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# Modifying Weather on a Large Scale

Current proposals are either impractical or likely to produce cures that are worse than the ailment.

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Two streams of radiant energy, one directed downward and the other upward, dominate the climate and weather of the planet Earth. The downward stream of energy consists of the residual solar radiation absorbed by the earth's surface and atmosphere after about one-third is lost by reflection from aerosols, clouds, and earth. The upward stream is infrared radiation emitted to space by the earth and atmosphere, mostly from atmospheric water vapor, clouds, carbon dioxide, and ozone.

The latitudinal distribution of both radiative streams, averaged for the Northern Hemisphere winter third of the year (November, December, January, and February), is shown in Fig. 1, plotted from unpublished data computed by Gabites (*1*).

The climatic zones of decreasing temperature poleward are a direct result of the imbalance of heat received and lost. But this same temperature gradient creates a meridional circulation which transports poleward the excess energy received at tropical latitudes to make up the deficiency in polar regions. In the process, the winds and their burden of energy in the form of real and latent heat create weather.

In seeking to modify climate and weather on a grand scale it is tempting to speculate about ways to change the shape of these basic radiation curves by artificial means. Various proposals have been made for changing the albedo or reflectivity of large portions of the earth's surface in order to influence the percentage of solar radiation absorbed. Since the albedo of most of the earth's natural surfaces, such as ocean, forest, and ordinary bare ground, is quite small to begin with [3 to 14 percent (*2*)], and since it would be unwise to blacken grassland, which has an albedo as high as 30 to 35 percent and which is used for fodder, there remain only the deserts and snow fields to be considered as candidates for substantial albedo changes of the earth's surface.

## Blackening Deserts

Light-colored deserts such as the Mojave and Death Valley have albedos of between 25 and 30 percent, and this is presumed to be the case also for the Sahara and other tropical deserts. We select deserts in the tropics because this is the zone of average net excess of solar radiation.

From 40° north latitude to 40° south latitude the ratio of land to water is about 1:3. About one-tenth of the land surface in this belt is desert, or one-thirtieth of the total area.

Suppose by laying down a layer of carbon dust over the deserts the albedo is reduced by one-half (we neglect for the time being the practical problems of logistics and maintenance of the black surface against wind erosion and washout). The average albedo of the 40°N–40°S zone is 30 percent (*3*). If one-thirtieth of this area has its albedo reduced by one-half, then the average albedo of the total zone is reduced by about ½ percent. This will increase the average energy absorbed by the earth's surface in that zonal strip by 3.6 langleys (ly) (*4*) per day and the average temperature by 0.4°C.

## Blackening the Polar Icecaps

The other principal areas of light-colored natural earth's surface are the polar icecaps. Icecaps one to two miles thick, such as those in Greenland and Antarctica, are not considered to be worth blackening, since some of the extra absorbed energy will merely be utilized in melting the surface layer, from which water will percolate down into the snow and freeze again without run-off. There might be a slight increase in evaporation, but the process would be slow and perhaps self-defeating (*5*).

The thinner ice of the Arctic ice pack, of the order of 10 feet thick, is more susceptible to modification by blackening. The average albedo of the Arctic ice during the summer, when open pools of water are found, is probably close to 50 percent. It has been estimated that about 1 meter of the surface ice is melted in the course of the Arctic summer (*6*). What would be the increase in melt if the surface could be so blackened as to reduce the average albedo from 50 to 10 percent?

In 1953, when Fletcher's Ice Island (T-3) was near latitude 86°N, longitude 96° to 82°W (*7*), the monthly average insolation values shown in Table 1 were observed. The average value is nearly identical with the May–October 1950 average of 405 langleys per day observed by Yakovlev (*8*) on the Soviet Ice Floe Station North Pole–2 while it was in the

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Table 1. Average daily insolation, Fletcher's Ice Island, 1953.

| Month | Av. daily insolation (ly) |
|---|---|
| May | 534 |
| June | 650 |
| July | 445 |
| August | 309 |
| September | 78 |
| Average | 403 |

vicinity of latitude 76°N, longitude 166°W.

