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CHANGES IN THE GLOBAL ENERGY BALANCE

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CHANGES IN THE GLOBAL ENERGY BALANCE

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CHANGES IN THE GLOBAL ENERGY BALANCE

A REPORT TO THE U.S. ENVIRONMENTAL PROTECTION AGENCY

Alden McLellan IV

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Center for Climatic Research
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CHANGES IN THE GLOBAL ENERGY BALANCE

I. OVERVIEW AND SUMMARY

In the past few years, many of the populated areas of the earth have experienced disastrous weather. India's harvests have been decreasing. The monsoon rains in India and Africa have been late. The Sahara has expanded relentlessly southward. Russian wheat crops have failed. In Central America, crops failed, cattle starved and the intensity and frequency of hurricanes have increased. Floods and frost in the Midwest and drought in the Southwest have curtailed U.S. grain production. Best & Co. has reported that due to weather disaster the property/liability index of U.S. fire and casualty companies has dropped over 50% in the first eight months of 1974 (Barrons, 1974). The earth's climate is changing.

The main force driving the climate of the earth-atmosphere system is radiation. The incoming solar energy absorbed by this system is in approximate balance with the outgoing infrared radiant energy. However, variation in the earth's rotation, the radiation of the earth's surface, and the composition of the atmosphere are very important factors, for they govern the nature and magnitude of <u>changes</u> in the heat balance. This balance may be expressed mathematically as follows:

$$S(1-\alpha_T) = 4\sigma T^4_{\text{effective}} + m^* \frac{\partial T}{\partial t}$$

where S = the incoming solar radiation,

α_T = outside albedo at the top of the earth's atmosphere,

α = Stefan-Boltzman constant,

$T_{\text{effective}}$ = effective outside radiative temperature of the earth-atmosphere system,

M^* = effective mass of the earth-atmosphere system,

T = mean atmospheric temperature.

The term on the left-hand side of the equation represents the incoming energy, and the first term on the right-hand side represents the outgoing energy. The second term on the right-hand side represents the heat storage of the atmosphere-ocean system which is quite sensitive and is indicative of climatic changes.

We have considered the various components of the earth's energy budget, their magnitudes and relative importance, the influence of man's activities on the processes governing climatic change and the prospects concerning the future.

In this paper we have endeavored to estimate the effect of small changes of independent climatic variables on the global energy budget. In providing a discussion of these changes, we have approached the problem from an historical perspective. We have also investigated the components of these changing variables as to whether or not their change is due to natural causes or to man-related activities. At the end of our paper we arrive at conclusions as to the importance of climatic change and what man can do to better define the problems related to the variables that affect the energy budget.

The energy input necessary to drive the atmosphere's circulation comes from the intensity of sunlight at the top of the earth's atmosphere. From long-range historical evidence, we conclude that variation in this extrinsic parameter performs a minor role in decadal to millennial energy budget changes.

Carbon dioxide, another extrinsic climatic variable, is important in determining the temperature of the earth, since it absorbs and emits infrared radiation. If the increase in CO_2 were the only change in the energy budget, the earth's surface temperature should have been steadily rising at an increasing rate over the last century. However, observations have shown this has not been the case.

Estimates of emission and retention of particulate matter in the atmosphere lead us to conclude that this extrinsic parameter could indeed account for the mean annual change in temperature during the past century. By using lead as an indicator of man-related activities in atmospheric particulate emission, we estimate that 40%-50% of suspended solid matter in the earth's atmosphere is due to man. We have found that particulates from jet aircraft alone presently contribute approximately one-half the amount of stratospheric particulates as presently injected by natural volcanic activity. Locally emitted particulates from industrial activities, from agricultural processes, such as slash-and-burn clearings, and from windswept areas due to the overgrazing of land, can be distributed over the hemisphere in a relatively short time.

Since population, agricultural mechanization and industrialization are still expanding throughout the world, there is little that any one nation alone can do to reverse the trend of particulate emissions on a global scale. In order to obtain better data, we can search for other meaningful trace atmospheric constituents that parallel particulate emission and distributions. In particular, we should explore those trace constituents that are indicative of man's activities, such as DDT, as well as those that are indicative of natural causes. Also, the modeling of pollutant dispersion and behavior over large distance and time scales should be more intensively investigated.

II. COMPONENTS OF THE GLOBAL ENERGY BUDGET AND THEIR RELATIVE IMPORTANCE

There is abundant evidence that the earth's climate is subject to a wide variety of fluctuations, with periods ranging from decades to millenia, and that it is now changing. The atmosphere is a relatively stable system. The energy input, in the form of solar radiation, is absorbed by the earth and it is almost exactly balanced by the emitted terrestrial infrared radiation, otherwise the mean temperature would change much more rapidly than it does. This nearly perfect balance is the key to the heat budget changes that have occurred in the past, are occurring now, and will occur in the future.

Variations in parameters both extrinsic and intrinsic to atmospheric processes serve to modify the climate. For a discussion of extrinsic and intrinsic climatic variables, see Bryson (1974). We shall be concerned here with parameters extrinsic to the internal feedback mechanisms of the atmosphere itself. The important leverage points of the extrinsic control variables of climatic change concern the radiation balance of the atmosphere, and they control it by fundamentally changing the composition of the atmosphere. For example, the heat balance can be changed significantly by altering the delicate radiation balance described above by changing solar radiation, content of CO_2 and particulate matter concentration. In discussing the various important atmospheric components below, we will estimate the present order of magnitude of change in these components.

A. SOLAR RADIATION

The annual average total radiation per unit time incoming at the top of the earth's atmosphere on a unit surface perpendicular to the sun's rays (definition of the solar constant) is 1.95 cal cm^{-2} min^{-1} (136.0 mW/cm^2) (Drummond, 1970).

New active cavity radiometers have been developed for the absolute measurement of optical radiant flux. Using these new radiometers the solar constant was measured at an altitude of 25 km. It was determined to be 137.0 mW/cm^2 with an absolute uncertainty of less than ± 2% (Willson, 1971). Changes of the solar constant, even of the order of 1 percent, have not been firmly established even though there have been many suggestions of variations (Kondratiev and Mikolsky, 1970) including variation in sun spot activity and solar flares.

1. Distribution of Solar Radiation

The fundamental regimes that govern the distribution of solar energy act continuously (or quasi-continuously) within the earth's atmosphere or at its boundaries. The numerical rates in the schematic Figure 1 are given relative to the incoming solar energy available at the top of the atmosphere. Radiative regime I describes the effect of primarily atmospheric carbon dioxide as it affects the long wavelength portion of the radiation budget. Radiative regime II describes for the most part the effect of atmospheric particulates on the short wavelength portion, and regime III contains the effects of the lower boundary and clouds.

