

## Weather Modification by Carbon Dust Absorption of Solar Energy

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### ABSTRACT

Growing global population pressures and predicted future food and energy shortages dictate that man fully explore his potential use of solar energy. This paper investigates the possibility of beneficial weather modification through artificial solar energy absorption. A variety of physical ideas related to artificial heat sources on different scales of motion are considered. Interest is concentrated on the feasibility of mesoscale ( $\sim 100$ – $300$  km) weather modification through solar energy absorption by carbon aerosol particles of size  $\sim 0.1$   $\mu\text{m}$  or less. Particles of this size maximize solar energy absorption per unit mass.

It is hypothesized that significant beneficial influences can be derived through judicious exploitation of the solar absorption potential of carbon black dust. There is an especially high potential for this in the boundary layer over tropical oceans and in the formation of cirrus clouds and the consequent alteration of the tropospheric IR energy budget. If dispersed in sizes  $\leq 0.1$   $\mu\text{m}$ , solar energy absorption amounts as high as  $\sim 2 \times 10^{10}$  cal  $\text{lb}^{-1}$  per 10 h or about  $4 \times 10^{11}$  cal per dollar per 10 h can be obtained. This is a tremendously powerful heat source, especially if it stimulates additional radiation energy gains from extra cloud formation and/or enhanced surface evaporation. Preliminary observational and modeling information indicates that this artificial heat source can be employed on the mesoscale ( $\sim 100$ – $300$  km) to achieve significant economic gains by means of precipitation enhancement and tropical storm destruction alleviation. It may also be possible to use carbon dust to enhance precipitation over interior land areas, alter extratropical cyclones, inhibit high daytime summer temperatures and severe weather, prevent frosts, and speed up springtime snowmelt in agriculturally marginal regions.

A discussion of this physical hypothesis from the meteorological, radiational, engineering and ecological points of view is made.

### 1. Introduction

#### a. Purpose

This paper is written for the purpose of opening a dialogue on a new area of potential weather modification—mesoscale weather modification from solar energy interception by small carbon particles. It would appear that present-day weather modification may need a broader scientific outlook. Nearly all the weather modification efforts over the last quarter century have been aimed at producing changes on the cloud scale through exploitation of the saturated vapor pressure difference between ice and water. This is not to be criticized, but it is time we also consider the feasibility of weather modification on other time-space scales and with other physical hypotheses.

#### b. Physical hypothesis

Most of the sun's energy penetrates through the earth's atmosphere to the surface. A large extra atmospheric heat source would result if some of this incoming solar energy could, instead, be absorbed directly within the atmosphere.

From 60–80% of the incoming solar radiation ( $I_0$ ) in cloud-free areas reaches the earth's surface. In the tropics this figure is 80%. As pictorially shown on the left portion of Fig. 1, the largest portion of incoming solar energy is absorbed at the earth's surface. Most of this energy subsequently goes into evaporation or evapotranspiration. Because sea surface temperatures vary little diurnally, the over-sea boundary layer does not experience a large daily heating cycle as is common over land.

If a significant portion of the incoming solar energy over the seas could be absorbed in the atmospheric boundary layer over a mesoscale area ( $\sim 100$ – $300$  km wide) during daylight hours, an artificial stimulation of mesoscale convection would likely result. This might be accomplished by carbon particle interception of solar radiation as shown on the right side of Fig. 1. Fig. 2 compares the extra boundary layer shortwave heating which is possible in 10 h due to 15% extra absorption of incident solar radiation with the usual 10 h net long- and shortwave radiation of the tropical troposphere as determined by Cox and Suomi (1969).

Mesoscale heating rates of this magnitude will produce energy perturbations in the layers in which they are applied 5–10 times greater than those of the IR cooling rates. It is hypothesized that these carbon-

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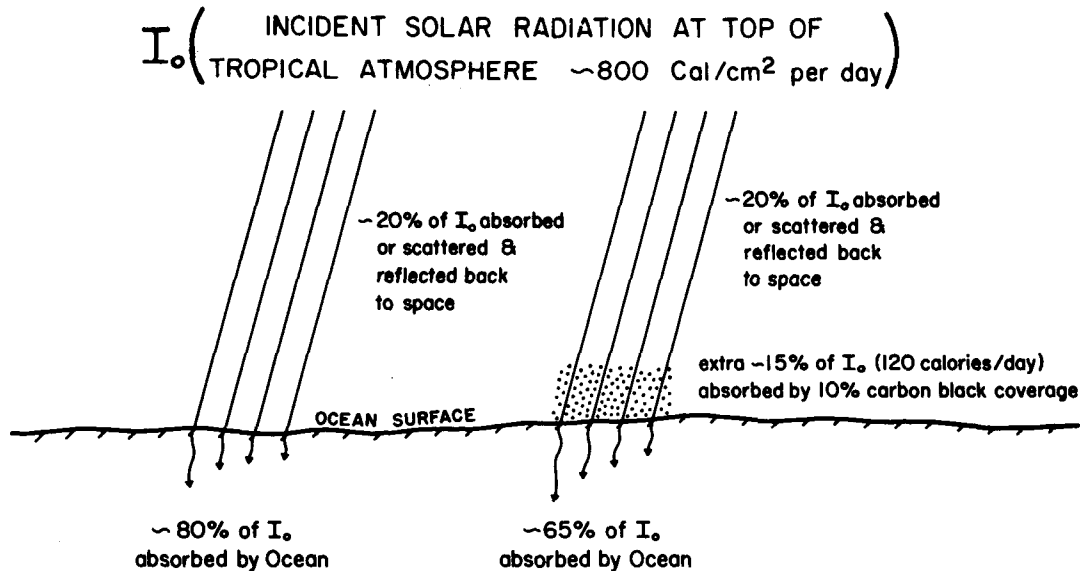


FIG. 1. Contrast of clear air tropical conditions with normal solar absorption by atmosphere-ocean (on left) with extra solar absorption with 10% aerosol coverage in boundary layer (on the right).

particle-induced mesoscale solar energy perturbations can produce significant beneficial weather alterations at very favorable cost-benefit ratios.

#### c. Method of particle distribution

It appears that it will be possible to manufacture  $\sim 0.1 \mu\text{m}$  size carbon particles directly from liquid petroleum products (i.e., hydrocarbons) on aircraft or from ship or land surface sites. Section 2 discusses how it is possible to obtain about 50% mass yield of small carbon particles directly from the burning of liquid hydrocarbons. It is proposed that carbon particles be directly generated in the desired size range and dispersed at the places where modification is desired without storing. This prevents handling and clumping problems. Feasibility studies are in progress to determine the best methods of manufacture. It is highly desirable that the carbon particles be manufactured at individual dispersion sites. Liquid petroleum can be much more easily handled and dispersed than can solid carbon dust purchased from the factory.

Once formed by burning, the mechanical turbulence of the atmosphere and the extra convection induced by the solar absorption will mix the air of the seeded area so as to promote sufficient horizontal spread of the particles.

#### d. Magnitude of extra solar energy gain

Sub-micron carbon particles will absorb approximately 1.5 times the solar energy incident upon their cross-sectional area. If dispersed in sizes of  $\sim 0.1 \mu\text{m}$ , a 10% cross-sectional area of carbon particles will absorb about 15% of the incident solar energy and will require carbon amounts of only  $\sim 25 \text{ kg km}^{-2}$

( $\sim 200 \text{ lb mi}^{-2}$ ). This will provide extra energy gain to a 50 mb thick layer in the upper troposphere or in the planetary boundary layer equivalent to  $\sim 2\frac{1}{2} \text{ cal cm}^{-2}$  (or  $10^\circ\text{C}$ ) per 10 h of solar heating. One kilogram of carbon black dust can absorb more than 40 billion calories of solar radiation in a single 10 h period. Among energy sources used by man only nuclear energy compares with carbon black as a source of accumulation of energy per unit mass, and no known substance compares as a source of energy per unit cost. Carbon particles cost about  $10\text{¢ kg}^{-1}$ , or  $\$100 \text{ 000}$  per 1 million kilograms.

Fig. 3 portrays the carbon particle masses needed for 10% cross-sectional area coverage over various areas (dotted areas). These are compared with the size of the typical hurricane cloud cluster to show the possibility of mesoscale weather modification.

#### e. Types of possible mesoscale weather alteration

(i) Rainfall enhancement from extra solar energy absorption in the boundary layer.

(ii) Cirrus cloud generation, with consequent reduction of tropospheric radiation loss. This might be employed to produce cloud cluster growth or intensity increase, reduce high daytime temperatures, and inhibit frost occurrence.

(iii) Reduction in intensity of the hurricane's inner-core circulation.

(iv) Cumulonimbus enhancement over selected land regions in need of precipitation when the natural evaporation rates are high.

(v) Alteration of extratropical cyclones.

(vi) Inhibiting frost by raising daytime temperature.

(vii) Accelerating snowmelt in agricultural areas.

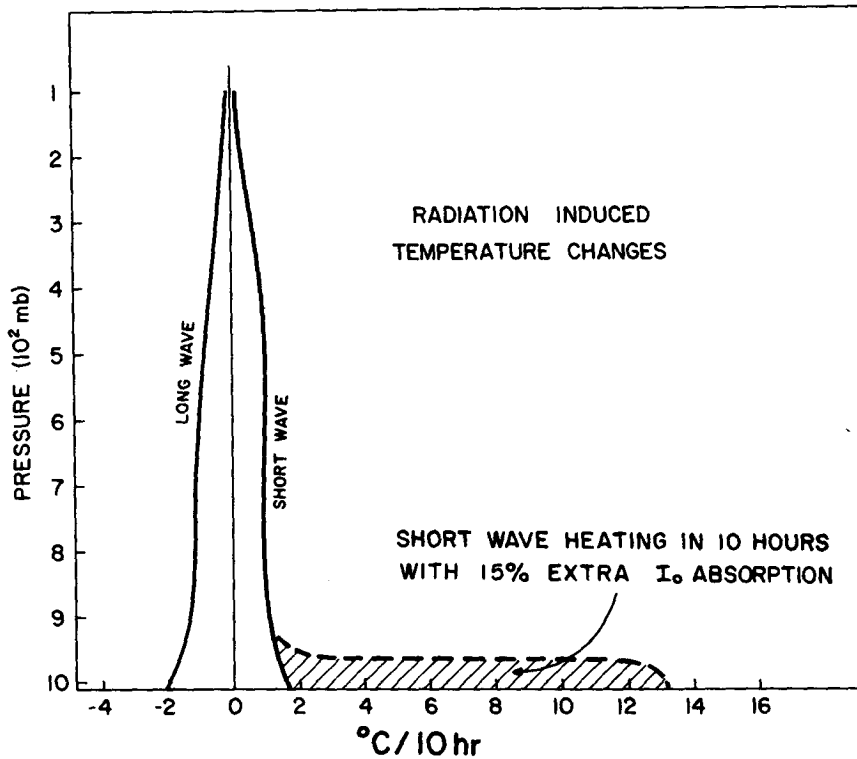


FIG. 2. Comparison of 10 h heating-cooling rates due to long- and shortwave radiation in clear regions with the extra boundary-layer-induced heating (shaded area) which is possible in 10 h from 15% artificial solar absorption.

These are a few of the potential applications to which the interception of solar energy on a mesoscale might be used by man. There are probably also many other atmospheric situations in which man could benefit from application of a heat source of the magnitude here discussed.

The most likely locations for carbon dispersal are in the upper troposphere, which will result in the formation of cirrus clouds inhibiting IR energy loss, and in the planetary boundary layer over the oceans.

1) CIRRUS CLOUD REDUCTION IN IR ENERGY LOSS. In addition to the extra solar energy absorbed by the carbon dust, the increased cloudiness resulting from this solar absorption will itself act to inhibit tropospheric longwave energy loss and bring about an additional energy concentration. This is especially true with regard to the formation of layered cirrus clouds. Cox (1968, 1971, 1973) has studied the influence of cirrus shields on the tropospheric infrared (IR) cooling and finds a major reduction in the amount of net cooling compared to the outgoing radiational cooling occurring with clear sky conditions. Fig. 4 compares the IR cooling differences between a clear atmosphere and an atmosphere which contains a thick cirrus shield.

2) ENHANCED EVAPORATION. The direct solar heating of boundary-layer air by carbon absorption is but one

of two primary influences which occur. If accomplished over water bodies, the enhanced solar heating of the air should also stimulate an increase in evaporation. The increased warming of the air will stimulate extra vertical mixing and downward penetration of

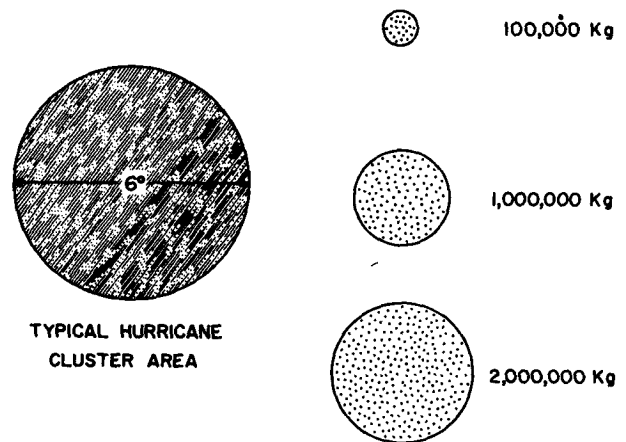


FIG. 3. Comparison of typical hurricane cluster area (6° latitude diameter) with the areas (dotted) of 10% carbon black coverage which are possible with various amounts of carbon black dust. Estimating the cost of carbon dust to be \$0.10 kg<sup>-1</sup>, these three area coverages would require carbon amounts of \$10 000, \$100 000 and \$200 000.

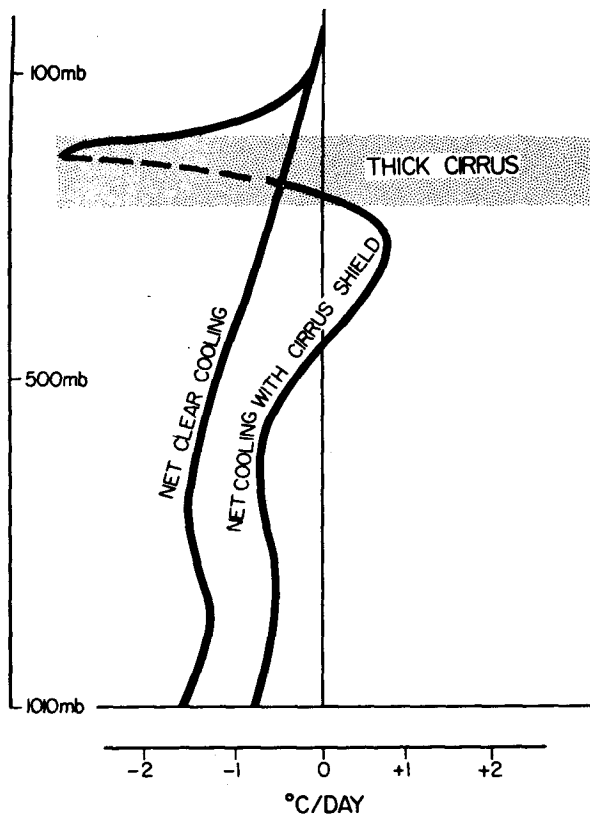


FIG. 4. Comparison of infrared cooling occurring in a clear tropical environment and in one with a thick cirrus shield, from the information of Cox (1971).

upper level drier air to the ocean surface. This drier air will increase the water vapor pressure difference between the ocean and the air and lead to increased evaporation rates. Evaporation rates may perhaps be increased by double or more their normal values. This evaporation influence can also continue for many hours after the heating has taken place. The energy for this increased evaporation, however, will come largely from the ocean and not the air. Thus, it may be possible for the carbon dust solar heating to extract more energy from the ocean than would be extracted normally. The potential buoyancy of the low levels will be enhanced by the extra water vapor content.

#### f. Synopsis

By utilizing the very large energy gains which are available from sub-micron carbon particle absorption of solar energy, man may be able to implement a number of beneficial mesoscale weather modification schemes. The following sections discuss many of the technological, radiational, ecological and meteorological requirements and questions which are likely to be encountered in this type of modification.

## 2. Feasibility of carbon particle generation and dispersal

Most of the large-scale carbon dust weather modification operations envisaged require the relatively rapid production and dispersal of very large quantities of sub-micron carbon particles. The carbon black industry produces over 3 billion pounds of carbon black annually, a sizeable percentage of which is in the sub-micron size range, using technology which has been well known and widely published for decades. The furnace process is used to produce virtually all commercial carbon black. It is strongly believed that this process is easily applicable to the production of the sizes and amounts of carbon particles required for effective weather modification.

We are seeking to establish beyond any reasonable doubt the feasibility of ground and airborne generation of clouds of carbon particles in the fraction of a micron size range at a rate of 10 000 to 50 000 pounds of carbon per hour. Feasibility as used here means that all process steps and types of devices are now in use separately on a large scale so that, given adequate funds and the help of organizations and personnel highly skilled in each of the parts of the process, the basic engineering design of a full-scale prototype unit could be started. At the present time generation of carbon dust clouds from surface sites (ground or ship based) is quite feasible using approximately the same equipment and technology as is used by the carbon black industry. However, since airborne generation would greatly increase the number of possible applications, it is very important to demonstrate the feasibility of this particular method of generation. It will be assumed that demonstration of the feasibility of airborne generation will be sufficient proof of the feasibility of ground or sea surface (i.e. ship) based generation. The alternatives studied are listed below:

1) REDISPERSSION OF CARBON MADE PREVIOUSLY. Commercial carbon black has been taken aloft in various aircraft and has been dispersed into the air through venturi devices utilizing air flow to produce the necessary shear of particles for dispersion. This method is judged impractical for the large amount of carbon discharge required by this project. Between 200 and 1000 bags per hour of beaded carbon would have to be handled, opened, finely ground, and fed through a dispenser. While this might be done in a large aircraft (e.g., a Boeing 747 or the shorter 747SP) the cost of modifying and equipping the aircraft would be very large. A special crew of about 5 to 10 people would be required to handle the carbon in a plane. Degree of dispersion would leave much to be desired, and this alone could make this method impractical.

