Extended Industrial Revolution and Climate Change

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The earth's climate has changed noticeably within man's recorded history and much more dramatically during that longer period whose record we must examine in the geology of earth's crustal rock. To plan an intelligent use of our resources, we must frame our plans in a total environment; and the earth's climate is perhaps the determinant factor in this environment. We must understand how the climate is going to change and whether man's activities can influence climate. It is clear that if our activities are of sufficient scale to cause the climate to deteriorate, then they might also be made to improve it, at least for some minority of the earth's population. Understanding is also important on the part of those whose interest might be restraining such experiments.

Fundamentals of Climate

The fundamental physical processes determining climate have been understood for many years. Any object will tend to cool off by radiating electromagnetic energy at a rate proportional to the fourth power of its absolute temperature. This energy is radiated as discrete quanta (or photons) in a spectrum of wavelengths characteristic of the temperature of the source, peaking at a wavelength that is inversely proportional to that temperature. We see then that a hot object emits energy rapidly, peaked at short wavelengths, while a cool one emits energy slowly, peaked at long wavelengths. Figure 1*a* (adapted from *Robinson* [1970]) shows the spectra from the sun and from the earth. Note that the sun's spectrum is populated well into the ultraviolet (shorter wavelength than the visible spectrum which runs from 0.4 to 0.8 microns) and far into the infrared.

If the earth had no atmosphere, the equilibrium temperature of its surface would be just high enough to radiate away as much heat in infrared radiation as it received in the form of 'insolation' or incoming solar radiation. (We neglect here the small amount of heat reaching the earth's surface from its own interior, namely, 10^{-4} × incoming solar radiation [*Stacey*, 1969].) If the earth had a simple atmosphere of molecules which did not interfere with the insolation, but which absorbed infrared radiation, then this atmosphere would absorb some of the outgoing infrared radiation emitted by the surface of the earth and would warm up. This warm atmosphere would now itself become an infrared radiator, and some of its radiation would be directed toward the surface of the earth. This 'greenhouse effect' would clearly cause the earth's surface temperature to rise.

Our real atmosphere is much more complicated than this. The insolation has the high energy (ultraviolet) end of its spectrum absorbed by oxygen in the upper atmosphere (Figures 1*b* and 1*c*), some of its blue light is diffused by Rayleigh scattering from water molecules and dust particles (making the black sky blue, and the white sun red, Figure 1*d*), and all parts of the insolation spectrum suffer some absorption and reflection by clouds and aerosols. So the real atmosphere presents us with a somewhat reduced and considerably diffused solar beam, and in turn it is warmed both by the direct insolation and by the outgoing infrared from the earth's surface. The most efficient absorber of infrared radiation in the lower atmosphere is water vapor, but CO_2 and O_3 are more important in the upper atmosphere. The lower atmosphere or troposphere is mostly heated by contact with the warm surface of the earth

