Variations in Insolation, General Circulation and Climate[1]

By H. WEXLER, U.S. Weather Bureau, Washington, D.C.

(Manuscript received December 19, 1955; revised May 14, 1956)

Abstract

Two primary causes of variation in insolation—changes in solar output and in atmospheric transmission — are discussed, particularly with respect to basic changes in the mid- and high-latitude circulation pattern. Sunspot maxima in winter, on the average, are associated with greater tendency toward circulation blocks over the Northern Hemisphere and favorable conditions for heavy snow in regions known to have been glaciated in the past (Wisconsin) ice age. An explanation, based on an assumed greater insolation during sunspot maxima, is proposed. But summer weather conditions during sunspot maxima do not appear to favor preservation of the previous winter's accumulation of snow and ice. Hence an alternative explanation, based on *decreased* insolation accompanying periods of high atmospheric turbidity is proposed. The unequal response of continents and oceans to the decreased insolation causes heavy snow blankets to be deposited in areas known to have been glaciated and the lesser insolation in summer helps preserve a remnant of the snow until the next winter's contribution.

Introduction

The human race is poised precariously on a thin climatic knife-edge. Only 50° F represents the difference in temperature between the tropics and polar regions. The average temperature of the world today is estimated to be only 15° F warmer than that of the last ice age when thick ice covered large portions of North America and Europe. A long-continued warming or cooling of even 5° F can seriously affect the agricultural economy and threaten the survival of a nation. In light of these figures the reported warming of the earth as a whole by 1.5° F in the past century, due mostly to warmer winters in the past 50 years (WILLETT, 1950), must be considered with great seriousness as an indication of a climatic change which if long continued could have a crucial influence on the future of the human race on this planet.

What causes climatic unrest? Many theories have been advanced, ranging from variable energy emitted by the sun to changes in composition of the earth's atmosphere, to drifts and upheavals of continents, to changes in the orbital eccentricity and axis of the earth. The last two types of explanations are ignored here mainly because they cannot account for recent climatic fluctuations. If explanations can be found for these recent changes, it would appear likely that the same causes, differing perhaps in degree and duration, might explain some of the past glacial epochs.

The theories treated here are based on changes in radiation received at the earth's surface caused by variations in the sun's radiation or in passage of this radiation through the terrestrial atmosphere. These theories are particularly attractive because the unequal heating of the earth's surface and atmosphere is the basic cause of weather, and it therefore appears natural to associate climatic changes with changes in radiation reaching the ground (insolation).

---

[1] Much of the content of this paper was presented in talks before staff members of the Institute of Meteorology, Stockholm, 8 October 1954, and the Meteorological Office, London, 12 October 1954.

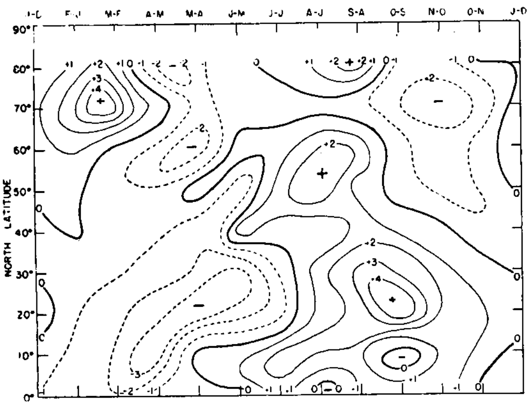

Fig. 1. Normal monthly change in poleward gradient of effective solar radiation; units, 10^{-2} ly min^{-1} (10° lat.)$^{-1}$ (after HARRIS, 1953).

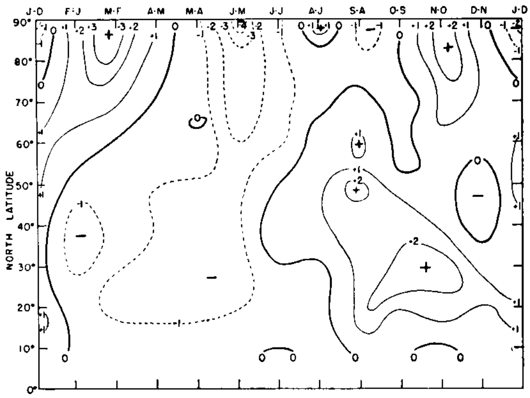

Fig. 2. Normal monthly change in sea level pressure, mb (after HARRIS, 1953).

In this paper, two hypotheses and supporting observations will be presented describing how variations in insolation can cause changes in general circulation and climate for various time-scales.

Hypothesis I — Increased insolation

Confining our attention at first to the winter season in the Northern Hemisphere, it will be argued that stronger insolation—whether caused by increases in solar output, atmospheric transmission or solar declination—will steepen the poleward gradient of the absorbed radiation; this in turn will increase the poleward temperature gradient of the continental atmosphere, increase the speed of the continental westerlies, and thereby increase the likelihood of large-scale instability and breakdown of the westerlies in the form of meandering planetary waves and cut-off anticyclonic and cyclonic eddies in the eastern portions of the oceans and western portions of continents (blocking). The new circulation patterns will produce new temperature and precipitation regimes for these regions.

The increased insolations and their time-scales are:

- *months*—increased insolation after the winter solstice
- *years* —increased insolation accompanying the maximum of the sunspot cycle
- *decades*—increased insolation caused by decreasing atmospheric turbidity in the past 40 or 50 years.

Months Time-Scale

Taking up first the months time-scale, Figs. 1 and 2 show the normal month-to-month poleward gradient changes of "effective" solar radiation absorbed by the atmosphere and the earth's surface (taking into account average albedoes) and corresponding month-to-month changes in normal northern hemispheric sea-level pressures, each being averaged around its respective latitude circle (HARRIS, 1953). From December to March an increase in radiation gradient occurs at middle and higher latitudes which is followed a half-month to a month later by increases in pressure at higher latitudes and decreases at lower latitudes—a usual indication of blocking. Following the reasoning given earlier, it would appear that the springtime maximum of blocking observed in the North Atlantic and Pacific Oceans (REX, 1950) owes its existence to the steepening of the poleward gradient of absorbed radiation over their respective up-wind continents—North America and Asia. In autumn the increase in pressure at higher latitudes with no immediately previous increase in radiation gradient can be explained by the thermal formation of shallow polar anticyclones at high latitudes as winter darkness sets in—as contrasted to the dynamically caused deep anticyclones of late winter and spring.