2) CARRYING ALOFT A COMMERCIAL CARBON BLACK FURNACE. This alternative is more costly and presents weight and power problems. The furnaces currently

in use are not designed for light weight or compactness. The problems could be solved in a very large aircraft, but the cost could be enormous.

3) USE OF A RAM JET ENGINE. This could be done except that such engines are not currently in use. An afterburner is in effect a ram jet added to a turbine jet engine. We mention this possibility only to indicate that it has been considered.

4) USE OF AFTERBURNER TYPE JET ENGINES TO GENERATE CARBON DIRECTLY. This alternative was considered by far cheapest, most effective, most convenient, and safest alternative. It was therefore chosen for detailed study.

As clearly revealed in published patents (Krejci, 1958; Latham and James, 1967; De Land, 1967; Friauf and Thorley, 1961a; Friauf and Thorley, 1961b), the carbon generation process essentially consists of burning a primary fuel with about 140 to 180% of theoretical air and then injecting a high molecular weight liquid hydrocarbon into the hot, turbulent combustion products of the primary fuel. A portion of the injected hydrocarbon and part of the hydrogen evolved from the hydrocarbon fuel burn instantly creating a highly luminous flame which is quenched from a theoretical flame temperature of some 3600–3800°F to an exit temperature of 2700–3000°F by the endothermic decomposition of that part of the hydrocarbon which is not burned. The decomposition products rapidly condense or polymerize into primary carbon particles which also tend to grow upon each other in chains much like a string of frog's eggs. The entire carbon-forming process, after injection of the hydrocarbon, is complete in a matter of milliseconds. There are patented ways to control the chaining tendency so as to give smaller or larger agglomerates and thus obtain the desired particle size.

It is fairly evident that the afterburner of a jet engine sets up almost ideal conditions for injecting a liquid hydrocarbon fuel into hot primary combustion gases with some residual oxygen content. Missing only are adjustments in air ratios, provisions for injecting the hydrocarbon through suitably cooled nozzles, provision of an elongated afterburner shell in order to allow sufficient time for carbon formation, and provision for supplemental cooling of the modified afterburner due to the highly luminous radiant flame. There may also be practical problems to be dealt with in protecting the aircraft body from too much heat from the streaming exhaust flame. The feasibility of adapting an afterburner-type jet engine to airborne carbon particle cloud generation has been discussed in detail in a feasibility study project report by Stokes and Reed (1973). Such an engine could be mounted easily on a portable test stand on the ground or on a ship for land or sea surface carbon generation. Fig. 5 shows how carbon dust would be generated and dispersed from a jet aircraft.

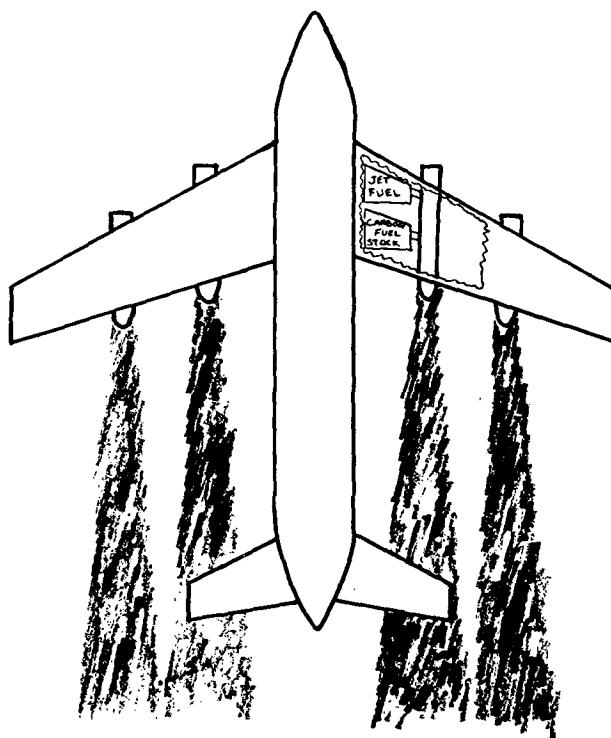


FIG. 5. Illustration of how carbon dust would be generated and dispersed from a jet aircraft.

It is necessary to have a stable, noncorrosive fuel which is liquid and pumpable at a reasonable temperature, preferably not much over 100°F. This condition can be met with certain commercial carbon black fuels. Some of the regular aircraft fuel tanks can be used provided precautions are taken against possible damage of any rubber or plastic linings, fittings, seals, etc., by the carbon fuel. The fuel can be kept warm in the tank with electrical immersion heaters powered by the aircraft electrical system. The wattage required is very small.

Having deduced that we could use an afterburner type jet engine to produce the kind and quantity of carbon wanted, we next had to check our findings with engine manufacturers to see if our proposal could be accomplished in a practical fashion. The results were indeed gratifying. The opinion firmly expressed was that existing jet engines could be modified by lengthening the afterburners and that such engines could be used in place. As an alternative to using engines that are wing mounted, a "flying test platform" could be used. This is a plane fitted with a device to lower a jet engine from the fuselage in flight, a commonly used method in engine development work.

An ideal aircraft would be a B-52 with its eight afterburner engines, four of which could be modified. Some re-piping of the fuel tanks would also be required. During takeoff all engines would be used in the normal

manner. In the air four engines would be switched to carbon production.

The approximate conditions that would apply before and after modification of a typical afterburner engine are shown in Figs. 6 and 7.

We have concluded that by slightly modifying readily available jet engines, 0.1  $\mu\text{m}$  carbon dust particles could be produced and dispersed into the air at a rate of 20 000–30 000 pounds per hour per engine. Roughly half of the weight of the carbon fuel would appear as carbon particles resulting in a carbon particle production cost of about 5–10¢ per kilogram. The operation would be safe and in every way feasible from the point of view of fuel combustion, mechanical and aeronautical aspects. Therefore, the carbon dust particles could be generated and dispersed from airborne sources as well as from land or sea surface sites. It is beyond the scope of this paper to go into the engineering details or costs, but these matters are under study. A program for the development and testing of prototype carbon particle generating engines using existing jet aircraft engines and test facilities has been proposed and outlined in the feasibility study report by Stokes and Reed (1973).

It is implied that the generation of carbon particles will be accomplished from moving sources such as an aircraft or ship. If accomplished from stationary land

sites, multiple sites will be employed. Any mesoscale seeding will involve multiple aircraft or ships. These moving or multiple stationary sources should insure proper horizontal spreading of the carbon particles. The ordinary mechanical turbulence of the atmosphere and the convection produced by the solar absorption will further act to horizontally mix these particles.

### 3. Radiation

#### a. Radiative properties of carbon black dust in the atmosphere

Carbon black dust consists of fine spherical particles composed of 95–99% pure carbon, the remainder being made up of volatile materials. The density of the carbon particles is about  $2.0 \text{ g cm}^{-3}$ . The high radiative absorptivity and low heat capacity ( $\sim 0.125 \text{ cal g}^{-1} \text{ }^\circ\text{C}^{-1}$ ) of carbon black make it an ideal agent for the interception of solar radiation and transfer of this heat to the surroundings by conduction. These properties are discussed in more detail later.

1) RADIATION CHARACTERISTICS OF CARBON BLACK. There are various available estimates of the complex index of refraction of carbon particles, which, in general, are in close agreement. The complex refractive index as estimated by Krascella (1965) is shown as

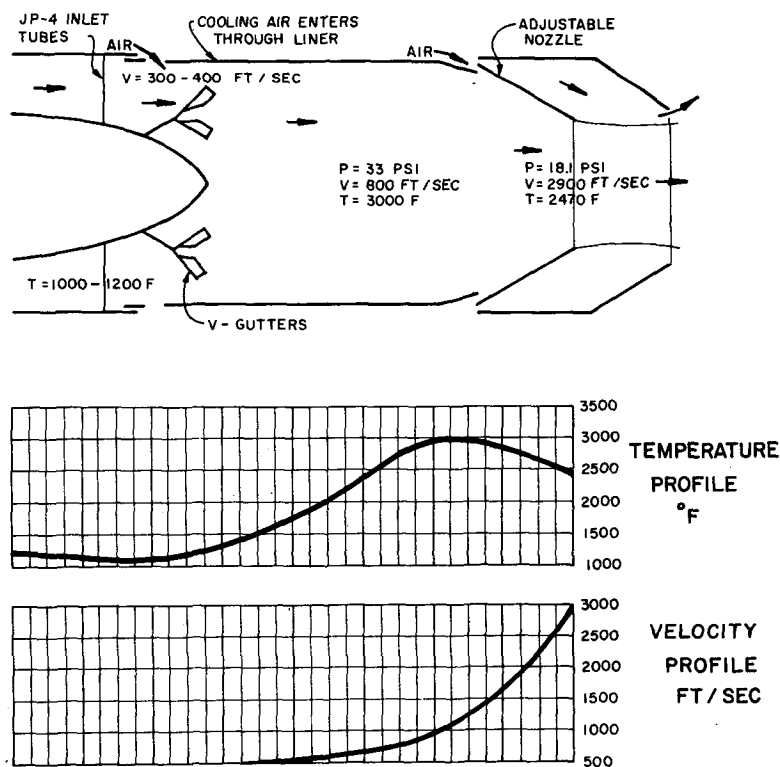


FIG. 6. Conditions existing in the afterburner and tailpipe assembly of a typical jet engine during afterburner operation (based on data for the J-57 and J-79 engines).

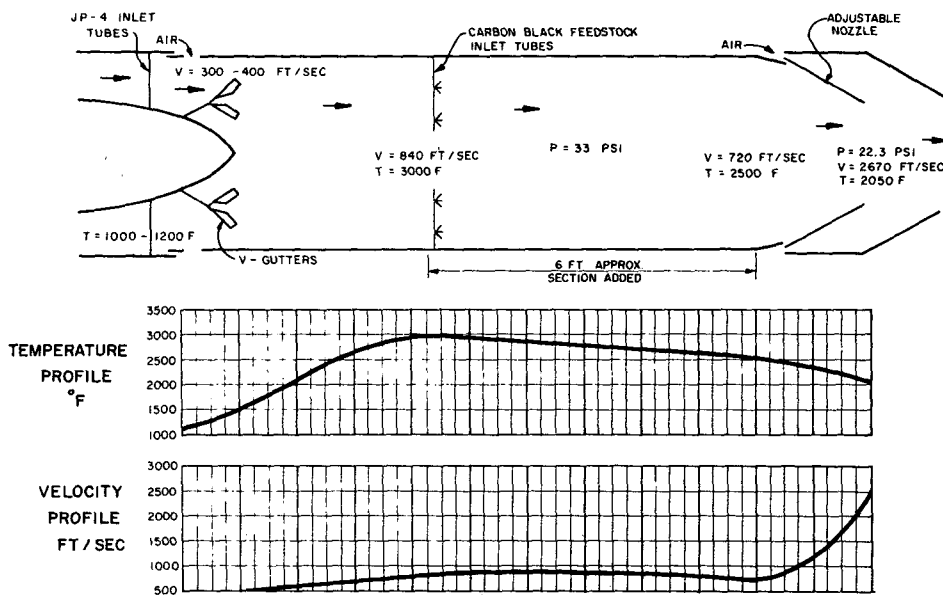


FIG. 7. Approximate conditions existing in the afterburner and tailpipe assembly of a jet engine modified for carbon production (based on estimates for the J-57 and J-79 engines).

a function of wavelength in Fig. 8. The absorption ( $\sigma_A$ ), scattering ( $\sigma_S$ ) and extinction ( $\sigma_E$ ) cross sections of spherical carbon particles computed by Mie scattering theory are shown as functions of the size parameter  $\alpha = 2\pi r/\lambda$  in Fig. 9 for particles of  $0.1 \mu\text{m}$  radius. These coefficients are defined as the ratios between the effective areas with which particles ab-

sorb, scatter and extinguish light and their actual geometric cross sections. They are functions of the refractive index of carbon, particle size, and the wavelength of the affected light. The coefficients are related as shown in Eq. (1):

$$\sigma_E = \sigma_A + \sigma_S = \text{extinction cross section.} \quad (1)$$

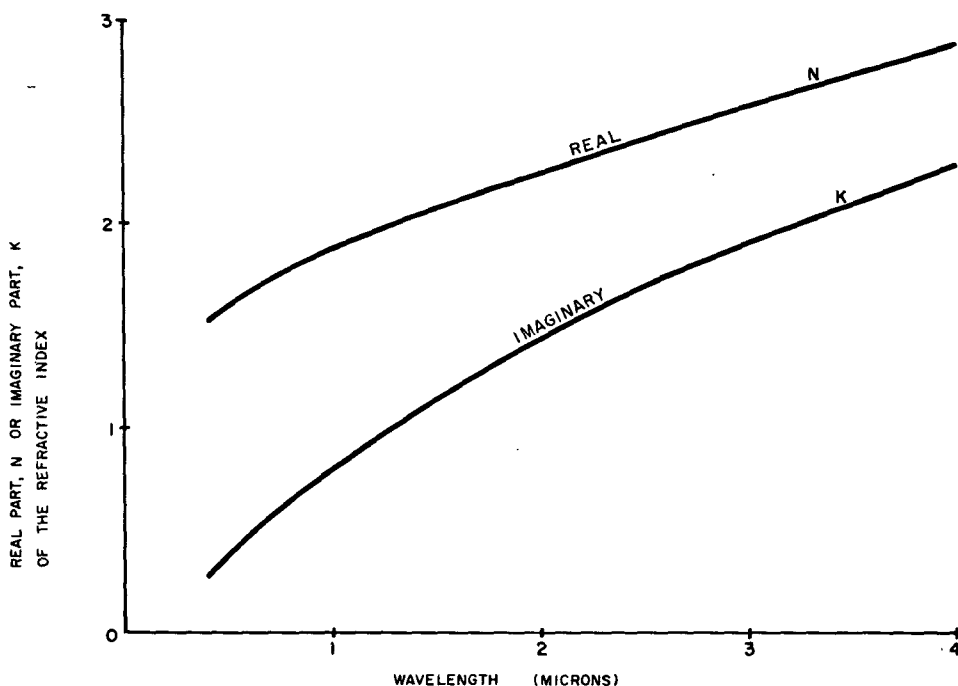


FIG. 8. Variation of the real and imaginary parts of the complex index of refraction of spherical carbon particles with incident wavelength (Krascella, 1965).

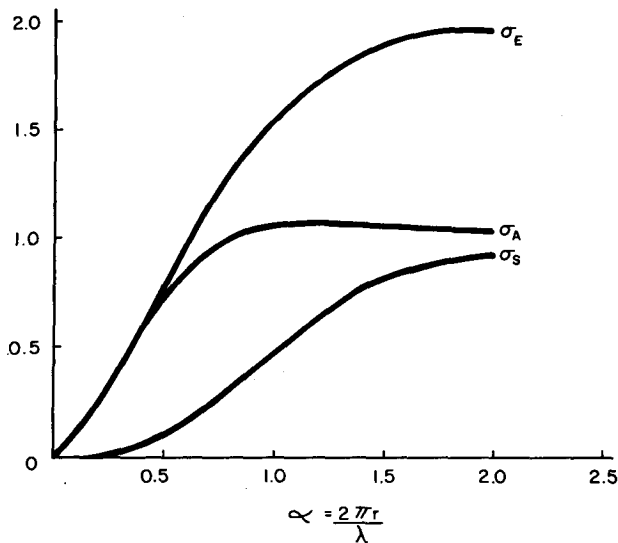


FIG. 9. Extinction ( $\sigma_E$ ), absorption ( $\sigma_A$ ) and scattering ( $\sigma_S$ ) cross sections of spherical carbon particles as functions of size parameter ( $\alpha$ ).

The values shown in Fig. 9 (Krascella, 1965) are in close agreement with experimental and theoretical estimates of the tinting strength of carbon black particles made by various carbon black companies. Marteney (1965), in a companion study to that of Krascella, obtained experimental absorptivities of carbon particles dispersed in air which are in close agreement with Krascella's theoretical values. Fenn and Oser (1962) estimated somewhat higher values of these parameters. Carbon black particles, when formed, are virtually all spherical and of relatively uniform size and composition. Since the particles will be dispersed into the air immediately after formation, the relevance of Mie scattering theory to light extinction by carbon particles seems to be reasonable.

2) CHARACTERISTICS OF THE CARBON CLOUD. For this study each carbon dust cloud was assumed to be composed of uniform carbon particles. The clouds were of large horizontal extent compared to their thickness, and each cloud or cloud layer was assumed to be homogeneous. Water vapor contents of the clouds were assigned according to standard atmospheric concentrations depending upon cloud height. All water vapor was assumed to be uncondensed.

The above assumptions were made for convenience of computation. Real situation variations from these assumed values are not felt to be large enough to alter greatly the results to be shown. Any of the assumptions can be varied to meet individual case refinement as desired.

3) OPTIMUM PARTICLE SIZE. For economic reasons it is desirable to maximize the amount of radiation absorbed by the carbon particles per unit mass. To do this the optimum particle size must be determined. Based on our computations and those of Fenn and

Oser (1962), Fenn (1964), and sources in the carbon black industry, the optimum radius is approximately  $0.05 \mu\text{m} \leq r \leq 0.1 \mu\text{m}$ . For simplicity we shall assume particles of  $r=0.1 \mu\text{m}$  for the remainder of this study. It is important to realize that light extinction per unit mass of carbon is not highly sensitive to particle size changes from 0.01 to 0.3  $\mu\text{m}$ . More detailed discussions of the optimum particle size can be found in Gray *et al.* (1974) and Frank (1973). Size quality control should not be a crucial problem.