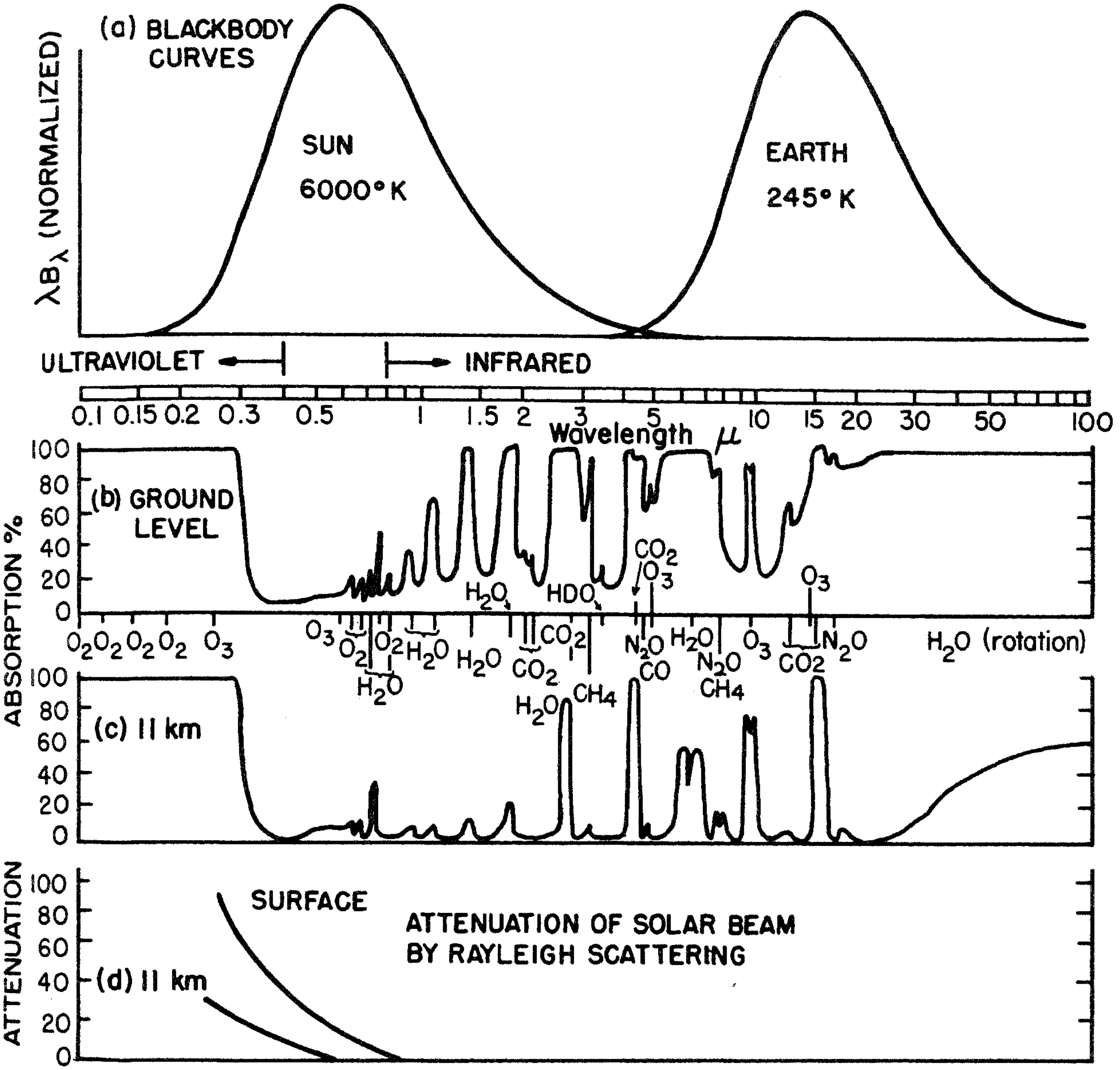

Fig. 1. (a) *Blackbody emission for 6000°K and 245°K, being approximate emission spectra of the sun and earth, respectively (since inward and outward radiation must balance, the curves have been drawn with equal areas—though in fact 40% of solar radiation is reflected unchanged);* (b) *atmospheric absorption spectrum for a solar beam reaching the ground;* (c) *the same for a beam reaching the tropopause in temperate latitudes;* (d) *attenuation of the solar beam by Rayleigh scattering at the ground and at the temperate tropopause.*

and by water vapor condensing in it, the former having been warmed and the latter having been evaporated by the sun's energy.

In the equatorial zone the solar beam comes from directly overhead, causing the earth's surface and the lower atmosphere (troposphere) there to become preferentially heated. The air in the equatorial troposphere expands and tends to spill over at the top, and this poleward motion in the upper troposphere drives the atmospheric circulation. The earth is a spinning globe, and the poleward flow brings the air closer and closer to the axis of rotation. The associated inertial forces (coriolis forces), from the point of view of an observer fixed on the earth's surface, deflect the poleward flow into an almost *totally circumpolar* upper westerly (eastward) flow. (An observer on one of the fixed stars would see that, as the high level air slides poleward from the equator, its rotation speeds up relative to the surface of the earth.) This gives us a tidy (but simplistic) picture of a troposphere whose slow convective rising at the equator and sinking at the poles is superimposed on a much more vigorous upper westerly flow, giving a toroidal activity in both hemispheres.