Years Time-Scale

The next time-scale, that of years, will be considered within the context of the 11-year sunspot cycle. During periods of maximum

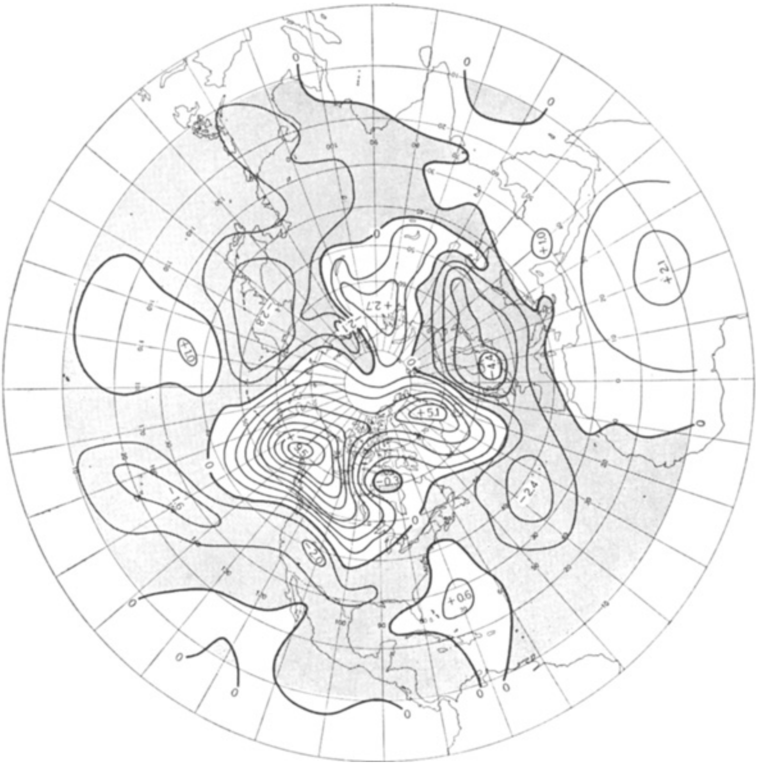

Fig. 3. Average pressure difference (mb), sunspot maxima minus sunspot minima, January 1900—1939.

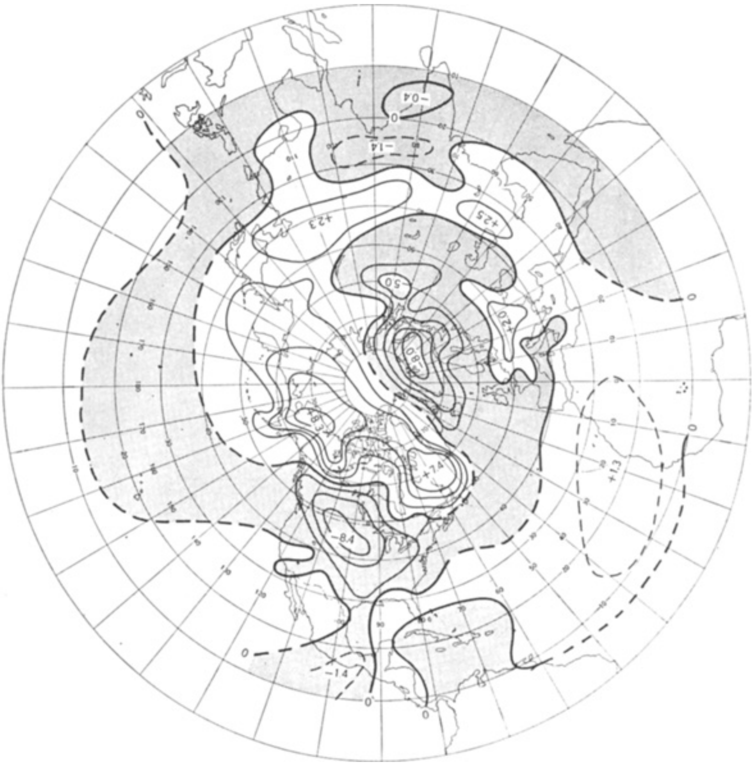

Fig. 4. Average temperature difference (°F), sunspot maxima minus sunspot minima, January 1900—1939. (Patterns over the oceans and large portions of Asia are based on too few data to be reliable.)

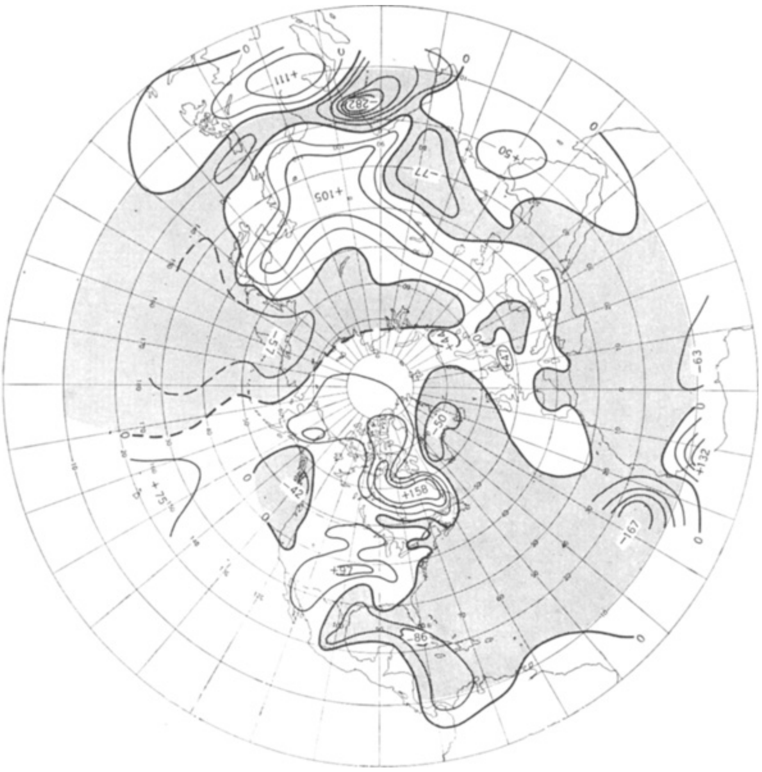

Fig. 5. Average precipitation difference, sunspot maxima minus sunspot minima, expressed as percentage of the average (normal) precipitation amounts, January 1900—1939. (Patterns over the oceans are based on too few data to be reliable.)

sunspottedness it is known from ionospheric observations that some ultraviolet components of solar radiation become much larger than during sunspot minima (MENZEL, 1948). There is less convincing evidence that with high sunspot numbers, the integrated spectrum of solar radiation received at the bottom of the atmosphere is also larger than during sunspot minima. In absence of adequate data, it will be assumed here that an atmosphere of normal cloudiness and transmission, when irradiated by a spotted sun, will have a higher value of insolation than is the case for a less spotted sun. Thus, as greater or lesser amounts of insolation accompanying the alternations of the sunspot cycle are received in winter, this would result in increases and decreases in poleward radiation gradients, with resulting changes in poleward temperature gradients, speed of the westerlies and downstream blocking frequency after the westerlies leave the continents. Let us now see if, in the winter, blocking patterns are found for the sunspot time-scale and also if they are more characteristic of sunspot maxima than the minima.

In Fig. 3 the average pressure difference between Januarys of sunspot maxima and those of the preceding sunspot minima are shown for the four cycles, 1900—1939,—the maxima and minima periods being defined as the respective greatest and smallest three consecutive January totals of sunspot numbers for each of the cycles. Thus, there are $4 \times 3 = 12$ maximum sunspot Januarys minus $4 \times 3 = 12$ minimum sunspot Januarys which were used in constructing Fig. 3.