If the ice is assumed to be fresh-water ice, then the melting of 1 meter would require 7200 langleys. Since the natural ice pack albedo is assumed to be 50 percent, this means that 25 percent of the 59,000 langleys of the insolation received during the melt period of May, June, July, and August is utilized in melting the ice. The remainder of the absorbed solar radiation is used in heating the ice to the melting point, and is absorbed by the sea water, fresh-water pools, and the air.

Suppose, now, that the pack-ice albedo is reduced by blackening from 50 to 10 percent. This will have two effects: first, 90 percent of the insolation will be absorbed instead of 50 percent; second, if the summer sky over the Arctic pack is overcast, as it generally is, then as Fritz (*9*) showed, the insolation itself will be reduced because of a decrease of secondary reflection from the cloud base. As an illustration of the latter point, if the solar zenith distance is 60° and the ratio of the cloud thickness to the mean free path of the radiation in the cloud is 3, then a decrease in albedo from 50 to 10 percent will decrease the insolation by one-sixth. If the same fraction, ¼, of the insolation ($I$) is utilized in melting the ice, then the energy so used for the 50-percent albedo is $I/2 \cdot 4$, while for the 10-percent albedo it is $I(9 \cdot 5 \cdot 1)/(10 \cdot 6 \cdot 4)$. The ratio of the latter to the former is 3:2, showing that 50 percent more ice, salt or fresh, is melted when the albedo is decreased from 50 to 10 percent.

## Logistic Requirements

To lay down a black layer 0.1 millimeter thick (*10*) over the Arctic ice pack and adjacent snow fields (from latitude 65°N to the North Pole), an area equal to $24 \cdot 10^6$ square kilometers, would take 1.5 billion tons of carbon. Similarly, to blacken the tropical deserts, an area equal to $8.5 \cdot 10^6$ square kilometers, would take 0.5 billion tons of carbon. The deposit of an even, uniform layer could best be accomplished by low-flying airplanes. If the Globemaster (C-124) type of cargo plane, capable of carrying 10 tons of carbon, were used, it would take 100 million sorties to lay down 1 billion tons of carbon black. This would take considerable time, and meanwhile wind erosion, melting, frost, and snow deposits would tend to dissipate or whiten the blackened snow cover, while drifting sand would tend to cover the blackened cover in the deserts.

Table 2. Effect of ice fog on net outgoing radiation, Fairbanks, Alaska, 4 Feb. 1953.

| Time of day | Temperature | Net outgoing radiation (ly/min) | Visibility (mi) | Ice fog |
|---|---|---|---|---|
| 1415 | −31°C | 0.076 | 10.0 | None |
| 1425 | −29°C | — | — | None |
| 1500 | — | 0.041 | — | Ice fog |
| 1540 | — | — | 0.50 | Ice fog |
| 2155 | −41°C | — | 0.25 | Ice fog |
| 2215 | — | 0.009 | — | Ice fog |

Table 3. Radiation losses to space in Fairbanks, Alaska, in January, when black-body (B-B) radiating surface is at various levels.

| Temp. of B-B radiating surface | Atmospheric pressure (mb) | Loss (ly/min) from | | | Total loss |
|---|---|---|---|---|---|
| | | Radiating surface | Water vapor | $CO_2$ | |
| −19.4°C at earth's surface | 1000 | 0.096 | 0.142 | 0.041 | 0.279 |
| −10.5°C at top of inversion | 832 | 0.123 | 0.126 | 0.041 | 0.290 |
| −55.9°C at tropopause | 209 | 0.134 | 0.009 | 0.041 | 0.184 |

## Ice Clouds and Outgoing Radiation

As an alternative to blackening large areas of the earth's surface to convert a greater percentage of the incoming solar radiation to useful energy, let us examine the possibility of reducing the return of infrared radiation to space. The formation of a sufficiently thick cloud having particles of diameters of about 10 microns—comparable to the wavelength of the strongest outgoing infrared radiation—can reduce the outgoing radiation and so decrease surface cooling. This has been demonstrated in a striking fashion in the ice fogs which generally form at temperatures of −30°C or below when moisture sources are available. In inhabited areas, such sources are chimney and steam vents; in uninhabited areas, these fogs result from openings in the ice cover of bodies of water or even from caribou herds and the like.

An example of the effect of an ice fog on the net outgoing radiation is shown in Table 2 by data collected at Ladd Air Force Base by Robinson and MacLeod (*11*).

