JOURNAL

OF

THE FRANKLIN INSTITUTE

DEVOTED TO SCIENCE AND THE MECHANIC ARTS

VOL. CLXXVI   AUGUST, 1913   No. 2

VOLCANIC DUST AND OTHER FACTORS IN THE PRODUCTION OF CLIMATIC CHANGES, AND THEIR POSSIBLE RELATION TO ICE AGES.*

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INTRODUCTION.

OLD lake beaches, glacial moraines, and various other geological records give indisputable evidence of numerous climatic changes. It appears, too, that these changes were irregular in their times of occurrence and irregular also in their intensity and duration. Many seem to have been mild and relatively fleeting, while a few were so profound and lasting as even to bring on ice ages and to cover extensive areas of the earth with glacial sheets, or, on the other hand, to melt these sheets away and to establish for long periods warm and genial climates over much the greater portion of the earth.

When this series of climatic changes began there is no sure means of knowing, for the records, especially those of glacial origin, grow gradually fainter and more scanty with increase

* Developed from an outline presented before the Astronomical and Astroph sical Society of America, at Cleveland, Ohio, January 1, 1913. Communicated by the author.

[NOTE.—The Frankl institute is not responsible for the statements and opinions advanced by contributors to the JOU NAL.]

of geologic age, and it is probable, therefore, that the effects of many of the earlier changes have long since been completely obliterated. But, however this may be, it is well-nigh certain that from the time of the earliest known of these changes down to the very present the series has been irregularly continuous, and the end, one might reasonably assume, is not yet. Change after change of climate in an almost endless succession, and even additional ice ages, presumably are still to be experienced, though, except small and fleeting changes to be noted below, when they shall begin, how intense they may be, or how long they shall last no one can form the slightest idea.

Numerous attempts, some of them invoking purely terrestrial and others extra-terrestrial or cosmical conditions, have been made to find a probable and at the same time an adequate physical basis for or cause of the known climatic changes of the distant past, and especially for those profound climatic changes that brought about the extensive glaciation that prevailed during the so-called ice ages; but nearly all the older suggestions have been definitely and finally abandoned, either because of inconsistency with known physical laws or abandoned because they are inadequate to meet the conditions imposed upon them by the results of geological investigations.

FACTS OF CLIMATIC CHANGES.

Among the more important facts with respect to climatic changes that appear to have been established, and which presumably, therefore, must be met by any theory that would account for such changes, or explain specifically the origin of ice ages, are the following:

(*a*) The climatic changes were several, probably many.

(*b*) They were simultaneous over the entire earth, and in the same sense; that is, colder everywhere at the same time (climatically speaking) or warmer everywhere.

(*c*) They were of unequal intensity.

(*d*) They probably were of irregular occurrence and of unequal duration.

(*e*) They, at least one or more, progressed with secondary variations of intensity, or with advances and retreats of the glacial edge.

(*f*) They have occurred from very early, probably from the earliest, geological ages down to the present, and presumably will continue irregularly to recur for many ages yet to come.

PRINCIPAL ICE-AGE THEORIES.

It would be easy to catalogue perhaps a score of more or less rational hypotheses in regard to the origin of the ice ages, and doubtless even a larger number that are quite too absurd ever to have received serious consideration, and to point out in each case the known and the suspected elements of weakness. But this would only be a repetition of what, in part at least, has often been done before and therefore could serve no good purpose.

As already stated, only a few of these hypotheses still survive, nor do all of even these few really merit the following they have. Apparently those which still claim each a large number of adherents are, respectively:

(*a*) *Croll's Eccentricity Theory.** This is based on the assumption that when the earth's orbit is most eccentric, or when the earth's maximum solar distance differs most from its minimum solar distance, ice will accumulate to a great extent over that half of the globe which has its winter during aphelion.

For some time Croll's theory was very generally accepted, and it seems still to have many adherents, despite the destructive criticisms of Newcomb [1] and Culverwell.[2]

The chief objections to Croll's theory are:

1. That the assumption that midwinter and midsummer temperatures are directly proportional to the sun's heat at these times is not at all in accord with observed facts.

2. That each ice age would be limited to a fraction of the precessional period, 21,000 years, which, according to most geologists, is too short a time. In fact, it is already longer than this whole period, according to the best evidence, since the culmination of the last ice age.

3. That the successive ice ages would have occurred *alternately* in the northern and southern hemispheres, instead of, as generally believed to have been the case, in both hemispheres *simultaneously*.

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* *Phil. Mag.*, 28, p. 121, 1864, and elsewhere.

[1] *Amer. Jr. Sci.*, 11, p. 263, 1876; *Phil. Mag.*, 17, p. 142, 1884.

[2] *Phil. Mag.*, 38, p. 541, 1894.

(*b*) *The Carbon Dioxide Theory.* This theory, advocated by Tyndall,[3] Arrhenius,[4] Chamberlain,[5] and others, is based on the selective absorption of carbon dioxide for radiation of different wave-lengths, and on its assumed variation in amount.

It is true that carbon dioxide is more absorptive of terrestrial than of solar radiations, and that it therefore produces a green-house or blanketing effect, and it is also probably true that its amount in the atmosphere has varied through appreciable ranges as a result of volcanic additions on the one hand, and of oceanic absorption and chemical combination on the other. But it is not possible to say exactly how great an effect a given change in the amount of carbon dioxide in the atmosphere would have on the temperature of the earth. However, by bringing a number of known facts to bear on the subject it seems possible to reach approximate conclusions. Thus from the experiments of Schlaefer[6] we know that at atmospheric pressure a column of carbon dioxide 50 centimetres long is ample for maximum absorption, since one of this length absorbs quite as completely as does a column 200 centimetres long at the same density. Also from the experiments of Ångström[7] and from those of E. v. Bahr[8] we know that the absorption of radiation by carbon dioxide or other gas increases with increase of pressure, and, what is of great importance, that both qualitatively and quantitatively this increase of absorption is exactly the same whether the given higher pressure be obtained by compression or by the addition of an inert gas.

Now the amount of carbon dioxide in the atmosphere is equivalent to a column of the pure gas, at ordinary room temperature and atmospheric pressure, of, roughly, 250 centimetres in length. Hence, according to the experiments just described of Ångström and E. v. Bahr, the carbon dioxide now in the atmosphere must absorb radiation very approximately as would a column 475 centimetres long of the pure gas at its average barometric pressure of, say, 400 millimetres. But Schlaefer's experiments above referred to show that such a column would

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[3] *Phil. Mag.*, 22, p. 277, 1861.

[4] *Phil. Mag.*, 41, p. 237, 1896.

[5] *Jr. Geol.*, 7, p. 545, 1899.

[6] *Ann. der Phys.*, vol. 16, p. 93, 1905.

[7] *Arkiv för Matematik, Astronomi och Fysik*, vol. 4, No. 30, 1908.

[8] *Ann. der Phys.*, vol. 29, p. 780, 1909.

be just as effective as one two or three times this length, and, on the other hand, no more effective than a column one-half or one-fourth as long.

Hence, finally, doubling or halving the amount of carbon dioxide now in the atmosphere, since this would make but little difference in the total pressure, would not appreciably affect the amount of radiation actually absorbed by it, whether of terrestrial or of solar origin.

Again, as already explained by Abbot and Fowle,[9] the water vapor always present in the atmosphere leaves, because of its high coefficients of absorption in substantially the same regions where carbon dioxide is effective, but little radiation for the latter to take up. Hence, for this reason, too, as well as for the one given above, either doubling or halving the present amount of carbon dioxide could alter but little the total amount of radiation actually absorbed by the atmosphere, and therefore, seemingly, could not appreciably change the average temperature of the earth, or be at all effective in the production of marked climatic changes.