The pattern is one of marked symmetry of pressure difference roughly about the Pole, with three positive cells of increasing magnitude being met as one proceeds westward from eastern Siberia, and three intervening negative cells of increasing absolute magnitude westward from Hudson's Bay. Each of the positive cells has a negative area to the south—characteristic of blocking—with the strongest block found in the eastern North Pacific Ocean, the next strongest in the North Atlantic, and the weakest in western Siberia.

The pressure differences were tested for statistical significance. In order to cut down on the amount of work only values at grid points of every twenty degrees of longitude around 60° N and 30° N were used. The standard deviations of January sea-level pressures at these grid points were secured from SCHUMANN and VAN ROOY (1951) and a normal deviate test was made. The test indicates that the pressure differences are larger than would be expected. For example, the probability of obtaining a value of 9.5 millibars at 60° N, 140° W is only .0024, the probability for the value at 60° N, 120° W, is .0028, at 30° N, 40° E, it is .0308. Of the thirty-six grid points tested, seventeen had normal deviates greater than 1.00, whereas only 11.4 are expected by chance. These probabilities are for values selected after looking at the data so they cannot be interpreted in the usual way. But even if this factor is considered, the pressure differences appear to be larger than expected by chance.

The strong Pacific block is probably a result of the increased thermal westerly winds over the vast continental complex of Asia, Europe, and North Africa, where the transformation of increased poleward gradient of absorbed radiation into increased atmospheric temperature gradient should also be the largest.[1] The next largest block in the Atlantic is downwind from the next largest continent, North America. The third and smallest block over western Siberia is probably a resonance phenomenon caused by the two oceanic blocks and the tendency of the large-scale planetary waves to be three in number in the Northern Hemisphere.

Note from Fig. 3 that the 3 blocks are almost 120° of longitude apart. But it is interesting to see that the Pacific block is located 50° to 70° of longitude downwind of the Asiatic coast while the Atlantic block is only 20° to 40° downwind from the North American coast. Although the phase of the blocking wave train is fixed mainly by land-ocean thermal contrasts, planetary wave dynamics must enter in an important way to cause an eastward shift of the entire wave train.

The pressure-difference patterns found by sunspot differences can be used to predict the temperature-difference patterns by realizing that the lines of constant pressure-difference represent wind-difference stream-lines. In this way the increased advection of cold air from Canada southward into the United States should bring with it lower temperatures during sunspot maxima; Fig. 4 shows that during sunspot maxima an average January in Montana is 8.4° F colder than one during minima.[1] Likewise, the strong advection of maritime air into the interior of Alaska, northeastern North America and most of Greenland should account for the higher temperatures observed there during sunspot maxima. Following the same line of reasoning, during maximum sunspottedness central Europe is warmer, northern Europe colder.

The significance test used for the pressure-difference chart could not be applied to the temperature-difference chart because standard deviations of monthly temperatures are not readily available. The temperature differences for seven sunspot cycles were secured for two cities, Havre and Duluth. A *t*-test was made to determine whether the mean of the seven values differed significantly from zero. The probabilities were .12 for Havre and .10 for Duluth. Since these two cities were chosen from among many the probabilities do not appear to be unusual. Perhaps seven values are too few to test whether the temperature differences are real.

Even the precipitation-difference patterns shown in Fig. 5 can be explained by quite simple and conventional meteorological reasoning from the pressure and temperature difference patterns shown in the two preceding figures. For example, the drier region in the west coast of Canada and northwest coast of the United States can be explained by the increased "chinook" or foehn winds shown in Fig. 3,

---

[1] Because of the larger thickness of the water layer over which heat from the absorbed radiation is distributed, the ocean surface temperatures respond only very slightly to changes in insolation as compared to land surface temperatures.

[1] In six out of seven sunspot cycles, from 1877 to 1949, the January temperatures for North Dakota and Montana are lower in sunspot maxima than in sunspot minima.

and also the southward displacement of the usual Pacific storm tracks by the blocking in the Gulf of Alaska. This southward shift of storm tracks combined with the greater lift of air caused by the higher dome of polar air in the western and central United States also accounts for the much greater precipitation in that region, mostly as snow. From Fig. 3 it can be seen from the much stronger polar continental anticyclone over central Canada and the slightly stronger Bermuda anticyclone that an intense Polar Front would exist along the Appalachian Mts. The temperature difference chart in Fig. 4 bears this out. This would be a region of strong cyclogenesis with heavy snow deposits in the Great Lakes and Laurentian Regions.

Referring again to the circulation change encouraging foehn winds along the west coast of Canada and southeastern Alaska, such winds would allow more insolation, warmer and drier air, and decreased precipitation to prevail during maximum sunspottedness, encouraging rapid glacial recession in that region. But during minimum sunspottedness, the circulation-difference pattern would be reversed, more storms would move inland from the Gulf of Alaska, encouraging heavy snow deposits and thus favoring glacial growth and expansion.

A correlation between sunspot number and fluctuations of termini of outlet glaciers of the Juneau Ice Field in southeastern Alaska has been set forth (LAWRENCE, 1953) which adds support to the deduction described in the preceding paragraph. Through a span of 200 years Lawrence inferred from geological evidence that at each sunspot minimum the glaciers expanded and built end moraines. This cyclic fluctuation of glaciers was superimposed on a gradual recession which in the past 30 years has proceeded at an accelerated rate.

The year-by-year study of the economy of the Kårsa and Stor Glaciers of Northern Scandinavia (AHLMANN, 1953) shows a net loss during the 1940's and early 1950's, but with temporary gains during the 1947—48, 1948—49 seasons, which years, incidentally, coincide with the recent very pronounced sunspot maximum. Glaciers in Glacier National Park, Montana, which had experienced rapid decreases in area and volume between 1902 and 1940 suffered only moderate losses between 1945 and 1950, with at least one glacier, Grinnell, undergoing an increase (DIGHTMAN and BEATTY, 1952).

Both of these recent Scandinavian and Montana glacial increases agree with the sunspot-glacier relationships deduced by the summary of the four sunspot cycles shown in Figs. 3, 4 and 5. However, according to this relationship the 1948—49 budget year should also have been a period of glacial decline in southeast Alaska but instead it was a period of increase (AHLMANN, 1953).

Decades, Time-Scale

Let us consider now the past half century or so of warming which has been particularly marked in the North Atlantic subarctic in winter. For example, in absence of sunlight the average January mean temperature at Spitsbergen from 1912 to 1937 has increased by 24° F. From long-wave radiation reasoning alone, such a temperature increase would require a secular increase of the downcoming atmospheric long-wave radiation by 30 %. An increase of atmospheric carbon dioxide content by 10 % could not account for such an increase of atmospheric radiation. (Nor would it account for cooling trends observed over large areas, such as the 3° to 5° F drop in January temperatures in the Great Basin of the United States from 1910 to 1952.) An explanation must therefore be sought in terms of wind changes—bringing air of more southerly origin into this region of extraordinarily large horizontal temperature gradient.