However, if we have been describing a fairly real atmosphere, we have not been describing a real earth. The real earth is mostly covered with water of sufficient depth that the ocean circulation patterns can themselves be very complicated and take hundreds of years. Irregular patterns of dry land masses rise out of the oceans, and the polar regions are snow covered. The dry land parts reflect less and absorb more of the insolation than does the open sea, and the snow covered parts absorb less and reflect more, with the result that the upper westerly circumpolar 'geostrophic' flow carries the air over regions of vastly different surface temperature. In addition, some of the dry land parts rise out of the sea further than others, and the geostrophic flow must be deflected over and around these mountain barriers. The combination of the perturbations due to the presence of mountains and due to uneven heating are chiefly responsible for the atmospheric circulation being much more complicated that the simple picture drawn above [*Saltzman*, 1968].

The topographical and thermal anomalies on the surface below, together with the effects of the coriolis accelerations due to the earth's rotation, to some extent distract the main geostrophic flow into piling air up in some regions and stretching it out in others. In the near surface 'mixing layer' (where we live), this materializes in the existence of corresponding regions of high and low pressure, respectively. As buoyancy strives to restore uniformity, the high is at the bottom of a sinking column of air and the low is at the bottom of a rising column. The coriolis acceleration forces the divergent flow at the bottom of the high into a slowly expanding anticyclonic (clockwise from the top) vortex, and the confluence at the bottom of the low into a slowly collapsing cyclonic vortex. (Both directions are reversed in the southern hemisphere.) Cyclonic disturbances of this type usually have dimensions of one or two thousand kilometers.

Although the growth of a large-scale vortex or eddy is often intimately connected with a definite location on the surface of the earth below, once formed it will characteristically move off across the earth's surface under the influence of many factors including the upper westerly flow. As it moves across the surface of the land and sea like a giant vacuum cleaner (for example, in the case of a low), it sets up a series of smaller-scale eddies in its wake. These secondary vortices typically have dimensions of the order of hundreds of kilometers (hurricane) down through kilometers (typical thunderstorm dimension) and meters (dust devil). The entire disturbance can move thousands of tons of air containing large amounts of stored energy between regions of different temperatures.

The atmosphere can then be pictured as an enormous heat engine, driven by the sun's energy and 'rejecting' waste heat to interstellar space. The heat source tends to be located near the earth's surface in the equatorial zones, and the sink at the top of the atmosphere. The working fluid is moist air, which transports heat continuously from source to sink, from equator to poles, from bottom to top, while extracting 'useful' work to provide its own kinetic energy. This energy too is eventually dissipated in heating at the earth's surface and also within the atmosphere itself. Therefore both this energy and the 'rejected' heat percolate up to the top of the atmosphere by convection, advection (eddy transport), condensation, and infrared radiation, to be finally radiated into interstellar space. This picture is complicated by coupling to the sea and to the polar ice. The ocean is driven partly by atmospheric 'wind stress' and partly by direct solar heating, but although the times involved in large-scale atmospheric motions are of the order of a few weeks, the deep ocean circulation is known to be complicated and to take hundreds of years. Melting the polar ice would absorb a very large amount of latent energy and would probably require similar or longer times, although *Fletcher* [1969] thinks fluctuations in the extent of antarctic sea ice may have caused changes in the strength of the general circulation on a much shorter time scale. Despite the long times involved, we are very interested because the temperature of the sea is expected to have a considerable effect on the composition of the atmosphere. The extent of polar ice affects the earth's albedo (reflectivity) and hence the amount of solar energy absorbed; it also covers up part of the surface available for air-sea interaction.

If we ignore for the moment possible energy contributions from various human activities and the possibility of variation of solar activity, we see that our climate depends on the details of how energy percolates upward (and poleward) from the earth's surface to the top of the atmosphere. It appears that to understand climate we must understand the detailed behavior of the atmosphere and its interaction with the sea, the land, and the polar ice.

Models of the Atmosphere

The analysis of the above percolation process is called atmospheric dynamics. The basic physical processes are understood and the system can be described by a set of coupled differential equations (some of which are nonlinear), referred to by meteorologists as the 'primitive' equations of atmospheric dynamics. This system of differential equations unfortunately does not fall into that very small, select category that can be solved analytically in closed form, and we are forced to go to their finite difference analogue system and integrate them on a large digital computer.