Nevertheless, in spite of both the above objections, there appears to be at least one way by which a change, especially if a decrease, in the amount of carbon dioxide in the atmosphere might affect temperatures at the surface of the earth, so that we are not yet in position to say that no such change was ever an appreciable factor in the production of an ice age.

Further discussion of this particular point will be taken up later, after the introduction of certain observational evidence that seems to bear on the subject.

We will now return to the existing ice-age theories and consider briefly just two more before coming to the main body of the paper.

(*c*) *The Solar Variation Theory.* This is based on the assumption that the solar radiation has waxed and waned, either cyclically or irregularly, through considerable ranges and over long intervals of time.

This theory is seductively attractive,—it looks so simple, so sufficient, and so safe from attack. But if impossible to disprove, it is equally difficult to establish, and therefore it should conditionally be put aside, held in reserve, as it were, as a last

[9] Annals of the Astrophysical Observatory, Smithsonian Institution, vol. 2, p. 172, 1908.

resort, in favor of a more complete search for and examination of other possible causes, for, after all, the supposed solar changes, for which we can assign no probable cause or causes, may never have happened.

(*d*) *The Elevation Theory*. This theory assumes the simultaneous (geologically speaking) rise or fall of many, possibly all, land areas through a range that may have amounted to several thousand feet. It is argued that such movements would account for not only the phenomena of the ice ages, but also for, among other things, the many suboceanic canyons, such as that of the Hudson, the St. Lawrence, the Congo, and others.

This theory is mentioned here not because of the number of supporters it has at present, for obviously this number is not large, but because any such changes in elevation that it supposes, whether local or general, if they ever took place—and apparently great changes in elevation have occurred—must have affected the climates of the regions that so moved, and therefore must have been a factor—no one knows how great—in the production of at least regional, if not world-wide, climatic changes of the past.

These three theories, then, omitting *d*, which but few support, of the origin of the ice ages, namely: The eccentricity theory, the carbon dioxide theory, and the solar variation theory, are the only ones that at present appear to have many adherents, and even these few seem more likely to lose than to gain in number and strength of defenders. The first has failed utterly under searching criticism; the second has been sadly impaired; while the third, provokingly secure from all tests, is strong only as and to the extent that other theories are disproved or shown to be improbable.

The above introduction brings us to the essential purpose of this paper, to the discussion of a factor in the production of climatic changes including, possibly, even those great changes incident to the advance and retreat to maximum and minimum of glaciation. It may not have been the chief cause of our greatest climatic changes, or even a large contributing factor, but nevertheless a factor, possibly of large size, and therefore worthy of consideration.

The factor in question is

VOLCANIC DUST IN THE UPPER ATMOSPHERE.

After the outline of the following discussion had taken shape it was found, on looking up the appropriate literature, that the brothers P. and F. Sarasin [10] had suggested, a number of years ago, that the low temperature essential to the glaciation of ice ages was caused by the absorption of solar radiation by high volcanic dust-clouds.

But the idea that dust of this nature, when scattered through the atmosphere, may lower the temperature of the surface of the earth was already old, having been advanced at a much earlier date,—in fact, long before even the existence of ice ages had been suspected, much less attempts made to find their cause. Thus in May, 1784, Benjamin Franklin (and he may not have been the first) wrote as follows:

> During several of the summer months of the year 1783, when the effects of the sun's rays to heat the earth in these northern regions should have been the greatest, there existed a constant fog over all Europe, and great part of North America. This fog was of a permanent nature; it was dry, and the rays of the sun seemed to have little effect toward dissipating it, as they easily do a moist fog, arising from water. They were indeed rendered so faint in passing through it that, when collected in the focus of a burning-glass, they would scarce kindle brown paper. Of course, their summer effect in heating the earth was exceedingly diminished.
>
> Hence the surface was early frozen.
>
> Hence the first snows remained on it unmelted, and received continual additions.
>
> Hence perhaps the winter of 1783–4 was more severe than any that happened for many years.
>
> The cause of this universal fog is not yet ascertained. Whether it was adventitious to this earth, and merely a smoke proceeding from the consumption by fire of some of those great burning balls or globes which we happen to meet with in our course round the sun, and which are sometimes seen to kindle and be destroyed in passing our atmosphere, and whose smoke might be attracted and retained by our earth; or whether it was the vast quantity of smoke, long continuing to issue during the summer from Hecla, in Iceland, and that other volcano which arose out of the sea near that island, which smoke might be spread by various winds over the northern part of the world, is yet uncertain.
>
> It seems, however, worth the inquiry, whether other hard winters, recorded in history, were preceded by similar permanent and widely-extended summer fogs. Because, if found to be so, men might from such fogs con-

[10] *Verhandlungen der Naturforschenden Gesellschaft in Basel,* vol. 13, p. 603, 1901.

jecture the probability of a succeeding hard winter, and of the damage to be expected by the breaking up of frozen rivers in the spring; and take such measures as are possible and practicable to secure themselves and effects from the mischiefs that attend the last.[11]

The idea, then, that volcanic dust may be an important factor in the production of climatic changes is not new, though just how it can be so apparently has not been explained, nor has the idea been specificially supported by direct observations. This is not to be taken as a criticism of the above-mentioned pioneer paper by the brothers Sarasin, for indeed the arguments, now easy, were at that time impossible, because the observations upon which they largely are based had not then been made. Indeed the *absorption* of radiation by volcanic dust, by which they supposed the earth's temperature to be lowered, can now be shown to be, of itself alone, not only insufficient, but even productive, in all probability, of the opposite effect—of a warming instead of a cooling of the earth's surface.

To make this point clear: Consider a thin shell of dust about the earth and let I be the average intensity of the normal component of solar radiation on it. Further, let a be the dust's coefficient of absorption for solar radiation, independent, presumably, of intensity, and b its coefficient of absorption for terrestrial radiation. Obviously, in the case of equilibrium, all the energy absorbed by the dust is radiated away; half of it, very approximately, to the earth and half of it to space. Hence, starting with I as the solar radiation normally incident, per unit area and unit time, upon the dust layer, we have, if there is no reflection and no scattering,

aI = rate of absorption of solar radiation.

$I(1-a)$ = intensity of solar radiation reaching earth, or lower atmosphere.

$\frac{1}{2}aI$ = intensity of dust radiation, resulting from above absorption, reaching earth.

Summing these two radiations incident upon the earth, we have

$$I(1-a)+\frac{1}{2}aI=I\left(1-\frac{a}{2}\right).$$

Eventually, when equilibrium is established, the earth must lose the same amount of radiation that it gains, though, of

[11] See Sparks's "Life of Benjamin Franklin," vol. 6, 455-457 (cited in *Proceedings of the Amer. Phil. Soc.*, vol. 45, p. 127, 1906).

course, chiefly through a different spectral region, and therefore, after a time, assuming the earth to absorb all incident radiation,

$I\left(1-\frac{a}{2}\right)$ = the intensity of the outgoing as well as that of the incoming radiation.

Of this the dust absorbs, per unit area and unit time,

$$bI\left(1-\frac{a}{2}\right),$$

of which, in turn, one half is radiated to space and one half back to earth, there to be reabsorbed and again radiated. The intensity of the normal radiation now reaching the earth is

$$I\left(1-\frac{a}{2}\right)+\frac{b}{2}\,I\left(1-\frac{a}{2}\right),$$

of which the second term becomes, after a time, the increase in the intensity of the outgoing radiation. Hence, after further absorption and re-radiation by the dust layer, the next increment of radiation to the earth is

$$\left(\frac{b}{2}\right)^2 I\left(1-\frac{a}{2}\right),$$

and so on indefinitely.