The suggested explanation runs along familiar lines upon realization that the series of catastrophic volcanoes that plagued the Northern Hemisphere during the 19th and early 20th centuries (e.g., Tomboro in 1815, Krakatoa in 1883, Peleé, Santa Maria, Colima in 1902—04) terminated in 1912 with the eruption of Katmai. Each of these violent volcanoes ejected several cubic miles of finely divided dust into the atmosphere, which slowly settled out over the years. Daily solar radiation measurements, first available at the time of Krakatoa, showed a three-year decrease of direct solar radiation of 10 % to 20 % as far away as France. Assuming that half of the scattered radiation is lost to Earth, this means a drop of 5 % to 10 % of radiation from the sun and sky.

From 1900 to 1938, clear weather measurements of radiation from the sun and sky made in the United States and Europe have shown an increasing trend, averaging 0.1 % per year. From 1915 to 1938, 19 of the 24 years have been above the 39-year normal (WEXLER, 1953). Likewise, from 1926 to 1952, the annual average of the direct solar radiation intensity measured at the Smithsonian Solar Station at Montezuma, Chile, has increased by 2 %.

These increases in solar radiation in recent decades can be interpreted either as evidence that the atmosphere is slowly ridding itself of volcanic dust and has become more transparent to solar radiation, or that the sun itself is emitting more energy. In view of the fact that the major rise of solar radiation intensity occurred after the 1912 Katmai eruption, it is likely that the first premise is correct. The outgoing long-wave radiation from earth to space would not be affected significantly by the presence or absence of the small, micron-sized volcanic dust particles in the atmosphere.

It is of interest to note that in Willett's compilation of world temperatures (WILLETT, 1950) the 1885—89 pentad, which follows the Krakatoa explosion, has the lowest winter temperature in the past century. Following a steady rise in the next three pentads there is a sharp temperature drop in the 1905—09 pentad, after the eruptions of Peleé, Santa Maria and Colima. This is followed by a continuous rise to 1940 although there appears to be lesser rises in the 1915—19 pentad (Katmai?) and the 1935—39 pentad (Chilean Andes eruptions of 1932?).

The increased insolation observed in clear weather would tend to increase the global temperature over the years unless there were compensating increases in world cloud amount, which is not possible to determine since secular changes in cloud amount have been compiled for only a few stations. However, because of evidence that volcanic dust particles serve as efficient ice and condensation nuclei in the atmosphere (SCHAEFER, 1950) and are even suspected of increasing precipitation downwind from volcanic eruptions (ISONO and KOMABAYASI, 1954) it is likely that the continued volcanic dust "fall-out" of the past decades has served to decrease average world cloudiness, thus increasing even more the global insolation.

Applying the same reasoning used earlier, because of a cleaner atmosphere an increase in global insolation in winter would not only cause an average world-wide warming, but the resulting increase in poleward gradients of insolation and continental temperatures would cause greater blocking in the eastern portions of the Pacific and Atlantic Oceans, and a greater meridional austausch there which, because of the spherical shape of the earth, would give the largest temperature rises at higher latitudes, as has been actually observed in recent decades.

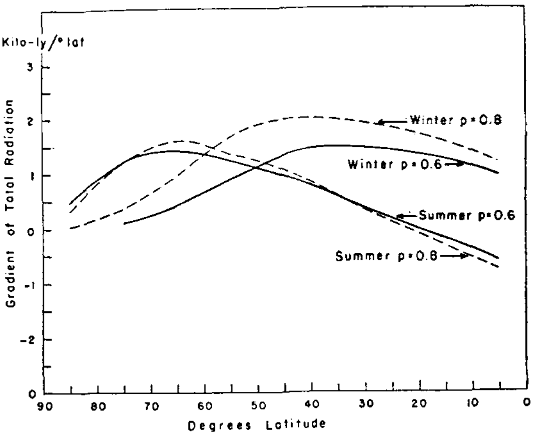

Fig. 6. Poleward gradient of total (sun and sky) radiation against latitude for a clear atmosphere, $p = 0.8$, and for a turbid atmosphere, $p = 0.6$, winter and summer.

An important link in this chain of reasoning is given in Fig. 6. There it is seen that if the transmission, p, of the atmosphere is increased, the poleward radiation gradient is also increased significantly in winter, but not in summer.

Sunspots and Glaciation

In this section the advantages and shortcomings of the sunspot hypothesis of glaciation will be described under the assumptions that the sun has long-period variations of the order of glacial periods and that the sunspot difference patterns of pressure, temperature and precipitation (Figs. 3, 4 and 5) are also characteristic in geographical distribution of the glacial-interglacial difference patterns, but differ in duration and perhaps in degree. In this way many features of the latest of the Pleistocene glaciations—the Wisconsin Ice—can be accounted for.

The Pacific, Atlantic, and Siberian blocks would provide the winter conditions favorable for (1) *the simultaneous growth of three major ice sheets, one over most of Canada and the adjacent United States, another over Scandinavia and the third over northwestern Siberia*—these are each associated with contemporary winter conditions favorable for glaciation in those same regions (see Figs. 4 and 5); (2) *the greatest southward extent of the ice in the United States*—the largest block being located downwind of the largest continent, Asia, intensifies the flow of polar air from the Canadian cold-air source region into the United States, which combined with the greatly increased precipitation in the same region creates and nourishes the snow and ice fields in central and eastern North America and extends the southern boundary of this ice to latitudes far south of those found elsewhere (38° in the United States compared to 50° in Europe and 60° in Asia); (3) *distribution of ice in Central and Southern Europe*—in Central Europe the increased warmth brought about by enhanced flow of air from the ocean would raise the winter mean temperature to above freezing and inhibit formation of snow and ice fields except in the highlands; in particular, the Alpine ice growth would be favored by the low temperature and high precipitation regimes of the cut-off Mediterranean cyclones which usually accompany the Atlantic block; (4) *the milder climate in central Alaska* (Péwé, 1953)—the Pacific blocking eddy brings into the interior of Alaska warmer maritime air from the Pacific Ocean; (5) *origin of the "Baffin Type" glacier caps found in Peary Land and in the Canadian Archipelago*—the increased flow of maritime air from the Atlantic would favor increased precipitation and glaciation in those areas; this favorable winter condition for glaciation is lacking today and nourishment is supplied by "... immediate refreezing of much of the melt water of summer." (Baird, 1952). These glaciers are thought to be survivors of the glacial period before the climatic optimum of several thousand years ago.

It might appear puzzling at first sight that an ice age could be caused by an increase in the sun's energy of a few per cent; since this should be expected to increase world temperature if *all* this increased energy could penetrate to the earth's surface and become available for heating it and the atmosphere above. However the increased insolation would create a new circulation pattern which would promote the formation of extensive and persistent cloud covers in middle latitudes.

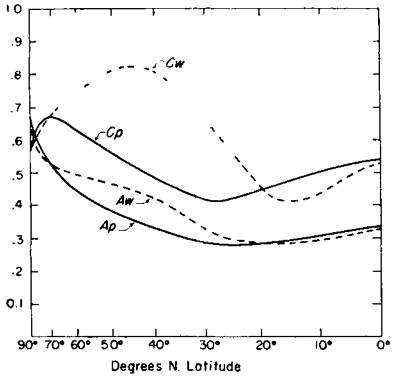

Fig. 7. Present annual cloudiness (C_p) and albedo (A_p) and assumed Wisconsin Ice Age annual cloudiness (C_w) and albedo (A_w), for the Northern Hemisphere.