We immediately get into a practical difficulty since the details of this energy percolation involve important nonlinear coupled processes right down to dimensions of a small storm or a squall line, say of the order of a kilometer, and beyond. Even the largest computers cannot manage a global calculation with this attention to detail. There are two obvious ways around this difficulty, and both involve specification and/or parameterization of part of the problem. By specification we mean fixing, as in specifying the distribution of ocean surface temperatures which are to be subsequently held constant, and by parameterization we mean expressing as a dependent variable through known physical or empirical relations, as in giving the rate of vertical convective energy transport as a function of the temperature lapse rate.

General Circulation Models. The primitive equations are integrated over a large region, often a hemisphere or the whole globe, using a finite differencing scheme with an integration step as small as is practical. For example, the stepping grid might be 200 kilometers square horizontally and the atmosphere might be divided into as many as 18 layers vertically. Such coarse integration stepping does not allow the simulation of the sub-grid scale eddy transport and diffusion phenomena, and these must be parameterized. Investigators (for references see *Smagorinsky* [1969], *Oliger* [1970], *Mintz* [1968]) variously specify or parameterize conditions of humidity, cloud and snow cover, etc. It is also customary to specify the ocean surface temperature distribution, but *Manabe and Bryan* [1969] have recently done some initial numerical experiments with a joint ocean-atmosphere general circulation model. General circulation models use fantastic amounts of computing time and have always saturated the existing generation of computers. There have always been parts of the problem that have clearly warranted more detailed computation, and this has ensured that the most comprehensive model of any given period has required about one day's computer time to integrate one day's weather. This is especially striking when we see that computing speed has increased three orders of magnitude since 1953, and it will have increased a further two orders of magnitude when the ILLIAC IV comes on [*Smagorinsky*, 1969].

Simple models. Typically, a vertical column of atmosphere at midlatitudes is divided into several layers. Both large *and* small scale lateral transport phenomena are, of course, now parameterized or specified, usually as zonal averages, along with cloud and snow cover, humidity, etc. Such models [*Budyko*, 1969; *Sellers*, 1969; *Manabe and Wetherald*, 1967] do, however, have the virtue of computational speed and lend themselves to initial investigations of the effects of various attempts at climate tinkering, such as that of changing the atmospheric content of aerosols and carbon dioxide. At least one investigator (compare *Manabe and Wetherald* [1967] with the subsequent work, *Manabe and Bryan* [1969]) has used a one-dimensional model to try out schemes of parameterization intended for eventual incorporation into a general circulation model. Since their very nature implies a heavy reliance on specification and parameterization, the simple vertical models tend to suppress synergistic effects, and some of their predictions ('all other things being equal') have been rather extravagant. The climate changes they predict will clearly affect the general circulation of the atmosphere, and tend to invalidate their original parameterization of the lateral transport phenomena. The sharpness of the distinction between the seasons may also change, but they ignore seasonal variations entirely.