In the end, then, when the ultimate equilibrium is attained, the intensity of the total normal radiation reaching the earth, I_e, is given by the equation,

$$I_e = I\left(1-\frac{a}{2}\right)\left\{1+\frac{b}{2}+\left(\frac{b}{2}\right)^2+\cdots+\left(\frac{b}{2}\right)^\infty\right\}$$

$$\text{or } I_e = I\left\{1+k\,(b-a)\right\} \quad \ldots\ldots\ldots \quad \text{(A).}$$

in which

$$k=\frac{1}{2}\left\{1+\frac{b}{2}+\left(\frac{b}{2}\right)^2+\cdots+\left(\frac{b}{2}\right)^\infty\right\}.$$

Now b is positive, and therefore k is also positive. Hence

$$I\left\{1+k\,(b-a)\right\} \gtreqless I,$$

according as $b \gtreqless a$.

That is to say, the total amount of radiation reaching the earth is increased, unchanged, or decreased by the surrounding dust layer according as the dust's coefficient of absorption of terrestrial radiation is greater than, equal to, or less than its coefficient of absorption of solar radiation.

Now in the case of many, if not all, rocky materials, such as make up the particles of volcanic dust, the coefficient of absorption is much greater for terrestrial radiation than for solar radiation,[12] or, in terms of the above symbols, in the case of volcanic dust b is greater than a. Hence, so far as mere absorption of radiation is concerned, the only action mentioned by the brothers Sarasin, a veil of volcanic dust, in all probability, would slightly *increase* and not decrease, as they supposed, the average temperature of the earth.

But, then, absorption is not the only effect of a dust veil on radiation; reflection and scattering both are important and must be fully considered.

These actions, however, reflection and scattering, depend fundamentally upon the ratio of the linear dimensions of the particles concerned to the wave-length of the incident radiation, and therefore, before undertaking to discuss them in this connection, it will be essential to determine the approximate size of the individual grains of floating volcanic dust, and also the average wave-lengths, weighted according to energy, of solar and of terrestrial radiation. It will be desirable, also, to consider whether or not, and if so how, dust of any kind can remain long suspended in the atmosphere. And this point will be examined first, since, obviously, the longer the dust can float the more important, climatically, it may have been in the past and in the future may again become.

Atmospheric Regions.—The atmosphere is divisible into the stratosphere and the troposphere; or the isothermal region and the convective region; or, in other words, the region, in middle latitudes, at and beyond about 11 kilometres above sea level where, being free from vertical convection, ordinary clouds never form and the turbulent, stormy region below this level which is frequently swept by clouds and washed by snow and rain. The

[12] Coblentz, Publications of Carnegie Institution of Washington, Nos. 65 and 97.

physical reason for or cause of the existence of the isothermal region is well known,[13] and is such that we feel quite sure that ever since the earth was warmed by solar radiation, as at present, rather than by internal heat, the temperature of its atmosphere beyond a certain level, whatever its composition, must have varied but little, as it now varies but little, with change of altitude, and therefore that this region must then have been free, as it now is free, from clouds and condensation. Obviously, then, in the past, as in the present, and as it must continue to be so long as the earth shall have an atmosphere, any volcanic or other dust, that by whatever process was gotten into and distributed through the isothermal region where there were no clouds or other condensation to wash it out, must have drifted about till gravity, overcoming the viscosity of the atmosphere, by slow degrees pulled it down to the region of clouds and storms. How long such a process must take depends, of course, upon a number of things, among which the size of the particles is vitally important. And this brings us to the next consideration.

Size of Volçanic Dust Particles.—For two or three years after the eruption of Krakatoa, in 1883, also after the eruptions of Mount Pelée and Santa Maria, in 1902, and again after the eruption of Katmai, in 1912, a sort of reddish-brown corona was often, under favorable conditions, observed around the sun. It was 10 degrees to 12 degrees wide, and had an angular radius, to the outer edge, of 22 degrees to 23 degrees. This phenomenon, known as Bishop's ring, clearly was a result of diffraction of sunlight by the particles of volcanic dust in the upper atmosphere, and therefore furnished a satisfactory means for determining the approximate size of the particles themselves. The subject has been rather fully discussed by Pernter,[14] who finds the diameter of the particles, assuming them spherical, to be approximately 185×10^{-6} cm., or 1.85 microns. The equation used has the form

$$r = \frac{m}{\pi} \frac{\lambda}{\sin \vartheta}$$

in which r is the radius of the dust particle, λ the wave-length of the diffracted light (here taken as 571×10^{-7} cm., or 0.571

[13] Humphreys, *Astrophys. Jr.*, 29, p. 14, 1909.
Gold, Proc. Roy. Soc., Series A, 82, p. 43, 1909.

[14] *Met. Zeit.*, 6, p. 401, 1889.

micron), ϑ the angular radius of the ring, and m a numerical term which for the outer edge of the ring, and successive minima, has the approximate values,

$$\frac{\pi}{2}(n + 0.22),$$

in which $n = 1,2,3,$—, respectively.

Now, since the width and angular dimensions of Bishop's ring, as seen at different times and under different circumstances, have varied but little, the above value, 1.85 microns, may provisionally be assumed to be the average diameter of those particles of volcanic dust that remain long suspended in the atmosphere.

Time of Fall.—The steady or terminal velocity of a sphere falling in a fluid, assuming no slip between fluid and sphere, is given by Stokes's [15] equation:

$$V = \frac{2}{9} g r^2 \frac{(\sigma - \rho)}{\mu},$$

in which V is the velocity of the fall, g the acceleration of gravity, r the radius of the sphere, σ the density of the sphere, ρ the density of the fluid, and μ its viscosity.

However, there always is slip, so that the actual velocity of fall is, according to Cunningham,[16]

$$V = \frac{2}{9} g r^2 \frac{(\sigma - \rho)}{\mu} \left(l + A \frac{l}{r}\right),$$

in which l is the free path of the gas molecules, A a constant, and the other symbols as above explained.

Obviously l, other things being equal, is inversely proportional to the gas density, or pressure, if temperature is constant. Hence

$$V = \frac{2}{9} g r^2 \frac{(\sigma - \rho)}{\mu} \left(l + \frac{B}{rp}\right) \cdots (1).$$

in which B is a constant for any given temperature, p the gas pressure, or, if preferred, barometric height.

Now a series of valuable experiments by McKeehan [17] has shown that for 21° C., and when p is the pressure in terms of millimetres of mercury,

$$B = .0075 \pm 3.$$

[15] *Math. and Phys. Papers,* vol. 3, p. 59.

[16] Proc. Roy. Soc., 83 A, p. 357, 1910.

[17] *Phys. Rev.,* 33, p. 153, 1911.

The value of μ, for dry air, is also closely known from the careful work of Breiterbach,[18] Schultze,[19] and Fischer,[20] all of whom obtained substantially the same values. At 26° C., as computed by Millikan [21] from the results obtained by these observers,

$$\mu = 1863 \times 10^{-7}.$$

Therefore, remembering that μ varies as the square root of the absolute temperature, it is easy to compute, by the aid of equation (1), the velocity of fall of volcanic dust, assuming gravity to be the only driving force. There is, of course, radiation pressure, both toward and from the earth, as well as slight convective and other disturbances, but presumably gravitation exerts the controlling influence.

