quarters of a mile wide, seven-eighths of a mile long, and 1,500 feet deep.

In February and March, 1903, not less than 12 maximum eruptions took place from the very high and beautiful volcano of Colima in southern Mexico (altitude about 13,000 feet).[1] A photograph taken on March 7 shows the column of smoke projected to a height of about 17 miles.

From these records it seems to us probable that the decreased solar radiation of 1888 to 1893 was caused by the volcano of Bandai-San supplemented by Mayon, Vulcano Island and others, and that the depression of solar radiation whose maximum was in 1903 may be attributed to the volcano of Santa Maria in Guatemala, supplemented by that of Colima in Mexico.

Observations were made in 1901, 1902 and 1903 at the Astrophysical Observatory in Washington on the transmission of the atmosphere for different wave lengths. We take the following data from a summary of these measurements published by Mr. Abbot in 1903.[2]

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[1] See Journal of Geology, Vol. 11, for a finely illustrated description.

[2] Smithsonian Miscellaneous Collections (Quarterly Issue), Vol. 45, p. 79.

TABLE 4. COEFFICIENT OF ATMOSPHERIC TRANSMISSION FOR RADIATION FROM ZENITH SUN.

Date.	Transmission coefficients for unit air mass.										
	Wave-length.										
	0.40 μ	0.45 μ	0.50 μ	0.60 μ	0.70 μ	0.80 μ	0.90 μ	1.00 μ	1.20 μ	1.60 μ	2.00 μ
October 25, 1901	....	....	0.81	0.82	0.89	0.94	....	0.95	0.96	0.95	....
November 2, 1901	....	....	0.80	....	0.87	0.92	....	0.94	0.95	0.94	....
March 21, 1902	....	....	0.83	0.80	0.84	....	....	....	....	0.87	....
May 8, 1902	....	....	0.89	0.77	0.90	0.94	....	0.95	0.94	0.91	....
September 11, 1902	....	....	0.80	0.78	0.87	0.89	0.92	0.92	0.94	0.93	....
October 9, 1902	....	....	0.70	0.78	0.84	0.87	0.89	0.90	0.91	0.93	....
October 15, 1902	....	....	0.73	0.78	0.86	0.89	0.90	0.91	0.93	0.96	0.94
October 16, 1902	....	....	0.50	0.58	0.79	0.82	....	0.86	0.90	0.91	....
October 22, 1902	....	....	0.84	0.82	0.88	0.91	0.93	0.94	0.94	0.95	....
November 15, 1902	....	....	0.75	0.79	0.83	0.89	0.91	0.92	0.93	0.95	0.96
February 19, 1903	0.67	0.64	0.66	0.72	0.76	0.80	0.83	0.85	0.86	0.90	0.92
February 25, 1903	0.48	0.60	0.66	0.68	0.74	0.83	0.88	0.90	0.93	0.93	0.92
March 3, 1903	0.40	0.48	0.66	0.73	0.79	0.84	0.87	0.89	0.92	0.96	0.96
March 25, 1903	0.47	0.50	0.57	0.66	0.72	0.76	0.79	0.81	0.84	0.88	0.89
March 26, 1903	0.52	0.58	0.62	0.68	0.77	0.80	0.81	0.83	0.85	0.89	0.90
April 17, 1903	0.55	0.60	0.69	0.77	0.80	0.82	0.87	0.90	0.94	0.97	0.97
April 28, 1903	0.39	0.52	0.56	0.64	0.71	0.74	0.76	0.78	0.82	0.88	0.89
April 29, 1903	0.46	0.49	0.56	0.66	0.72	0.76	0.77	0.80	0.83	0.88	0.90
July 7, 1903	0.42	0.60	0.66	0.69	0.77	0.82	0.85	0.86	0.88	0.89	0.86
General mean	0.484	0.557	0.700	0.730	0.808	0.847	0.856	0.884	0.903	0.920	0.919
Mean of 1901-2	....	....	0.765	0.769	0.857	0.897	0.910	0.921	0.933	0.930	0.950
Mean of 1903	0.484	0.557	0.627	0.692	0.753	0.797	0.825	0.847	0.874	0.909	0.912
Percentage difference between mean of 1903 and that of 1901-2	....	....	20%	10%	13%	12%	10%	8.4%	6.5%	2.3%	4.1%

It appears that in 1903 as in 1912, the presence of volcanic haze caused a decrease of the transparency of the atmosphere, productive of nearly as much effect in the infra-red as in the visible spectrum.