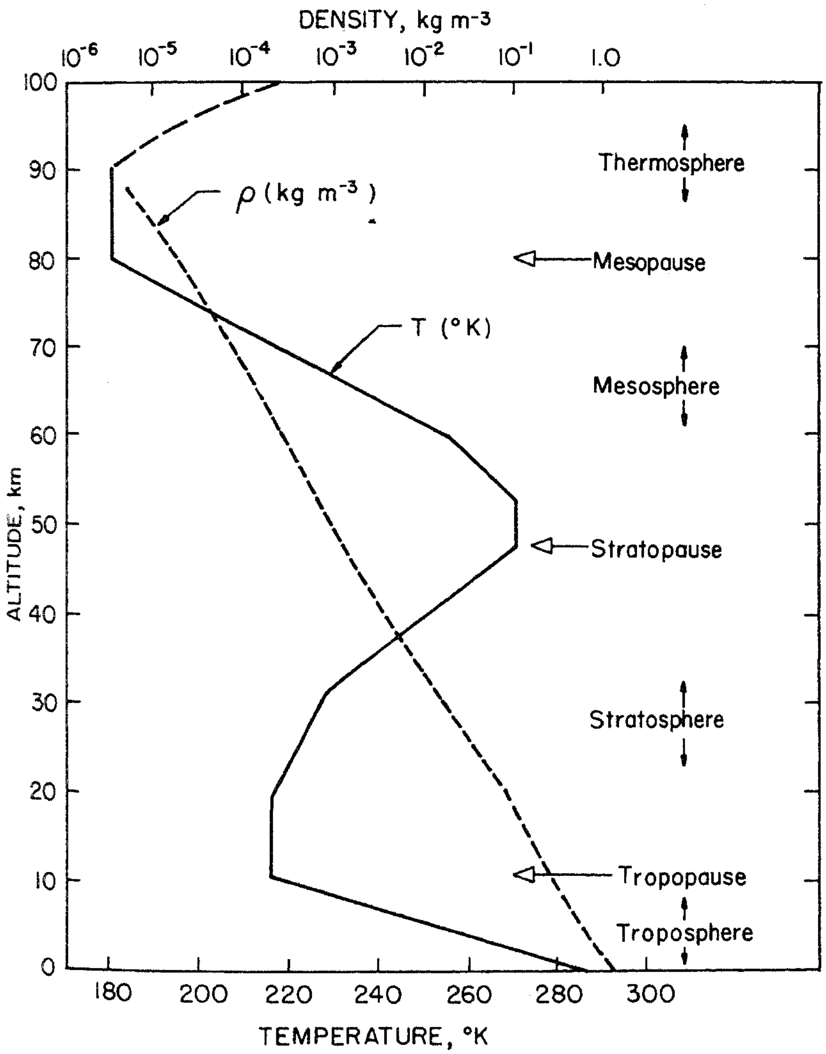

Fig. 2. Temperature and density profile according to the U.S. Standard Atmosphere, 1962, and the IUGG nomenclature, 1960.

Atmospheric Pollutants and Climate Change

Pollution of the troposphere and of the upper atmosphere has been much discussed recently. (Martell, unpublished report, 1970; *Robinson* [1970*b*]; *Kellogg* [1970]). After all the straw men have been introduced and duly knocked down, the following emerge as worth watching: carbon dioxide, aerosols, and stratospheric water vapor; and in a slightly different sense, heat from man's energy conversion. The temperature and density distributions of the atmosphere are given in Figure 2 for reference.

Aerosols. Aerosols are hard to deal with, largely because these small airborne particles have such a variety of sizes, optical properties, and atmospheric residence times. Over most of the size range of interest, they scatter the insolation predominently in the forward direction, and make the atmosphere turbid or hazy. They also tend to scatter some of the light in the backward direction near 180°, and they tend to absorb some of it both on the way down, and again, if reflected from the earth's surface, on the way up. The backscattering tends to reduce the amount of solar energy available to the earth's heat budget, and the absorption tends to warm up the atmospheric layer containing the aerosol. If this layer is high enough, cooling of the near surface environment results, and *Mitchell* [1970*a*] points out that the recent global cooling trends may be caused by the umbrella of fine dust cast into the stratosphere by recent volcanism. *Bryson* [1968] thinks the cooling trend is due to man-generated turbidity, and he cautions against the possibility of triggering another ice age, but a recent calculation by *Mitchell* [1971] shows that typical man-made aerosols in the lower layers of the troposphere lead to net heating of the near-surface environment in most cases. A more detailed discussion with references to the original research is given by *Robinson* [1970*b*]. The residence times of the most noticeable aerosols are short, because of dry fallout and washout, and it seems that natural aerosols from vegetation, dust storms, salt sea spray predominate in regions far from industrial areas.

Water vapor in the stratosphere. The question of increase of water vapor in the stratosphere has arisen during the controversy over the proposed SST, or supersonic transport. Opponents of the program point out that the normal stratospheric water vapor content is very low, essentially because mixing of the troposphere with the stratosphere is weak, and the mixing process requires the water to go through a very cold region (see Figure 2) in which the rising tropospheric air would presumably be dehumidified. It has been estimated that 400 SST's flying 4 flights a day each would introduce 150,000 tons of water vapor to the stratosphere per day or .025% of the total amount naturally present in the altitude range in which the SST's would fly. Since the horizontal large-scale eddy transport processes are well developed in the stratosphere, this water vapor will certainly spread out, and indeed might be fed continously into the tropical tropopause cold trap, and have a relatively short residence time. This is at present a matter of some controversy, and if on the other hand the residence time is very long, it is worth noting that the above rate would lead to doubling in 10 years.