The appearance of an ice fog caused the net loss of radiation to decrease to one-eighth of the initial value, and this decrease occurred in spite of the decreasing solar radiation received from the setting sun.

The ice crystals comprising the ice fog are equant solid ice particles with rudimentary crystal faces, of diameter between 10 and 20 microns; they have been given the name "droxtals" by Thuman and Robinson (*12*). They are formed by the freezing of supercooled water drops condensed from water vapor discharged into the atmosphere from chimneys and steam vents. The fog thus formed is confined vertically by the strong temperature inversion and extends upward about 100 feet. If the whole layer between the ground and the inversion top could be filled by an ice fog, the outgoing radiation from the surface would approach zero and the top of the ice fog would serve as the "black-body radiator," in place of the ground. Since the top of the ice fog would be at a higher temperature than the ground, the radiation loss to space would thus increase. This would be a short-lived process, however, since the top of the ice fog would cool rapidly, creating a sharp inversion just above, and diminishing the outgoing radiation, as is illustrated in Fig. 2.

The only way in which the *total* radiation loss to space from the ground and the atmosphere could be reduced would be to have the ice fog extend high enough so that the temperature of its top would always remain lower than that of the ground. This, in most cases, means extending the ice fog to the tropopause. Table 3, computed with the aid of Elsasser's diagram (*13*), illustrates what could be accomplished in reducing the total outgoing radiation under average January conditions at Fairbanks, Alaska. Thus, if the effective black-body radiating surface is transferred from the true ground to an artificial one at the tropopause, there is a 34-percent decrease in the total outgoing radiation to space from the vertical air column and underlying ground.

## Manufacture of the Ice Cloud

The cheapest and most effective way of producing an ice cloud would be by application of nuclear energy. Let us imagine the explosion of ten really "clean" hydrogen bombs, of 10 megatons each, at optimum depth in the Arctic Ocean to produce steam, which would then gush into the atmosphere, condense into water droplets, and freeze. If the entire 100 megatons of energy were used in this way to convert sea water into droxtals of 14-micron median diameter, and if these particles were spread uniformly over the area from latitude 65°N to the Pole, from the surface to the tropopause at 8 kilometers, there would then be approximately 1 droxtal per cubic centimeter and therefore 1 square centimeter of obstruction per square centimeter of area—in other words, the obscuration of the surface by the ice cloud would be complete. Diffuse infrared radiation loss from the surface would then be diminished to at least $e^{-2} = 0.14$ of the original value, in agreement with Table 2. The explosions would have to be well distributed throughout the Arctic basin to take advantage of the existing winds to spread the floating droxtals over the entire basin but prevent transport of large quantities outside. A winter high-index situation, characterized by strong westerly winds throughout most of the troposphere at middle latitudes, rotating about a polar vortex, would "contain" the polar atmosphere and thus represent the optimum circulation pattern for establishment of a widespread, quasipersistent ice cloud over the Arctic basin.

A difficult requirement of the experiment would be to insure the conversion of a major portion of the vaporized sea water into droxtals of the median diameter best calculated to block off infrared radiation from the ground and to remain in the atmosphere for the longest time.

If the experiment were performed in winter, there would be no appreciable solar radiation to encourage the evaporation of the ice particles. After a while, of course, some particles would tend to be carried southward into sunlit areas. Because of heating of these particles by solar radiation and the warming of the carrier air currents by the usual subsidence accompanying southward-moving polar air masses, the droxtals would evaporate and thus not interfere with incoming solar radiation at middle and lower latitudes.

## Effects of Ice Cloud on Radiation Balance and Temperature

With reference to Fig. 1, suppose that the return radiation to space from latitude 65°N to the Pole is reduced by 50 percent by the presence of the 8-kilometer-deep ice cloud. This decrease, which is represented by the shaded area under the curve marked OR, amounts to an average of 150 langleys per day for each square centimeter of the $24 \cdot 10^6$ square kilometers comprising the north polar area. This area is about 5 percent of the total area of the earth. If the in-