VOLCANOES AND TERRESTRIAL TEMPERATURES

We have made some preliminary study to determine if the haziness produced by volcanoes causes a decreased temperature at the earth's surface.

Taking the year 1912, we find from the international ten-day mean values published by the German Marine Observatory that the high altitude stations of southwestern Europe, namely: Pic du Midi, Puy de Dôme, Brocken, Schneekoppe, Säntis, and Hoch-Obir give a very marked indication of a decrease in temperature with respect to the normal beginning about the middle of July. The seven stations named are very consistent with one another in this indication as shown in the table on page 20.

In order to see if a similar effect was caused by the dust cloud emanating from Krakatoa in 1883 we have studied the temperature departures for Pic du Midi, Puy de Dôme and Schneekoppe for the years 1882 to 1884 inclusive, but there does not appear to have been at that time any such marked decrease of temperature following the eruption of Krakatoa, August 27, 1883, as occurred in July, 1912. Nevertheless at Pic du Midi there was a very well marked decrease in the daily temperature range beginning with September, 1883. We have found for some other stations a similar decrease of the daily temperature range following the volcano of Krakatoa.

In table 6 temperature departures are given for seven stations of the United States for 1912. The stations selected are from the most cloudless region of the country. They are arranged in two groups with regard to whether they show a tendency to lower temperatures during and after July. Leadville and Flagstaff, two high stations, agree in this respect with the European high stations.

The temperature of the earth is a function of so many variable quantities that general or cosmical effects are often greatly obscured by local ones. From studies which have been made by various authors it appears, however, that there is a periodicity of terrestrial temperature corresponding in time to the sun-spot cycle of about eleven years. Koppen, Arctowski, Nordmann, Newcomb, Abbot and Fowle, and others have found that there is an increased temperature at the time of minimum sun spots. The increase of temperature is in fact

TABLE 5. TEMPERATURE DEPARTURES,[1] 1912. HIGH STATIONS S. W. EUROPE.

Station.	Month.																	Mean.
	February.			March.			April.			May.			June.			July.		
	Decade.			Decade.			Decade.			Decade.			Decade.			Decade.		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	
Pic du Midi	+1.6	+1.9	+6.6	+1.0	0.0	+4.8	+0.1	−0.7	−0.9	+3.2	+6.3	−1.4	−2.5	+1.1	+2.7	−2.3	+0.6	+1.24
Puy de Dôme	+1.5	+2.8	+7.1	+0.8	+0.1	+4.1	−0.6	−1.9	−0.3	+2.9	+6.2	−1.4	−2.0	+0.6	+0.6	−2.0	+2.9	+1.26
Brocken	−0.6	+5.4	+5.5	+3.1	+2.4	+2.4	−1.1	−2.1	+0.6	−0.7	−0.3	−3.1	+1.3	−2.4	+0.2	−1.0	+4.4	+0.82
Schneekoppe	0.0	+5.0	+4.7	+4.1	+0.9	+1.4	−2.4	−4.9	−1.6	−2.1	+0.1	−1.6	+1.4	−1.8	−0.3	−2.0	+1.1	+0.12
Säntis	+0.5	+2.6	+7.0	+1.4	−0.1	+2.0	−1.5	−3.6	−0.8	−0.4	+2.1	−0.9	−0.4	−0.7	+0.2	−1.2	+3.9	+0.60
Hoch-Obir	+1.2	+2.6	+4.4	+2.3	+1.2	+2.4	−0.3	−6.3	−2.5	.....	+2.3	−0.4	.....	−0.5	.....	−1.9	−0.3	+0.30
Mean of all	+0.70	+3.58	+5.88	+2.12	+0.75	+2.85	−0.97	−3.22	−0.92	+0.48	+2.78	−1.47	−0.52	−0.62	+0.57	−1.73	+2.10	+0.69