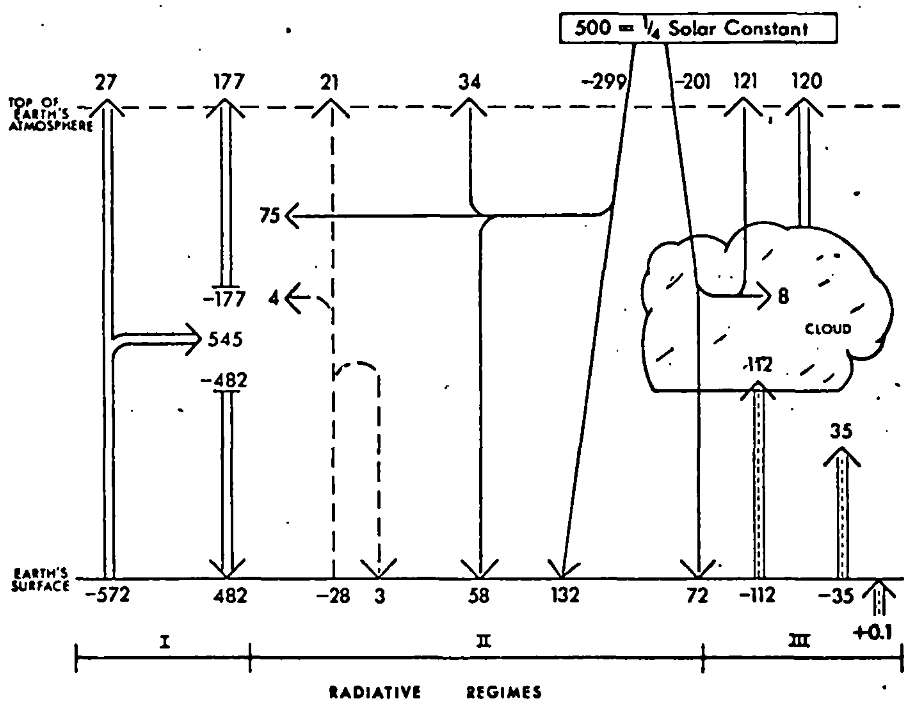

Figure 1. The distribution of solar radiation within the earth's atmosphere and at its boundaries. The numerical rates of radiative energy transfer are relative to the solar energy constant. (Budyko and Kondratiev, 1961; Lettau, 1973.)

On an annual average, twice the solar radiation available at the poles is available at the equator, because the incoming solar radiation on a unit horizontal surface is more direct in equatorial than in polar regions. Outgoing radiation depends strongly on the effective temperature of the atmosphere, but this temperature does not vary much from equator to pole. Thus, there is only a small change of emitted radiation with latitude (Viebrock and Flowers, 1965, 1968). Hence, there is an excess of incoming solar radiation over emitted infrared radiation in equatorial regions and a deficit in the polar regions. Large-scale atmospheric circulation forced by the unequal geographic heating and cooling is made quite complicated due to the earth's rotation and topography. However, these atmospheric motions, together with radiative processes, help produce the two fundamentally distinct layers within the atmosphere; the troposphere and stratosphere. The qualitative difference in lapse rate between these two layers and the tropospheric scavenging processes lead to an important difference in the residence times of various atmospheric constituents in these two regions. A knowledge of the growth rates and lifetimes of these constituents can give an estimate of future climatic changes. This will be considered later in more detail.

2. Solar Radiation Over Large Time Scales

The total incoming solar radiation also depends on the earth-sun distance and on the solar elevation angle. These depend on the earth's orbital characteristics, such as the orbit's eccentricity, the obliquity of the ecliptic, and the longitude of the perihelion with respect to the spring equinox. As calculated from celestial mechanics, these orbital elements show very slow variations with periods on the order of 10^5 years for the eccentricity, 4×10^4 years for the obliquity, and about 2.1×10^4 years for the precession period. The variations of solar radiation input with respect to these orbital parameters were also studied extensively by Milankovich (1930), Broecker (1968), and Kutzbach, et al. (1968). Surface temperature fluctuations during the past 4×10^5 years may have been influenced by changes in these orbital elements (Emiliani, 1966), but the time scales of these cycles are on the order of 10^4 to 10^5 years. Thus we conclude that this variation in sunlight intensity at the top of the atmosphere plays a minor role in decadal to millennial energy budget changes.

B. CARBON DIOXIDE

Carbon dioxide is a trace gas within the atmosphere with a concentration of about 320 ppm (0.03% by volume). It is increasing about 1 ppm annually (Machta, 1972). Even though it is only a trace gas, it has an important role in determining the temperature of the earth by being an efficient absorber and emitter of infrared radiation. By absorbing the infrared radiation that is emitted by the earth's surface and reradiating it back toward the earth, the rate of surface cooling is decreased. It is just this effect that can cause atmospheric temperature variations from changes in CO_2 concentration.

1. Past and Future CO_2 Concentration Increase

Measurements of the carbon dioxide concentration have only been made on a systematic basis since 1958. These observations, from Swedish aircraft (Bolin and Bischof, 1969), at Point Barrow (Kelley, 1968), in the Antarctic (Brown and Keeling, 1965), and at Mauna Loa, Hawaii (Pales and Keeling, 1965) distinctly show the increase in concentration of CO_2 over the past decade (see Figure 2).