4) DIVISION OF THE SOLAR SPECTRUM. To average the general transmission function, the solar spectrum must be divided into finite bands, and average values of the extinction coefficient and optical depth must be determined for each band. These parameters vary rather smoothly with changing wavelength. However, water vapor absorption is quite irregular with respect to wavelength. It is therefore desirable to choose bands such that each of the absorption bands of water vapor will coincide with one of the defined spectral bands. In the spectral bands with no water vapor absorption, water vapor absorption will be zero, and in the bands which coincide with water vapor bands, average values may be determined. (The solar constant value used is  $1.95 \text{ ly min}^{-1}$ ). Eighteen spectral divisions were used. More detailed discussions of this method are given in reports by Frank (1973) and Gray *et al.* (1974).

5) METHOD FOR SOLVING THE EQUATION OF RADIATIVE TRANSFER THROUGH A CLOUD. A method developed by Korb and Möller (1962) was used to solve the general equation of radiative transfer through a cloud [as developed by Chandrasekhar (1960)]. The radiation field was broken up into  $2+2\pi$  fluxes; one directed upward, one downward, and  $2\pi$  fluxes in the horizontal plane. This breaks the general transfer equation into a series of linear differential equations which give absorption, transmission and reflection of radiation as percentages of total incident radiation. These equations are shown in the Appendix for the cases where surface albedo is zero and where surface albedo is non-zero.

The absorption, reflection and transmission were determined for each given zenith angle and optical depth for a narrow spectral band, and the results were summed for all spectral bands to give total values for given zenith angle and optical depth. Nine zenith angles from  $0^\circ$  to  $80^\circ$  at  $10^\circ$  intervals were chosen. For simplicity, calculations of daily absorption assumed a 12 h day with the sun directly overhead at noon. The total absorption and transmission per day for each optical depth was obtained by time-averaging the values over the 10 h 40 min period with zenith angles  $<80^\circ$  in computation steps of  $10^\circ$  zenith angle change (40 min). Water vapor absorption within the cloud was also included in the computations.

The above radiation model was run assuming no surface reflection and also for various albedos by



introducing an upward diffuse radiation field using mean values of the scattering function components. Intensity of the upward scattered field varied with albedo and the amount of light initially transmitted through the cloud.

Solar irradiances at the top of each cloud were reduced using calculations by Dave and Furukawa (1966) to account for ozone ( $O_3$ ) absorption and molecular scattering above the cloud top. Molecular scattering within the cloud was not considered. Absorption and scattering by molecular oxygen ( $O_2$ ) and carbon dioxide ( $CO_2$ ) is insignificant for the purposes of these calculations and was not taken into account. Effects of natural tropospheric aerosols were not considered in these calculations.

For each cloud configuration studied, the total absorption of solar radiation by carbon and water vapor was calculated. The absorption of the equivalent volume at the same altitude due to water vapor alone was then calculated. It was assumed that water vapor in the air around the test cloud would absorb radiation at the rate of the carbon-free air. Since the evaluation of carbon black as a heat source was the object of this study, the net effectiveness of the carbon was the difference between the total solar radiation absorbed by the carbon cloud and the radiation that would be absorbed without the carbon cloud. It was expected that the carbon and water vapor cloud would absorb less than the sum of the absorptions of a carbon-only cloud and a water-vapor-only cloud due to the redundancy of the absorption characteristics of the two substances at longer wavelengths. This proved to be the case, but the loss in efficiency was very small.

### b. Results

1) **ABSORPTION IN THE TROPICAL ATMOSPHERE.** It is felt that the tropical atmosphere presents good opportunities for beneficial large-scale weather modification. Particular interest is centered on carbon black dust seeding into the tropical boundary layer (1013–950 mb). Absorptions were first computed for clouds containing 4.0 cm and 5.0 cm of precipitable water vapor (ppw) but no carbon to simulate clear air absorption in the tropical atmosphere. These are the amounts of water vapor found above 950 mb and 1013 mb, respectively, in a mean tropical cloud cluster. It was found that the 5.0 cm ppw atmosphere absorbed only about 5% more radiation per day than did the 4.0 cm ppw atmosphere. This indicates that 95% of the solar radiation absorbed daily by a 5.0 cm ppw atmosphere is absorbed by the portion of that atmosphere containing the uppermost 4.0 cm. Since so little solar radiation ( $\sim 9$  ly day $^{-1}$ ) is absorbed by the lowest 1 cm ppw, no significant redundancy in absorption by water vapor and carbon would occur in a carbon dust cloud dispersed between 1013 and 950 mb in the

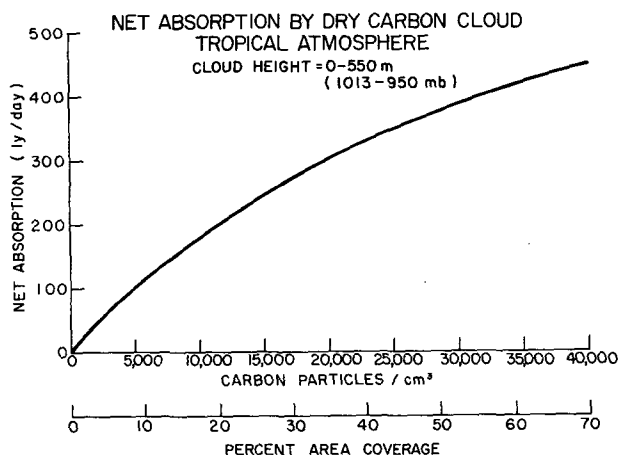


FIG. 10. Net absorption of solar radiation by a dry carbon cloud in the tropical boundary layer.

tropics. Therefore, such a carbon dust cloud can be treated as a dry cloud to a reasonably high degree of accuracy.

Calculations of absorption by a dry carbon cloud in the tropical boundary layer (1013–950 mb) were made using reduced values of solar energy incident at the 950 mb level to approximate the effects of water vapor, ozone and molecular scattering. A surface albedo of 10% was assumed. Net absorption as a function of carbon concentration is shown in Fig. 10. An increasing loss of efficiency of absorption per unit mass occurs at increasing densities as progressively less solar radiation penetrates to the lower levels of carbon, especially at high zenith angles. Therefore, from an economic point of view it is desirable to cover large areas with low concentrations if the magnitude of heat gain to carbon dust expended is to be maximized. A carbon particle concentration of 10 000 particles  $cm^{-3}$  represents 18% horizontal area coverage for this cloud model. This would require only 45 kg of carbon black dust per square kilometer of horizontal cloud area.

2) **ABSORPTION BY CARBON DUST IN THE MID-LATITUDE STANDARD ATMOSPHERE.** Computations of daily absorption were made for a cloud extending from sea level to 11 km containing 2.8 cm ppw, the approximate mid-latitude standard atmospheric water vapor content, and carbon particle concentrations from zero to 2000 particles  $cm^{-3}$ . It was assumed that such a carbon cloud might be used to intensify existing broadscale circulations. Total absorptions and net usable absorptions (total absorption minus natural clear air water vapor absorption) per day are plotted as functions of cloud density in Fig. 11. Absorption rates are plotted as a function of zenith angle for each particle concentration in Fig. 12. This shows the relative effects of decreasing incident solar radiation and increasing optical path length with zenith angle change. It can readily be seen that when dealing with

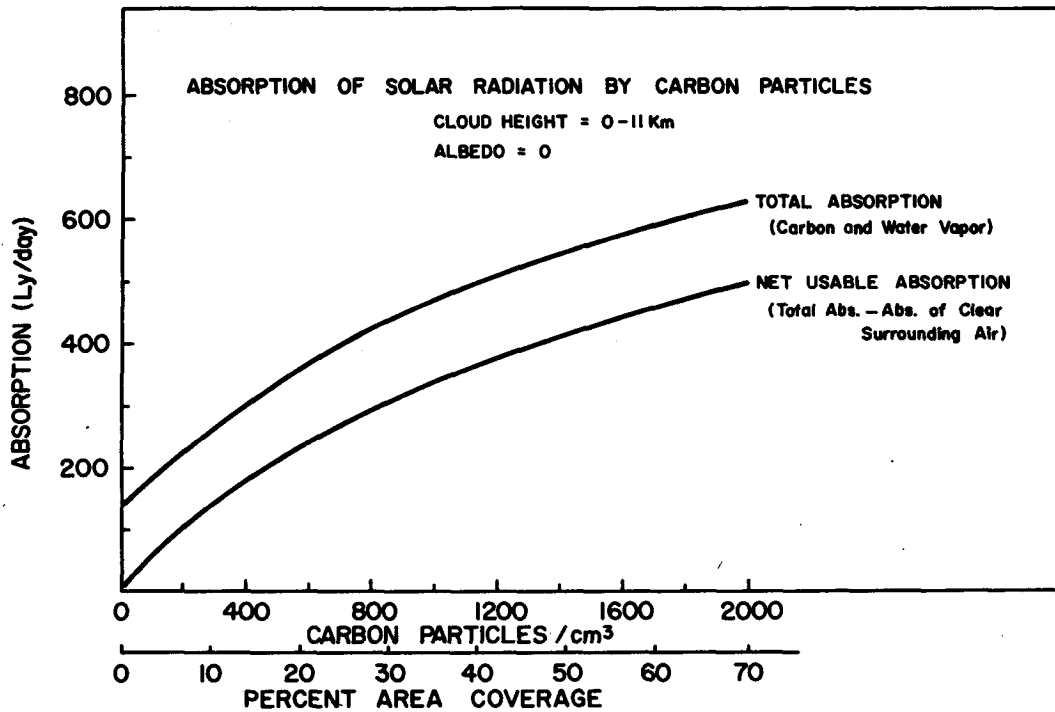


FIG. 11. Total and net usable absorption of solar radiation by carbon particles and water vapor.

large concentrations of carbon dust, efficiency is considerably lower at zenith angles  $>60^\circ$ , which comprises roughly a third of the 12 h day. Operations requiring large concentrations of carbon black for intense local heating would be most economical during the mid-day hours, while those requiring only moderate concentrations ( $N < 500$  particles  $\text{cm}^{-3}$ ) would be efficient throughout the entire solar day.

3) INFLUENCE OF WATER VAPOR ABSORPTION. To obtain an estimate of the magnitude of the efficiency loss due to the redundant absorption tendencies of carbon and water vapor at higher wavelengths, absorption values of a 0-11 km carbon cloud were calculated assuming water vapor content to be zero. The results are plotted in Fig. 13 along with the total and net usable absorption potential for the mid-latitude model. The absorption loss increases with

particle concentration, and the ratio of lost absorption to net usable absorption increases slightly. The lost absorption ranges from 0% to about 14% of net usable absorption for the densities tested.

4) LONGWAVE RADIATION LOSS. To develop a complete heat budget of a carbon black cloud, it is necessary to consider the loss of absorbed radiation due to vertical longwave radiant flux divergence. Korb and Möller (1962) calculated values of longwave flux divergence of various carbon clouds for a 24 h day. They considered  $\text{CO}_2$  and water vapor to be selective absorbers and the carbon particles to be gray absorbers. Standard mid-latitude atmospheric values of water vapor concentrations were used. Results are shown in Table 1. The difference between flux loss from a cloud consisting of carbon, water vapor and  $\text{CO}_2$  and a similarly dimensional cloud consisting only of water vapor and  $\text{CO}_2$  represents the loss of effective heating by the carbon black. In the most extreme case, the 1-6 km cloud with a carbon concentration of  $1 \times 10^4$  particles  $\text{cm}^{-3}$ , the effective loss is only  $10.3 \text{ cal cm}^{-2} \text{ day}^{-1}$  which represents only about 2% of the total solar radiation absorbed in one day by such a cloud. At very high altitudes (the 10-11 km cloud) there is a slight relative gain of longwave radiation by the cloud. Thus, longwave flux should not have a significant effect on the net radiative energy gain of carbon seeded air. It is assumed, therefore, that virtually all radiation absorbed by the cloud will be directly converted into heat within the absorption layer.

TABLE 1. Longwave radiation flux divergence loss by various aerosol cloud models (Korb and Möller, 1962).\*

Cloud height (km)	Longwave flux divergence ( $\text{cal cm}^{-2} \text{ day}^{-1}$ )				
	$\text{H}_2\text{O, CO}_2$ and carbon		Net loss by carbon	$\text{H}_2\text{O, CO}_2$ and carbon	
	$\text{H}_2\text{O and CO}_2$ Cloud (1)	$(N=10^3 \text{ cm}^{-3})$ Cloud (2)		$(N=10^4 \text{ cm}^{-3})$ Cloud (3)	Net loss by carbon Cloud (3) - Cloud (1)
1-2	-33.7	-34.3	-0.6	-38.6	-4.9
5-6	-23.3	-23.3	0.0	-24.9	-1.6
1-6	-126.9	-128.0	-1.1	-137.2	-10.3
10-11	-14.3	-14.1	+0.02	-11.8	+2.5

\*Negative values indicate loss.

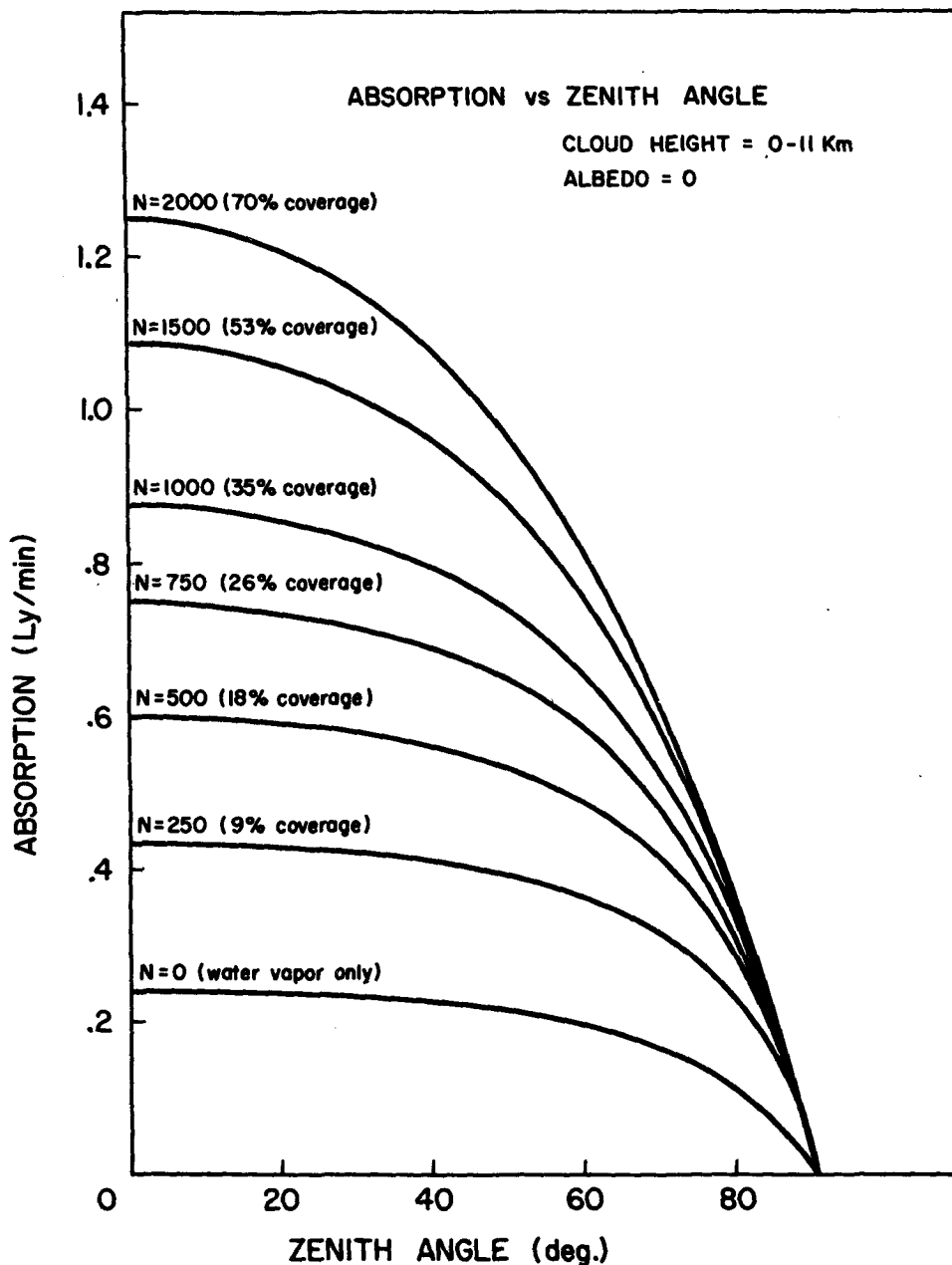


FIG. 12. Variation in absorption of solar radiation with zenith angle.

This finding agrees well with the results of a thermodynamic heat transfer analysis of the carbon particles by the authors in which it was found that about 95% of the absorbed solar energy is conducted to the surrounding air while about 5% is emitted as longwave radiation. Part of the emitted radiation is reabsorbed by carbon particles and water vapor within the carbon cloud resulting in the very low net longwave radiative flux divergences found by Korb and Möller.