Water vapor in the stratosphere can affect climate mainly in two ways: it can modify the temperature structure of the atmosphere through the greenhouse effect, and it can cause an increase in cloud formation in the lower stratosphere. *Manabe and Wetherald* [1967] estimate that if the water vapor in the whole stratosphere were doubled, the greenhouse effect would raise the temperature of the air near the earth's surface about 0.5° while tending to cool the stratosphere. If the doubling takes place only in the lower 1/6 of the stratosphere, we can expect a smaller effect. The situation with respect to cloud formation is less clear. Nacreous clouds in the lower stratosphere are thought to result from fluctuations of relative humidity giving local saturation. It is feared that their formation may be enhanced and made more general because we propose to add this water vapor from SST's at a time when we are also mixing more and more CO_2 (from our various industrial activities) into the whole atmosphere. The addition of such greenhouse molecules has the effect of raising the temperature of the atmosphere near the earth's surface while *lowering the temperature of the stratosphere* and rendering regions of saturation more widespread [*Newell*, 1970; *Study of Critical Environmental Problems (SCEP)*, p. 104, 1970]. It seems clear that widespread cloudiness in the stratosphere would have its effect on climate , but because of the uncertain optical properties of such clouds, it is difficult to predict what the effect would be [*Manabe*, 1970*a*]. *Note that we have not concluded that there will be no effect, but rather that we do not as yet understand the effect.* This suggests we consider the SST program with more caution, not less.

Carbon dioxide. Carbon dioxide is a necessary product of the combustion of fossil fuels, and although it is considerably heavier than air, atmospheric circulation keeps it well mixed, with the result that its concentration is almost constant throughout the troposphere and stratosphere. It is an infrared absorber and contributes to the earth's radiation balance through the greenhouse effect. Its absorption characteristics are known (cf. Figure 1), and the effect of increasing the atmospheric concentration of CO_2 on the earth's surface temperature has been the subject of several numerical modeling experiments. Our combustion of fossil fuels will probably grow at about 4% per year (doubling every 17.5 years) but fortunately all the CO_2 we produce doesn't remain in the atmosphere. The present atmospheric concentration is 320 ppmv (parts per million by volume). We currently produce about another 2 ppmv each year, of which about 50% remains airborne [*SCEP*,p. 54, 1970]. It seems that on the long term the CO_2 concentration may be fairly well buffered chemically at the interface between the sea and the sea floor sediments, but of course the doubling time quoted is far shorter than the ocean circulation time [*Frisken*, 1970]. On the short term it should be noted that since a gas like CO_2 is less soluble when the water warms up, and since the oceanic reservoir of CO_2 is more than 50 times the atmospheric reservoir [*Plass*, 1959], the CO_2 dissolved in the ocean constitutes a destabilizing mechanism in climate variation. Cautious extrapolation of present trends, in the hope that about 50% of the released CO_2 will continue to disappear, still leads to about 380 ppmv by 2000 A.D. [*SCEP*, p. 54, 1970].

If the diseconomies of possible resultant climate change are not considered, the combustion of fossil fuels is at present the most economical source of energy generally available to man. Even if the developed countries move toward nuclear energy, the developing countries of the world can be expected to embrace fossil fuel combustion enthusiastically within the foreseeable future. Even if zero population growth can be achieved fairly soon, and even if at some later point a satisfactory living standard were to be realized for all, the total energy requirements must still increase slowly on the long term. This is because all the good things become used up, dispersed, less concentrated, less retrievable. For example, even the seams of coal will become small and more difficult to work, since we shall have already burnt up the best ones, and we shall get less net energy per ton because we shall have to use more to dig it up. We must make no mistake about it: we cannot afford to fail to understand the effects of increased atmospheric concentrations of carbon dioxide on our climate, because if it doesn't do much harm, we probably want to increase it at least during the foreseeable future. (Coal-Burning is seen to be distinct from SST operation, for which our need seems less than clear.)