The following table of approximate velocities and times of fall for volcanic dust was computed by substituting in equation (1) the given numerical values, namely:

$g = 981 \frac{\text{cm.}}{\text{sec.}}$

$r = .000092$ cm.

$\sigma = 2.3$, approximate density of Krakatoa dust.

$\rho = 0$, being negligible relative to σ.

$\mu = 1760 \times 10^{-7}$, appropriate to $-55°$ C., roughly the temperature, in middle latitudes, of the isothermal region.

$B = .0056$, appropriate to $-55°$ C.

p = millimetres barometric pressure.

Velocity and time of fall.

Height in kilometres	Barometric pressure[22]	Centimetres per second	Seconds per centimetre
40	1.84	0.82173	1.2170
30	8.63	0.19419	5.2695
20	40.99	0.05992	16.690
15	89.66	0.04048	24.703
11*	168.00	0.03280	30.44
0	760.00	0.02522†	39.65†

* Isothermal level of middle latitudes.

† Temperature 21° C.

According to this table it appears that spherical grains of sand of the size assumed, 1.85 microns in diameter, would re-

[18] *Ann. der Phys.*, 5, p. 168, 1901.

[19] *Ann. der Phys.*, 5, p. 557, 1901.

[20] *Phys. Rev.*, 28, p. 104, 1909.

[21] *Phil. Mag.*, 19, p. 215, 1910.

[22] Humphreys, JOURNAL OF THE FRANKLIN INSTITUTE, 165, p. 215, 1913.

quire more than one year to fall from only that elevation already reached by balloons, 37.7 kilometres, down to the under surface of the isothermal region, at the height of 11 kilometres.

As a matter of fact, volcanic dust, at least much of it, consists of thin-shelled bubbles or fine fragments of bubbles, and therefore must settle much slower than solid spheres, the kind above assumed. Indeed, the finest dust from Krakatoa, which reached a great altitude, probably not less than 40 nor more than 80 kilometres, was from two and a half to three years in reaching the earth, or, presumably, as above explained, the upper cloud levels.

At any rate, volcanic dust is so fine, and the upper atmosphere above 11 kilometres so free from moisture and vertical convection, that once such dust is thrown into this region, as it obviously was by the explosions of Skaptar Jökull and Asamayama in 1783, Babuyan in 1831, Krakatoa in 1883, Santa Maria and Pelée in 1902, Katmai in 1912, and many others, it must require, as a rule, because of its slow descent, from one to three years to get back to the earth. And this clearly has always been the case since the earth first assumed substantially its present condition, or had a cool crust and a gaseous envelope.

Obviously, then, we have only to determine the present action of such dust on incoming solar and outgoing terrestrial radiation in order to reach a logical deduction as to what its effect on climate must have been if, through extensive volcanic activity, it ever for a long or even considerable term of years more or less continuously filled the upper atmosphere, as conceivably may have happened. And the same conclusion in regard to the possible effect of dust on the climates of the past clearly applies with equal force to the climates of the future.

Action of Dust on Solar Radiation.—Since solar radiation at the point of maximum intensity [23] has a wave-length less than 5×10^{-5} cm., or half a micron, and since fully three-fourths of the total solar energy belongs to spectral regions whose wave-lengths are less than 10^{-4} cm., or one micron, it follows that the cubes of solar wave-lengths must, on the whole, be regarded as small in comparison with the volume of a volcanic dust particle—the diameter of which, as we have seen, is nearly 2 microns.

[23] Abbot and Fowle, Annals Astrophys. Obsy., Smithsonian Inst., vol. 2, p. 104, 1908.

Hence, in discussing the action of volcanic dust on incoming solar radiation, we can, with more or less justification, assume the particles to be opaque through reflection or otherwise, and therefore use Rayleigh's [24] arguments as applied to a similar case.

Let r be the radius of the particle, n the number of particles per cubic centimetre, and a the projected joint area of these particles. Then, for random and sparsely-scattered particles,

$$a = n\pi r^2$$

Hence, on dividing a plane parallel to the wave front into Fresnel zones, we see that for each centimetre traversed the amplitude of the radiation is reduced in the ratio of 1 to $1 - n\pi r^2$, therefore, if A is the initial amplitude, and A_x the amplitude after passing through x centimetres of the uniformly dusty region, we have, assuming $n\pi r^2$ to be only a small fraction of a square centimetre,

$$A_x = A(1 - n\pi r^2)^x = Ae^{-n\pi r^2 x}$$

Further, if I is the initial and I_x the final intensity, then

$$I_x = Ie^{-2n\pi r^2 x}$$

Hence, in the case of volcanic dust, where, as already explained, $r = 92 \times 10^{-6}$ centimetres,

$$A_x = Ae^{-n\pi x (92)^2 10^{-12}}$$

and

$$I_x = Ie^{-2n\pi x (92)^2 10^{-12}}$$

Presumably the particles of dust are not absolutely opaque and therefore I_x probably is a little larger than the value here given, though even so this value is at least a first approximation.

Action of Dust on Terrestrial Radiation.—Terrestrial radiation, at the point of maximum intensity, has a wave-length of, roughly, 12×10^{-4} centimetres, and therefore the wave-lengths of nearly all outgoing radiation are large in comparison with the diameters of those volcanic dust particles that remain long suspended in the atmosphere. Hence, while such particles largely *reflect* solar radiation, as is obvious from the whiteness

[24] *Phil. Mag.*, 47, p. 375, 1899.

of the sky when filled by them, they can only *scatter* radiation from the earth, according to the laws first formulated by Rayleigh,[25] whose papers must be consulted by those who would fully understand the equations which here will be assumed and not derived.

Let E be the intensity of terrestrial radiation as it enters the dusty shell, or as it enters the isothermal region, and E_y its intensity after it has penetrated this region, supposed uniformly dusty, a distance y centimetres; then, remembering that the dust particles are supposed to be spherical, we have

$$E_y = Ee^{-hy}$$

where

$$h = 24\pi^3 n \frac{(K' - K)^2}{(K' + 2K)^2} \quad \frac{T^2}{\lambda^4},$$

in which n is the number of particles per cubic centimetre, K the dielectric constant of the medium, K' the dielectric constant of the material of the particles, T the volume of a single particle, and λ the wave-length of the radiation concerned.

But $K = 1$, and, since the dust seems generally to be a kind of a glass, it may not be far wrong to assume that $K' = 7$. Hence, with these values,

$$h = 11\pi^3 n \; \frac{T^2}{\lambda^4}, \text{ nearly.}$$

Relative Action of Dust on Solar and Terrestrial Radiation.—To determine whether such a dust layer as the one under discussion will increase or decrease earth temperatures it is necessary to compare its action on short wave-length solar radiation with its action on long wave-length radiation from the earth.

In the case of solar radiation, as explained,

$$I_x = Ie^{-2n\pi x(92)^2 10^{-12}}$$

Clearly, then, the intensity of the solar radiation is reduced in the ratio of 1 to e, or

$$I_x : I = 1 : e$$

when $$x = \frac{10^{12}}{2n\pi(92)^2} \text{ centimetres} = \frac{188}{n} \text{ kilometres, approximately.}$$

[25] *Loc. cit.*

On the other hand, in the case of terrestrial radiation, where

$$E_y = Ee^{-11\pi^3 n \frac{T^2}{\lambda^4} y},$$

the intensity is reduced in the ratio of $1 : e$, or

$$E_y : E = 1 : e,$$

when $$y = \frac{\lambda^4}{11\pi^3 n T^2} \text{ centimetres,}$$

in which $$T = \frac{4}{3}\pi\,(92)^3\,10^{-18}$$

and $\lambda = 12 \times 10^{-4}$, the region of maximum intensity.