5) INFLUENCE OF SURFACE ALBEDO. The effects of varying surface albedo upon total daily absorption were taken into account by applying the upward dif-

fuse radiation field described earlier to the mid-latitude cloud model. The effects are the same for the tropical boundary layer cloud. Computations were made for surface albedo values ( $A_s$ ) of 0%, 10%, 20%, 30% and 50%. The increase in net absorption due to surface albedo is greatest between concentrations of about 500 and 1500 particles  $\text{cm}^{-3}$  peaking at about 1000 particles  $\text{cm}^{-3}$  (35% area coverage). It decreases with higher concentrations due to greater initial interception of light and hence lower reflected values. Even with a 35% surface albedo increase net absorption is changed by only 15% or less. Therefore, although the

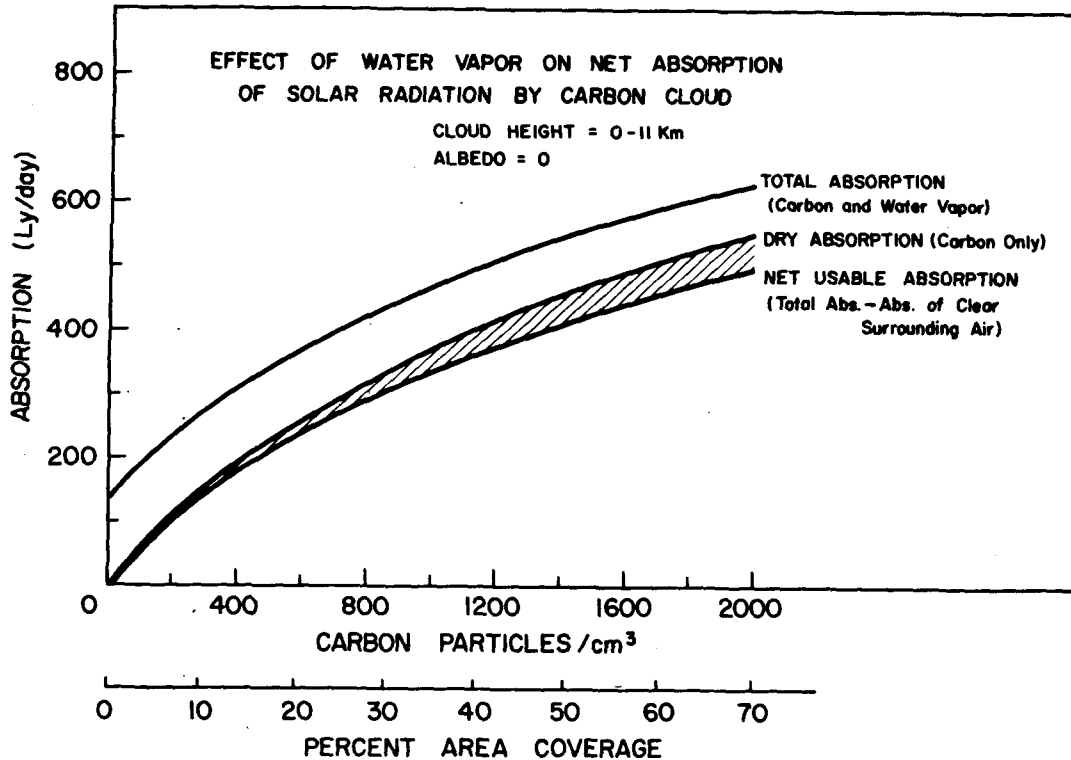


FIG. 13. Loss of efficiency of carbon absorption due to redundant absorption by water vapor.

effects of surface albedo upon absorption are not negligible, they are low enough to be safely neglected in many situations without greatly affecting results.

6) **ABSORPTION DISTRIBUTION IN THE VERTICAL.** For application of this study to actual operations, it is necessary to know how the absorbed radiation is distributed vertically through the cloud. To obtain an approximation of this a 4 km thick layer was divided into four directly adjacent 1 km thick layers. For each carbon particle concentration, absorption in each carbon layer was computed, the top layer first, the top plus the second layer next, and so forth. By simple subtraction the amount of solar radiation absorbed in each layer was determined for this homogeneous cloud model. Total absorption was greatest in the upper layer and decreased in each succeeding layer as the amount of light incident at the top of each layer became less. As particle concentrations increased, the percentage of absorbed light which was absorbed in the upper layer increased sharply. Therefore, if vertically homogeneous heating is required, the particles must be distributed with lowest concentrations at the top increasing to the heaviest concentrations at the bottom of the cloud.

7) **PARTICLE SIZE DISTRIBUTION IN THE VERTICAL.** It was felt that due to relatively high extinction of light in the shorter wavelengths, the light incident upon lower layers of a carbon cloud would exhibit longer median wavelengths than would light incident

upon upper layers. A significant increase in median wavelength would indicate that larger particles would be required to maintain optimum absorption per unit mass. A four-layer cloud model 4000 m thick was used to evaluate this effect. For each of three different carbon particle concentrations, light incident upon the top of each layer was estimated by subtracting previously absorbed light from initial incident light intensities for each spectral region. The median wavelength of light incident upon each layer was calculated.

Computations were made for carbon particle concentrations of 4000, 10 000 and 20 000 particles cm<sup>-3</sup>. The expected increase in wavelengths of solar light at lower levels did occur, but the variations in optimum particle size were small (Frank, 1973). Therefore, for carbon particle concentrations likely to be used in weather modification work, uniform particle sizes can be used without appreciable loss of absorption efficiency per unit mass.

8) **CARBON BLACK DUST AS AN ARTIFICIAL ATMOSPHERIC HEAT SOURCE.** The characteristic of carbon dust which makes it so attractive as an atmospheric heat source is the extraordinary quantity of solar radiation which can be absorbed by a unit mass of carbon. Virtually all of the absorbed radiation is realized as sensible heat gain by the air. Ten percent area coverage (25 kg per square kilometer) of carbon dust provides enough heat to increase the mean temperature of the air within the boundary layer (surface

to 950 mb) at a rate of about  $1^{\circ}\text{C h}^{-1}$  for a 10 h period. Such enormous heating rates open the possibility of meso- or synoptic-scale weather modification.

9) COMPARISON OF CARBON DUST RADIATION ABSORPTION WITH OTHER AEROSOL ABSORPTION. Many researchers have estimated that atmospheric aerosols absorb significant amounts of incoming solar radiation. The question then arises whether analogies exist between the radiative effects of existing atmospheric aerosols, either natural or man-made, and the here-proposed carbon dust cloud.

The two primary radiative differences between the proposed carbon dust cloud and existing natural man-made atmospheric aerosols are 1) differences in the absorption and scattering properties of the aerosols, and 2) differences in the spatial distribution and amounts of the particles. Carbon dust particles of sub-micron size are highly efficient absorbers of solar radiation and exhibit very low levels of backscatter. In contrast, typically 33–100% of the solar radiation extinction due to most atmospheric aerosol samples is reflected. This normally results in a cooling of the earth/atmosphere system by most atmospheric aerosols as well as an increased atmospheric stability. By contrast, the carbon cloud virtually always results in a net warming of the earth/atmosphere system. In addition, the proposed spatial and vertical distributions of carbon dust particles will be much different from those of most of the normal atmospheric aerosols. This distribution should, in general, lead to a destabilizing of the atmosphere column.

Atmospheric aerosols with some significant effect on solar radiation attenuation are in the approximate size range of  $0.01 \leq r \leq 1 \mu\text{m}$  and absorb and scatter according to Mie theory. Particles smaller than  $r \approx 0.01 \mu\text{m}$  are generally very poor absorbers of solar radiation while particles much larger than about  $r \approx 1.0 \mu\text{m}$  do not have enough total surface area to absorb much solar radiation due to their low number concentrations.

The imaginary part of the complex index of refraction ( $k_2$ ) for natural aerosols, which determines their absorptivity, has been measured to be about  $k_2 \approx 0.01$ , although Eiden (1966) has measured tentative values as high as  $k_2 = 0.1$  for very heavily polluted urban air. These values are much less than the  $0.28 \leq k_2 \leq 2.30$  values exhibited by carbon over the solar spectrum. Although the exact dependence of aerosol absorption on the imaginary part of the complex index of refraction is difficult to specify precisely, computations of particle absorptivities by others show that carbon particles should absorb from 5 to 100 times more solar radiation per particle than would most atmospheric aerosols in the most effective size range ( $0.01 \leq r \leq 1.0 \mu\text{m}$ ). The proposed carbon dust configurations exhibit much higher particle concentrations in the highly absorbent  $0.01$ – $1.0 \mu\text{m}$  size range than do most natural and man-produced aerosols. However,

during extreme urban air pollution episodes the particulate concentrations in this size range can equal or occasionally slightly exceed the proposed carbon dust concentrations (Whitby *et al.*, 1971). Such an urban aerosol backscatters a significant amount of solar radiation. This reduces surface heating. In addition, aerosol concentrations of this magnitude usually occur only during meteorological conditions highly unfavorable to developing convection (e.g., subsidence inversion) and over land, which is less favorable for producing horizontal heating gradients than the oceanic boundary layer site proposed for carbon dust seeding.

Although it is tempting to compare localized natural aerosol concentrations to the proposed carbon dust clouds, none of the normally occurring atmospheric aerosols have radiative characteristics or spatial distributions similar enough to the carbon dust clouds to allow any meaningful analogies to be drawn. *Therefore, it is unlikely that any such natural aerosols would result in an atmospheric response similar to the response which a carbon dust cloud would be expected to produce.* The report by Gray *et al.* (1974) gives a more detailed discussion of the radiation differences between carbon and natural aerosols.

#### 4. Discussion of proposed modification schemes

The physical basis for each of the proposed meso-scale weather modification schemes will now be briefly discussed. More complete discussion is given in previous reports by Gray (1973b) and Gray *et al.* (1974).

##### *a. Rainfall enhancement from boundary layer solar energy gain*

Precipitation enhancement from weather system genesis or intensification upwind from coastlines with onshore flow is believed to be a likely possibility. There are many coastal and adjacent inland regions in the tropics and subtropics which need additional precipitation and which have onshore flow. If tropospheric vertical wind shears are not too large, it is very likely that mesoscale weather system genesis or enhancement is possible.

It must be emphasized that we are discussing meso-scale heat sources of the approximate size shown in Fig. 3 and the resulting mesoscale convective patterns which are induced. *We are not discussing the direct stimulation of individual cumulus elements.* The individual cumulus elements will result as a consequence of the extra mesoscale low-level mass and water convergence.

It is envisaged that a carbon-particle-induced meso-scale energy source will cause a mesoscale convergence and upward vertical motion response. This would result in enhanced mesoscale cumulus convection. If enough extra convection occurs, and if tropospheric vertical wind shears are not too large, this extra

cumulus heating is likely to feedback to the mesoscale system and keep it going or intensify it. Maintenance and growth can occur after the original solar heat source has dissipated. Fig. 14 shows how a weak mesoscale cloud cluster system might be generated upwind from a tropical coastline.

As discussed by Gray (1973a), Williams and Gray (1973) and Ruprecht and Gray (1974), a typical tropical cloud cluster has surface pressure anomalies of but  $\frac{1}{2}$  to 1 mb. Wind speeds in the system do not differ significantly from those in the surrounding clear areas. These cloud clusters have mean tropospheric temperature anomalies of but a small fraction of 1°C. The net available potential energy (both thermal and moist) of such clusters also does not differ significantly from the available potential energy which is theoretically possible from a carbon dust heat source of 1–2 million kilograms. Therefore, it does not seem unreasonable that if atmospheric thermal stability is in a conditionally unstable state, a carbon dust energy source to the boundary layer as proposed here might act to generate or enhance a tropical cloud cluster system.

*b. Cirrus cloud generation and modification possibilities*

A number of important economic benefits could be derived if man could artificially form cirrus shields at desirable times. This might include intensification of cloud clusters, agricultural gains to be derived from reduction of excessively high daytime temperatures, reduction of early morning frost, and other benefits. The authors believe cirrus cloud generation can be economically accomplished through the dispersing of carbon particles in the upper troposphere from jet aircraft. This is made possible by the natural conditions of the upper troposphere: transparency to solar energy, upper level lapse rates close to the dry adia-

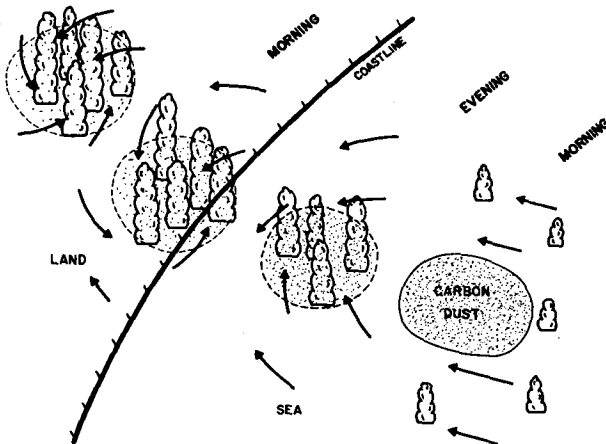


FIG. 14. Plan view portrayal of how carbon dust seeding  $\frac{1}{2}$  to 2 days upwind from tropical and subtropical coastlines might act to generate or enhance a weak mesoscale weather system.

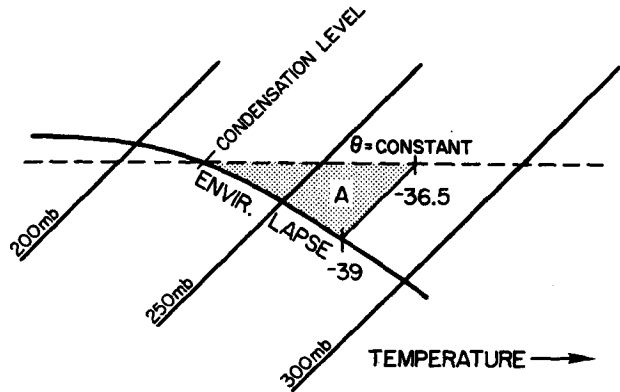


FIG. 15. Tephigram portrayal of a typical upper tropospheric environmental lapse rate of temperature (solid line) and how an artificial warming at the 275 mb level of 2.5°C would bring about a dry-adiabatic lapse rate between 275 mb and a supposed condensation level of 225 mb if moisture conditions were low. The area A portrays the amount of solar energy gain which would be required to bring about a dry-adiabatic lapse rate between these levels.

batic, and very high vertical gradients of saturated mixing ratio with respect to water ( $w_s$ ) and ice ( $w_{s,i}$ ). Saturated mixing ratios decrease 80 to 95% for air lifted distances of but 30 to 60 mb. Even when air humidity is very low saturation can be obtained for this air by lifting it 25 to 50 mb. It is likely that carbon dust absorption of solar energy can bring about the necessary warming to accomplish this upper level lifting to condensation. Fig. 15 shows an example of the typical amount of solar warming ( $2\frac{1}{2}$ °C) which would be required at 275 mb to bring about a dry adiabatic ascent to the 225 mb level. A 25 mb thick layer can be warmed  $2\frac{1}{2}$ °C in 75 min by the absorption of 15% of the incident solar energy. Assuming relative humidities with respect to water as low as 50 or 25%, the amount of lifting from 275 mb required to bring about saturation with respect to ice is 22 and 55 mb respectively. It may thus be possible for man to generate cirrus clouds at will over mesoscale areas through dispersal of carbon particles in the upper troposphere.

Assuming incoming solar energy in the upper troposphere in a cloud-free sky to be equal to two-thirds of the solar constant ( $\sim 1.3 \text{ cal cm}^{-2} \text{ min}^{-1}$ ), one can estimate the amount of solar heating required to bring about a dry-adiabatic lapse rate from any level to the level of condensation for various assumed relative humidities. For typical upper tropospheric lapse rates, vertical displacements of between 10–50 mb are sufficient to bring about saturation. At levels above 250 mb, lifting of 5–20 mb can usually cause saturation. Two hundred pounds of 0.1  $\mu\text{m}$  carbon particles will cover 10% of a square mile area and cause a  $\sim 15\%$  solar interception ( $15\% \times 1.3 \text{ cal cm}^{-2} \text{ min}^{-1}$ ). This would produce an energy gain of  $\sim 0.2 \text{ cal cm}^{-2} \text{ min}^{-1}$ , or enough energy to warm a 25 mb thick layer

$\sim 2^{\circ}\text{C h}^{-1}$ . Assuming the difference in the actual and dry-adiabatic lapse rates is as large as  $4^{\circ}\text{C (100 mb)}^{-1}$ , this solar energy gain will support upward vertical displacement of a 25 mb thick layer of 50 mb  $\text{h}^{-1}$  without the layer cooling more than the lapse rate. Regardless of the environmental relative humidity, this type of solar heating should produce a cirrus shield in a few hours. Previous proposals to form cirrus clouds by dispensing liquid water in the upper troposphere are quite logistically unfeasible on the mesoscale due to the massive amounts of liquid required.

Once an upward vertical motion has been established and the first cirrus clouds produced, the relative transparency of the initial cirrus to solar radiation should permit continual solar warming of the layer. This thin cirrus will, however, be largely opaque to the outward IR loss from lower levels. This continual solar warming should allow a gradual increase in the cirrus thickness until opacity is reached. At this time the extra solar absorption on the top of the cirrus deck should largely balance the extra IR cooling off of the top (Hall, 1968a, b). If seeding were to continue for a number of hours, the later seeding runs would probably have to be on top of the cirrus shield.

Once a thick cirrus cloud deck is formed with its typical prism-shape ( $\sim 200 \mu\text{m}$  long,  $30 \mu\text{m}$  wide)  $5 \times 10^5$  particles  $\text{m}^{-3}$  (Weickmann, 1947), it should persist for many hours—probably through the evening. Cirrus particles can last a long time according to Braham and Syers-Duran (1967). The cloud top IR cooling at night plus the energy accumulation underneath the cirrus shield (see Fig. 4) should likely stimulate upward motion and inhibit cloud dissipation.