In Fig. 7 there are plotted against sine of the latitude the present annual cloud amount and an assumed cloud amount at the time of the Wisconsin Ice maximum, both for the Northern Hemisphere and both weighted according to the present solar radiation received outside the earth's atmosphere in each latitude zone. In drawing this latter curve aid was derived from charts of present world cloudiness and the January sunspot maximum minus minimum charts given in Figs. 3, 4 and 5. Over the zone 20° to 70° latitude, comprising most of the areas affected by glaciers and more frequent cyclones, average cloudiness at the Wisconsin maximum was assumed to be 70 % compared to the present value of 50 %. Between 20° latitude and the equator the average cloudiness was assumed to be 46 % compared to the present value of 50 %. Both of these changes are in agreement with the equatorward shift of belts of maximum and minimum cloudiness accompanying the equatorward movement of the westerlies as the glaciers develop. The high cloud cover at middle latitudes during the Wisconsin maximum would be increased by the warmer and moister equatorial air (favored by decreased cloudiness equatorward of 20° latitude) meeting the cold continental air farther north and creating more frequent and vigorous cyclones, with their extensive frontal and convective cloud formation. Using values of cloud and surface albedo given by HOUGHTON (1954), the Wisconsin cloud amount curve was transformed into an albedo curve, which, together with Houghton's present albedo curve, is also shown in Fig. 7.

The critical dependency of global temperature on albedo is such that an 8° C drop would follow a rise in earth albedo from its present value of 35 % to 43 % (WEXLER, 1953). It has been estimated that a 11° C spread represents the difference in world temperature from interglacial to glacial periods, or 8° C from the maximum of glaciation to the present. It appears however that this is an estimate of average temperature changes in certain glaciated regions and not necessarily that of the earth as a whole since it was based mainly on observations of recessions and advances of snow lines in mountainous regions once covered by glaciers. Other regions such as central Alaska were undoubtedly enjoying temperatures higher than their contemporary glaciated regions during the Wisconsin Ice Age and perhaps even higher than their present day temperatures (PÉWÉ, 1953). Taking these warmer areas into account would bring the world temperature increase since the Wisconsin maximum down from its estimated value of 8 °C to perhaps half that value, say 4° C. This increase of 4° C in the Northern Hemisphere could be accounted for by a decrease in albedo from 38 % to 34 % corresponding to a decrease in cloud amount from 64 % to 54 %, as shown in Fig. 7.[1]

In order to build thick ice over the years, it is not only necessary to have an abundance of winter snow but the summer ablation must not eliminate entirely the winter accumulation of snow and ice. Although the sunspot difference charts for July show cool, cloudy conditions which would favor diminished ablation of the critical southern portions of the glaciated areas (WEXLER, 1953) these conditions cannot be explained by a reasonable atmospheric circulation model caused by increased insolation. There is a slim possibility, however, that a deep snow blanket, once laid down over a large area, can influence the summer climate in such a way as to prevent its own total disappearance. Since the principal causes for summer ablation of a snow field are turbulent transfer of heat downward from air to the surface and heating by solar radiation, the snow will tend to protect itself from these two wasting processes by various devices: high albedo of snow, creation of a turbulence-inhibiting surface inversion as warmer air from the snow-free areas moves over the snow field, formation of stratus clouds and fog over the melting snow which will increase the albedo even more.

Apart from this possibility, the principal weakness of the increased insolation hypothesis for glaciation described here is its inability to account for the cool, cloudy summers necessary to preserve a remnant of the preceding winter's blanket of snow.

Hypothesis II — Decreased insolation

An alternate way to explain changes in general circulation and climate would be to assume long periods of decreased insolation caused, for example, by intense volcanic activity which loads the atmosphere with vast quantities of floating dust.

Volcanoes and Glaciation

A pall of volcanic dust coming from a single volcano, Krakatoa, lowered the incoming solar and sky radiation by an average of 5 % to 10 % for three years. It is therefore reasonable to expect that during a period when volcanoes of the Krakatoa type might be erupting at yearly intervals, insolation would be reduced by even more than 10 %. Since the long-wave radiation sent upward by the earth and its atmosphere would not be appreciably affected by the micron-sized dust particles, a reduction of 10 % of the incoming solar radiation should eventually lower by some 7° C the mean temperatures of the earth's surface and its overlying atmosphere. This would encourage a greater proportion of solid precipitation in winter which, in favorable regions, would lay down extensive snowfields; during the shorter, cooler summers, these might not be entirely dissipated and so would provide a foundation for the next winter's snow and, if long continued, would build up thick ice-sheets. This reasoning is based on the assumption that the

---

[1] After the above paragraph was written the author learned that Wundt had earlier estimated that a world albedo increase of 3 % (from 44 % to 47 %) would account for a 4° C drop of the present world temperature to a value estimated to be characteristic of that at the last ice maximum (WUNDT, 1933).

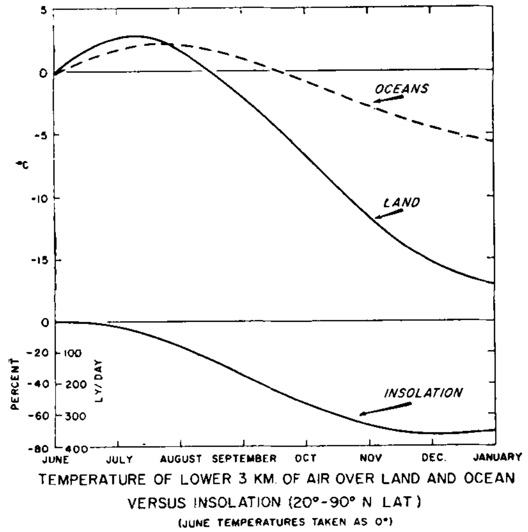

Fig. 8. Temperature of lower 3 km of air over land and ocean versus insolation (20°—90° N Lat.)

present winter precipitation amounts in the regions known to have been glaciated would not be appreciably decreased by the presence of volcanic dust. Let's examine this question.

The availability of the volcanic dust as possible sublimation, freezing or condensation nuclei might appear at first glance to favor increased precipitation if other natural nuclei were below the optimum concentration. However, the following factors would tend to decrease winter precipitation: (1) *lesser intensity of the atmospheric circulation* – the lowered meridional gradient of insolation caused by greater turbidity (smaller transmission coefficient, *p*, (see Fig. 6)) would decrease the intensity of the atmospheric circulation; the reduced wind speed would lower the evaporation of water vapor from the surface and the smaller meridional motions would reduce frontal activity and precipitation; (2) *greater stability of the atmosphere*—caused by greater absorption of solar radiation by the dust filled upper layers of the atmosphere and lesser absorption by the earth's surface and lower layers of the atmosphere; (3) *lowered temperature of the sea surface caused by decreased insolation*—this would tend to decrease evaporation but would take many years to accomplish because of the thick layers of the ocean required to be cooled. For example, if a dense volcanic dust pall should decrease insolation 20 % below normal, then the average temperature of a 100 meter thick surface mixed layer of ocean would drop 2.6° C in one year; but if the cooling were extended through the average depth of the oceans, 4000 meters, the average temperature drop in one year would be only 0.06° C.