Hence $$y = \frac{5700}{n} \text{ kilometres, approximately.}$$

Therefore, finally,

$$y : x = 30 : 1, \text{ roughly,}$$

or the shell of volcanic dust, the particles all being the size given, is some thirty-fold more effective in shutting solar radiation out than it is in keeping terrestrial radiation in. In other words, the veil of dust produces an inverse green-house effect, and hence, if the dust veil were indefinitely maintained, the ultimate equilibrium temperature of the earth would be lower than it is when no such veil exists.

The ratio 30 to 1 in favor of terrestrial radiation in its ability to penetrate the dusty atmosphere may at first seem quite too large, but it should be remembered that the dust particles in question are to terrestrial radiation in general as air molecules are to solar radiation, in the sense that in both cases but little more than mere scattering takes place. Now it is obvious that the dust particles are many-fold more effective in intercepting solar radiation, which they appear to do chiefly by reflection, than are an equal number of air molecules which simply scatter it; and hence it may well be that the above theoretically-determined ratio, 30 to 1, is no larger than the ratio that actually exists, or, at any rate, that it is of the correct order.

It must be distinctly understood that certain of the assumptions upon which the foregoing is based, uniformity of size, complete opacity and sphericity of the dust particles, for instance, are only approximately correct, but they are the best that at present can be made, and doubtless give at least the order of magnitude of the effects, which indeed, for the present purpose, is quite sufficient.

It may be well, in this connection, to call attention to the fact that excessively fine dust particles, or particles whose diameters are half, or less, the wave-length of solar radiation (region of maximum intensity), and which therefore remain longest in suspension, shut out solar radiation many-fold more effectively than they hold back terrestrial radiation. This is because both radiations, solar and terrestrial, are simply scattered by such small particles, and scattered according to the inverse fourth power of the wave-length.

Now the ratio of solar wave-length to terrestrial wave-length (region of maximum intensity in both cases) is roughly 1 to 25, and therefore the ratio of their fourth powers as 1 to 39×10^4, about. Hence, in the case of the very finest and therefore most persistent dust, the interception of outgoing radiation is wholly negligible in comparison with the interception of incoming solar radiation.

Let us next see what observational evidence, pyrheliometric or otherwise, we have bearing on the effect of volcanic dust on radiation.

Pyrheliometric Records.—Direct measurement of solar radiation by means of the pyrheliometer shows marked fluctuations from year to year in the intensity of this radiation as received at the surface of the earth. This subject has been carefully studied by Dr. H. H. Kimball,[26] of the United States Weather Bureau, and Fig. 1, kindly prepared by him for use in this article, graphically represents the course of pyrheliometric readings from the beginning of 1883 till and including April, 1913. The yearly values are given in terms of the average value for the entire period, and, therefore, percentages of this average do not represent the full effect of the disturbing causes, of which volcanic dust certainly is the chief.

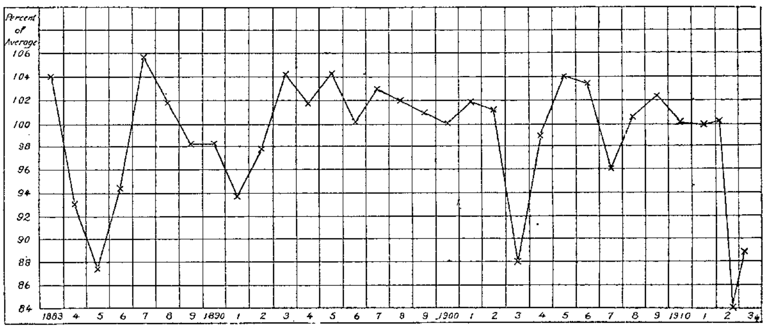
The marked decrease in the pyrheliometric readings for 1884, 1885, and 1886 doubtless were largely, if not almost wholly, due to the eruption of Krakatoa in the summer of 1883; the decreased values of 1888 to 1892 inclusive occurred during

[26] Bull. Mt. Weather Obsy., 3, p. 69, 1910.

a period of exceptional volcanic activity, but were most probably due essentially to the violent eruptions of Bandaisan (1888), Bogoslof (1890), and Awoe, on Great Sangir (1892); the low values of 1903 to the eruptions of Santa Maria, Pelée, and Colima; and the present low values, 1912–1913, to the recent (1912) explosion of Katmai.

There is then abundant pyrheliometric evidence that volcanic dust in the upper atmosphere actually does produce that decrease in direct solar radiation that theory indicates it should, and,

FIG. 1.



Annual average pyrheliometric values.

as the theory is well founded and the observations carefully taken, this mutual confirmation may be regarded as conclusive both of the existence of volcanic dust in the upper atmosphere (isothermal region) and of its efficiency in intercepting direct radiation from the sun.

It should be remembered, however, in this connection, that the intensity of the solar radiation at the surface of the earth depends upon not only the dustiness of the earth's atmosphere, but also upon the dustiness, and, of course, the temperature, of the solar atmosphere.

Obviously, dust in the sun's envelope must more or less shut in solar radiation just as, and in the same manner that, dust in the earth's envelope shuts it out. Hence it follows that when this dust is greatest, other things being equal, the output of solar energy will be least, and that when the dust is least, other things being equal, the output of energy will be greatest.

Not only may the intensity of the emitted radiation vary because of changes in the transparency of the solar atmosphere, but also because of any variations in the temperature of the effective solar surface, which, it would seem, might well be hottest when most agitated, or at the times of spot maxima, and coolest when most quiescent, or at the times of spot minima.

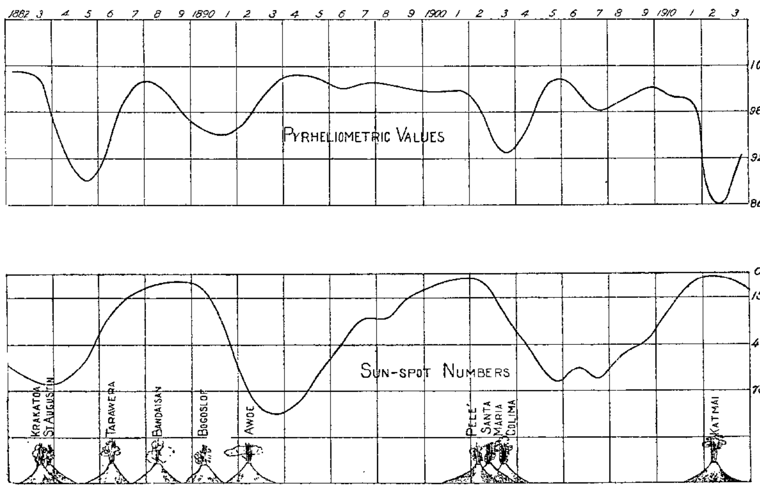
Now the dustiness of the solar atmosphere, manifesting itself as a corona, certainly does vary through a considerable range from a maximum when the sun-spots are most numerous to a minimum when they are fewest, and therefore, partly because of changes in the transparency of the solar envelope, and partly because of changes in the solar surface temperatures, if, as in all probability they do, such temperature changes take place, we should expect the solar constant also to vary from one value at the time of spot maximum to another at the time of spot minimum, and to vary as determined by the controlling factor, dust or temperature.

If the above reasoning is correct, it follows that pyrheliometric readings are functions of, among other things, both the solar atmosphere and our own terrestrial atmosphere; and as the former is altered chiefly by sun-spots or at least varies with their production and existence, and the latter by volcanic explosions, a means is at hand for comparing the relative importance of the two radiation screens.