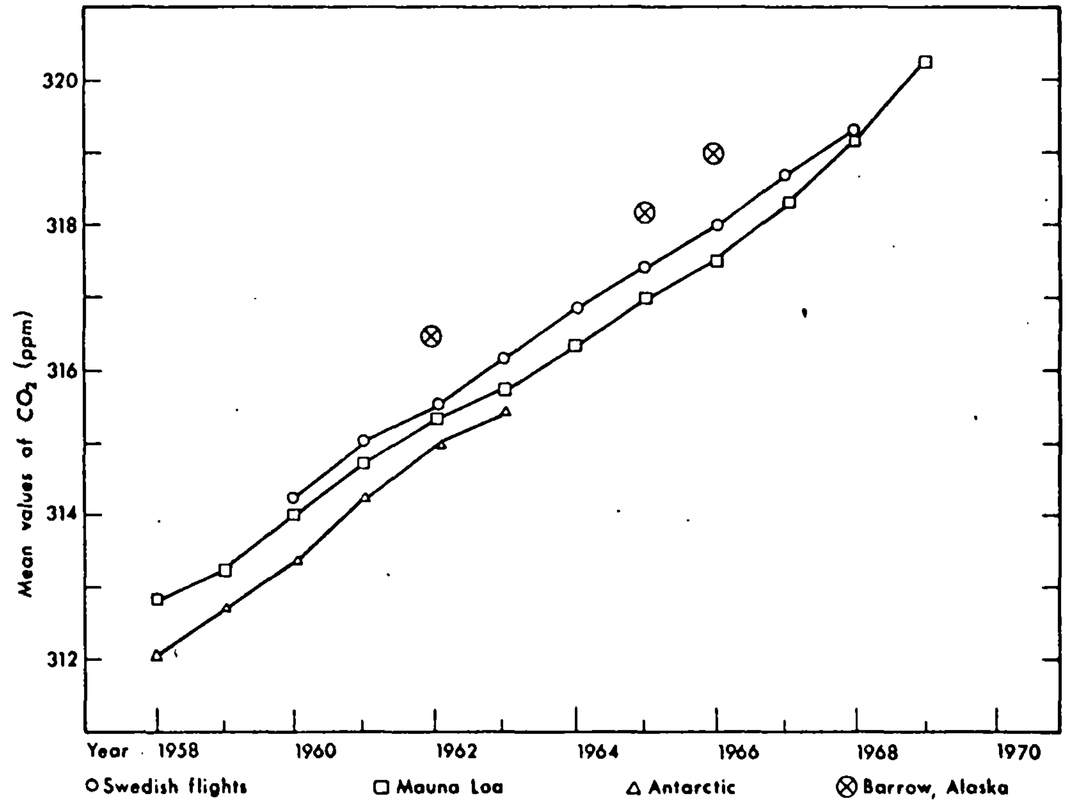

Figure 2. Annual mean values of CO_2 atmospheric concentration.

Both carbon dioxide and water vapor play important roles in modifying the vertical temperature distributions of the atmosphere by controlling the energy input and output via absorption and emission of infrared radiation. Whereas, water vapor concentration is an atmospheric intrinsic variable, in that it responds directly to the climate, carbon dioxide is an extrinsic variable, in that it is regarded as not responding to climate but rather to the consumption of fossil fuels (Machta, 1972).

Estimating future atmospheric CO_2 concentration depends on estimating the growth rate of man's use of fossil fuels and on the partitionings of CO_2 sinks among the atmosphere, oceans, and biospheric reservoirs. Estimates of this partitioning are uncertain at the present. However, if we assume a 4% annual growth in fossil fuel combustion and a continuation of the partitioning found during the 1958-1968 period, an increase in atmospheric CO_2 over the present levels of almost 20% by the year 2000 (from 320 to 379 ppm) can be expected.

2. The Effect of CO_2 on the Global Heat Budget

The question to ask at this time is what effect would this man-made increase of CO_2 have upon the earth's climate, all else being equal. Manabe and Wetherald (1967) have developed a model for calculating the effect of CO_2 concentration changes on the surface temperature of the earth. This model, which puts the entire atmosphere in radiative-convective equilibrium, allows for the overlapping of the 15μ band of CO_2 and the rotation band of water vapor. The model's atmosphere had a fixed relative humidity, a specified distribution of O_3 and included clouds. For an increase in CO_2 concentration from 300 to 600 ppm, their model raises the earth's surface temperature by 2.36°C.

The relationship between CO_2 concentration and surface temperature is non-linear. From Figure 3 we obtain

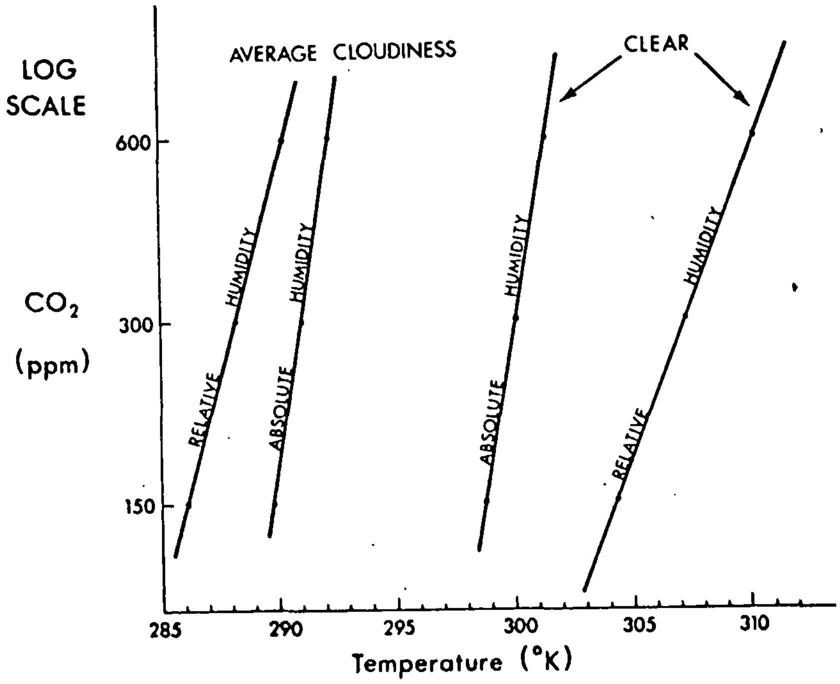

Figure 3. Equilibrium temperature of the earth's surface and the carbon dioxide concentration of the atmosphere. Note the exponential relationship. The data are from Manabe and Wetherald (1967).

$$T = k \log (CO_2),$$

where k is a constant.

For small changes, we obtain

$$\Delta T = k \frac{\Delta(CO_2)}{CO_2} .$$

Since the temperature increases by 2.36°C for a doubling of CO_2 concentration, we have

$$k = 2.36°C.$$

A change of CO_2 concentration of 20% over present levels, represented by a change of

$$\Delta(CO_2) = 60 \text{ ppm by the year 2000},$$

results in an increase in global average annual temperature of approximately 0.47°C. This is about 2/3 of that predicted in the report "GLOBAL ENERGY BALANCE" by InterTechnology Corporation (1973).

If this increase in carbon dioxide were the only cause of changes in the energy budget, then the mean global surface temperature should have risen steadily and smoothly at an increasing rate over the last century by about 0.25°C (Bryson, 1974). However, observations of mean global surface temperature have, in fact, shown a decrease since 1940. Thus, there are clearly other extrinsic parameters of greater importance that are influencing climatic change as far as surface temperature is concerned.

C. HEAT

Heat emitted into the atmosphere from man's activities of energy generation and consumption is a direct addition to the earth's energy budget. It is well-known that a concentration of heat sources in an urban area can indeed modify the local climate (Peterson, 1969). On the global scale, however, man-generated heat is not a significant factor in the heat budget because it adds much less than 1% to the net radiation average. From the 1969 United Nation's report, World Energy Supplies (SCEP, 1970), the thermal power of the world is estimated to be 5.5×10^6 megawatts (MW). Greenfield (1970) assumed a world growth rate of 5.7% annually, and arrived at 31.8×10^6 MW by the year 2000, a six-fold increase. If we average the present day heat power over the entire globe (5×10^8 km^2), we have a heat density of 1.1×10^{-12} MW/cm^2 or 1.1×10^{-6} W/cm^2, which can be compared with either the solar constant, 1.36×10^{-1} W/cm^2, which is the solar radiation incoming at the top of the earth's atmosphere, or the continental net radiation average of 6.7×10^{-3} W/cm^2 (SMIC, 1971).