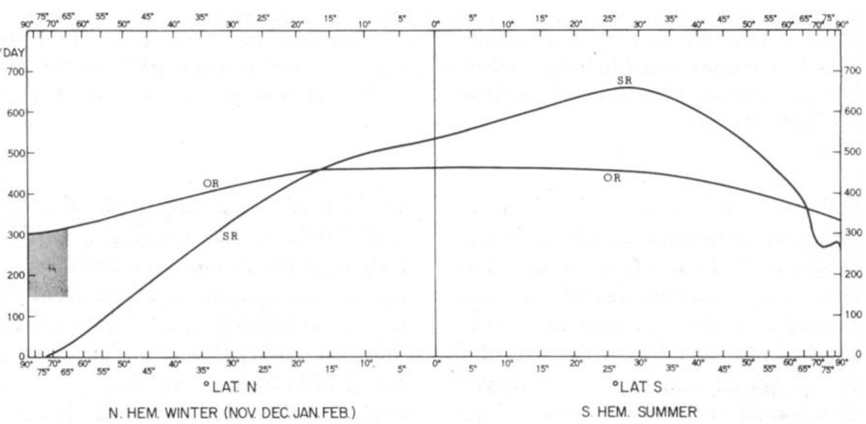


Fig. 1. Latitudinal distribution of unreflected solar radiation (SR) and outgoing radiation (OR) for the Northern Hemisphere winter third of year (November, December, January, and February).

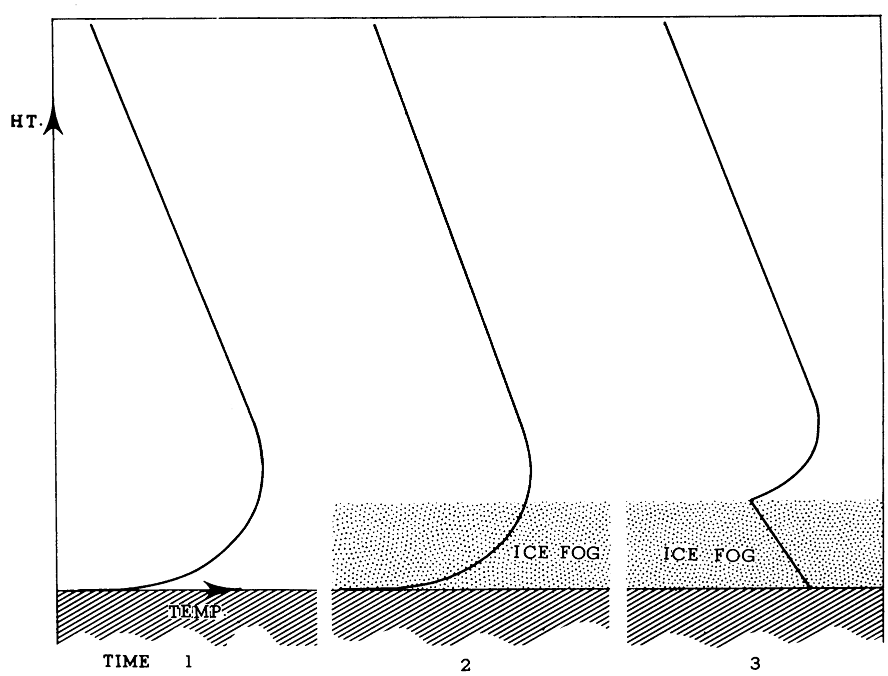


Fig. 2. Effect of shallow (a few hundred feet thick) ice fog on surface temperature inversion.