Station.	Month.																	Mean.
	July.			August.			September.			October.			November.			December.		
	Decade.			Decade.			Decade.			Decade.			Decade.			Decade.		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	
Pic du Midi	.....	.....	−2.8	−3.3	−3.5	−1.4	−1.2	−1.6	−2.6	−0.6	+1.0	−0.3	+1.1	−5.6	−1.0	.....	.....	−1.68
Puy de Dôme	.....	....	−1.3	−3.4	−4.5	−2.6	−5.3	−3.6	−2.9	−2.7	+0.3	−0.3	−2.9	−4.4	−2.4	.....	.....	−2.77
Brocken	.....	.....	+1.5	−2.4	−3.7	−2.1	−5.1	−2.6	−4.4	−3.9	−0.3	+0.5	−3.0	−0.9	−0.4	.....	.....	−2.06
Schneekoppe	.....	.....	+0.1	−1.6	−3.2	−3.4	−6.3	−6.9	−6.4	−4.5	−2.7	+0.1	−5.2	−3.0	−0.8	.....	.....	−3.37
Säntis	.....	.....	−0.7	−1.0	−3.8	−3.1	−6.2	−5.3	−5.4	−0.9	−0.2	−1.0	−4.5	−4.8	−2.3	.....	.....	−3.02
Hoch-Obir	.....	.....	−1.6	−1.8	−3.3	+1.0	−5.8	−6.6	−7.9	−2.9	.....	−0.5	−6.2	−2.8	−2.1	.....	.....	−3.38
Mean of all	.....	.....	−0.80	−2.25	−3.58	−2.10	−4.98	−4.43	−4.93	−2.58	−0.38	−0.25	−3.45	−3.58	−1.50	.....	.....	−2.68

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[1] Centigrade Scale.

greater than would be caused directly by the darkening of the sun by sun-spots, so that it is supposed that there is accompanying the spots some secondary influence affecting terrestrial temperatures. General fluctuations of temperature have also occurred which are not fully accounted for by the march of the sun-spots. We have endeavored to see whether a combination of the sun-spot influence with the effect of the volcanic haze on solar radiation will produce a more exact correspondence between the solar phenomena and the temperature of the earth.

Table 6. Temperature Departures[1] 1912. Cloudless Regions, United States.

Station.	Month.						Mean.
	Jan.	Feb.	March.	April.	May.	June.	
Leadville, Colo.	+0.5	−2.0	−0.6	−4.1	−0.5	−2.7	−1.57
Flagstaff, Ariz.	+1.6	+1.8	−1.7	−4.0	−1.9	−0.9	−0.85
Tucson, Ariz.	+0.7	−1.6	−2.9	−6.8	−2.4	+1.1	−1.98
Pueblo, Colo.	−3.0	+0.5	−7.2	−1.7	+0.1	−4.0	−2.55
Dodge, Kans.	−9.3	+0.9	−11.1	−1.6	+2.3	−5.0	−3.93
Santa Fe, N. Mex.	+0.4	−1.8	−1.8	−5.3	−1.3	−3.8	−1.93
El Paso, Tex.	+1.6	−2.5	−1.9	−4.7	−0.6	−1.8	−1.65

Station.	Month.						Mean.
	July.	Aug.	Sept.	Oct.	Nov.	Dec.	
Leadville, Colo.	−2.2	−1.8	−7.2	−1.8	+0.2	.....	−2.56
Flagstaff, Ariz.	−3.8	−1.6	−3.2	−0.9	+2.3	.....	−1.44
Tucson, Ariz.	−5.1	−2.7	−3.6	−3.8	−0.9	.....	−3.22
Pueblo, Colo.	−1.4	−0.1	−7.0	−0.9	+2.2	.....	−1.44
Dodge, Kans.	+0.9	0.0	−4.2	+1.6	+4.5	.....	+0.56
Santa Fe, N. Mex.	−0.5	+0.2	−2.5	−1.0	+1.0	.....	−0.56
El Paso, Tex.	+0.5	−0.8	−1.7	−0.2	−1.6	.....	−0.76

Referring to Fig. 3, the curve *A* is a smoothed representation of the average intensity of the direct solar radiation. The method of smoothing the curve is as follows, taking for example the year 1895: Add to the value for 1894 twice that for 1895 and that for 1896, and divide by 4. Curve *B* is the smoothed sun-spot curve as given by Wolfer. The sun-spot numbers run from 0 to about 80. Curve

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[1] Fahrenheit Scale.