Assuming a 747-type aircraft with a payload of  $\sim 200\,000$  lb can generate  $\sim 100\,000$  lb of carbon dust (see Section 2), it is seen that one aircraft could disperse 10% area coverage of carbon dust (and receive  $\sim 15\%$  solar interception) over an area of at least 500  $\text{mi}^2$ . If only 20–30 mb lifting were required for higher humidity conditions, the area of cirrus generation with the payload of one 747 aircraft is likely to be 1000–2000  $\text{mi}^2$ . Thus, depending on the number of aircraft used and the number of flight missions each aircraft makes, very broad-scale generation of cirrus clouds should be possible.

The ability to form thick and persistent cirrus shields at will could have important beneficial implications for a number of purposes. A cirrus shield could:

- 1) Fundamentally alter the IR radiation budgets underneath the cirrus shields in comparison with the surrounding cirrus-free regions as shown in Fig. 4. This will produce a large net radiation energy gain by the cluster region in comparison with its surroundings and lead to enhanced lower tropospheric convergence into the cluster. Recent studies of tropical

cloud clusters presently going on at Colorado State University show that radiation differences between the cloud cluster and its surroundings may be a primary physical mechanism for the maintenance of the cloud cluster. Thus, it appears reasonable to assume that the artificial generation of a mesoscale cirrus shield in a favorable conditionally unstable environment might lead to cloud cluster generation or to enhancement of a cloud cluster which does not possess a well-developed cirrus shield.

- 2) Reduce daytime surface temperatures and prevent the regional formation of "hot spots" in the lowest layer of the atmosphere. If applied during a number of the hottest summer days, this could have a beneficial influence on agricultural productivity by lessening the reduction in crop yields caused by higher summer temperatures (Benci and Runge, 1974). Cirrus cloud reduction of surface heating might also be utilized as an inhibitor of springtime and summer severe weather generation by reduction of daytime surface temperatures. Purdom (1973) has shown how morning cloudiness reduces afternoon thunderstorms and inhibits severe weather.

- 3) Reduce the severity of early morning frost conditions through the inhibition of longwave radiative cooling.

- 4) Increase human comfort and save fuel required for air conditioning by reducing temperatures over heavily populated regions on the hottest summer days.

### *c. Reduction of inner-core hurricane intensity*

The present NOAA Stormfury hurricane modification hypothesis (see Project Stormfury Annual Reports of 1971–72) and the one proposed here for carbon dust seeding rest with the physical idea of artificially interrupting a portion of the hurricane's low-level inflow which would normally penetrate to the eye-wall region and force it to rise, instead, at an outer radius. As extensively discussed by Gray (1973b), angular momentum and surface friction considerations dictate that hurricane intensity is crucially dependent on the amount of mass inflow and the radius to which the boundary layer inflow penetrates toward the storm center. Rapid and sizable reductions in the hurricane inner-core wind structure would likely occur if the boundary layer inflow could be artificially reduced by but 5–10%. It is hypothesized that if sizable areas surrounding the hurricane cloud cluster can be seeded in the boundary layer with 1–2 million kilograms of carbon black dust, the effect will be to stimulate additional cumulus convection either at the place of the carbon seeding, or at radii inside the carbon seeding but beyond the radius of maximum winds. If the outer boundary layer surrounding the hurricane can be artificially warmed at a rate of about  $\frac{1}{2}$ – $1^{\circ}\text{C h}^{-1}$  for a period of 10 h, a significant stimulation will be given to cumulus convection at radii beyond the eye-wall

cloud. This could lead to a decrease in the inner-core maximum wind velocities. A significant decrease in storm damage should result. The carbon dust must be placed sufficiently upstream in the moat region surrounding the cloud shield so that it does not advect too far underneath the cirrus shield before its solar heating can be accomplished.

Fig. 16 more explicitly shows how enhancement of buoyancy from extra heating and evaporation will lead to more artificially induced cumulus convection at radii beyond the eye-wall cloud.

#### d. Cumulonimbus enhancement over selected land regions

It is hypothesized that a significant location change and/or enhancement of cumulonimbus convection may be possible over land areas where the potential for cumulus convection is already high. This is especially likely over land areas which have a high amount of evapotranspiration. There most of the solar energy gain goes to evaporation rather than increase of the sensible temperature. If the land areas are moist or have dense vegetation, much of the incoming radiation goes to evaporation or storage and the diurnal warming cycle is damped. In these situations the carbon dust might be used to warm the boundary layer more rapidly and to dictate where the initial daytime convection would occur. A localized concentration of the morning and early afternoon solar

heating would likely produce extra cumulonimbus convection and precipitation if the potential for cumulus convection was already high.

Over land the carbon dust also might be used in selective situations as an elevated heat source (if dispersed from aircraft) and could act as a stimulant to earlier and more concentrated cumulus convection. Especially favorable situations would be areas where large-scale low-level convergence is present, such as around low pressure systems and along fronts. Here daytime cumulus convection would be expected to occur first in the selectively seeded areas where the earliest warming occurs. Early morning stable conditions act to inhibit convection. Any large-scale upward forced circulation would likely relieve itself in the areas which first became thermally unstable. With carbon particle seeding man might have some choice in where this initial destabilization occurs.

#### e. Alteration of extratropical cyclones

A significant economic gain might result if weak extratropical storm systems could be intensified in dry regions such as the western United States. This would likely result in extra precipitation. Modest cyclone intensification might be accomplished by warming selected areas to the east of the extratropical cyclone and stimulating extra cumulus convection just east of the storm center. The sinking motion asso-

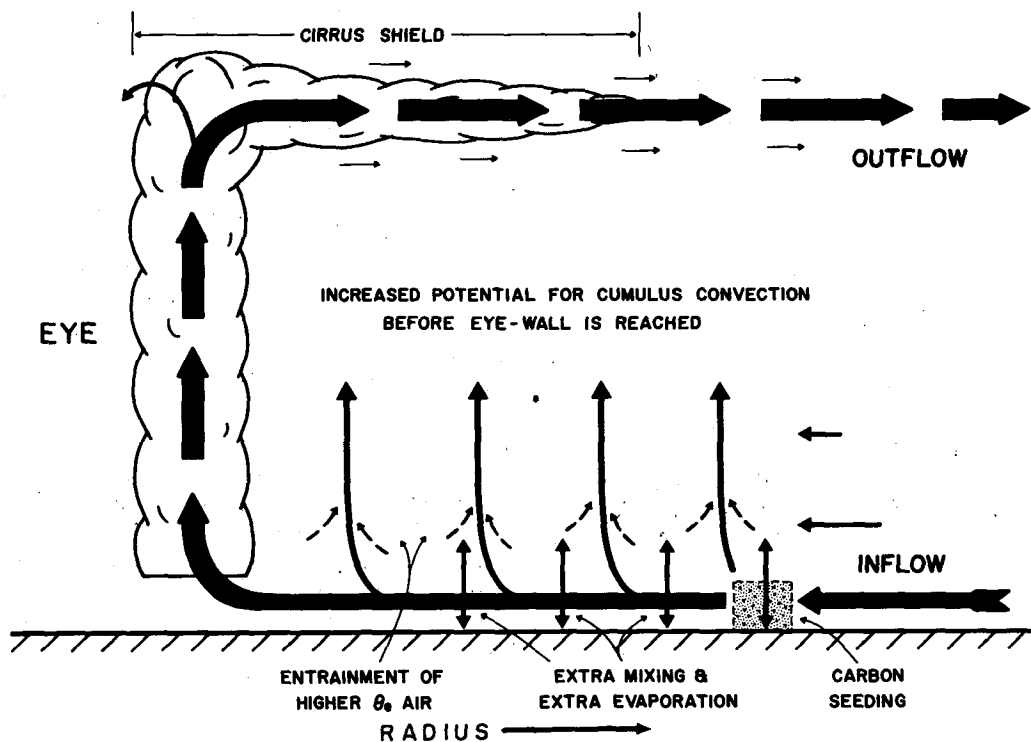


FIG. 16. Idealized view of how an increase of low-level temperature-moisture through carbon dust interception of solar radiation would lead to extra hurricane enhancement of deep cumulus convection at outer radii and tend to cause less low-level mass penetration to the eye-wall cloud region.



ciated with this additional convection should warm and slightly intensify the cyclone. Tracton (1972) has previously indicated that cumulus convection plays a significant role in extratropical cyclogenesis.

When cyclones are intense, move slowly, or are stationary, flooding conditions, heavy snow, and high sea conditions can produce considerable economic loss. This is especially true in the heavily populated areas along the U. S. East Coast and in western Europe. Economic benefit would result in some cases if the intense cyclones could be artificially weakened. Solar energy input to the cold center of the extratropical cyclone at middle or upper tropospheric levels would likely act to produce a modest but significant cyclone weakening, especially in late winter or in the spring when more solar energy is available.

There are times when flood conditions have occurred or are anticipated when additional rainfall would be very detrimental. At these times it might be meteorologically and economically feasible to disperse carbon particles in the adjacent less vulnerable flood regions and stimulate extra convection at these locations. The enhanced convection in the surrounding regions would likely reduce the low-level convergence and resulting cumulus convection over the flooded area.

#### *f. Inhibiting frost*

Another potential use for carbon particle absorption might be the warming of the boundary layers over land when evapotranspiration rates are high as discussed in Section 4d, or over the sea in coastal regions with onshore flow. The extra particle solar absorption would result in higher daytime surface temperatures. This is likely to result in a small rise in the next morning's low temperature which might be important in marginal frost conditions.

#### *g. Accelerating snowmelt in agricultural regions*

There are several large, relatively flat agricultural areas in the world where a snow cover persisting late into the spring can cause a costly reduction in the length of the growing season. The Great Plains of North America and Russia are good examples. When these areas are snow covered, they typically have surface albedos of from 40–90% depending upon the age and condition of the snow and have relatively strong inversions just above the boundary layer. Large amounts of carbon dust particles can be dispersed from inexpensive ground generators into the boundary layer. By warming the boundary layer air under proper conditions it should be possible to accelerate the spring melt of the snowpack, thereby increasing the growing season. The high albedo of the snow surface would cause a strong upward diffuse solar radiation flux and thus increase the efficiency of the carbon absorption. Absorption would take place from

both the upward and downward fluxes. In addition, the carbon particles should have a relatively long boundary-layer residence time due to the strong inversion which should permit multiple-day use of the carbon. This scheme is not to be confused with previous experiments of placing carbon dust on top of the snow, where the mass of carbon to area coverage rates are prohibitive.

A carbon dust cloud of 10% horizontal area coverage could absorb on the order of 50 cal per day depending on latitude, date, weather and snow cover conditions. This is enough heat to warm a 1 km layer of air about 4°C per day. It is not clear just how much of this absorbed energy would result in additional snowmelt, but given multiple-day usage of the carbon, the effect might be substantial. Diamond (1953) has shown that when air temperatures are above 0°C and relative humidities are low (~20%), an increase in air temperature of 5°C can increase the snowmelt rate enormously through increased heat transfer from the air to the snow. On days when the air temperature would normally remain at or just below freezing, the heating of the boundary layer air by 3–4°C could result in significant snowmelt when natural snowmelt levels might be very low.

### **5. Evidence for the hypothesis**

#### *a. Observational and theoretical evidence*

There are several natural phenomena which illustrate the formation of clouds and precipitation resulting from a localized atmospheric heat source. Although these phenomena differ in several ways from the proposed carbon dust heat source, some important analogies between the observed effects of natural heat sources and the expected effects of a carbon dust heat source can be made.

1) **HEAT ISLAND INFLUENCES.** Islands and peninsulas typically form daytime heat and cloud islands by giving off energy to the air passing over them. This often produces a sea breeze and/or daytime cloudiness over or just downwind from the islands and peninsulas. The surrounding sea areas typically have much less cloudiness. Satellite pictures clearly show that persistently high daytime cloud concentrations are observed to occur over and just downwind from large tropical and subtropical islands.

Table 2 depicts the percentages of summertime afternoon cloud cover over various large tropical islands and peninsulas as compared with their surrounding bodies of water. In this study the water area considered was that surrounding the land with an area three times and a radius twice that of the land. As can be seen in this table the cloud cover over land is approximately 2–3 times that over the adjoining water. This is true not only for the average case but for most of the individual day cases as well.

TABLE 2. Influence of islands and peninsulas on afternoon cloudiness.

Land bodies	Percent of cloud cover over large islands or peninsulas				Percent of cloud cover over surrounding water			
	Jun (Dec)	Jul (Jan)	Aug (Feb)	Mean	Jun (Dec)	Jul (Jan)	Aug (Feb)	Mean
West Pacific								
Ocean	51	47	42	47	20	15	16	17
Taiwan								
Hainan								
Philippines								
East Indian								
Ocean	35	34	37	35	14	15	10	14
Sumatra								
Borneo								
Celebes								
Java								
New Guinea								
Caribbean Sea	32	29	35	32	11	10	12	11
Yucatan								
Cuba								
Hispaniola								
Puerto Rico								
Madagascar	41	41	29	37	10	18	13	13
North Australia	14	25	24	22	6	15	19	14
Total	36	35	34	35	13	15	13	14

There have been several observational and theoretical studies of the heat island effects of individual islands. Malkus (1963) showed that in the absence of synoptic-scale disturbances, the small flat Caribbean island of Anegada produced showering clouds over the island while no precipitation occurred from clouds in the surrounding ocean area. Malkus and Stern (1953), Smith (1957) and Estoque and Bhumralkar (1969) have developed numerical models of the heat island effect which show increasing tendencies for cloud formation with increasing island ground temperatures. One of the most complete studies of this effect was made by Bhumralkar (1972). He compared the results of his numerical model with observational data obtained over Grand Bahama Island on days with temperature, moisture and wind conditions similar to the input values of his model. Computed and observed cloud and precipitation patterns agreed very well. This allowed some conclusions to be formed as to the nature of the heat island effect produced by the 10 km wide island in the presence of a prevailing cross-island wind. It was found that in the absence of synoptic disturbances, the heated island perturbed the atmosphere enough to cause rainfall on the leeward side of the island or just off the leeward shore. The strength of the created disturbance increased with higher island temperatures and lower wind velocities. It was unexpected that a 10 km by 130 km island could actually produce precipitation from its heating cycle alone.

The heat island effect differs from the proposed carbon dust heating scheme in two major ways:

1) The heat island is stationary and can provide heat to a given air mass only during the time the air

is over the heat source. With windy conditions the air may not be over the island for a very long period of time. By contrast, the carbon dust travels with the air mass and heats it throughout the day. Air motion does not matter.

2) Carbon dust conducts heat to the air mass directly while the transfer of heat from a heated island surface to the air by conduction, convection and infrared radiation is a slower, more inefficient process. Daytime heating often lags considerably behind the sun, particularly when surface moisture is present and solar energy goes into evaporation.

Since tropical island heat sources appear to be sufficiently strong to cause clouds and precipitation to form on days with no synoptic disturbances, it seems likely that the more efficient carbon dust heat sources covering a larger area might also develop deep cumulus convection and precipitation in certain situations.

Other evidence of cloud formation due to local heating of the lower atmosphere was presented by Purdom (1973). His study of satellite photographs over the United States showed that areas which are free of early morning cloud cover and which are wholly or partially surrounded by regions with early morning clouds are preferential areas for the development of thunderstorms and mesoscale convective systems. It was concluded that the differential solar heating between the clear and cloudy areas was responsible for the organization of strong convection in those areas which were free of morning cloudiness. It seems reasonable that differential heating of the lower atmosphere by a carbon dust cloud might result in similar dynamic responses.

Henz (1974) has recently studied the areal distribution of spring and summer cumulonimbus genesis relative to the Colorado Plains and the Front Range of the Rocky Mountains. Fig. 17 and Table 3 from his paper show the much higher incidence of thunderstorm (TRW) genesis over the elevated terrain features of the western edge of the Plains. This higher TRW frequency is believed to result from the terrain-induced elevated heat sources which produce steeper lapse rates and enhanced upslope convergence. These elevated sources or "hot spots" produce more than seven times as many TRW's per unit area as the Plains region to the east. The question then arises as to whether it is possible to artificially generate similar types of elevated heat sources using carbon dust dispersed from aircraft.

2) URBAN HEAT ISLAND EFFECT. Recent studies of the effects of large urban areas upon their local environments have shown that precipitation amounts and thunderstorm frequencies and intensities tend to be greater immediately downwind from certain cities than in the upwind sectors (Changnon and Huff, 1973; Changnon, 1968; Beebe and Morgan, 1972; Atkinson, 1968). The urban industrial areas affect the

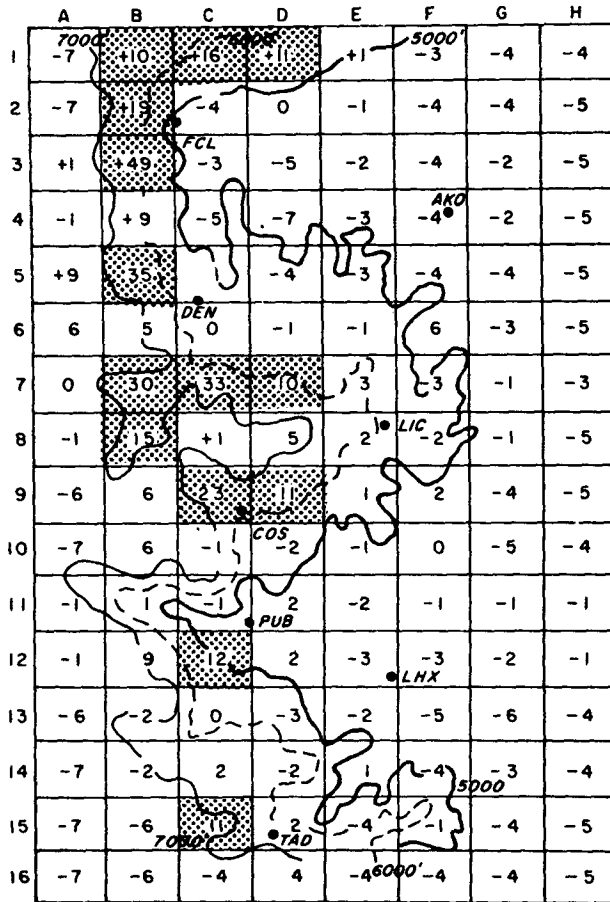


FIG. 17. Number of thunderstorm echoes generated in the eastern half of Colorado in each 30x45 km rectangular box above the mean of all grid boxes for 1970-71. Values higher than 10 have been shaded. These have been denoted as "hot spots" (from Henz, 1974).

environment through the release of sensible heat, aerosols, gaseous pollutants, moisture, by altering low-level turbulence patterns, and by altering the natural land/air energy transfer characteristics. It is extremely difficult to obtain quantitative measurements of the magnitudes of all of these effects, but one important dynamic effect of an urban area is generally considered to be the creation of an artificial heat island. In the presence of a moderate prevailing wind, this heat island takes the form of a hot plume as the city heats the air advecting over it.