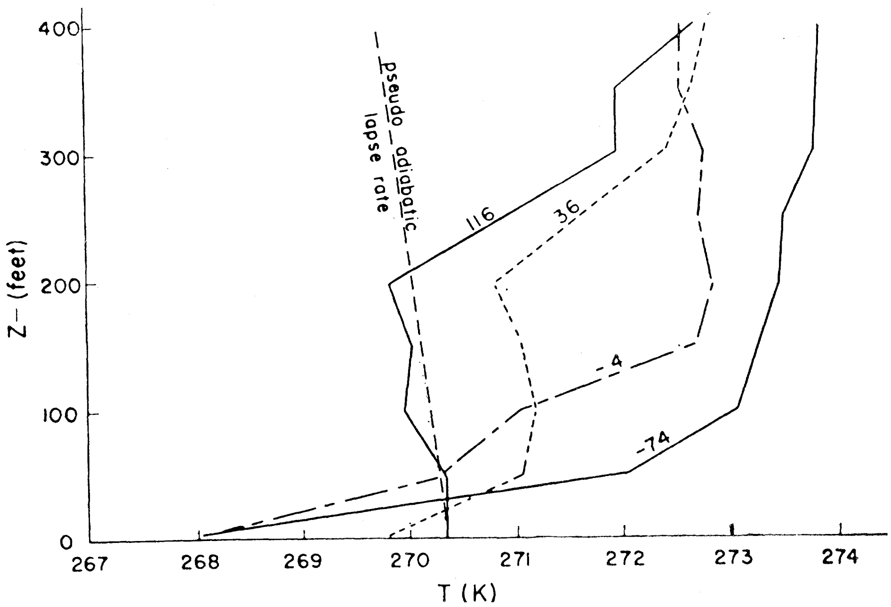


Fig. 3. Vertical temperature distribution at selected times before and after fog formation on the night of 9 Dec. 1947, in Hanford, Washington. Time in minutes before (—) and after the fog is presumed to have reached a height of 200 feet is indicated by numbers on the soundings. Z, height; T(K), temperature in degrees Kelvin. [After Fleagle, Parrott, and Barad (*14*)].

coming solar radiation remains the same, then, in order to maintain a heat balance for the earth as a whole, each square centimeter of that portion of the earth south of latitude 65°N must increase its outgoing radiation by an average of 8 langleys per day; this represents an average warming of the atmosphere and underlying surface of 1.3°C. If the compensating heating were confined only to the region from latitude 0° to 65°N, the warming would be 2.8°C. The "crossover point" or intersection of the incoming solar radiation curve (SR) and the outgoing radiation curve (OR) would be displaced toward the equator by 1° of latitude in the first case and by 2° of latitude in the second case.

## Meteorological Consequences of the Ice Cloud

*Arctic basin.* The ice cloud, by preventing direct loss of radiation from the surface to space and serving as a blackbody radiator upward and downward, would greatly increase the surface temperature by eliminating completely the characteristic surface-temperature inversion (*12*). In January, the inversion averages 9°C at Fairbanks, Alaska, and 17°C at Yakutsk, Siberia, and may on individual days be two or three times larger.

The loss of radiation at the top of the ice cloud but not at the bottom would result in a temperature decrease with height within the cloud, particularly over the Arctic basin itself, where appreciable quantities of heat from the sea are conducted upward through the thin ice cover. Fleagle, Parrott, and Barad (*14*) have shown that, even over land, a shallow fog layer will change a stable lapse rate to a steep one, and that, if certain critical conditions of absorption coefficient and coefficient of eddy conductivity above the fog layer are fulfilled, the lapse rate will beome unstable. The appearance of a 200-foot-thick fog layer at Hanford, Washington, (Fig. 3) changed a 5°C-per-100-foot surface inversion to a slightly unstable lapse rate and increased the surface temperature by 2.3°C in two hours. A strong temperature inversion formed just above the fog layer.

In the artificial ice cloud, a similarly induced steep lapse rate would encourage convective currents and condensation which would help renew the cloud, while the tropopause inversion would prevent upward diffusion of the cloud particles.

The elimination of the radiation loss directly from the Arctic ice pack would result in a less heavy accumulation of ice than normally occurs during the winter. There would of course still be some freezing, caused by the advection of cold air from the adjacent continental areas not affected by the ice cloud.

The area of the present Arctic ice pack is roughly $8 \cdot 10^6$ square kilometers. If the ice cloud persists for the four winter months and eliminates 80 percent of the average radiation loss of 0.06 langleys per minute (*15*) from the ice surface, this would amount to a total of $5.5 \cdot 10^{18}$ calories saved each day of the 4-month winter period, or $1.8 \cdot 10^{18}$ calories per day averaged for the year. Now the annual heat transport poleward across latitude 63°N in the North Atlantic Ocean, according to Jung (*16*) is $0.7 \cdot 10^{18}$ calories per day. Presumably, a large fraction of this energy flows into the Arctic basin and very little energy enters through the Bering Straits from the Pacific Ocean. Thus, the ice cloud would prevent direct radiative loss of energy to space at a rate at least twice that at which energy is brought in by ocean currents to the Arctic basin. However, as is indicated in Table 2, there would still be a leakage of energy to space by radiation from the top of the ice cloud, which would be supplied both by conduction of heat through the ice and by advective transfer of energy from the south. Since there would be no ice cloud in summer, the normal insolation would induce normal summer melting of the ice. Thus, it appears that one of the principal effects of the ice cloud would be to accelerate greatly the disappearance of the Arctic ice pack which is now believed to be under way (*17*).