In order to put man as a heat-generating source into perspective with other natural sources, Table 1 lists various heat inputs into the earth's atmosphere. It is to be noted that the annual rate of fossil-fuel burning by man is of the same order of magnitude as the infrared radiation energy received from a full moon.

Heat from man's activities over the past three decades is a small fraction of the global energy budget. However, there are local conditions and indirect feedback situations where a large amount of geographically concentrated heat can modify the water vapor content and cloudiness (albedo), which are intrinsic climatic parameters that can modify the heat budget over fairly large geographic areas.

1. Ocean-Atmosphere Heat Exchange

An example of an intrinsic climatic factor is the sea surface, whose optical and thermal properties are variable and depend strongly on long-term average conditions in the atmosphere. The ocean mass is hundreds of times that of the atmosphere, but its properties cannot be rapidly changed in depth. However, the surface layers can change annually.

The contribution of the ocean heat transport to the global heat budget has been estimated for various latitudinal belts (using mostly Atlantic weather-ship data) by Budyko (1971). These data indicate that the heat transport produced by the oceans serves to moderate atmospheric heat differentials. Large scale oceanic fluctuations can result in temperature perturbations of a degree or so within latitudinal belts. Meridional heat transport produced by oceans leads to readjustments of the distribution of the atmospheric heat budget, but it cannot produce

TABLE 1

SELECTED ENERGY SUPPLY RATES FOR THE EARTH*

	(10^9 Watts)
1/4 Solar Constant (extra-atmospheric irradiance)	178,000,000
Insolaton Absorbed at Ground Level	90,000,000
Dissipated by Friction in Atmospheric Circulations	1,500,000
Photosynthesis (production by living vegetation)	40,000
Geothermal Heat (by conduction in crust)	32,000
1970-Rate of Fossil-Fuel-Burning by Man	8,000
Infrared Radiation From Full Moon	5,000
Dissipated by Friction in Ocean Currents and Tides	3,000
Solar Radiation Received via Reflection from Full Moon	2,000
Dissipated by Friction in Solar Tides of the Atmosphere	1,000
1910-Rate of Fossil-Fuel-Burning by Man	1,000
Human Body Heat	600
Released by Volcanoes and Hot Springs (geo-convection)	300
1960-Rate of Hydroelectric Power Production	240
Dissipated as Heat in Lightening Discharges	100
Radiation from Bright Aurora	25
Received from Space by Cosmic Radiation	15
Dissipated Mechanical Energy of Meteorites	10
Total Radiation from all Stars	8
Dissipated by Friction in Lunar Tides of the Atmosphere	5
Solar Radiation Received as Zodiacal Light	2

long-term global trends. However, there is no doubt that the oceans affect the world's climate in very important ways. As an intrinsic parameter, it reduces the latitudinal temperature gradients and reduces the atmospheric seasonal temperature variations.

D. PARTICULATE MATTER

Suspended particles are observed throughout the entire earth's atmosphere. These particles have an effect on the global energy budget by their modification of the atmospheric radiation balance through the scattering and absorption of light (McCormick and Ludwig, 1967). The sizes of the particles that are suspended in the atmosphere range from about 10^{-7} cm ($10^{-3}\mu$) to about 10^{-2} cm ($10^{2}\mu$). In general, these particles produce Mie scattering in which most of the radiation is scattered in the forward direction. Some of the radiation is scattered into space, some of it is absorbed, some reaches the surface of the earth and is absorbed there. Thus, these atmospheric particles can change the total sunlight scattered by the earth into space. In this way, the global albedo is modified. However, these particles also radiate energy in the infrared spectrum modifying the field of terrestrial radiation in a manner that depends on the optical properties of the particles and the temperature structure of the atmosphere (Peterson and Bryson, 1968A, 1968B).

Atmospheric particulate matter can produce important changes in the global heat budget, but the sizes, types, and concentrations of particles respond only in

---

* These whole globe averages represent annual gigawatts (10^9W) of power totaled over the earth's surface (Lettau, 1973).

part to the climate. If for some reason surface winds increase, more particulates are blown up into the atmosphere, which will tend to cool the earth, which in turn may modify the wind patterns. There is a feedback process. But particulate matter is a variable that for the most part is extrinsic to the heat budget, in that the quantity and quality of particles depends on the entry into the atmosphere of soil, rock and chemical debris through natural and man-made processes (Peterson and Junge, 1971). In fact, an evaluation of man's contribution relative to those of natural processes is particularly desirable since it is quite substantial and is amenable to control.

1. Global Emission of Particulates

Estimates of the magnitude of emission or formation of particles less than about 20μ radius in the lower part of the atmosphere are given in Table 2 with the range of values that can be found in the literature. From the wide range in many of these estimates, it can easily be seen that there is very little precise data on global particulate emissions and a wide disparity in assumptions made to arrive at these estimates.

TABLE 2 *

ESTIMATES OF PARTICLES SMALLER THAN 20μ
EMITTED TO OR FORMED IN THE ATMOSPHERE

Atmospheric Particulates from Natural Sources		
1. Soil and rock debris (natural)	50-250	(10^6 metric tons/year)
2. Forest fires (natural)	1-50	
3. Sea salt	(300)	
4. Volcanic debris	25-150	
5. Particles formed from gaseous emissions: H_2S, NH_3, NO_x, and hydrocarbons	345-1100	
	421-1850	
Atmospheric Particulates from Man-Made and Man-Accentuated Sources		
1. Soil and rock debris (agricultural)	50-250	
2. Forest fires and slash-burning agric.	2-100	
3. Particles (direct emission)	10-90	
4. Particles from gaseous emissions: SO_2, NO_x, and hydrocarbons	175-325	
	237-765	

The estimates used in Table 2 can be found in Goldberg, 1971; Robinson and Robbins, 1971; Peterson and Junge, 1971; Hidy and Brock, 1970; Mitchell, 1970; Went, 1970; Shannon, et al., 1970; and NAPCA, 1970.

* Original data taken from SMIC Report, 1971.

In some cases it is quite difficult to assign the origin of these particulates to direct human activities, to historic or even prehistoric misuse of the land (such as overgrazing), or to natural phenomena. Lacking any other information, we divided the soil and rock debris estimate into two equal categories; one from man-made and man-accentuated sources; the other from natural sources. Forest fires and slash-burning agriculture were also equally divided. Slash-burning agriculture is wholly due to man, but many forest fires are also man-caused.

From Table 2, we see that particulate matter arising from man's activities accounts for 40% to 50% of all particulates in the earth's atmosphere. The relative variability of the "natural" and "man-made" portions of the atmospheric particulate load is as important as the relative magnitude; however, it has not yet been adequately explored.