Fig. 2 shows one such comparison. The upper curve gives smoothed annual average pyrheliometric readings (not solar constants, though closely proportional to them) and the lower curve sun-spot numbers. It will be noticed that in their most pronounced features the two curves have but little in common, and that the great drops in the pyrheliometric values occur simultaneously with violent volcanic explosions, as already explained, and not at the times of sun-spot changes. Hence it appears that the dust in our own atmosphere, and not the condition of the sun, is the controlling factor in determining the magnitudes and times of occurrence of great and abrupt changes of insolation intensity at the surface of the earth.

This is what the curves positively show, but it is not all they indicate. From 1894 to 1901 there were no volcanic explosions, so far as known, of importance, and therefore during this time the upper atmosphere must have been more or less uniformly free from dust. But there seems to have been, during this interval, a slow decrease in the pyrheliometric values, and presumably, therefore, in the solar constant; also during exactly this same interval the number of sun-spots slowly decreased. Again, from 1905 to 1911 the same general trends of the curves, a decrease in the pyrheliometric values simultaneously with a decrease in the number of sun-spots, repeat themselves. Hence the indication—it is impossible yet to call it a certainty—seems to be that the solar constant, and hence, presumably, the effective surface temperature of the sun, is a little, though not much, greater at the times of spot maxima than at the times of spot minima.

FIG. 2.



Relation of pyrheliometric values to sun-spot numbers and volcanic eruptions.

Surface Temperatures.—If a veil of dust actually should intercept as much as one-fifth of the direct solar radiation, as Fig. 1 indicates that at times it does, it would seem that in those years the surface temperatures of the atmosphere should be somewhat below the normal. Of course, the great supply of heat in the ocean would produce a lag in this effect, and, besides, there must be both an increase of sky light by scattering and some interception of earth radiation by the dust which, since it is at great altitudes, receives the full, or nearly the full, planetary radiation of the earth. This increase of sky radiation, together with the return terrestrial radiation, obviously compensates in some measure for the loss of direct insolation.

However, measurements made by Abbot[27] at Bassour, Algeria, during the summer of 1912, show that at this time and place the direct radiation and the sky radiation, which obviously included both the scattered solar radiation and some return terrestrial radiation, were together less by about 10 per cent. than their normal combined values; and there is no reason to think that in this respect Bassour was at all different from other places, probably the whole earth, covered by the veil of dust. Clearly, then, if this decrease in the radiation received should continue indefinitely, the ultimate radiation of the earth would also decrease to the same extent, or 10 per cent. Now, since the earth, or rather the water vapor of the atmosphere, radiates substantially as a black body and therefore as the fourth power of its absolute temperature, it follows that a 10 per cent. change in its radiation would indicate about a 2.5 per cent. change in its temperature. But the effective temperature of the earth as a full radiator, which it closely approaches, is about 256° C.[28] Hence a change of 10 per cent. in the radiation emitted would imply 6.4° C. change in temperature, an amount which, if long enough continued, would be more than sufficient to produce glaciation equal to the most extensive of any known ice age.

As above implied, not much lowering of the temperature could be expected to take place immediately, but, still, some cooling might well be anticipated. To test this point the temperature records of a number of high altitude (together with two or three very dry) inland stations have been examined. High altitudes were chosen because it might be expected that the temperature contrast between normal and dusty years would be greatest where the amount of atmosphere traversed below the dust layer is least; and the condition that the stations should also be inland was imposed because these are freer, presumably, than many coast stations, from fortuitous season changes. Thus, stations in the eastern portion of the United States are rejected because of the great differences in the winters, for example, of

[27] Smithsonian Miscellaneous Collections, vol. 60, No. 29, 1913.

[28] Abbot and Fowle, Annals Astrophys. Obsy., Smithsonian Institution, vol. 2, p. 175, 1908.

this section depending upon conditions wholly independent, so far as known, of variations in the intensity of direct radiation.

The number of stations was still further limited by the available recent data. Hence the records finally selected, and kindly put in shape by the Climatological Division of the United States Weather Bureau, Mr. P. C. Day in charge, for use in this article, were obtained at the following places:

TABLE I.

STATIONS WHOSE DATA WERE USED.

Name.	Latitude.	Longitude.	Elevation in feet.
America.			
Baker	44° 46′ N.	117° 50′ W.	3,466
Bismarck	46° 47′ N.	100° 38′ W.	1,674
Cheyenne	41° 08′ N.	104° 48′ W.	6,088
Denver	39° 45′ N.	105° 00′ W.	5,291
Dodge City	37° 45′ N.	100° 00′ W.	2,509
El Paso	31° 47′ N.	106° 30′ W.	3,762
Helena	46° 34′ N.	112° 04′ W.	4,110
Huron	44° 21′ N.	98° 14′ W.	1,306
North Platte	41° 08′ N.	100° 45′ W.	2,821
Red Bluff	40° 10′ N.	122° 15′ W.	332
Sacramento	38° 35′ N.	121° 30′ W.	69
Salt Lake City	40° 46′ N.	111° 54′ W.	4,360
San Antonio	29° 27′ N.	98° 28′ W.	701
Santa Fe	35° 41′ N.	105° 57′ W.	7,013
Spokane	47° 40′ N.	117° 25′ W.	1,929
Winnemucca	40° 58′ N.	117° 43′ W.	4,344
Yuma	32° 45′ N.	114° 36′ W.	141
Europe.			
Mont Ventoux	44° 10′ N.	5° 16′ E.	6,234
Obir	46° 30′ N.	14° 29′ E.	6,716
Pic du Midi	42° 56′ N.	0° 8′ E.	9,380
Puy de Dôme	45° 46′ N.	2° 57′ E.	4,813
Säntis	47° 15′ N.	9° 20′ E.	8,202
Schneekoppe	50° 44′ N.	15° 44′ E.	5,359
Sonnblick	47° 3′ N.	12° 57′ E.	10,190
India.			
Simla	31° 6′ N.	77° 12′ E.	7,232

In Table II the first column gives the year in question. The second column gives the average departure in degrees F., for the seventeen American stations, of the annual average maximum, as determined from the monthly average maxima, from the normal annual maximum, or average of a great many annual average maxima. The third column gives smoothed values, determined from the actual values in the second column as follows:

$$S = \frac{a + 2b + c}{4},$$

in which S is the smoothed value, b the actual value pertaining to the particular year for which S is being computed, a and c the actual values for the next previous and the next succeeding years respectively. The fourth and fifth columns give respectively the actual and the smoothed average departures of the annual average minima, while the sixth and seventh columns give the corresponding average departures of the annual average means.

TABLE II.

AVERAGE TEMPERATURE DEPARTURES FROM TEMPERATURE NORMALS.

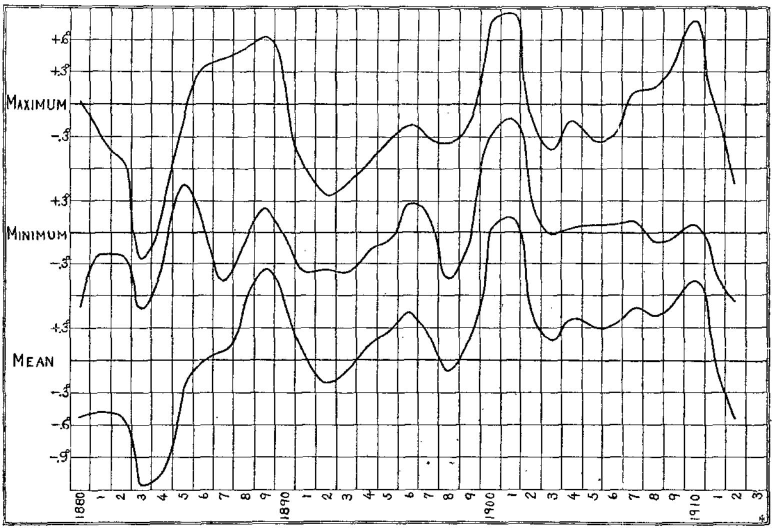
America.