It is reported by Ahlmann that in the 20-year interval from 1924 to 1944, the Arctic ice pack decreased in area from $9 \cdot 10^6$ to $8 \cdot 10^6$ square kilometers. Also, the average thickness decreased from 365 centimeters in 1893–96 to 218 centimeters in 1937–40, or by an extrapolated value of 65 centimeters from 1924 to 1944. If the ice has 15-per-mill salinity, its heat of fusion is 50 calories per gram. The melting of $8 \cdot 10^{18}$ grams of ice is equivalent to $4 \cdot 10^{20}$ calories in excess energy received in the 20-year period, or $0.055 \cdot 10^{18}$ calories per day. This represents about 8 percent of the net heat transport poleward by Atlantic Ocean currents across latitude 63°N, as computed by Jung (*16*), or 0.15 percent of the net energy transport (both real and latent) by winds across latitude 70°N, as computed by Starr and White (*18*). In other words, an increase of 8 percent in oceanic transport of energy northward into the Arctic basin, or of 0.15 percent in air transport of energy, could account for the observed melting of the Arctic ice pack in the period from 1924 to 1944.

However, the disappearance of the Arctic ice pack would not necessarily be a blessing to mankind. Although this would open up the Arctic Ocean to shipping, the substitution of open water for 8 million square kilometers of ice pack and the rise of surface temperatures would increase greatly, by evaporation, the water content of the Arctic air. In winter this warmer and moister air would interact with the cold air over the adjacent continents, creating strong cyclones, which would deposit heavier and more frequent snows in coastal areas than now occur. This would increase the size of existing glaciers and cause new ones to form, thus endangering existing communities in the sub-Arctic by creating a new "ice age." Indeed, a theory of ice ages, even for middle latitudes, based on the phenomenon of an open Arctic Ocean, has recently been proposed by Ewing and Donn (*19*).

*Equatorial belt.* If an increase in outgoing radiation in regions south of latitude 65°N is required to restore the global balance of radiation with respect to sun and space, this would raise the average temperature of these regions from 1.3° to 2.8°C, depending on whether the readjustment is confined to the Northern Hemisphere or includes the Southern Hemisphere, as described earlier. The elevation of the outgoing radiation curve with respect to the incoming radiation curve (which would in the first approximation remain unaffected by the ice cloud but which might change later as the average cloud distribution becomes affected) would draw the "crossover" points of the two radiation curves closer to the equator.

These crossover points are significant because they represent the latitude at which the poleward transports of energy resulting from the excess of solar radiation in the tropics reach their maxima. Since the transport of energy is accomplished mainly by horizontal eddies of the dimensions of cyclones and anticyclones, the equatorward shift of the latitude of maximum transport poleward would mean a corresponding shift equatorward of the eddies responsible for this transport—a wintertime storm characteristic. Furthermore, the amount of energy to be transported would be reduced, so the eddying motion need not be so intense. The trailing fronts of the southerly displaced cyclonic storms would increase the precipitation of the tropical zones.

*Middle latitudes.* In winter the North Temperate Zone would become warmer and would be located between two dominant storm tracks—one in the sub-Arctic, created by warmer and moister Arctic air masses interacting with cold continental polar air masses and creating more intense storms than normal, and one in the subtropics, having less intense cyclones than normal and displaced a few hundred miles farther south than normal. It would thus appear that the southern portion of the Temperate Zone—say, from latitude 35°N to 50°N —would have less winter precipitation than normal but that the northern portion, from latitude 50°N to 65°N, would have heavier precipitation.

## General Remarks

Apart from practical considerations involved in the manufacture and maintenance of a widespread artificial ice cloud over the Arctic, it is of some interest to predict what the meteorological consequences might be.