2. Natural Particulates - Volcanic Activity

Volcanic activity has probably been the most important variable source of atmospheric particulates throughout history. Its variability matches that of climatic changes. Hamilton and Seliga (1972) have convincingly shown that the temperature over the Greenland and Antarctic ice sheets decreases as the volcanic dust falling on those ice sheets increases (and vice versa) over the past hundred millenia. Bryson (1971) and Reitan (1971) have shown that in the last hundred years a major control of the global mean temperature in the Northern Hemisphere has been volcanic dust augmented by man's contribution.

Budyko (1969) has shown from direct measurements of the solar radiation normally incident at the ground under cloudless skies that the atmospheric transmittance varied during the past century such that the highest values occurred in the warm period of the 1920's and 1930's, when volcanic activity was at a minimum. All of the above facts imply that, throughout history, as volcanic activity increased, atmospheric particulate loading increased, more solar radiation energy was reflected back into space and the mean global temperature of the earth decreased (and vice versa). However, in the past thirty years something new has occurred. Volcanic activity was at a relatively low ebb until the fifties when it began to increase. One would expect that a global cooling would follow this increase in activity, but both the mean temperatures as well as the measured radiation intensity in the Northern Hemisphere began to decrease well before the 1950's. This suggests another source of atmospheric particulate loading which became significant by 1940 (Bryson, 1974; Flowers, McCormick and Kurtis, 1969).

Mitchell (SCEP, 1970) has calculated that the average stratospheric loading of very fine particulate matter ($0.1 - 1.0\mu$) due to volcanic activity over the past century was about 4.2 million metric tons. He assumed that only 1 percent of the ejected matter from the major eruptions reached the stratosphere, and he assumed a residence time of 14 months. If we assume a steady state situation, this implies that an average of 3.6 million metric tons of volcanic particulates was injected into the stratosphere in an average year over the past century. Lamb (1970) has compiled a "Dust Veil Index" (D.V.I.) that is an indicator of atmospheric particulate loading due to worldwide volcanic activity. Lamb (1970) obtained an average D.V.I. of 300 over the past century, but, due to the decrease in volcanic activity after 1915 or so, he obtained an average of less than 10 for the Dust Veil Index over the past three decades. If Mitchell's estimation of 3.6 million metric tons/year for an average over the past century corresponds to a D.V.I. of 300, we arrive at the annual average of 120,000 metric tons/year of volcanic particulates injected into the stratosphere over the past three decades corresponding to a D.V.I. of 10. Presently, commercial jet aircraft alone emit particulates into the stratosphere at one-half of this rate, as discussed below.

3. Man-Related Particulates

If the increase in man's activities is the source of this increased particulate material, then there should have been a nearly exponential increase in the atmospheric loading from man's by-products in the middle third of this century. A number of observations indicate that this has indeed been the case (Peterson, 1969).

In the drier monsoon region the explosive population growth has led to overuse of the land and extreme dust loading of the atmosphere (Carlson and Prospero, 1974), and in the wetter tropical regions, an increase in agricultural slash-and-burn rotation rates has led to increased production of smoke.

A rapid increase of dust fall on the Caucasian and Altai (Davitaya, 1974) snowfields began about 1930 to 1940, indicating at least a rapid increase in soil deflation in eastern Europe or the Near East.

A similar increase in the lead fall on the Greenland ice cap shows the same pattern (Murozumi, et al., 1969). Figure 4 shows the variation of anthropogenic lead dust fall at Camp Century, Greenland, from about 1880 to 1960 showing the rapid increase in man-made particulates since 1930.

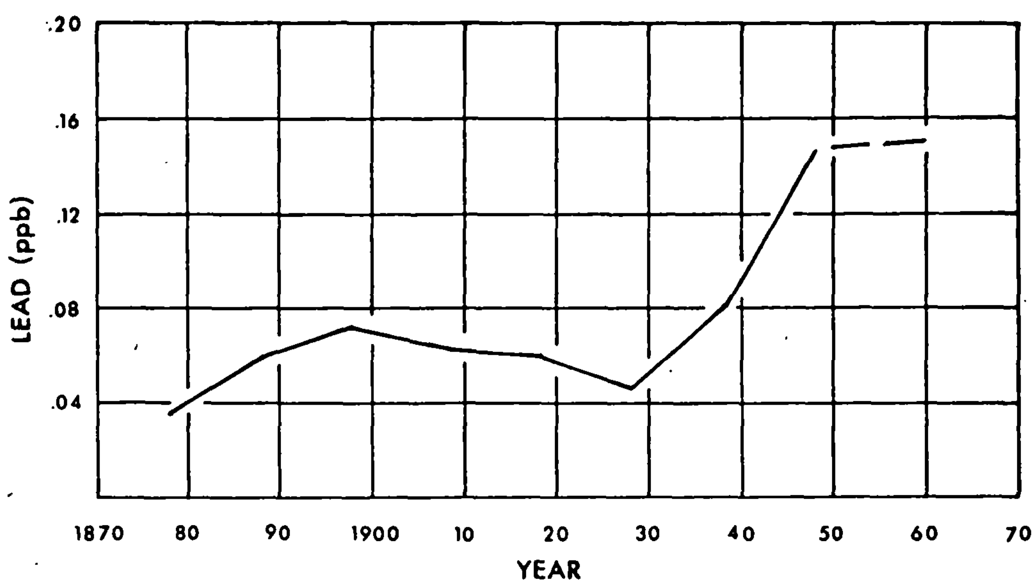

Figure 4. Variations of man-made lead dust fall at Camp Century, Greenland, from about 1880 to 1960. Note the rapid increase in atmospheric lead since 1930. The concentration is measured in parts per billion (ppb). (After Murozumi, 1969).

4. Jet Aircraft Particulate Emissions

Downie (1974) made a study of transcontinental commercial jet aircraft flights over the United States and the North Atlantic. He found that during the winter months these aircraft were cruising above the tropopause almost 90% of the time. At these higher latitudes, the tropopause is generally low during the cold season.

The following data on particulate emissions of commercial jet engines was given by Forney (1974). Low smoke engines are those that power the 747, DC10 and the L1011. The cruise altitude for these planes is on the order of 30,000 to 35,000 feet at a speed of MACH 0.85. At 35,000 feet at maximum thrust the fuel flow per engine is 2900 kg/hr. At 80% of maximum thrust the flow is 2250 kg/hr. At 30,000 feet at maximum thrust the fuel flow is 3300 kg/hr, and at 80% of maximum thrust the flow is 2700 kg/hr.