Year.	Maxima. Actual.	Maxima. Smoothed.	Minima. Actual.	Minima. Smoothed.	Means. Actual.	Means. Smoothed.
1880........	−1.3	+0.03	−1.8	−0.68	−1.7	−0.50
1881........	+0.2	−0.30	+0.6	−0.20	+0.1	−0.48
1882.......	−0.3	−0.50	−0.2	−0.20	−0.4	−0.50
1883........	−1.6	−1.33	−1.0	−0.70	−1.3	−1.15
1884........	−1.8	−1.20	−0.6	−0.28	−1.6	−1.05
1885........	+0.4	−0.18	+1.1	+0.43	+0.3	−0.30
1886........	+0.3	+0.35	+0.1	+0.10	−0.2	−0.03
1887........	+0.4	+0.38	−0.9	−0.45	0.0	+0.07
1888........	+0.4	+0.53	−0.1	−0.13	+0.5	+0.53
1889........	+0.9	+0.63	+0.6	+0.23	+1.1	+0.85
1890........	+0.3	+0.15	−0.2	−0.05	+0.7	+0.58
1891........	−0.9	−0.58	−0.4	−0.38	−0.2	+0.05
1892........	−0.8	−0.85	−0.1	−0.33	−0.1	−0.20
1893........	−0.9	−0.73	−0.7	−0.38	−0.4	−0.08
1894........	−0.3	−0.55	+0.4	−0.18	+0.6	+0.13
1895........	−0.7	−0.35	−0.8	−0.08	−0.3	+0.25
1896........	+0.3	−0.18	+0.9	+0.28	+1.0	+0.45
1897........	−0.6	−0.30	+0.1	+0.13	+0.1	+0.28
1898........	−0.3	−0.65	−0.6	−0.45	−0.1	−0.13
1899........	−0.8	−0.13	−0.7	−0.10	−0.4	+0.25
1900........	+1.4	+0.78	+1.6	+0.90	+1.9	+1.23
1901........	+1.1	+0.83	+1.1	+1.08	+1.5	+1.35
1902........	−0.3	−0.13	+0.5	+0.38	+0.5	+0.53
1903........	−1.0	−0.43	−0.6	−0.05	−0.4	+0.18
1904........	+0.6	−0.15	+0.5	+0.05	+1.0	+0.38
1905........	−0.8	−0.30	−0.2	+0.08	−0.1	+0.33
1906........	−0.2	−0.30	+0.2	+0.08	+0.5	+0.33
1907........	0.0	+0.10	+0.1	+0.10	+0.4	+0.50
1908........	+0.6	+0.15	0.0	−0.08	+0.7	+0.43
1909........	−0.6	+0.38	−0.4	−0.05	−0.1	+0.55
1910........	+2.1	+0.80	+0.6	+0.08	+1.7	+0.75
1911........	−0.4	+0.03	−0.5	−0.35	−0.3	+0.05
1912........	−1.2	−0.70	−1.0	−0.63	−0.9	−0.53

Fig. 3 shows the graphical equivalents of the smoothed portions of Table II.

It will be noticed that the three curves of Fig. 3, marked max., min., and mean respectively, are, in general, quite similar to each other. Hence, because of this mutual check and general agreement, we feel reasonably certain that any one set of tem-

FIG. 3.



Smoothed averages of the annual average temperature departures of 17 American stations.

perature data, the means for instance, furnishes a fairly safe guide to the actual temperature and climatic fluctuations from year to year or period to period.

Table III gives the weighted actual average departures and the smoothed departures in degrees F. of the annual mean temperatures of the selected seventeen American, seven European, and one Indian stations listed in Table I.

The average departures were calculated in accordance with the more or less correctly coefficiented equation,

$$D = \frac{4A + 2E + I}{7},$$

in which D is the weighted departure, A the smoothed average American, E the smoothed average European, and I the smoothed

Indian departure of the mean annual temperature from the normal annual temperature.

Table III, extended, as well as the scanty early data, mainly from the given stations, will permit, back to 1872, is graphically represented by the continuous light curve at the bottom of Fig. 4. In 1880 and again in 1901 the curve probably does not very closely represent world-wide temperature departures, being, presumably, at both places quite too low, owing, in each case, to an abnormally cold single month in America.

TABLE III.

WEIGHTED DEPARTURES OF MEAN TEMPERATURES FROM NORMAL TEMPERATURES.

World.

Date.	Actual.	Smoothed.	Date.	Actual.	Smoothed.
1872	−0.78	−0.30	1893	−0.34	−0.06
1873	−0.65	−0.47	1894	+0.34	+0.03
1874	+0.20	−0.34	1895	−0.21	+0.10
1875	−1.12	−0.61	1896	+0.49	+0.28
1876	−0.40	−0.60	1897	+0.34	+0.45
1877	−0.48	−0.32	1898	+0.61	+0.46
1878	+0.07	0.00	1899	+0.27	+0.59
1879	+0.33	+0.04	1900	+1.19	+0.76
1880	−0.50	−0.13	1901	+0.40	+0.55
1881	+0.14	−0.02	1902	+0.20	+0.13
1882	+0.14	−0.16	1903	−0.30	+0.10
1883	−1.04	−0.68	1904	+0.81	+0.20
1884	−0.79	−0.61	1905	−0.51	+0.01
1885	+0.17	−0.09	1906	+0.23	+0.05
1886	+0.11	+0.03	1907	+0.23	+0.30
1887	−0.29	−0.05	1908	+0.51	+0.21
1888	+0.26	+0.24	1909	−0.43	+0.11
1889	+0.74	+0.57	1910	+0.69	+0.30
1890	+0.54	+0.40	1911	+0.23	+0.09
1891	−0.21	+0.06	1912	−0.80	−0.40
1892	+0.10	−0.09			

From 1907 to 1911 the dotted curve gives the average temperature departures for the American stations only, and presumably represents world temperature departures much more closely than does the continuous light line for the same time. This is because of two or three exceptionally cold summer months in Europe.

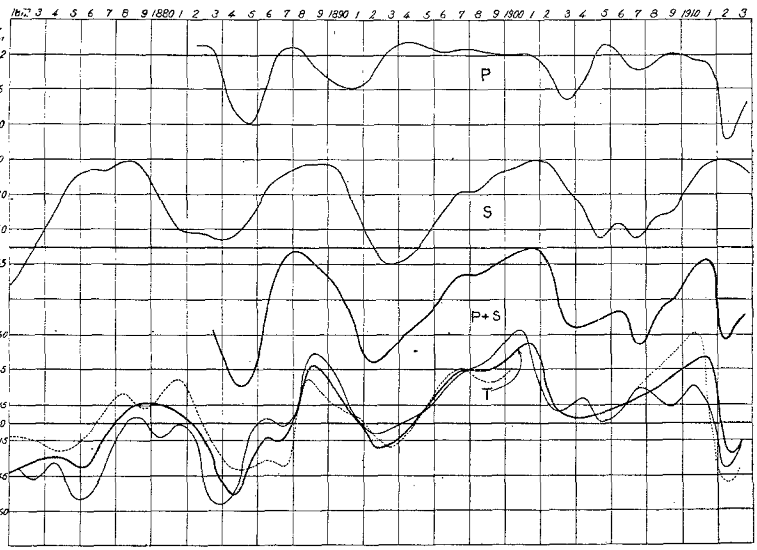
The dotted curve from 1872 to 1900 gives the smoothed averages of the annual temperature departures from the normal temperatures of the following stations as computed from the actual departures given by Nordmann:[29] Sierra Leone, Recife

[29] *Revue Général des Sciences,* August, 1903, pp. 803–808.
Annual Report, Smithsonian Institution, 1903, pp. 139–149.