Heat from man's energy conversion. We are concerned here with all the energy converted, not just the part 'rejected' as waste heat into the river, because virtually all the 'useful' part is eventually converted into heat also. Except in the very local problem of thermal pollution of small bodies of water, then, we want the total energy converted. In 1967 this was 5.88×10^9 metric tons of coal equivalent (Joel Darmstadter, Resources for the Future, Inc., personal communication), or corrected to 1971 at 4% increase per year, 5.9×10^{12} watts, continuously. On the other hand, the earth intercepts the solar flux of 2.0 langleys/minute for a total of 1.76×10^{17} watts. Since about 50% of this is absorbed at the earth's surface [*Robinson*, 1970*a*], we are now working at about 1/15,000 of the absorbed solar intensity. It has been argued by some of the model builders that 1% may be a noticeable perturbation, and we will achieve this at our present growth rate of 4% per annum in 130 years. The implication is that if this has no noticeable effect on climate, then 17.5 years later we will have the experimental information for 2% of the present surface absorption of insolation, and so on, until 120 years later our industrial activities reach the 100% level.

Sellers [1969] has estimated that by the time we reach the 5% level we should have experienced global warming by more than 10°C, and eventual melting of the polar ice caps. The resultant climatic regimes would presumably be completely different from those we experience today. As was noted earlier and is discussed more fully below, these estimates are crude and likely to indicate only general tendencies. Response of the climate of the real atmosphere is likely to be more complicated than that of the simple model used by Sellers, and less extreme.

Climatic Change and the Numerical Models

As *Mitchell* [1970*b*] points out, climatic change is a fundamental attribute of climate, which means in the first place that climate is not easy to define, and in the second place that the changes induced by man's activities may initially be very difficult to extract from climate's 'autovariation.' If we want to isolate undesirable effects at an early stage, we will have to augment our observation of the real climate with information from numerical experiments with the best available models.

However, despite the known shortcomings of the one-dimensional models, the general circulation models are, at present, time consuming and expensive to run, and most available predictions of climate change have been made using the simpler models. These calculations have yielded what is, at least at first sight, a disagreement among climatologists as to whether the climate is going to warm up or cool down. On closer examination, however, this disagreement appears to be the recorded part of a sometimes heated dialogue between experts in a rapidly developing field as they try out a new way of parameterizing some part of the problem (such as the effects of moist convection), or as they parameterize a previously specified quantity (such as snow cover). In the same paper in which he made his often quoted 'prediction' that doubling the atmospheric concentration of CO_2 would lead to an increase of 10°C in surface mean temperature, *Möller* [1963] makes an almost never quoted disclaimer to the effect that a 1% increase in general cloudiness in the same model would completely mask this effect. Möller was making a first stab at the following synergism: Concentration of CO_2 is increased, causing increased greenhousing and increased temperature. Increased temperature leads to increased evaporation from the sea, and thus to higher absolute humidity (assuming fixed relative humidity), and since H_2O molecules are even more effective infrared absorbers than CO_2 molecules, the warming trend is reinforced. We can easily see why he wanted to make the disclaimer. The very increase in absolute humidity that reinforced the warming trend through infrared absorption might lead to increased cloudiness (or indeed to increased precipitation and winter snow cover) and thus, through reflection of insolation, to a considerable buffering of the warming trend. This paper is also of interest from another point of view, since it is part of an extended dialogue and was not intended to bear alone the bright spotlight of public interest. In this first step, Möller made the approximation of making the radiation balance at the earth's surface. The next step was made by *Manabe and Wetherald* [1967] using a radiative and convective atmosphere temperature adjustment scheme worked out earlier by *Manabe and Strickler* [1964], which enabled them to more nearly treat the atmosphere as the continuum of infrared luminous fuzz that it is. They found that the same doubling of the CO_2 gave them only a 2.4°C temperature rise, and that this could be masked by a 3% increase in low cloud. *Robinson* [1970*b*] gives a historical survey of the various estimates of the effect of increased carbon dioxide concentration in the atmosphere.

The inherent inability of the simple models to deal with more than one parameter at a time has always limited their utility to that of 'educational toys.' With a system as complex and difficult to understand as the earth's climate, this is a considerable utility, but it should be borne in mind that any tendency toward climate change will have a corresponding tendency to change the general ocean-atmosphere circulation. This means that there would be tendencies toward change in the energy transport processes and also, for example, in the amount of cloud cover. The model meanwhile calculates on, with an inappropriate strength for the energy transport and an inaccurate value for the amount of solar energy available.