On the average, the emission index (E.I.) for carbon particulates under the above cruise conditions is 0.02 gm/kg of fuel. For the Boeing 707 engines under similar conditions, the carbon particulate E.I. is 0.1 gm/kg. For an E.I. of 0.1 gm/kg, the size distribution is as follows:

35%	of	the	carbon	particles	are	less	than 0.01μ
60%	"	"	"	"	"	"	" 0.05μ
75%	"	"	"	"	"	"	" 0.10μ
99.85%	"	"	"	"	"	"	" 0.50μ

Not only are carbon particulates emitted, but also sulfur particulates (aerosols) are emitted. If we assume a sulfur component in the fuel of 0.05% by weight, the emission index for sulfur dioxide is 1.0 gm/kg of fuel. (Also, if we assume an hydrogen-carbon ratio of 2 for the fuel, the E.I. for water is 1300 gm/kg.)

The world fleet of operational commercial jet aircraft totals about 5,100 (Irons, 1974). The annual average worldwide utilized flight time per day per jet aircraft is on the order of 7-1/2 hours (Irons, 1974). In order to estimate the carbon particulates emitted into the stratosphere due to jet aircraft, let us assume:

1. A mixture of types of engines, 2700 kg/hr of fuel flow/engine;
2. An average of three engines per aircraft;
3. An annual average of 7-1/2 hours flight time per day for 5,100 jet commercial aircraft;
4. An average emission index (E.I.) for carbon of 0.05 gm/kg; and
5. Neglect all military aircraft operations (military operations are approximately 10% of commercial operations).

Let us also assume that for 90% of the time during one-third of the year, these aircraft cruise above the tropopause. Then from these data, we arrive at 1696 metric tons of carbon particulates from commercial jets emitted into the stratosphere each year.

Engine residue also consists of sulfur dioxide and sulfur trioxide particulates which are oxidized in the lower stratosphere through photochemical reactions. Sulfur trioxide immediately hydrolizes to form sulfuric acid, H_2SO_4, and samples show that these H_2SO_4 droplets are usually on the order of tenths of a micron in size (Cadle, et al., 1970). Since the E.I. of sulfur dioxide is twenty times that of the carbon particulates, and the H_2SO_4 weight equivalent of sulfur dioxide is 98/64 times the sulfur dioxide, this increases the loading of particulates in the stratosphere to 33,900 metric tons/year due to sulfur dioxide alone; or about 52,000 metric tons/year of H_2SO_4 particulates. Thus, commercial jet aircraft emit over 50,000 metric tons of particulates a year into the stratosphere. This is to be compared with volcanic activity, which injects particulates into the stratosphere at approximately twice this rate (120,000 metric tons/year, see above).

5. Lead - A Man-Made Pollutant Indicator

Lead is one trace substance in the atmosphere that is due wholly to man's activities. Natural sources contribute only insignificantly to present concentrations of atmospheric lead (LEAD, 1972). An accurate estimation of contemporary natural lead background is difficult since man has mined lead for many centuries. Natural concentrations have been estimated to be about 0.0005 $\mu g/m^3$ (Patterson, 1965) from airborne dust containing on the average 10-15 ppm of lead (Chow and Patterson, 1962) and from gases diffusing from the earth's crust (Blanchard, 1966). This amount is insignificantly small. Data from the National Inventory of Air Pollutant Emission and Controls of the Environmental Protection Agency in Research Triangle Park, North Carolina, show that the inorganic emission from the combustion of leaded gasoline constitutes approximately 98% of the total emission (184,000 tons/year) of lead into the atmosphere directly from man's automotive activities within the United States. Thus, there is geographically, a logarithmic increase in atmospheric lead concentration from mid-ocean to the seashore, to suburban and urban environments. There is far less lead in mid-ocean than near urban environments, so that if one is to attempt to get a handle on the concentration build-up and atmospheric scavenging time of particulates due to man's activities by using an analogy with the lead data, one must proceed with caution.

From Table 2, we see that the yearly global aerosol production is on the order of 10^9 tons of which about 50% are anthropogenic. The amount of particulates that is retained from this aerosol generation can be estimated from the known values of lead production and lead content. From above, the yearly release of lead into the atmosphere in the United States is on the order of $2x10^5$ tons/year and that almost all of this is due to man (mostly from the use of leaded gasoline). Goldberg and Gross (1971) have estimated the global yearly release of lead into the atmosphere to be 610,000 tons. The National Academy of Sciences (1973) has misquoted the results of Goldberg and Gross (1971) by indicating that one-third of the global emission of lead into the atmosphere is due to natural sources. In fact, only an insignificant portion of the total comes from natural sources (LEAD, 1972).

Annual ice layers from the interior of northern Greenland show that lead concentrations increased from less than 0.0005 $\mu g/kg$ of ice at 800 B.C. to more than 0.2 $\mu g/kg$ in 1965 (Murogami, 1969). The sharpest rise occurred after 1940 (see Figure 3). However, in the Southern Hemisphere the rise in lead concentration after 1940 was not as sharp. In the Antarctic continental ice sheet the concentration rose only to 0.02 $\mu g/kg$ after 1940. This difference is ascribed to barriers to north-south tropospheric mixing, which hinder the migration of aerosol pollutants from the Northern Hemisphere, where most industrial emissions occur, to the Antarctic.

In most cities, the average atmospheric concentrations of lead in 1953-1966 ranged from 1 to 3 $\mu g/m^3$, but non-urban stations averaged 0.1 - 0.5 $\mu g/m^3$, and the concentrations at very rural stations were less than 0.05 $\mu g/m^3$ (U.S.H.E.W., 1962, 1966, 1968). McMullen, et al., (1970) showed that in remote areas an average concentration of 0.022 $\mu g/m^3$ exists. Let us assume an average worldwide concentration of 0.02 $\mu g/m^3$. From this figure we will estimate the atmospheric retention for lead particulates.

6. Atmospheric Residence Time for Lead

The surface area of the earth is $5x10^8$ km^2. If we assume an equivalent atmospheric depth of 2000 meters, the volume is 10^9 km^3 or 10^{18} m^3. The total lead content of the atmosphere is 2.0×10^{16} gm, assuming a concentration of 0.02 $\mu g/m^3$. This is equal to 20,000 metric tons. As mentioned above, Goldberg and Gross (1971) have estimated the global yearly release of lead into the atmosphere to be 610,000 tons. Thus, the atmospheric retention factor is on the order of 3.3×10^{-2}. From the retention factor, we have estimated the mean residence time of lead in the atmosphere to be on the order of 12 days. Other published results have shown lead residence time to be 7-30 days (LEAD, 1972). Other studies using various radioactive tracers have given lifetimes of particulates in the lower troposphere ranging from six days to two or more weeks (SMIC, 1970).

7. An Erroneous Estimation for the Residence Time

However, measurements of atmospheric lead concentrations over the Indian Ocean and northern Asia (Egorov, et al., 1970), where the concentrations are expected to be smallest on a worldwide basis, were extrapolated to the entire atmosphere by the Academy of Sciences (1973) to obtain 500 tons in the earth's atmosphere. This leads to a retention factor of 10^{-3}, or a mean residence time of only 8 hours! If the residence time is, indeed, as short as eight hours then the distance of travel of air parcels from the lead source is quite short. Measurements made as far away as many times this eight-hour travel distance cannot possibly be used to estimate the mean global value.