It is interesting to compare the relative magnitude of the sensible heat emitted into the air in a large urban industrial area due to energy consumption with the heat added to the air by carbon particles during an operation of the magnitude envisaged (~1x10<sup>6</sup> kg of carbon over ~4x10<sup>4</sup> km<sup>2</sup>). Although energy consumption is not the only heat source of an urban area, it will be assumed to be the dominant source for the very large areas.

Estimates of energy consumption density levels for several large urban industrial areas by Flohn (1971) indicate that the largest urban heat sources are about 10<sup>4</sup> km<sup>2</sup> and consume energy at an approximate rate of 10 W m<sup>-2</sup>. Even if light prevailing winds of only 10 km h<sup>-1</sup> are assumed, the average contact time of air parcels with the heat source would be only about 5 h during a 10 h period. By comparison, a carbon cloud with 10% horizontal area coverage would add heat to the air at an average rate of about 110 W m<sup>-2</sup> for the entire 10 h period. Therefore, air would be heated over 20 times as much by a carbon cloud as it is by the energy consumption of a large urban heat source during a 10 h daylight period. The carbon cloud also covers about 4 times as large an area as the largest urban industrial complexes resulting in a total heat addition to the air 50-100 times greater than that of the large hypothetical urban area.

It is encouraging that a heat source as relatively small as an urban heat plume apparently can cause increases in convective activity and precipitation in certain locations, although the relative importance of the heat island effect and cloud physics effects are not well understood at this time. It seems likely that a heat source of the magnitude proposed for carbon dust operations would, if placed selectively in the atmosphere, cause a much greater atmospheric response.

b. Numerical modeling evidence

A number of early numerical modeling results lend various degrees of support to the carbon dust physical hypothesis. The results from some of these models will now be briefly discussed.

1) BOUNDARY-LAYER MODELING. Deardorff (1973) has run an initial test on the influence of artificial boundary layer heating in an oceanic, one-dimensional, tropical subcloud layer model. He assumed an artificial boundary-layer heat source of 1/4°C h<sup>-1</sup> for 10 h. This is only a quarter of the amount of heating which is being proposed; nevertheless, substantial influences occurred. The results of the model are shown in Fig. 18. The model ran for 4 days in a normal state, and then the heating was applied. After 10 h the heating was abruptly shut off. The effects upon cloud base (h),

TABLE 3. Relationship of thunderstorm initiation to elevation (from Henz, 1974).

Location	Number of blocks	Percent area	Number of TRW	Percent TRW	Ratio TRW / Area (%)
Plains <5000'	66	52	263	28	0.54
5000-9000'	62	48	684	72	1.49
5000-7000'	35	27	525	55	2.05
7000-9000'	27	21	159	17	0.80
"hot spot"	14	11	383	41	3.68
Total	128	100	947	100	

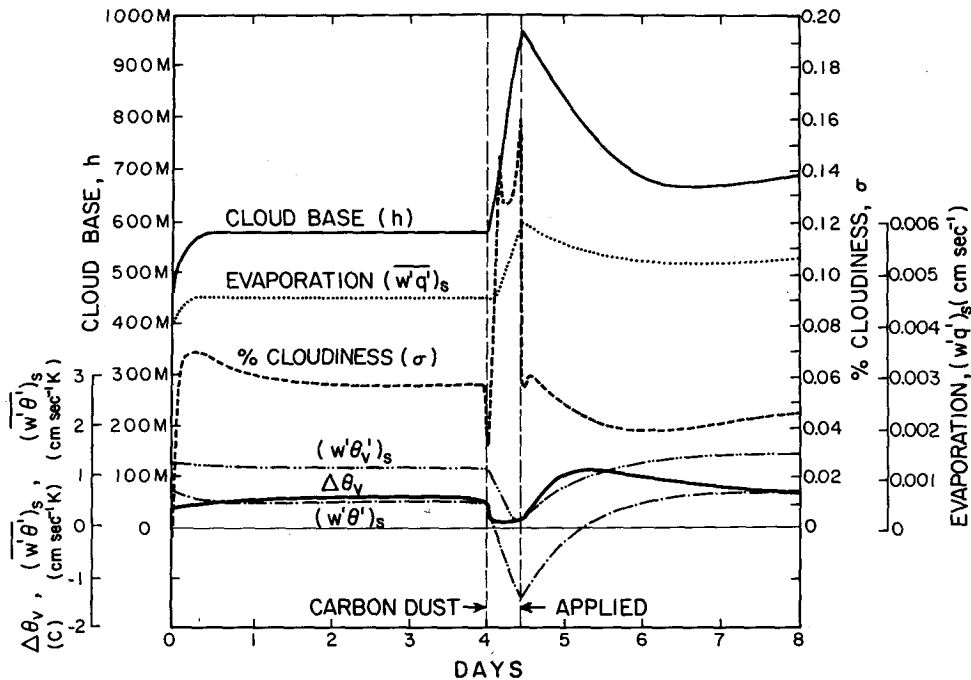


FIG. 18. Deardorff (1973) test to determine the influence of carbon dust energy input. An energy input rate equivalent to  $0.25^{\circ}\text{C h}^{-1}$  has been applied during the first 10 h of Day 5.

percent area of cumulus cloudiness ( $\sigma$ ), evaporation  $(\overline{w'q'})_s$ , and ocean-air virtual potential temperature difference ( $\Delta\theta_v$ ) are shown in this figure from Deardorff's paper.

To quote from Deardorff's report on the influence of the extra heating:

"The first result, of course, is a warming of the mixed layer. This warming causes  $\Delta\theta_v$  to decrease drastically from  $0.55^{\circ}\text{C}$  to about  $0.1^{\circ}\text{C}$  in 4 hours, and causes the relative humidity to drop. The first effect causes  $h$  (the cloud base) to rise from 580 m to 980 m at the end of the 10-hour period. Both effects together cause convective cloud-base level to rise. . . . This causes  $\sigma$  (percent area with cumulus) to more than double after the end of only the third hour following initiation of the enhanced heating rate. A dip in  $\sigma$  just as the heating is first applied reflects the decreased relative humidity before  $h$  has had a chance to rise. As expected  $(\overline{w'\theta'})_s$  decreases and even becomes negative, while  $\overline{w'\theta'_v}$  only barely stays positive by the end of the 10th hour. The enhanced cloud induced mixing causes the boundary layer specific humidity to decrease to a minimum of  $13.1 \times 10^{-3}$ , and thereby causes increased surface moisture flux (evaporation) to persist long after application of the carbon black has ceased."

"Although the model takes no account of dissipative effects such as horizontal diffusion, it does strongly support one portion of Gray's hypothesis. Increased convective activity is predicted to occur despite a reduced surface virtual temperature flux during the modification period. The much increased depth of the mixed layer, moreover, suggests that the convective clouds will have greater diameters and reach greater heights. The model could not treat cases with greater applied heating rates, unfortunately, because  $(\overline{w'\theta'})_s$  then becomes negative and the model invalid."

This artificial stimulus to cumulus convection was obtained with a boundary-layer heating of only

$\frac{1}{4}^{\circ}\text{C h}^{-1}$ . The authors are proposing boundary-layer heating rates 2-5 times the amount which Deardorff has tested here. A favorable enhancement of convection is indeed indicated.

2) MESOSCALE TROPICAL MODEL. A three-dimensional primitive equation mesoscale numerical modeling effort underway at Colorado State University also lends support to the envisaged influences of carbon dust induced heat sources.

This model is being developed to simulate processes which occur on scales below the normally predicted synoptic scales. The model is an outgrowth of a previous model devised by Harrison and Elsberry (1972) and Harrison (1973).

When the assumed artificial carbon dust heating of  $\sim 5^{\circ}\text{C } 10 \text{ h}^{-1}$  per 100 mb is placed in the lowest layer of this eight-layer tropospheric model, a very large atmospheric response occurs. The extra carbon dust heating induced vertical motion at the top of the boundary layer is  $\sim 180 \text{ mb day}^{-1}$ . After 10 h of integration the lower tropospheric convergence increases to  $\sim 30 \times 10^{-6} \text{ s}^{-1}$ . This is approximately five times larger than the average  $4^{\circ}$  convergence occurring in the typical tropical cloud cluster (Williams and Gray, 1973). Thus, it appears that the implementation of this extra heat source on a mesoscale over the tropical or subtropical oceans would, indeed, have a significant influence on generation and/or enhancement of tropical weather systems. Much more modeling experimentation must be accomplished, however, before this influence can be firmly established.

3) HURRICANE INTENSITY REDUCTION. Gray (1973b) has extensively discussed the potential of hurricane inner-core intensity reduction from carbon dust induced outer radii boundary-layer heating of  $\frac{1}{2}$  to  $1^\circ\text{C h}^{-1}$ . This outer heating modification hypothesis has recently been tested in the Rosenthal (1970, 1971a, b) circular symmetric tropical cyclone model and has been found to verify the physical hypothesis to a high degree (see report by Gray, *op. cit.*).

The Rosenthal model is a seven-level primitive equation model containing the water vapor cycle and parameterized cumulus convection. The radial interval is 10 km and the time step 2 min. In an overall sense it appears to handle the basic dynamics of the hurricane quite well.

The model is initialized with a symmetric vortex with maximum winds of  $7\text{ m s}^{-1}$  at 250 km radius. The model is then integrated in time. It slowly builds up a moist layer during the first 70 h of integration and then intensifies rapidly to a hurricane vortex with maximum winds of  $\sim 50\text{ m s}^{-1}$  at a radius of 25 km in another 80–100 h. The vortex then stops intensifying and remains in an approximate steady state for several days. It is the latter steady state that is used for energy response experimentation.

Artificial heating values have been input to the steady-state stage at the four black dots shown at radii of 415 and 425 km and at the surface and 900 mb in Fig. 19. A heating rate of  $\frac{1}{2}^\circ\text{C h}^{-1}$  has been applied at these grid points for a 10 h period to simulate the solar heating of the carbon dust. This heating is then discontinued.

The maximum artificial heating influences are felt about 24 h after integration is started. It takes 12–24 h for the effects of the outer heating to manifest itself into changes in the inner core of the hurricane.

Fig. 19 shows the influence of this heating rate on the tangential winds after 10 and 24 h. Note that the maximum reductions in the horizontal winds occur where these values were previously the highest. After 24 h the wind at the surface at the radius of maximum winds is reduced by  $15\text{ m s}^{-1}$  (30% reduction from the original value). The surface kinetic energy at the radius of maximum winds has been reduced by 60% of its original value. Similar reductions occurred in the radial and vertical motions.

If these hurricane modification results are realistic, then a large potential for alleviating hurricane destruction may be possible.

4) INDIVIDUAL CUMULUS MODEL. Lopez's (1973a, b) whole lifetime cumulus cloud model offers other supporting evidence. This model has tested the influence of increased boundary layer temperature and relative humidity on individual Cb growth. The model shows that boundary-layer temperature increases of but  $1\text{--}2^\circ\text{C}$  can lead to significant increases in Cb convection (with all other factors held constant). It also shows the large influence that a small increase in the

boundary-layer specific humidity can have on the intensity and depth of cumulus convection. It appears that an energy or moisture input into the boundary layer would have a very significant influence on the enhancement of extra cumulus convection.

5) CLOUD AND CLOUD ENVIRONMENT MODELING. Orville (1965a, b, 1968) and his group (Orville and Sloan, 1970a, b; Chang and Orville, 1973) have investigated the influence of elevated heat sources on the generation and enhancement of cumulus convection, and their findings appear to offer additional supporting evidence. He and his group have shown that elevated heat sources of the magnitude  $\frac{1}{4}\text{--}\frac{1}{2}^\circ\text{C h}^{-1}$  per 100 mb (as developed by mountains) produce substantial early day generation and enhancement of cumulus convection as compared to the surrounding lower terrain areas. This can be qualitatively verified by anyone living near the mountains in the summer.

If dispersed from aircraft or elevated terrain, the proposed carbon dust heat source is likely to act as an elevated heat source and allow for concentration of lower level convergence and cumulus convection in selective areas over land or the ocean. The magnitude of the elevated heat source which is possible from carbon dust can be as large as that produced by mountains. If man is able to control the place, time, size and intensity of this elevated heat source, a significant local stimulation of cumulus convection and precipitation may be possible.

6) MESOSCALE MOUNTAIN MODEL. Dirks (1969) has developed a two-dimensional mesoscale circulation model with a sloping (1/10) heat source similar to that developed by a mountain during its diurnal solar heating cycle. Starting from rest, Dirks develops a substantial mesoscale mountain-plains cellular circulation system after only 2 h of integration. An analogous type heat source might also be possible with the carbon dust heating mechanism. There is much to be learned, however, about how the mountain terrain and the mountain heat source interact with one another. Would a similar type of circulation be developed for an identical heat source without the mountain?

7) SUMMARY. Preliminary numerical modeling evidence indicates that an artificial heat source of the size and magnitude here discussed would likely produce a significant alteration of the mesoscale environment.

## 6. Comparison of the hypothesis with previous radiation modification proposals

To date, research on the subject of solar weather modification has been centered on fog and natural cloud dissipation and on developing and enhancing individual cumulus. Downie (1960), Fenn and Oser (1962) and Van Straten *et al.* (1958) have previously discussed the use of carbon.

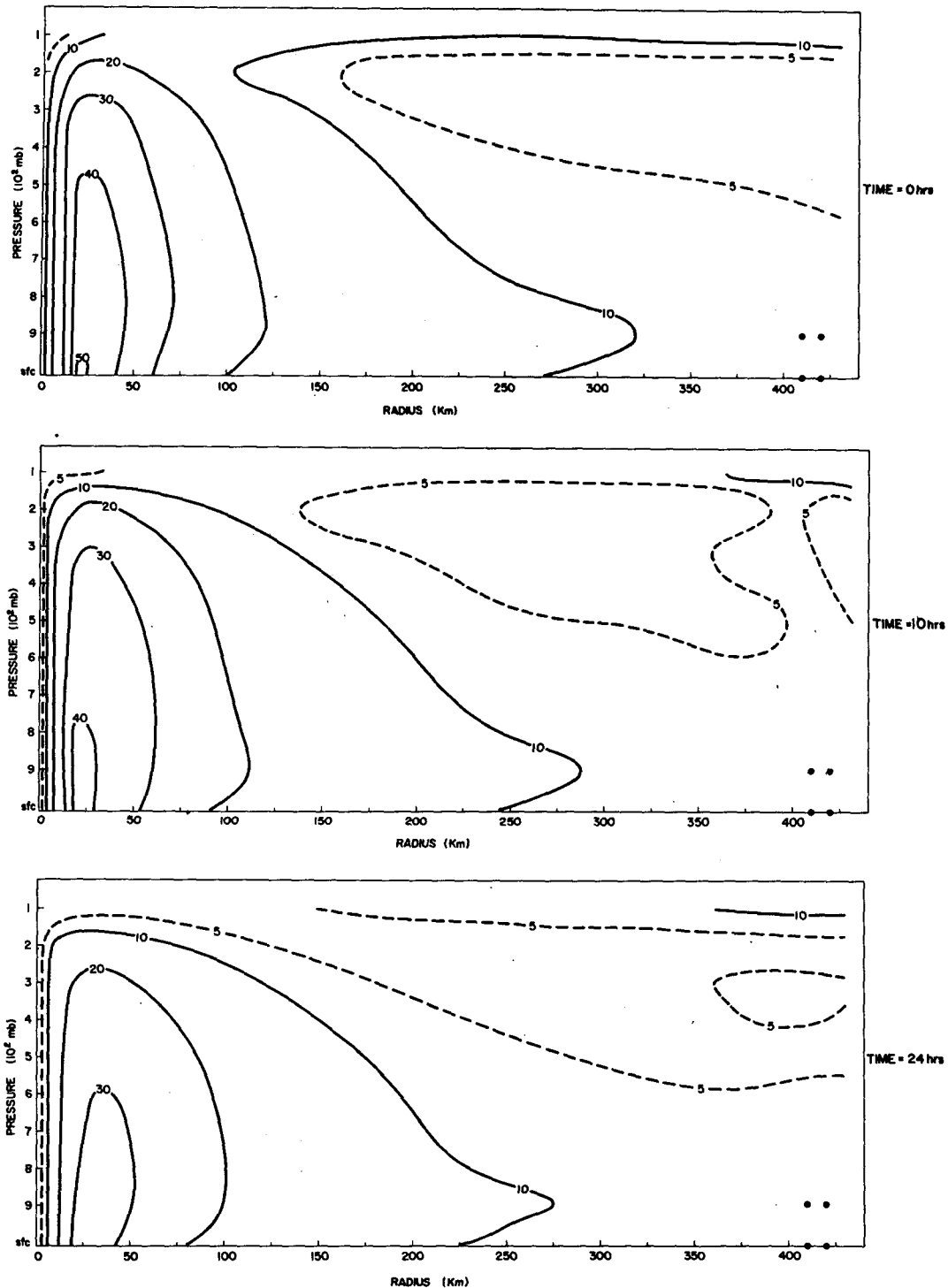


FIG. 19. Rosenthal (1971a, b) symmetric model total wind speed ( $\text{m s}^{-1}$ ) at various time periods as a result of artificial heating rate of  $\frac{1}{2}^\circ\text{C h}^{-1}$  for the first 10 h applied at the four grid points shown at the lower right.