All these factors considered together, would seem to indicate lesser winter precipitation during periods of prolonged volcanic dust palls over a *homogeneous* earth. But for the Northern Hemisphere of the *actual* earth, with its massive land and ocean contrasts, one of the major reasons – that of decreased meridional motions – cited above in support of decreased precipitation would no longer be valid. For, in a period of reduced insolation, the continental temperature would drop much more rapidly than the ocean temperatures and initially (that is for the several decades it would take for the oceans to cool significantly), the *winter* contrast in temperature between continent and ocean would increase markedly. For example, as shown in Fig. 8, a 20 % decrease in insolation following the summer solstice leads, after the usual time lag, to a 5° C decrease in the average temperature of the lower three kilometers of air over land compared to only 2° C over the oceans. The increased temperature contrast between continents and oceans should introduce fundamental changes in the winter circulation and weather patterns over the Northern Hemisphere.

An attempt was made to construct a new 700-mb contour chart for January during 20 % reduced insolation by the following method:

a) The present day average insolation chart for North America was constructed, using the data for the U. S. from Fritz (1949) and data from Canada from Mateer (1955).

b) A new chart was then constructed showing the insolation received at the ground during January when only 80 % of the present cloudless day insolation was observed at latitude 40° N.

c) The two sets of insolation isopleths were plotted on the same chart and arrows drawn to indicate the southward displacement that present isopleths would have to undergo to become coincident with those for 20 % reduced insolation.

d) Since it appears likely that over the snow-covered interior of the continent the thickness (proportional to average temperature) between 1000 mb and 700 mb depends primarily on the insolation received (conduction of heat from below being negligible), the present day normal thickness lines 1000 to 700 mb, were displaced southward by exactly the same distances that the insolation isolines were under 20 % reduced insolation.

e) Under the assumption that the 1000 mb surface remains unchanged (a poor assumption but an inescapable one at present) the new 700 mb chart was constructed by subtracting the new thickness pattern from the present 1 000 mb normal heights, and the result is shown as Fig. 9. No changes in the 700 mb pattern were made on the west coast because there the maritime air was assumed to be in equilibrium with the ocean surface whose temperature would be but slightly lowered during the first few years of reduced insolation. On the other hand changes in the 700 mb pattern were made on the east coast and beyond that to the mid-Atlantic Ocean because the air in this area, coming from the colder North American continent, would definitely be colder, despite its travel over the warmer ocean.

In Fig. 9 an intense cyclonic trough is found over the eastern coastal area, with marked confluence of polar and tropical air over the eastern half of the United States. A strong anticyclonic ridge is found over the eastern North Atlantic Ocean with a tendency for cyclonic trough over North Africa—a signature of a blocking pattern. A similar blocking pattern is observed on the west coast of North America.

This essentially thermally derived pattern is bound to undergo dynamic modification as the changed flow patterns over the Eurasian and North American continents react on each other. It is probable that calculations and experiments now getting under way will shed light on the changes to be expected, but on the basis of qualitative reasoning it appears that the changes may be as follows:

a) extension southward of the lobes of the polar cyclone over the North American and Asiatic continents, that is, the two main troughs in the westerlies now located near the east coasts of North America and Asia would be intensified and perhaps displaced slightly westward;

b) the warm, moist air from the oceans, not much changed in temperature from before the dust pall, would encounter at the coastal areas deeper and colder continental air masses than formerly and deposit heavier precipitation, mostly as snow; in North America this would be particularly true along the Gulf and Atlantic Coasts although there would be significant over-running of moist Pacific air from the northwest over the western slope of the dome of polar air;

c) in the United States the southern ends of these elongated polar troughs would be vulnerable to "cut-off" by the warmer Pacific air thus causing closed cyclones aloft and heavy precipitation, mostly snow, through the Great Lakes region and Laurentians;

d) the air moving around these low-latitude "cut-off" lows would tend to create anticyclonic circulations to the northeast, in a manner typical of the "figure-eight" constant vorticity trajectories so often seen on the daily synoptic charts;

e) in North America, these dynamically created anticyclones would be located near the Baffin Strait and southern Greenland, and its induced influx of moist maritime air would produce the heavy precipitation regimes needed to form the glaciers in Baffin Land mentioned earlier;

f) the cold northerly flow found on the east side of these high latitude anticyclones would

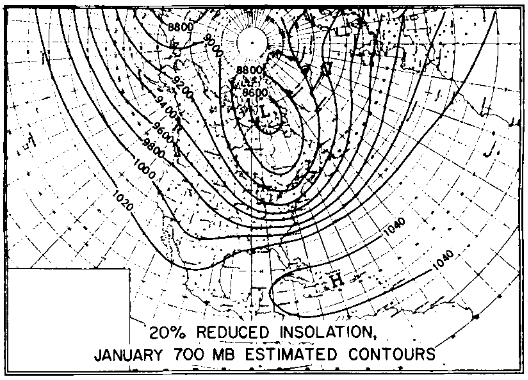

Fig. 9. Estimated average January 700 mb contours, 20 % reduced insolation.

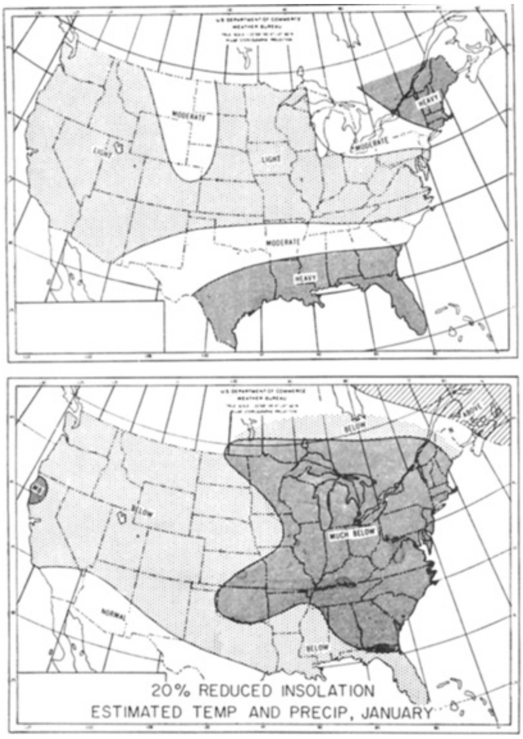

Fig. 10. Estimated January temperature and precipitation patterns for 20 % reduced insolation. Temperature departure shown in lower chart, precipitation classes in upper.

become moist and unstable in its passage over the North Sea and bring cold, snowy weather to the west coast of Scandinavia;

g) from vorticity considerations the same flow of air would induce a westerly trough centered near the Urals which, by the transport of warmer moister air over the deep dome of Siberian polar air, would lead to heavy winter snows in northwest Siberia;

h) again from vorticity considerations a ridge would be found over central Siberia and a deeper than normal trough on the Asiatic Pacific Coast; this trough would encourage formation of a broad ridge of high pressure in the eastern Pacific.