8. Analogy to Atmospheric Particulates

If the conservative retainment factor of 0.033 is applied to total global particulates production, we have about 5×10^7 tons of particulates in the atmosphere at present. Since 40% or more of this is due to man-related activities, 2×10^7 tons of atmospheric particulates may be controlled. According to Barrett (1971), an increase of 2×10^6 metric tons of atmospheric particulates is capable of lowering the mean annual global temperature of 0.4°C. Thus, man's activities are adequate to account for the hemisphere's cooling since 1940.

9. Worldwide Distribution of Locally-Emitted Particulates

It has been shown that dust emitted from various geographic areas can easily be distributed globally (Jackson, et al., 1973). Circumglobal transport of aerosolic dust was traced through radioactive debris, biological material, filtration of air, and oxygen isotope abundance measurements in quartz isolated from dust and from soils sediments having dust origin. A strong momentum source is supplied by large-scale cyclonic storms, where descending air enters the mixed volume, producing gusts of strong wind at the ground. Vertical fluxes of soil material during dust storms reach the order of 10 $\mu g cm^{-2}$ sec^{-1}. The general circulation moves the dusty air with great speed throughout the entire hemisphere (Carlson and Prospero, 1974).

10. Evidence for Global Movement of Local Particulate Matter

Much information has been accumulated in recent years that shows that particulate matter emitted locally into the atmosphere can easily be distributed over global distances. Geosynchronous satellite images have shown that particulate matter from slash-and-burn agriculture in Central America can be dispersed over thousands of kilometers (McLellan, 1972, 1973). Carlson and Prospero (1974) have documented particulate matter over the Caribbean for the last five years. The source of this material is the African continent. Hot desert winds blowing across the grassland of the sub-Sahara have been picking up large quantities of soil and distributing it across the Equatorial Atlantic. As a result of increased deflation of soil material during the severe drought of the last seven years, skies over Barbados and other Caribbean isles have become as hazy as the air over urban areas of the United States. Measurements of dust at Barbados rose from 6 $\mu g/m^3$ in 1966, to 8 $\mu g/m^3$ in 1968, to 15 $\mu g/m^3$ in 1972, to 24 $\mu g/m^3$ in 1973. Their measurements suggest that the threefold increase in dustiness since the start of the African drought has contributed to a 10-15% reduction in solar energy reaching the sea surface in the tropical Atlantic.

11. Dynamical Means of Worldwide Particulate Loading

The mechanism of transport of the Saharan dust is similar to the transport of dust from other large arid regions. The transport occurs in large-scale pulses which take several days to move 3 to 4 thousand kilometers. Before each pulse reaches the coastline, the air is subjected to prolonged, intense heating, which causes strong mixing in an air layer which may be 15,000 to 20,000 feet deep in summer. As this hot, dusty air emerges from the continent's coast, it is undercut by relatively cool, moist winds which confine the polluted air to altitudes above 4,000 to 6,000 feet. Over the ocean, the warm, polluted air becomes sandwiched between the low level moist air below and the 15,000 to 20,000 foot level, which corresponds to the top of the mixing layer over the arid land. In this manner the dust travels over oceans above the moist layers in which cloud and shower activities do effective scavenging. In this manner, dust emitted into the atmosphere from local sources can be distributed worldwide.

III. HISTORICAL GLOBAL ENERGY CHANGES

It is well known that the climate of the world is different now from what it was during the Pleistocene "Ice Age." A number of researchers have investiaged the fluctuations of the energy budget during the post-glacial period. During this century there have been a number of papers which dealt with the climate change that started in the nineteenth century, and a few reports dealing with the reversal of the trend since 1940 to 1950. Some of these will be discussed here.

The fact of changes in the earth's energy budget in the past is well known, but the magnitude and causes of the changes are less well documented and understood. For the last century there are sufficient data to make some moderately reliable estimates of the climate change and some cruder estimates of causal factors.

A. AN EXAMPLE OF PAST CLIMATIC CHANGES

The past 2,000 years is not only a period for which we have a great deal of information, but also it is one of the distinct climatic episodes within the Holocene. However, over this long a period, the time resolution of the data is too coarse for us to explore the question of climatic change on the decadal scale. On the other hand, Bergthorson (1962) has reconstructed the decadal mean annual temperature for Iceland over the past 1000 years from the historic records of the duration and extent of sea ice on the Icelandic shore. He calibrated the ice record against the observed climatic data for the past 150 years. A regression equation was derived that provides a decadal temperature plot for the past millennium (see Figure 4). It is sometimes thought that the climate during the period from 1931 to 1960 was a "normal" climatic period; however, Figure 5 puts this recent period into historical perspective. There has been nothing like it in the past 1000 years.

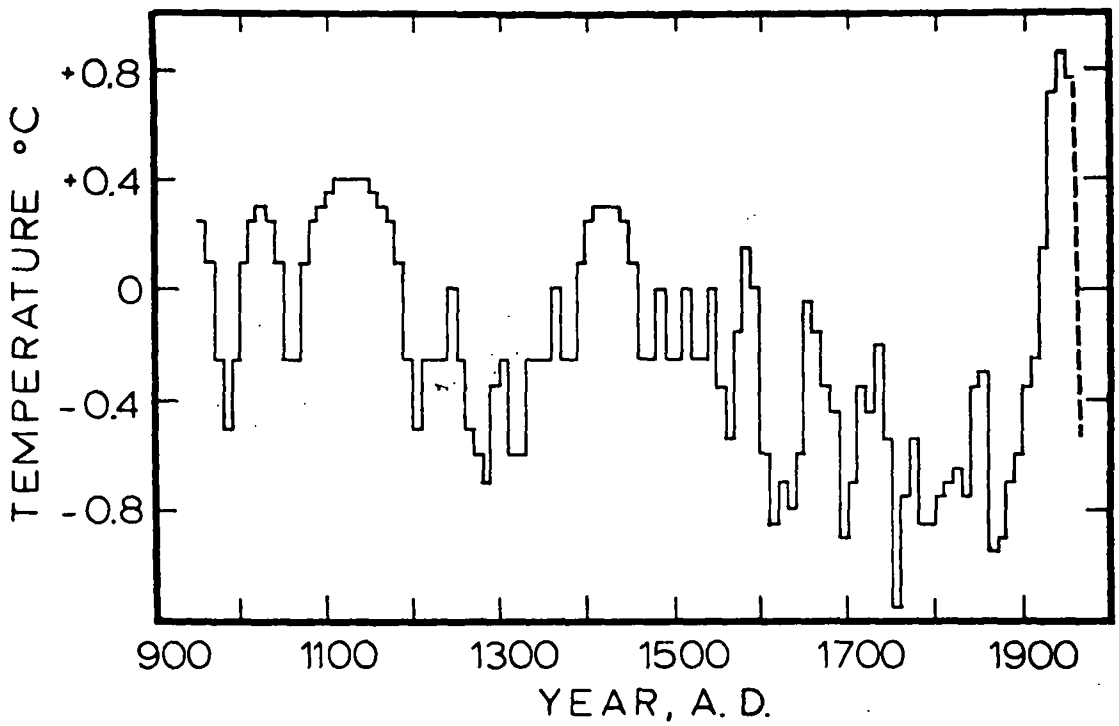

Figure 5. Mean annual temperature in Iceland over the past millennium (after Bergthorson, 1962). The dashed line indicates the rate of temperature decline in the period 1961 to 1971.