The Naval Research Laboratory seeded eight cumulus clouds with 1–3 kg of carbon black in July 1958 (Van Straten *et al.*, 1958). All of the clouds dissipated to some extent, but observation and instrumentation capabilities were insufficient to establish

a definite causal relationship. In addition, clear air at the approximate level of existing cumulus cloud bases was seeded on five runs during the same series of tests. Small clouds were observed to form in all cases. Once again it was impossible to establish definite causal

relationships. The overall feeling of the test group was that the carbon black did seem to help dissipate existing clouds and form small ones in clear air, but the natural variability of cumulus clouds and the inadequacy of monitoring techniques prohibited any conclusive results.

Laboratory tests by the Naval Research Laboratory in 1958 showed that carbon black did increase dissipation rates of artificially created fogs in cloud chambers which were subjected to heat lamps. However, neither the dissipation mechanism nor the radiative properties of carbon black were quantitatively well established.

The Geophysics Research Directorate made 18 runs seeding small clouds and clear air over the period October 1958–April 1959 (Downie, 1960). Carbon amounts from 1–3 kg per mission were used. Results were less successful than those observed earlier by the Naval Research Laboratory. A few clouds dissipated, but others did not. Clear air seeding produced no obvious results although a few small clouds occasionally formed in the test areas. The test personnel concluded that no definite effects of carbon black on clouds could be substantiated through their test results.

In general, these early experiments with carbon black suffered from four major shortcomings:

- 1) The existing knowledge of the radiative properties of carbon black was entirely inadequate to provide realistic estimates of the energy processes occurring in the atmosphere.

- 2) The amounts of carbon used were much too small. Small-scale diffusion effects could easily dissipate the heat absorbed and overpower the effects of the heat accumulation.

- 3) Severe logistical and clumping problems associated with the handling and dispersal of the carbon particles were encountered.

- 4) Adequate observation and instrumentation capabilities to enable conclusive analysis of field test results were not available.

The previous research by Downie and Silverman<sup>2</sup> (U. S. Air Force Cambridge Research Laboratories), Van Straten<sup>2</sup> and Rusk'n<sup>2</sup> (U. S. Navy Research Laboratory) and Smith<sup>2</sup> (private industry), etc., in general, proved not to be promising. The amounts of carbon used (5–20 kg) were not consistent with the purposes. Dispersing and clumping problems were encountered. Previous work in the late 1950's and early 1960's was conducted on a scale (generating or intensifying individual cumulus) and with a technology (dispersing already manufactured carbon) which were entirely different than the ones proposed here.

By contrast, this research is concerned with the feasibility of carbon particle modification on the mesoscale

(~100–300 km on a side) using amounts of 1–2 million kilograms. We are planning to directly manufacture the carbon dust on aircraft or from carbon particle generating sources on ships or at surface sites. By direct manufacture of the carbon black dust from field sources, one avoids the clumping, packing and logistical problems involved with using carbon particles from the factory.

### Coating Surfaces with Black Material

The ESSO Oil Company of New Jersey (Black and Tormy, 1963; Black, 1963) has explored the possibility of boundary layer heat augmentation from coating land surfaces with black-top (tar). The prospects are not very encouraging. The black-top program has suffered from three basic drawbacks:

- 1) The surface air blows over the few miles of black tar field in just a few minutes. Only a relatively small heat input can be made per unit mass of air. The carbon dust scheme, in contrast, has the carbon particles moving with the air mass. The energy input over a number of hours can be very large.

- 2) The land surface would naturally warm up and heat the air above to an appreciable extent without the black tar. The black top heating is only the difference between its heating and the natural surface land heating which would normally occur. In contrast, when applied over the ocean, nearly all of the solar absorption by the carbon dust is extra energy gain relative to the surrounding air.

- 3) The envisaged area coverages of the black top of ~100 km<sup>2</sup> are too small to have a significant influence. By comparison the authors are proposing the carbon dust heating of areas of 10 000 to 100 000 km<sup>2</sup>.

Attempts at melting snow fields by coating them with carbon dust also have been generally unfeasible. Dispersing the carbon dust from aircraft or helicopters requires that the carbon sink to the ground before the winds sweep it away. This requires carbon particles of 100–1000 μm radius. These particles are too large to have an economically feasible area to mass ratio except in very highly restricted conditions.

It may thus be concluded that the previous weather modification field programs in radiation alteration were, in general, on much too small a scale and did not have the best physical justification.

### 7. Cost-benefit considerations

It is estimated that carbon dust can be generated for about \$0.10 per kilogram. A 10% cross-sectional area coverage by 0.1 μm radius particles would require ~25 kg of carbon per square kilometer (or ~200 lb per square nautical mile). To cover a (200 km)<sup>2</sup> or (100 n mi)<sup>2</sup> square area would require ~1 million kilograms of 0.1 μm carbon particles. This would

<sup>2</sup> Personal communication.

result in absorption of about 15% of the incident solar radiation and would require about \$100 000 worth of petroleum products. If the cost of dispersal of the carbon from surface sources (ship and land sites) is 1–2 times the cost of the petroleum products and the cost of dispersal from aircraft is 3–4 times the cost of the petroleum, an estimate for a 1 million kilogram carbon particle seeding operation would be 1) from surface sites ~\$0.3 million, and 2) for aircraft sources ~\$0.5 million.

The papers by Gray (1973b) and Gray *et al.* (1974) present more discussion of the economics of carbon dust dispersion, etc. It is envisaged at this time that the surface releases would be used primarily for tropical and subtropical mesoscale precipitation augmentation, cyclone modification, and enhancement of snowmelt. Aircraft operations would be more suitable for hurricane intensity reduction and cirrus cloud generation. We have estimated that economic gains from the above types of modification on individual days can be as much as \$10 to \$100 million [see Gray *et al.* (1974) and Gray (1973b) for more discussion]. If this is so, then very favorable 10 to 1 or 100 to 1 economic gains can be realized.

Although these estimates are quite crude, they do indicate that favorable cost-benefit ratios may indeed be realized for a number of carbon dust schemes. Even though petroleum prices are likely to continue to rise in the future, so too will other prices. As petroleum costs are only 20–30% of the total costs of the experiment, these ratios should not be significantly altered by the rising price of petroleum. In addition, there are many human benefits such as prevention of loss-of-life and hunger, etc., on which a price tag cannot be placed.

## 8. Environmental impact

To evaluate the environmental impact of generating carbon particles and dispersing them into the atmosphere in relatively large amounts (1–2 million pounds per operation), it is convenient to divide the subject into five major areas. These are:

- 1) Toxicity of the carbon black particles.
- 2) Effects of the by-products of the carbon generation process upon human health.
- 3) Long-term effects of carbon black and its by-products upon the atmosphere.
- 4) Impact of the carbon black dust upon the oceanic ecosystem.
- 5) Temporary esthetic effects of the carbon upon the local area.

Each of these areas will be treated separately below.

### a. Toxicity of carbon black

The carbon particles used in weather modification work will probably be dispersed as they are generated

by the incomplete combustion of fossil fuels. Until the actual apparatus has been designed and field tested, it will not be possible to determine the exact chemical composition of the carbon black produced. Therefore, this section is limited to discussion of toxicity studies performed with various existing commercial carbon blacks. The studies mentioned below employed carbon blacks of several different sizes produced by a variety of processes. It is felt that the carbon blacks generated in weather modification work would be essentially similar to some of these commercial varieties tested.

Most carbon weather modification proposals call for dispersal of carbon dust into the atmosphere over the sea about one day upwind of any major land area. Therefore, the initial carbon cloud [concentration of  $40 \mu\text{g m}^{-3}$  ( $1 \mu\text{g m}^{-3} = 10^{-6} \text{g m}^{-3}$ )] should diffuse to relatively low concentrations before encountering a populated area.

Carbon black particles are composed primarily of elemental carbon with variable amounts of oxygen, hydrogen, sulfur, and trace amounts of ash components. They are produced by the combustion of one or more hydrocarbons in an oxygen deficient environment and subsequent condensation of the carbon either in furnaces or in long rows of natural gas burners known as channels. Furnace blacks, which are of the most interest for the purposes of this study, are typically 95–99% pure carbon. For most purposes, carbon black can be treated as a basically inert substance.

The most complete study of the physiological effects of carbon black was performed by Nau *et al.* (1958a, b, 1960, 1962) and was sponsored by the state of Texas. They studied the effects of ingestion, skin contact, subcutaneous injection, and inhalation of carbon black by animals. Fourteen different types of carbon particles ranging from approximately 0.005 to 0.1  $\mu\text{m}$  in diameter were used. These are the size ranges we propose for modification. Ten of the blacks were produced by variations of the furnace method (the process most likely to be used in weather modification operations), and four were manufactured by channel processes. The results of their tests are discussed in more detail in Gray *et al.* (1974). Briefly, they showed that:

1) **INGESTION OF CARBON BLACK.** Ingestion by mice of large amounts of carbon black, as supplied by the industry or after benzene extraction, produced no changes from normal. Ingestion of a pure carcinogen produced abundant tumors in the mice, but eating carbon black which had absorbed some of the carcinogen caused no effects. Apparently, the carcinogen lost most of its toxicity when absorbed by the carbon. Carbon black appears to be harmless when ingested. This result is not surprising since carbon black has been used for years as a certified food coloring in certain foods (jelly beans, licorice, gum drops, etc.) with no reported ill effects.



2) SKIN CONTACT. The second phase of the Nau *et al.* (1958b) tests dealt with possible effects of various types of carbon black upon prolonged skin contact. The results showed that there were no detectable changes from the normal in hamsters, mice, guinea pigs, rabbits or monkeys regardless of the amount of carbon contacted by the skin or the exposure time.

3) SUBCUTANEOUS INJECTION. Tests of the effects of carbon black when injected under the skin were performed on mice and rabbits to simulate the possible intrusion of carbon into the body through skin lacerations or abrasions. It was found that injecting carbon black under the skin caused no significant changes from normal.

4) INHALATION OF CARBON BLACK. Hamsters, mice, guinea pigs and monkeys were placed in dust inhalation chambers for 7 hours per day, 5 days a week. Monkeys were exposed to carbon black for up to 13 000 h while the mice were exposed for virtually their entire lifetimes. Carbon black concentrations of  $2400 \mu\text{g m}^{-3}$  for furnace blacks and  $1600 \mu\text{g m}^{-3}$  for channel blacks were used. These concentrations are substantially higher than the carbon concentrations proposed for use in carbon black weather modification. Initial carbon concentrations during field operations would probably be on the order of  $40 \mu\text{g m}^{-3}$  and would decrease steadily with time. This is 1/40 to 1/60 of the amounts that were used in the inhalation studies.

Results of the inhalation tests showed that there were measurable accumulations of carbon dust in the lungs of test animals only after breathing relatively large concentrations of carbon dust for exposure times greater than about 400 h. No malignancies or other related disorders were encountered in test animals. These results indicate that inhalation of carbon black has no undesirable effects other than long-term particle accumulation in the lungs. This accumulation represents a health hazard only when it occurs in the lower respiratory tract, particularly in the alveoli sacs of the lower lungs where oxygen and carbon dioxide are exchanged between air and the blood. As discussed in the National Air Pollution Control Administration Report No. AP-49 (1969), this intake and deposition of particles upon the alveoli is strongly size-dependent. Fig. 20 from this report shows that there is a minimum efficiency in particle deposition within the alveoli for particles on the order of  $r=0.1 \mu\text{m}$ . These are the size carbon particles to be manufactured for weather modification operations. Therefore, the carbon particles used in this study are less likely to be retained in the alveoli than most natural or other man-made aerosols.

The Environmental Protection Agency (EPA), in the *Federal Register* of 23 December 1971, has set contaminants standards by mean geometric average of weight of particles per cubic meter. The minimum level representing the onset of undesirable particulate levels has been established as  $70 \mu\text{g m}^{-3}$ . By way of

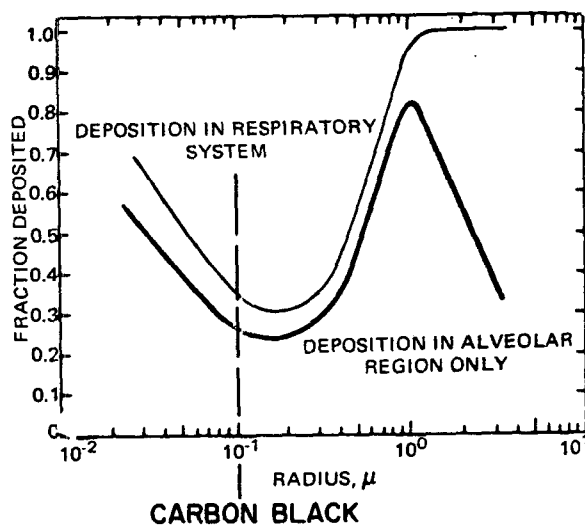


FIG. 20. Calculated fraction of particles deposited in the respiratory tract as a function of particle radius. [This figure represents the calculated efficiencies of deposition of particles of various sizes in the tracheobronchial and alveolar regions of the respiratory system and shows the size for minimum efficiency (from NAPCA Report AP-49, 1969).] The broken line shows the  $0.1 \mu\text{m}$  carbon particles to be used.

comparison, the particulate loadings of the proposed carbon experiment would initially be only about  $40\text{--}50 \mu\text{g m}^{-3}$  (representing 10% equivalent horizontal area coverage by the carbon) and should decrease considerably due to diffusion and rainout before the carbon cloud would be advected inland over a populated area.

Table 4 shows typical particulate loadings over different sizes of United States cities. It is clear that the carbon cloud, even at its initial concentration (10% area coverage), represents a much smaller aerosol loading than would be found over any of these cities on an average day. This factor together with the low retention efficiency in the alveoli of  $0.1 \mu\text{m}$  size particles, the relatively short exposure time to be expected from advection of a carbon cloud over a populated area, and the nontoxicity of the carbon particles point to the conclusion that inhalation of carbon particles dispersed during the proposed operation will not constitute a hazard to human health.

#### b. Health effects of the by-products of carbon generation

The by-products of carbon black generation are water vapor ( $\text{H}_2\text{O}$ ), carbon dioxide ( $\text{CO}_2$ ), carbon monoxide ( $\text{CO}$ ), nitric oxide ( $\text{NO}$ ), nitrogen dioxide ( $\text{NO}_2$ ), and small amounts of various gaseous and particulate hydrocarbons. Since the exact fuel and generator design are not yet known, it is not possible to state exactly what proportions and amounts of each of these substances will be present. However, it is fairly well established that there will be at least 0.5 lb of carbon produced from each pound of fuel consumed. Two of the gases,  $\text{CO}_2$  and  $\text{H}_2\text{O}$ , are not considered

TABLE 4. Summary of NASN suspended particulate samples ( $\mu\text{g m}^{-3}$ ) for urban stations by population class, 1957-1963 (from Stern, 1968).

Population class	Number of samples	Number of stations	Minimum	Maximum	Arithmetic mean	Geometric mean
1. 3 million and over	316	2	57	714	182	167
2. 1-3 million	519	3	34	594	161	146
3. 0.7-1.0 million	1191	7	14	658	129	113
4. 0.4-0.7 million	3053	19	18	977	128	112
5. 0.1-0.4 million	9531	92	10	1706	113	100
6. 50 000-100 000	5806	81	6	982	111	93
7. 25 000-50 000	1606	23	5	679	85	71
8. 10 000-25 000	484	6	11	539	80	63
9. <10 000	150	5	22	396	100	84

pollutants. Another, NO, is essentially non-toxic but is of interest because of its rapid conversion to NO<sub>2</sub> in the atmosphere and because of its role in the formation of photochemical smog. For the purpose of estimating maximum effects, it will be assumed that CO will be produced in a quantity equal to 25% of the initial fuel weight and that the combined nitrogen oxides (NO and NO<sub>2</sub>) and the gaseous hydrocarbons will be produced in amounts equal to 10% of fuel weight. This should provide very generous overestimates of their concentrations. It is assumed that a large-scale weather modification operation might utilize as much as 2 million pounds of carbon black requiring the consumption of about 4 million pounds of fuel. Using the above criteria, amounts of 1 million pounds of CO and 400 000 pounds of nitrogen oxides and hydrocarbons will be assumed. A carbon cloud of this magnitude will cover approximately 40 000 km<sup>2</sup> at 10% horizontal area coverage. The proposed cloud would extend from the surface to about 0.5 km when initially dispersed. The volume of the model cloud is approximately  $2 \times 10^{13}$  m<sup>3</sup>. The concentrations of the by-product gases as initially dispersed together with proposed EPA standards are shown in Table 5. It is highly probable that the concentrations of the by-product gases would be significantly reduced from the values shown by the time the carbon cloud drifted

over any populated area. Particulate hydrocarbons are not differentiated from other particulates in EPA standards. Their effect on the total particulate loading of the atmosphere is insignificant compared to the effects of the carbon particles themselves on that loading, and the particulate hydrocarbons will not be considered separately here.

From Table 5 it is obvious that the carbon by-product gases produced will be insignificant compared to proposed pollution standards. Since the concentrations of all of the gases in Table 5 should be reduced by an order of magnitude before the carbon cloud is advected over land, it seems safe to say that the by-products of the carbon generation process should not create any important pollution problems.