From thermal considerations it is likely that both the Asiatic and North American east coasts would have more intense polar troughs, the stronger trough being found over east Asia. One might then wonder why this stronger trough would not favor glaciation in that area even more so than in eastern North America, although it is known that North American glaciation far exceeded that of east Asia. The answer appears to be in the unobstructed flow of moist air from the Gulf of Mexico northeastward over the eastern United States where as storms develop, the moisture can be precipitated over areas known to have been glaciated. In contrast, because of mountain barriers, there is no such easy access of moist air from the Indian Ocean and Bay of Bengal into comparable latitudes in China.

The estimated temperature and precipitation patterns for January, under 20 % reduced insolation, as computed by the objective techniques developed by the Extended Forecast Section of the U. S. Weather Bureau, are shown in Fig. 10.

In summer, the dust pall would not only reduce insolation, the westerlies would be displaced farther south than normal, thus eliminating the high-level summer anticyclone found normally over the mid-West and responsible for accentuation of the intense heat found there. The winter snow blanket would thus have a better chance of surviving a summer characterized by lower temperatures, reduced insolation during clear weather, and increased cloudiness caused by increased storminess associated with stronger westerlies displaced southward. Calculations indicate that a mid-July weather chart during 20 % reduced insolation would be similar to that of a present early June chart insofar as the net radiation (insolation minus outgoing radiation) accumulated since January is concerned. Actually since January and subsequent months would be cooler because of the reduced insolation, the mid-July weather chart would probably be similar to that of the present mid-May.

After 25 years, say, of 20 % reduced insolation caused by a dust pall maintained by widespread volcanic activity, there would have been enough energy loss by this means alone to have cooled the oceans by an average of 1.6° C throughout their entire depth. Throughout this period, the Arctic ice pack would spread and thicken and in winter the continents would remain colder than the oceans, thereby encouraging the laying down of thick blankets of snow as described earlier. In summer, as the oceans become steadily colder, the contrast between the warm continents and cold oceans would increase, which would encourage monsoon-type invasions of the cooler maritime air deeper into the continent, with its attendant cloudiness, a condition favorable to summer preservation of the snow.

If the volcanic activity should cease and the dust settle out, the winter contrast between continent and ocean would be considerably reduced. For the oceans would warm up only very slowly, while those portions of the continents not covered by snow and ice would respond quickly to the increased insolation. The continental polar troughs in the westerlies would be less elongated and located nearer to the east coasts; the westerlies would thus become more zonal, maritime air would penetrate deeper into the continents, and replacement of the continental polar air by this milder air, plus the increased insolation, would discourage heavy snow accumulation; in North America, the Pacific air moving down the Rocky Mts. would produce chinook conditions which would add to the warmth and dryness of the air. Any snow that did survive into the summer would meet a speedy demise because of increased clear weather insolation, the emergence of the upper level continental anticyclone and decreased cloudiness.

Comparison of the sunspot and volcanic hypothesis of glaciation

In summary, it appears that the decreased insolation hypothesis of glaciation has the advantage over the increased insolation hypothesis, mainly because the cool, cloudy, stormy summers would be more favorable for preservation of the winter snow, which, under either hypothesis, should be equally abundant in the regions known to have been glaciated. In both hypotheses, winters would be of the "low index" type, characterized by atmospheric blocks and their strong meridional motions.

However, in putting forth two alternate hypotheses – one based on increased insolation and the other on decreased insolation – which might explain heavy winter precipitation over areas known to have been glaciated in the last ice age, an apparent paradox has risen.

The first hypothesis seeks to explain a blocking pattern by an increased westerly flow emerging from the continents to the oceans – the increased zonal winds being caused by a stronger meridional gradient in insolation over the continent. The evidence, though to a large extent empirical, being based on analogy with the increased insolation after the winter solstice, has some theoretical support in Rossby's criterion for the initiation of the horizontal hydraulic jump (ROSSBY, 1950). An excellent synoptic case history of fast-moving westerlies breaking down into blocks in the eastern North Pacific and Atlantic Oceans from February 22 to March 9, 1949, is described by CRESSMAN (1950). The number (three) and locations of blocking anticyclones are determined empirically by the sunspot difference charts as illustrated in Figs. 3, 4 and 5.

The second hypothesis seeks to explain the initiation of a winter blocking pattern by the formation of intense upper troughs over the eastern portions of North America and Asia – these troughs being caused by the increased temperature contrast between continent and ocean under reduced insolation. In contrast to the first hypothesis, there exist no empirical or theoretical guide-posts which will enable a convincing estimate to be made of the resulting general circulation patterns. But it appears reasonable to expect that the appearance on the eastern coasts of deeper than "normal" troughs should, by vorticity considerations, cause a larger amplitude planetary wave pattern downwind, giving rise to blocking anticyclogenesis in the eastern portions of the North Atlantic and Pacific Oceans. But it need not necessarily follow that the resulting blocking pattern is similar in all respects to that caused by increased insolation.

An interesting conclusion is that if, in winter, both increased and decreased insolations lead to greater incidence of oceanic blocking patterns, then under "normal" insolation the blocking patterns should be less frequent.

In summer the decreased insolation hypothesis, in contrast to that based on increased insolation, would call for a "high index" type of circulation, with its protective features for snow. In summary, it appears that the decreased insolation hypothesis is to be preferred over the increased insolation hypothesis because its induced circulation patterns can cause substantial winter snow cover in the right places but, in addition, its summer circulation patterns permit more snow to survive.

The two hypotheses as outlined here are each dependent on the unequal thermal response of continent and ocean to changing insolation. Since the Southern Hemisphere, particularly in middle latitudes, is essentially maritime (less than 6 % of the area between 30° and 65° South Latitude is covered by land) one might expect that this hemisphere would react quite differently to changing insolation than would the Northern Hemisphere. The winter-time low index blocking patterns characteristic of the Northern Hemisphere during either maximum sunspottedness or long continued abnormally high atmospheric turbidity would be absent in the Southern Hemisphere. Thus, the large continental ice sheets found in the Northern Hemisphere at elevations only a few hundred feet above sea level, would be absent in the Southern Hemisphere. Only the highlands type of glacier would be found on the Southern Hemisphere mountains and plateaus. This latter type of glacier suffers its principal ablation by insolation in summer (AHLMANN, 1953). Assuming then that the winter-time nourishment of the highlands glaciers in the Southern Hemisphere remains essentially the same, the variations of glaciers would depend primarily on the insolation received in the summer. A lesser insolation would preserve more of the glacier until the next winter's snows, thus causing glacial growth, while a greater insolation would waste the glacier more than could be replenished the following winter, causing glacial decline. Thus, the remarkable recession of highlands glaciers observed over large areas in the Northern and Southern Hemispheres in the past decades might well be accounted for by the increasing trend toward higher insolation noted since before the turn of the century, particularly after 1915 (WEXLER, 1953).