C is a combination of *A* and *B*. They are taken in the following proportions: Multiply the percentage departure of radiation shown in *A* by 6[1] and subtract from it the sun-spot number for the given year. Curve *D* represents the departures of mean maximum temperature for 15 stations of the United States distributed all over the country. It is smoothed in the same manner as curve *A*. Curve *E* represents the departures of temperature for the whole world, also smoothed in the same manner as curves *A* and *D*. The data for the curves *D* and *E* are taken from Annals, Astrophysical Observatory, Vol. 2, p. 192, and from the *Monthly Weather Review*.

Although there is a considerable degree of correspondence between curve *B* and curve *D* yet it is not hard to see that there is also much discordance. For example, the sun-spot maximum of 1893 was greater than that of 1883 or 1906, yet the temperature curve *D* indicates a gradual increase of temperature for the three periods. Also the temperature had begun to fall in 1890, although sun-spots were still at the minimum; and the temperature had begun to rise in 1892, although sun-spots had not yet reached their maximum. Similar discrepancies occur in other parts of the curves.

When, however, we compare the curves *C* and *D*, that is to say, the combination of the effects of sun-spots and volcanic haze with the mean maximum temperature for the United States, the correspondence of the curve is most striking. It seems to us in consideration of this, that there can be little question that the volcanic haze has very appreciably influenced the march of temperature in the United States. When we take the march of temperature for the whole world the correspondence, though traceable, is not so striking; but in this case there are so many conflicting influences at work that it is perhaps too much to expect so good an agreement.

In view of this slight preliminary study of temperatures, it seems to us that the question of the effect of volcanic haze on terrestrial temperature is well worth serious consideration. Although a large group of stations may by their contrary local influences mask the influence of the haze, we believe it may be found eventually that temperatures are influenced, perhaps as much as several degrees, by great periods of haziness such as those produced by the volcanoes of 1883, 1888 and 1912.

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[1] Perhaps a better result would have come if 5 instead of 6 had been used.