We need not be satisfied with the mainly qualitative reasoning given here. Recent advances in knowledge of the general circulation of the atmosphere should make it possible in a few years to achieve a more accurate quantitative estimate of the meteorological consequences of an extensive polar ice cloud.

When serious proposals for large-scale weather modification are advanced, as they inevitably will be, the full resources of general-circulation knowledge and computational meteorology must be brought to bear in predicting the results so as to avoid the unhappy situation of the cure being worse than the ailment.

### References and Notes


1. J. F. Gabites, thesis, Massachusetts Institute of Technology (1950).
2. *Smithsonian Meteorological Tables*, R. J. List, Ed. (Washington, D.C., 1951).
3. H. G. Houghton, "On the annual heat balance of the Northern Hemisphere," *J. Meteorol.* 11, 1 (1954).
4. A langley is equivalent to 1 calorie per square centimeter.
5. On the south polar plateau in the summer of 1957–58, H. Hoinkes observed that dark areas on the snow surface soon frosted over as the water vapor, liberated from the snow by evaporation, formed frost feathers in the 5- to 10-centimeter layer just above the surface.
6. E. L. Corton, "The Ice Budget of the Arctic Pack and its Application to Ice Forecasting," *Tech. Rept. No. TR-6* (U.S. Navy Hydrographic Office, Washington, D.C., 1954).
7. A. P. Crary, "Arctic ice island research," *Advances in Geophysics* (Academic Press, New York, 1956), vol. 3.
8. G. N. Yakovlev, "Radiation regime of the Central Arctic," *Trans. Arctic Sci. Research Inst.* (1957), vol. 207; "Solar radiation as the chief component of the heat balance of the Arctic ice," report to the International Conference on the Study of Sea Ice, National Academy of Sciences, Washington, D.C., 1958.
9. S. Fritz, "Illuminance and luminance under overcast skies," *J. Opt. Soc. Am.* 45, 820 (1955).
10. This is one-fifth the thickness of the layer used by Landsberg in his artificial-snow-melt experiments [see H. E. Landsberg, *Bull. Am. Meteorol. Soc.* 21, 102 (1940)].
11. E. Robinson and J. A. MacLeod, "Wiresonde Observations During the 1952–53 Winter at Eielson Air Force Base, Alaska," *Stanford Research Inst. Publs. Sci. Rept. No. 3* (1954).
12. W. C. Thuman and E. Robinson, "Studies of Alaskan Ice Fog Particles," *Stanford Research Inst. Publs. Sci. Rept. No. 2* (1953). Also appears in *J. Meteorol.* 11, 151 (1954).
13. W. M. Elsasser, "Heat Transfer by Infrared Radiation in the Atmosphere," *Harvard Meteorol. Studies No. 6* (1942).
14. R. G. Fleagle, W. H. Parrott, M. L. Barad, "Theory and effects of vertical temperature distribution in turbid air," *J. Meteorol.* 9, 53 (1952).
15. H. Wexler, "Observations of nocturnal radiation at Fairbanks, Alaska, and Fargo, N. Dakota," *Monthly Weather Rev. Suppl.* 46 (1940).
16. G. H. Jung, "Heat Transport in the North Atlantic Ocean," *Agr. Mech. Coll. Texas Tech. Rept. No. 55-34T* (1955).
17. H. W. Ahlmann, "Glacier Variations and Climatic Fluctuations," *Am. Geog. Soc. Bowman Mem. Lectures, Ser. 3* (1953); N. N. Zubov, *V. Tsentre Arktiki* (Moscow, 1948), a translation of E. Hope, *Arctic Ice and the Warming of the Arctic* (Ottawa, 1950), chap. 6, 7. R. A. McCormick of the U.S. Weather Bureau has computed that it would take a minimum of 100 years to melt the Arctic ice pack by pumping water across the Bering Straits, as has been suggested by A. B. Markin of the Moscow Institute of Power. An ice cloud would require less than 10 years.
18. V. P. Starr and R. M. White in "Studies of the Atmospheric General Circulation," *Mass. Inst. Technol. Final Rept.* (1954), pp. 186–242.
19. M. Ewing and W. L. Donn, "A theory of ice ages," *Science* 123, 1061 (1956).