The question might well be asked, however, whether the polar ice accumulations in both hemispheres have also undergone simultaneous declines. In the Arctic there is evidence (AHLMANN, 1948) that from 1924 to 1942 in the area north of Siberia alone, the summer ice pack has diminished by 1,000,000 km^2, or 12 % of the area of the *total* Arctic ice pack. It is not known whether there has been a similar decline in the Antarctic – either in the pack ice or the inland ice. But botanical evidence gathered on nunataks by the Norwegian-British-Swedish Expedition of 1949—52, 65 miles inland and 170 miles from their base at Maudheim, Queen Maud Land, indicated no recent[1] subsidence of the inland ice (SCHYTT, 1955). If this is characteristic in general of the inland ice of Antarctica, then one would be forced to the conclusion that the recent glacial recessions, so characteristic of the Arctic, particularly in the Greenland, Iceland and Scandinavian areas, do not have a counterpart in the Antarctic. The extensive glaciological and meteorological observations planned in Antarctica during the International Geophysical Year of 1957—58 should throw considerable light on this question; if it turns out that the Antarctic inland ice has not generally subsided in recent decades or centuries, this would lend support to the thesis propounded here, namely, that the climatic variation in the polar regions of the two hemispheres need not necessarily move in parallel, and that because of the greater land-ocean contrast in the Northern Hemisphere, variations in insolation would be expected to have a much greater influence on the circulation of the Northern Hemisphere, and therefore on the climate over large areas in that hemisphere.

Future changes

What can be said of the future? Will the present warming trend continue? It would appear from the reasoning given here that after many years of volcanic dust "fall-out" the atmosphere cannot become much more transparent to solar radiation, so that from this viewpoint alone, there should be no further significant increase of insolation and temperature. However, to add to atmospheric storage of volcanic dust, there have been small volcanoes since 1912, such as those of

(1) April 1932 in the Chilean Andes which decreased direct solar radiation at the Smithsonian Solar Station at Montezuma, Chile, 800 miles to the north, by 3 % during the next 3 months, although there was no effect at Table Mt., California;

(2) June 1951, on Fogo Island of the Cape Verde group which decreased insolation by 8 % and visibility as far away as Florida for 4 days;

---

[1] According to a verbal communication from lichenologist George Llano, it might take as much as 500 years for lichens to become established on newly exposed Queen Maud Land nunataks.

(3) July 1953, Mt. Spurr (near Anchorage' Alaska) volcano, following which direct solar radiation values at Table Mt., California, decreased by 3 % to 5 %, and those at the Blue Hill Observatory, Milton, Massachusetts, by 5 % to 10 % for 6 months, one of the two longest periods of radiation deficit noted at the latter place since the inauguration of the solar observations 20 years previously.

Since even relatively minor volcanoes can decrease the solar radiation intensities received at the earth's surface by significant amounts, it appears likely that prolonged periods of explosive "Krakatoa" type volcanoes could have larger effects and encourage persistent glaciation in the manner and places indicated above.

There remains the future output of the sun. There is lack of agreement among solar physicists whether the energy from the sun in its present stage of development can vary by more than one or two per cent estimated during current sunspot cycles.

Thus the problem of predicting the future trend of climate of Planet Earth would seem to depend on predicting the future energy output of the sun and the future transmission of the atmosphere to solar radiation. The latter prediction would depend on the ability to foretell future volcanic eruptions of major intensity.

REFERENCES

AHLMANN, H. W:SON, 1948: The Present Climatic Fluctuation. *Geogr. Journ.*, CXII, Nos. 4—6, pp. 165—195.

— 1953: *Glacier Variations and Climatic Fluctuations*. Bowman Memorial Lectures, Series Three, American Geographical Society, New York.

BAIRD, P. D., 1952: The Glaciological Studies of the Baffin Island Expedition, 1950, Part I. Method of Nourishment of the Barnes Ice Cap. *Journ. of Glaciol.*, **2**, No. 11, p. 2.

CRESSMAN, G. P., 1950: Variations in the Structure of the Upper Westerlies, *Journ. Met.*, **7**, No. 1, pp. 39—47.

DIGHTMAN, R. A., and BEATTY, M. E., 1952: Recent Montana Glacier and Climatic Trends. *Mo. Wea. Rev.*, **80**, pp. 77—81.

FRITZ, S., 1949: Solar Radiation During Cloudless Days, *Heating and Ventilating*, **46**, No. 1, pp. 69—75.

HARRIS, M. F., 1953: Normal Monthly Change in Sea Level Pressure and in the Gradient of Effective Solar Radiation. *Mo. Wea. Rev.*, **81**, pp. 193—194.

HOUGHTON, H. G., 1954: On the Annual Heat Balance of the Northern Hemisphere. *Journ. Met.*, **11**, No. 1, pp. 1—9.

ISONO, K., and KOMABAYASI, M., 1954: The Influence of Volcanic Dust on Pecipitation. *Journ. Met. Soc. Japan*, Series II, **32**, Nos. 11—12, pp. 345—353.

LAWRENCE, D. B., 1953: Periodicity of Deglaciation in North America Since the Late Wisconsin Maximum, Part I. Recession of the Past Two Centuries. *Geogr. Ann.*, XXXV, H. 2, pp. 83—104.

MATEER, C. L., 1955: Average Insolation in Canada During Cloudless Days. *Can. J. Technol.*, **33**, pp. 12—32.

MENZEL, D. H., 1948: Earth-Sun Relationships. Chapter IV, 4, in *Centennial Symposia, Harv. Observ. Memo.*, No. 7, Cambridge, Mass.

PÉWÉ, T. L., 1953: Brief Review of Pleistocene Events and Climatic Changes. Paper presented at Fourth Alaskan Science Conference, Juneau, Alaska.

REX, D. F., 1950: Blocking Action in the Middle Troposphere and Its Effect Upon Regional Climate. II The Climatology of Blocking Action. *Tellus*, **2**, No. 4, pp. 275—301.

ROSSBY, C.-G., 1950: On the Dynamics of Certain Types of Blocking Waves, *Journ. Chinese Geophys. Soc.*, **2**, No. 1, pp. 1—13.

SCHAEFER, V. J., 1950: The Occurrence of Ice Crystal Nuclei in the Free Atmosphere. *Gen. Electric Res. Lab., Occas. Report No. 20, Project Cirrus*, Schenectady, New York.

SCHUMANN, T. E. W., and VAN ROOY, M. P., 1951: *Analysis of the Standard Deviation of Atmospheric Pressure over the Northern Hemisphere*, Dept. of Transport, Weather Bureau, Union of South Africa, Pretoria, South Africa.

SCHYTT, V., 1955: Account of Glaciological Journey on pp. 143—149 contained in *The White Desert* by John Giaever, Dutton & Co., New York.

WEXLER, H., 1953: Radiation Balance of the Earth as a Factor in Climatic Change, Chapter 5 in *Climatic Change* (H. Shapley, Editor), Harvard University Press, Cambridge, Mass. (The Press has kindly given permission to reproduce Figs. 3, 4 and 5 in this paper.)

WILLETT, H. C., 1950: Temperature Trends of the Past Century, *Centenary Proceedings of the Royal Meteorological Society*, pp. 195—206.

WUNDT, W., 1933: Änderungen der Erdalbedo während der Eiszeit. *Meteorol. Zeit.* Bd. **50**, No. 7, pp. 241—250.