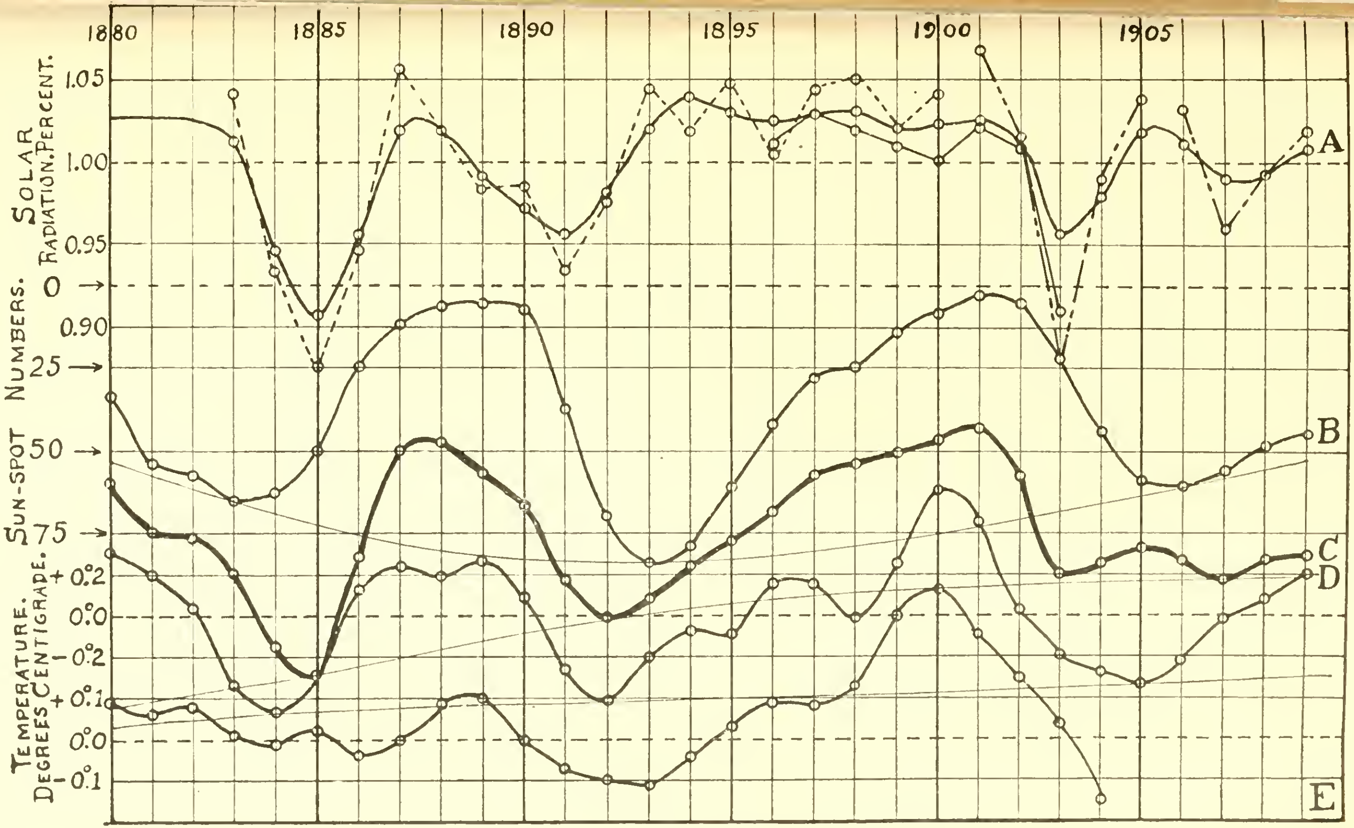

FIG. 3.—Solar radiation, sun-spots and temperatures.

A Observed and smoothed mean, annual, noon, solar radiation. (Kimball.) Volcanic effects, 1885, 1891, 1903.
B Wolfeis smoothed sun-spot numbers.
C Combined solar radiation and sun-spot numbers.
D Smoothed annual mean departures, United States maximum temperatures (15 stations).
E Smoothed annual mean departures, world temperatures (47 stations).

SUMMARY

The transparency of the atmosphere was much reduced in the summer of 1912 by dust from the volcanic eruption of Mount Katmai, June 6 and 7.

Evidence of the dust appeared at Bassour, Algeria, on or before June 19, and at Mount Wilson, California, on or before June 21.

The total direct radiation of the sun was reduced by nearly or quite 20 per cent at each of these stations when the effect reached its maximum in August.

In the ultra-violet and visible spectrum the effect was almost uniform for all wave-lengths, but was somewhat less in the infra-red.

From Bassour experiments, including measurements by two methods of the radiation of the sky, it appears that the quantity of heat available to warm the earth was diminished by nearly or quite 10 per cent by the haze. There is, however, some indication that this was in part counterbalanced by a decrease in the earth's radiation to space, caused by the haze.

Similar periods of haze followed great volcanic eruptions in former years. The influence of Krakatoa, Bandai-San, Mayon, Santa Maria, and Colima seems to have been recorded by measurements of solar radiation, and caused pronounced decrease in the direct solar beam from 1883 to 1885, 1888 to 1894, and 1902 to 1904.

Evidence is presented that the dust layer of 1912 affected terrestrial temperatures, especially of high stations.

A remarkable correspondence is found between the average departures of the mean maximum temperature for 15 stations of the United States and a curve representing a combination of the sun-spot numbers of Wolfer and the departures from mean values of the annual march of direct solar radiation from 1883 to 1909.