B. OTHER INVESTIGATIONS INTO RECENT CLIMATIC CHANGE

Other historical work has been done by Lysgaard (1949). He presented overlapping thirty-year mean temperatures for Copenhagen for the period of 1798 through 1947. Two trends appear to have prevailed: downward by about 0.8°C until the 1860's, then upward by about 1.1°C to 1947. Other local records, such as those at Vienna, Winnipeg, Edinburgh, and Central England, in general, also show the warming trend from the late 1800's to about the middle of the present century. In the last two or three decades, however, the trend seems to have been reversed (Lamb, 1966). This trend reversal, this current cooling trend, is of concern today.

Mitchell (1961) summarized many records from a worldwide array to show that the mean temperature of the earth rose until 1940, then leveled off and started to decline. It appears that the decline has continued to the present time. Of course, not all individual records show the decline, but a rapid cooling appears in the overall average, so that the mean temperature approaches that of a century ago. Thus, from an historical standpoint the recent drop in the earth's mean atmospheric temperature at the surface is quite rapid and quite large, and there are no signs that the trend is abating. The surface temperature of the North Atlantic Ocean has also dropped (Rodewald, 1973).

IV. WHAT CAN MAN DO NOW?

We have estimated that 40% or more of the earth's atmospheric particulate loading is due directly or indirectly to man's activities. Since population growth, mechanization, and industrialization are still under way in large parts of the world, and if we attribute a large portion of the recent increase in atmospheric turbidity to human activities, it appears that there is little that any one nation can do alone to reverse the trend globally. Nevertheless, if the analysis and order of magnitude estimations in this paper are correct, it indicates that we should study the problem much more intensively than we have done to date. Man, even in modern industrial cultures, is too vulnerable to environmental changes to ignore even what may appear at first glance to be trivial problems.

The world community is presently short of resources for the production of energy. If nations find it in their interest to invest heavily in expanding large-scale strip mining operations for coal, phosphate, oil shale or other resources in semi-arid regions. it is quite important that thorough investigations be carried out of the effects of these operations on the future trend of atmospheric particulate loading. Any analysis of the magnitude of the rock handling operations of these large operations, such as the western U.S., oil shale will produce many cubic miles of finely pulverized material. Even a small fraction of this material entering the atmosphere as fugitive dust cannot be ignored.

Changes in mean temperatures, in temperature extremes, in precipitation, in the length of the growing season, or in intensity of sunlight reaching the earth's surface, can lead to widespread modifications in the distributions and survival-patterns of plants and animals. If these changes occur over large or heavily-populated areas, as appears to be happening in Northern Africa, their effects can be enormous, as they affect the global patterns of the non-human biota and the food supply of man.

V. TO BETTER DEFINE THE PROBLEM, WE NEED...

There are a number of areas where further investigation can yield results toward obtaining better estimates of particulate components. A search for other meaningful atmospheric trace constituents that parallel particulate emissions and concentrations should be begun. Known trace constituents should be explored that are indicative of man's activities, such as DDT, and those that are indicative of natural causes in certain geographic areas of the world. It is known that there is DDT concentration of the order of 10-100 ppb within the African dust over Barbados (Risebrough, et al., 1968; Risebrough, 1974). It is known that there is 60 ppm of DDT concentration in the dust from India as it moves out over the Indian Ocean (Goldberg, 1974). An investigation into the use of DDT in these two regions, and the extent of agriculture, may provide one with a handle on the relationship of man-induced and naturally-induced particulates.

Plume and dispersion models for the larger urban regions should be developed to account for the trajectories that cover thousands of kilometers. It is well known that the classical gaussian plume models fail when extrapolated over very large distances, yet these models are still used for description of global dispersions. These models can be enhanced by the use of synoptic weather maps, satellite images and data from various ground based sampling stations. Intense local pollution over urban areas and industrial regions often travels over hundreds and thousands of kilometers downstream without large horizontal dispersion and apparently is carried along isotropic surfaces into the stratosphere. The modeling of large-scale dispersions of plumes into the stratosphere should be carried out.

It is not yet known how often or how quickly the long distance transport of polluted air masses leads to rainy areas. How long does it take for these air masses to reach remote areas, such as Mauna Loa, Hawaii, or Point Barrow, Alaska?

Lettau and Lettau (1964) devised a general expression for the intensity of particulate fallout in the absence of rain based on time variations of beta-activity in surface air, due to worldwide tropospheric distribution of debris from nuclear testings. They estimated that the average residence time of debris in the troposphere to be 65 days if the only cleansing process were dry-fallout. Work along these lines using other trace constituents should be investigated.

It is also critical that the significant injections of stratospheric particulate material by jet aircraft selectively over the U.S.-Atlantic-European Sector be explored with General Circulation Models.

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16. ABSTRACT

The report gives results of a study to determine the effect of aerosols on the earth's climate. There is much evidence that the earth's climate has undergone a wide variety of fluctuations. Over the past hundred millenia, as the earth's surface temperature has decreased, volcanic dust in the atmosphere has increased (and vice versa). The report estimates that at least 40% of today's atmospheric particulate loading is due to man-made or man-accentuated sources. For the past 30 years, although the earth's annual mean temperature has been decreasing, volcanic activity has not been increasing. Carbon dioxide and waste heat production have been increasing, but these processes tend to increase the global temperature rather than to reduce it. Man's production of particulates in the past 30 years has been increasing at a rapid rate. It is estimated that the loading rate of particulates from commercial jet aircraft into the stratosphere, where the residence time is much longer than in the troposphere, is almost half of that due to volcanic activity. The study recommends that studies should be carried out to obtain better data for more meaningful estimates for the sources and sinks of atmospheric particulates.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Heat Transfer	Air Pollution Control	13B, 20M
Aerosols	Jet Aircraft	Global Energy Balance	07D, 01C
Earth Atmosphere		Particulates	04A
Climate			04B
Volcanic Ejecta			08G
Carbon Dioxide			07B

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