(or Pernambuco), Port au Prince, Trinité, Jamaica, Habana, Manila, Hong Kong, Zikawei, Batavia, Bombay, Island of Rodriguez, Island of Mauritius.

All these, or practically all, are low-level stations, and most of them either tropical or semi-tropical, and therefore should show in general a smaller temperature range than the high altitude stations whose temperature departures are given by the continuous fine line curve. Hence, all things considered, the average temperature departures as calculated from the two sets

FIG. 4.



Smoothed pyrheliometric, sun-spot, and temperature curves.

of stations agree remarkably well, so that one can say with a fair degree of confidence that the heavy curve *T* approximately represents the average of the departures of the mean annual temperatures from the normal annual temperatures of the entire earth, or that *T* is the curve of world temperatures.

Relation of World Temperatures to Pyrheliometric Values.—Curve *P*, also of Fig. 4, gives the smoothed course of the annual average pyrheliometric readings, as computed from the actual values given in Fig. 1. The insolation intensity data, covering the whole of the depression that has its minimum in 1885, were obtained at a single place, Montpellier, France, by a single observer, L. J. Eon,[30] who confined himself to noon observations with a Crova actinometer. It may be, therefore, that merely local and temporary disturbances produced a local insolation curve that was not quite parallel to the curve for the entire world. At any rate, the drop in the solar radiation values obviously was due to dust put into the atmosphere by the explosion of Krakatoa in August, 1883, and it would seem that the effects of this dust both on the surface temperatures and on pyrheliometric values must have been greater during the latter part of 1883 and in 1884 than they were in 1885, when much of the dust certainly had already settled out of the atmosphere, and this supposition is well supported by the pyrheliometric and temperature drops that immediately followed the volcanic explosions of 1903 and 1912, and their partial recovery within a single year. Nevertheless, the pyrheliometric values must be accepted as obtained. Indeed, they appear to be somewhat supported by the fact that the coldest year following the similar, though more violent, explosion of Asamayama, just one hundred years earlier, was not the year of the explosion, 1783, nor the following year, but 1785.

It is probable that in the earlier, as certainly in the later, of these unusual cases the dust was thrown to such great altitudes that the finer portions were nearly, or quite, two years in reaching the lower level of the isothermal region. Clearly, too, much of this dust, while perfectly dry, probably was so fine as merely to scatter even solar radiation, and yet on reaching the humid portions of the atmosphere the particles may have gathered sufficient moisture to assume reflecting size, and therefore seriously to interfere with insolation. This is merely suggested, but in no wise insisted upon, as a possible explanation of the unusual pyrheliometric lag after the explosion of Krakatoa.

It is obvious, from a mere glance, that the pyrheliometric and the temperature curves, or curves *P* and *T*, have much in common. This is especially marked by the large and practically simultaneous drops in the two curves in 1912, following the eruption of Katmai. But while a relation between these curves thus appears certain, the agreement is so far from perfect as

[30] Bulletin météorologique du Département de l'Herault, 1900.

to force the conclusion that pyrheliometric values constitute only one factor in the determination of average world temperatures.

Sun-spots and Temperature.—It has been known for a long time that the curve of sun-spot numbers, curve S, Fig. 4, and the curve of earth temperatures, curve T, follow or parallel each other in a general way, in the sense that the fewer the spots the higher the temperature, with, however, puzzling discrepancies here and there. Both these facts, the general agreement between the phenomena in question and also their specific discrepancies, are well shown by the curves S and T of Fig. 4, and, while the discrepancies are marked, it is obvious that, on the whole, the agreement is quite too close to leave any doubt of the reality of some sort of connection between sun-spots and atmospheric temperatures. Just how or by what process this relation exists will be discussed below.

Combined Effect of Insolation Intensity and Sun-spot Influence on Atmospheric Temperatures.—Since it is obvious that the insolation intensity and the number of sun-spots each exerts an influence on the temperature of the earth, it is clear that some sort of a combination of the two curves P and S should more closely parallel the temperature curve T than does either alone. It is probable that the sun-spot effect is not directly proportional to the actual number of spots, but, however this may be, the direct combination of the curves P and S gives the resultant $P + S$, which, as a glance at the figure shows, actually parallels the curve of temperatures T with remarkable fidelity. Exactly this same combination, from 1880 to 1909, has just been made by Abbot and Fowle,[31] whose lead in this important particular is here being followed, and the resultant curve found to run closely parallel to the curve of "smoothed annual mean departures" of the maximum temperatures of fifteen stations in the United States.

Probably the most striking point of agreement, as shown by Fig. 4, between the combination curve and the temperature curve, occurs in 1912, where, in spite of the fact that the sun-spots were at a minimum, the temperature curve dropped greatly and abruptly; obviously because of the simultaneous and cor-

[31] Smithsonian Miscellaneous Collections, vol. 60, No. 29, 1913.

responding decrease in the intensity of solar radiation produced by the extensive (presumably world wide) veil of Katmai's dust.

Temperature Variations Since 1750 as Influenced by Sun-spots and Volcanic Eruptions.—Sun-spot numbers[32] month by month are fairly well known since July, 1749, and so, too, are the annual temperature variations[33] from about the same time, and therefore the data are at hand for comparing these two phenomena over a continuous period of a little more than 163 years, or from at least the beginning of the year 1750 to the present date. Fig. 5 makes this comparison easy. The bottom curve gives the smoothed annual temperature departures, as computed from Köppen's actual annual departures, using all stations, while the top curve follows Wolfer's annual average sun-spot numbers. Of course, the earlier observations, both of sun-spots and of temperatures, were few in number and more or less unsatisfactory in comparison with those obtained during the past thirty, or even forty, years. Nevertheless, it is clear from Fig. 5 that at least since 1750, the date of our earliest records, and presumably, therefore, since an indefinitely distant time in the past, the two phenomena, atmospheric temperature and sun-spot numbers, have in general varied together, with, however, marked discrepancies from time to time. These we shall now consider, and show that they occurred, in every important case, simultaneously with violent volcanic eruptions.

Volcanic Disturbances of Atmospheric Temperature Since 1750.—It must be distinctly remembered that the earlier temperature records, because of their limited number, if for no other reason, can give us only the general trend of world temperatures. Again, the record back to 1750 of even violent volcanic eruptions is necessarily incomplete; and, besides, not all great eruptions decrease the world's temperature—only those that drive a lot of dust into the isothermal region. Extensive and long-continued sky phenomena, therefore, of the type that followed the eruption of Krakatoa, furnish the best evidence of volcanic violence in the sense here used. Finally, there can be no particular test save where the temperature is low in com-

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[32] Wolfer, Astronomische Mitteilungen, 93, 1902, and later numbers.

[33] Köppen, *Zeit. Österreich. Gesell. für Meterologie,* vol. 8, 241 and 257, 1873.