### c. Long-term atmospheric effects

To evaluate the long-term atmospheric effects of performing one or more carbon weather modification operations, it is necessary to establish the approximate residence time of the carbon particles in the atmosphere as well as the physical effects of the carbon upon the earth atmosphere system. The principal mechanisms for removal of aerosols from the atmosphere are rainout (particles becoming attached to raindrops during the condensation process) and washout (particles being captured by falling raindrops during precipitation). Particles on the order of  $r=0.1$   $\mu\text{m}$  will not fall out of the atmosphere from gravitational forces in any reasonable amount of time. Washout is an effective removal mechanism only for relatively large particles [larger than a few microns (Adam and Semonin, 1970); Kerker *et al.*, 1970; Peterson and Crawford, 1970)]. Therefore, rainout appears to be the principal removal mechanism for sub-micron aerosol particles.

Martel (1970) estimated that natural atmospheric particles in middle latitudes have residence times of about 6 days in the lower to middle troposphere. Studies of sediment patterns of eolian dust (land-derived dust carried by the air) from the floor of the Atlantic Ocean off West Africa by Chester (1972) indicate that the entire troposphere there is cleansed

TABLE 5. Concentrations of carbon by-product gases and proposed EPA standards.

Gas	Maximum initial dispersed concentration	Proposed EPA standards
CO	0.018 ppm	9 ppm (max 8 h concentration, not to be exceeded more than once per year).
NO, NO <sub>2</sub>	9 $\mu\text{g m}^{-3}$	100 $\mu\text{g m}^{-3}$ (annual arithmetic mean).
Gaseous hydrocarbons	9 $\mu\text{g m}^{-3}$	125 $\mu\text{g m}^{-3}$ (max 3 h concentration, not to be exceeded more than once per year).

of the eolian dust in less than 10 days. More than 70% of the eolian dust particles measured were smaller than  $4\ \mu\text{m}$  in diameter and were assumed to have been removed by precipitation scavenging, probably rainout. Natural aerosol particles range from about 0.01 to  $100\ \mu\text{m}$  in size with the greater number of particles being concentrated in the size range from 0.01 to  $0.1\ \mu\text{m}$  (Quanzel, 1970; Junge, 1955; Ikebe and Kawano, 1970; Junge and Jaenicke, 1971). Carbon particles of  $0.1\ \mu\text{m}$  radius should not differ greatly from mean atmospheric particles with respect to size. Although carbon particles differ in composition from most natural atmospheric aerosols, they should have aerodynamic properties similar to those of other basically inert particles. Therefore, an assumption that carbon particles dispersed in the lower troposphere (1000–700 mb) would have mean residence times of but 3 to 8 days seems reasonable. Carbon particles dispersed in the oceanic tropical boundary layer would likely be removed by rainout more quickly than average due to the high levels of convective activity found there.

Carbon particles dispersed in the atmosphere may affect the global scale climate in two ways. They may slightly decrease the earth-atmosphere system albedo, and they could redistribute solar energy in the vertical if some of the carbon were to reach the upper atmosphere. Being basically inert and highly hydrophobic, the carbon should not cause any changes in condensation nuclei or ice nuclei concentrations. The albedo decrease is due to the low backscatter of clouds of carbon particles (less than 2% for even a relatively dense carbon cloud) and their high absorptivity (Frank, 1973). A carbon cloud will absorb an appreciable amount of both incoming solar radiation and outgoing shortwave radiation reflected from the earth's surface. Since the albedo of the carbon cloud itself is less than 2%, the carbon particles should reduce the albedo of the earth-atmosphere system when located above virtually any normal surface type. The initial amount of solar radiation absorbed by 2 million pounds of carbon dispersed in one operation is about  $4 \times 10^{16}$  cal day<sup>-1</sup> assuming no loss of carbon during the first day. The extra absorption gain of the atmosphere/earth system due to the seeding would be about 10% of this value. This figure is insignificant compared to the roughly  $2 \times 10^{21}$  cal day<sup>-1</sup> of solar energy absorbed by the earth/atmosphere system (Sellers, 1965). It seems highly unlikely that any noticeable climatic change could result from such a small change in earth/atmosphere albedo. It is not too surprising that the addition of carbon to the atmosphere should have such a small effect on the earth's heat budget in view of the small fraction of the atmosphere's normal particulate loading which the carbon would constitute.

Each year about  $1530 \times 10^6$  metric tons ( $3.4 \times 10^{12}$  lb) of particles with diameters  $< 5\ \mu\text{m}$  are emitted into

the air (Peterson and Junge, 1971). This is over a million times more than the amount of carbon to be introduced from one operation ( $2 \times 10^6$  lb).

One important area of interest concerning possible climatic effects of carbon seeding involves the possible introduction of some of the particles into the stratosphere due to natural mixing processes. The exact amount of carbon which might possibly avoid scavenging long enough to reach the stratosphere is difficult to estimate, but it seems safe to say that it would be many orders of magnitude smaller than the amounts of particulates injected into the upper atmosphere periodically by volcanoes. One of the best documented of these eruptions was the Mount Agung (Bali) eruption of 1963 which increased the dust content of the stratosphere up to 30 times and decreased solar radiation at the surface by about 1% (Budyko and Pivovarova, 1967). Even this enormous injection of particulates into the stratosphere caused no noticeable changes in the temperature at the earth's surface during the 1–2 year residence time of the particles. It seems extremely unlikely that carbon seeding operations could cause any measurable effect in stratospheric aerosol concentrations or energy balance.

#### d. Carbon in the oceans

There has been some concern as to whether large amounts of carbon deposited on the ocean surface by precipitation scavenging would cause any detrimental effects to either the oceanic ecosystem or the physical characteristics of the sea surface. It seems likely that most of the carbon particles dispersed in the proposed seeding operation would fall directly onto the sea surface due to the amount of convective activity. Most of the particles so scavenged would agglomerate within the various precipitation drops to sizes on the order of  $1\ \mu\text{m}$ . Studies of eolian dust and other oceanic particulates indicate that the particles apparently sink to the ocean floor at a rate much faster than would be predicted by Stokes law, perhaps due to filter feeding organisms (Deleny *et al.*, 1967; Chester, 1972). Eolian dust is primarily composed of particles  $< 4\ \mu\text{m}$  in diameter. The rained-out carbon particles are generally inert and would be of the approximate size range of eolian dust deposited on the sea surface. Eolian dust is essentially hydrophilic while carbon dust is strongly hydrophobic. Hence the carbon particles would tend to remain on the sea surface somewhat longer than eolian dust particles. Once the particles become fully wetted, however, they should settle at a rate similar to that of the dust particles. Therefore, the overall time required for carbon particles to settle to the ocean floor should not be much longer than the 10–100 days (depending on particle size and ocean depth) required for eolian dust particles to sink. There should not be any significant buildups of carbon on the sea surface. If particles did accumulate on the ocean surface, they

would tend to form larger aggregates and then settle to the bottom. Hence, there should be no significant alteration of the air/sea interface energy exchanges. The carbon will not remain on the surface long enough to have any effect on the distribution of absorption of solar radiation in the upper layers of the water. It is concluded that carbon seeding operations will not alter the physical characteristics or energy processes of the oceans.

There have been no direct studies of the effects of carbon particles on the oceanic ecosystem. However, results of studies mentioned previously in this report indicate that carbon dust is non-toxic to a variety of mammals. The carbon itself is nearly chemically inert. There is no rational reason to assume that ingestion of carbon particles should prove toxic to any of the forms of sea life. By the time the carbon from a seeding operation is rained out of the atmosphere and mixed with sea water, the concentrations of carbon would be too low to have any appreciable effect upon the normal concentrations of particulates in the micron size range found in the oceans. It does not seem possible that sea organisms could experience any ill effects due to excessive particulate concentrations in the water resulting from carbon seeding operations. It appears that carbon seeding operations of the scale envisaged would have no noticeable effect on the oceanic ecosystem.

#### *e. Esthetic effects*

Perhaps the most frequently asked questions about the environmental effects of a carbon seeding operation concern the esthetic results of dispersing 2 million pounds of carbon into the air. It is natural for people to conjure up images of smokestacks in industrial cities belching out clouds of soot which fall over the city turning everything black. Fortunately, these images bear little resemblance to the effects of a carbon seeding operation.

The carbon particles dispersed during the proposed operation will be on the order of  $0.1 \mu\text{m}$  in radius. Particles of this size are not visible to the unaided eye and do not have an appreciable fall velocity when suspended in air. As a result, even if the carbon cloud were advected over a land area at the initially dispersed high concentrations, there would be no "fallout" of carbon particles dirtying the countryside. The uniformity of particle sizes of carbon manufactured by the furnace process is quite good, so very few fallout sized particles would be produced. Those that were, would probably fall out over the ocean in the day or more between the time the cloud is dispersed and the time the cloud is advected over land. Therefore, the esthetic impact of the carbon primarily concerns the appearance of the air containing the carbon.

In its initially dispersed concentration the carbon cloud would consist of a region approximately 200 km

across and 0.5 km high (assuming a horizontal area coverage of approximately 10%). The optical thickness of a vertical column of the cloud would be about  $\tau=0.1$ . If an observer were located on the sea surface at the center of the cloud at noon, the sun would appear about 9/10 as bright as it would from a point outside the cloud. Looking horizontally, 90% of the light would be obscured from objects about 12 km away (assuming unlimited visibility outside of the cloud). The probable appearance would be that of a rather hazy day. Most large United States cities frequently experience days with visibilities lower than this. Carbon concentrations of the above magnitude would occur only at the initial site of the seeding. By the time the carbon cloud had advected over a populated land area (one or more days) the concentration would be much lower. It is difficult to estimate exact dilution levels but based on diffusion estimates alone the concentration would likely decrease to 1/10 or less of the initial cloud value after one day. Therefore, the concentration of carbon particles over populated areas should be on the order of  $5 \mu\text{g m}^{-3}$  or less. This is considerably lower than the approximately  $30 \mu\text{g m}^{-3}$  of particulates which is average for non-urban areas in the United States and the nearly  $100 \mu\text{g m}^{-3}$  average for United States cities (Peterson and Junge, 1971). The esthetic effect of the carbon at most would be a slight reduction in visibility on the order of a few percent. Such a change would be scarcely noticeable since the day-to-day fluctuation in visibility over land areas is several times greater than the maximum carbon effect. In addition, the carbon cloud would continue to diffuse while over land, and by the end of the second day after dispersal it is doubtful if it would be visible at all. It appears that there will be at most a slight, temporary esthetic effect consisting of a small reduction in visibility with the appearance of a slight haze. There should be no other obvious effects of a carbon seeding operation sensed by people downwind from the seeding area except for the modification of the weather resulting from the operation.

#### *f. Conclusion*

It is concluded that for the amount, concentration and location of the proposed carbon dust seeding, no significant environmental hazards are evident. This is a very complex subject, however, and if these weather modification ideas should go forward, more ecological studies will be required.

### **9. Summary and potential problems**

We believe mesoscale weather modification with carbon dust to be very promising and we encourage more study and discussion of this topic. We wish to especially stress the likelihood of alteration when the

solar energy gains can tap other energy sources such as the reduced IR energy losses when cirrus clouds are formed and the probable increases in evaporation over the oceans from the downward mixing of drier air. There is a great deal more research that must be accomplished. More must be learned about:

- 1) How does the carbon horizontally diffuse in the boundary layer and in the upper troposphere?
- 2) How will the carbon warming affect the vertical diffusion and advection of the carbon dust during the heating day? How will the shielding of the carbon by the clouds affect the energy gain?
- 3) To what extent will the artificially enhanced cumulus convection act as a feedback mechanism to further intensify the mesoscale flow system in which it is imbedded?

There are a number of potential problems to be investigated before the real potential of this modification scheme can be fully realized. Nevertheless, our careful consideration of this subject leads us to believe that these as yet unresolved questions and problems

will not prove to be insurmountable hurdles. At the very least, we feel that these modification ideas should be given more consideration. Many of these modification ideas can be inexpensively tested in already developed numerical models. We encourage such model testing.

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APPENDIX

Equations for Absorption, Reflection and Transmission of Incident Solar Radiation<sup>3</sup>

1. For albedo = 0

$$\begin{aligned} \text{Transmission} &= T_0 & \text{Absorption} &= A_0 \\ \text{Reflection} &= P_0 & \text{Zenith angle} &= Z \end{aligned}$$

$$T_0 = \frac{1}{2 \cos z} \left[ \frac{(N-M) \left\{ \exp\{-[\sec z - (EF)^{\frac{1}{2}}]t\} - \exp\{-[\sec z + (EF)^{\frac{1}{2}}]t\} \right\} + (M+N) \left( \frac{P}{Q} - \frac{Q}{P} \right)}{\left( \frac{Q}{P} \right) \exp[(EF)^{\frac{1}{2}}t] - \left( \frac{P}{Q} \right) \exp[-(EF)^{\frac{1}{2}}t]} \right] + \exp[-(\sec z)t] \left( 1 + \frac{M+N}{2 \cos z} \right) \quad (A1)$$

$$R_0 = \frac{1}{2 \cos z} \left[ \frac{(N-M) \left( \frac{Q}{P} - \frac{P}{Q} \right) \exp(-t \sec z) + (M+N) \{ \exp[-t(EF)^{\frac{1}{2}}] - \exp[+t(EF)^{\frac{1}{2}}] \}}{\left( \frac{Q}{P} \right) \exp[+t(EF)^{\frac{1}{2}}] - \left( \frac{P}{Q} \right) \exp[-t(EF)^{\frac{1}{2}}]} \right] \quad (A2)$$

$$A_0 = 1 - T_0 - P_0 \quad (A3)$$

where

$$K_A = \text{Absorption quantity}$$

$$E = (\alpha_0 - \beta_0)(1 - K_A) - 1 \quad (A4)$$

$$F = (\alpha_0 + \beta_0)(1 - K_A) - 1 + \frac{2\alpha_{90}(1 - K_A)^2 \gamma_z}{1 - \gamma_{90}(1 - K_A)} \quad (A5)$$

<sup>3</sup> Derived by Korb and Möller (1962) from Chandrasekhar's equation of radiative transfer.

$$G = (\alpha_z - \beta_z)(1 - K_A) \tag{A6}$$

$$H = (\alpha_z + \beta_z)(1 - K_A) + \frac{2\alpha_{90}(1 - K_A)^2\gamma_z}{1 - \gamma_{90}(1 - K_A)} \tag{A7}$$

$$K = EH - G \sec z \tag{A8}$$

$$L = FG - H \sec z \tag{A9}$$

$$M = \frac{K}{\sec^2 z - EF} \tag{A10}$$

$$N = \frac{L}{\sec^2 z - EF} \tag{A11}$$

$$P = (EF)^{\frac{1}{2}} + F \tag{A12}$$

$$Q = (EF)^{\frac{1}{2}} - F \tag{A13}$$

$$t = \text{optical depth} = \int_0^h (\sigma_E N \pi r^2 + \rho_W K_W) dh \tag{A14}$$

where

$N$  = number particles  $\text{cm}^{-3}$        $\rho_W$  = density water

$r$  = radius particle =  $0.1 \mu\text{m}$        $K_W$  = absorption quantity of water vapor

$\alpha, \beta, \gamma$  are scattering coefficients and depend upon the zenith angle of the sun. Values used are:

	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
$\alpha$	0.325	0.320	0.313	0.305	0.295	0.282	0.265	0.244	0.218	0.184
$\beta$	0.108	0.111	0.115	0.119	0.124	0.129	0.140	0.152	0.165	0.184
$\gamma$	0.567	0.569	0.572	0.576	0.581	0.589	0.595	0.604	0.617	0.632

2. For albedo  $\neq 0$

$T_T$  = Transmitted

$R_T$  = Reflected

$A_T$  = Absorbed

$$T_T = \frac{T_0}{1 - q_1} \tag{A15}$$

where

$$q_1 = \frac{A_s \left[ \frac{(N' - M')(Q/P - P/Q)e^{-t} + (M' - N')\{\exp[-t(EF)^{\frac{1}{2}}] - \exp[t(EF)^{\frac{1}{2}}]\}}{(Q/P) \exp[t(EF)^{\frac{1}{2}}] - (P/Q) \exp[-t(EF)^{\frac{1}{2}}]} - (N' - M') \right]}{2} \tag{A16}$$

$$R_T = R_0 + q_2 T_T \tag{A17}$$

and where

$$q_2 = \frac{A_s \left[ \frac{(N' - M') \{\exp\{-[t - t(EF)^{\frac{1}{2}}]\} - \exp\{-[t + t(EF)^{\frac{1}{2}}]\}\} + (M' + N')(P/Q - Q/P)}{(Q/P) \exp[t(EF)^{\frac{1}{2}}] - (P/Q) \exp[-t(EF)^{\frac{1}{2}}]} + e^{-t}(2 + M' + N') \right]}{2} \tag{A18}$$

$$G' = (\bar{\alpha} - \bar{\beta})(1 - K_A) \tag{A19}$$

$$H' = (\bar{\alpha} + \bar{\beta})(1 - K_A) + \frac{2\alpha_{90}(1 - K_A)^2\bar{\gamma}}{1 - \gamma_{90}(1 - K_A)} \tag{A20}$$

$$K' = EH' - G' \quad (A21)$$

$$L' = FG' - H' \quad (A22)$$

$$M' = \frac{K'}{1 - EF} \quad (A23)$$

$$N' = \frac{L'}{1 - EF} \quad (A24)$$

$A_s$  = albedo expressed as a percentage

$$\left. \begin{aligned} \bar{\alpha} &= 0.275 \\ \bar{\beta} &= 0.135 \\ \bar{\gamma} &= 0.590 \end{aligned} \right\} \text{mean scattering coefficients.}$$

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