General circulation models, on the other hand, typically take hours to follow the simulation of one day's weather, and present indications are that at least in some respects they are not sufficiently sophisticated. For example, although general circulation models can presently follow simulation of humidity up to saturation, they then merely dump this immediately as precipitation. They do not generate and transport cloud cover, nor do they consider the associated change in the albedo. Thus we see that even the generation of computers presently under construction will not allow us to evolve climate for hundreds of years by running a general circulation model, even if we could convince ourselves that a unique climate would emerge from integrating weather. Climatologists have worried about the uniqueness of climate for many years, the haunting vision being that an ice-age climatic regime might be just as consistent with the present solar input, atmospheric composition, etc. as is our present climatic regime. *Lorenz* [1968] has worried about this from a mathematical point of view, concerning himself with the 'transitivity' of regions of solution of sets of coupled differential equations, and *Mitchell* [1970*b*] has considered the implications for defining climate and detecting its possible changes.

Some scientists feel it will be possible to get a working understanding of the long-term effects of our activities on climate by varying the input conditions of surface and atmospheric albedo, concentration of infrared absorbing molecules in the atmsophere, level of solar activity, etc. to the general circulation model and merely integrating until (hopefully) the initial transients die away. Smagorinsky (personal communication) and *Mitchell* [1970*b*] suggest that when a comprehensive set of such limited experiments have 'spanned parameter space,' we will finally begin to get some real understanding of what climate changes we can expect to actually take place rather than what the initial tendencies will be caused by a particular facet of man's industrial activities.

The model to be used for this activity should probably be an improved version for a joint ocean-atmosphere general circulation model, but some realistic way of generating and transporting cloud cover must be built into the model before its results will be generally accepted. Computing time will be a problem, as always, but the new ILLIAC IV [*McIntyre*, 1970] should help, particularly when the new intercomputer communication network being designed by the Advanced Research Projects Administration becomes available for routine use by the research community [*Roberts and Wessler*, 1970].

Open Questions and the Future

We are left with some uncertainty on the short term (say, the next 50 years) as to whether carbon dioxide and the greenhouse effect will raise the temperature significantly, or whether increased atmospheric turbidity due to man-made (or caused) aerosols will lower it significantly. There is a possibility that, since the doubling times are presently different, first the former and then the latter will occur [*Mitchell*, 1970*a*]. There is uncertainty about the effect of water vapor from SST's in the stratosphere. There is even the possibility that climate may not be a unique function of the boundary conditions, and that 'the flutter of a butterfly's wings' could trigger a large change from a warm climate to an ice age, for instance, or of course to a much hotter era than the present one. It is worth noting that we have been fluttering fairly hard, and remain uncertain whether we can detect our effect on the climate.

On the longer term (say, more than 100 years) we have the more serious problem of beginning to warm the climate directly with our own energy conversion. This will be with us (in slightly different degree at any one time) whether we derive our energy from coal fires, nuclear reactors, or from imaginary fusion generators. A bare earth (having no atmosphere or oceans) at a uniform temperature of 0°C would have to increase its temperature by approximately 50°C in order to double the rate at which it radiates heat away. We are interested in this number because if we continue to double our energy conversion rate every 17.5 years, in about 250 years it will equal the rate at which we absorb solar radiation at the earth's surface at the present time. A bare earth is ridiculously simple model, and our real earth with ocean and atmosphere would behave in a much more complicated way, but it is hard to see how it would not warm up considerably.

At the present there is apparently a little time to grapple with these problems. We need to conduct some fundamental research into the function of the land and the sea as reservoirs of atmospheric constituents, especially infrared absorbing molecules like carbon dioxide. We need to know what are the precise conditions that lead to cloud formation. We must monitor the effects of various kinds of clouds and aerosol hazes on scattering and absorption of solar radiation and infrared terrestrial radiation. We need to monitor the behavior of the ocean-atmosphere system carefully, watching for secular trends in temperature distribution, in the strength of circulation, in precipitation patterns, and in the concentrations of carbon dioxide, water vapor, and general cloudiness.

We must improve our general understanding of climate behavior through the performance of numerical experiments with climate models. The general circulation models are too time consuming to allow experiments in evolution of climate over extended periods of time, and they are also known to be much too naive in their present forms. The naivite is due in part to the considerable approximations made in the interests of computation speed, and in part to real gaps in the detailed understanding of the basic physical processes involved. New development in computer technology like ILLIAC IV will help with the speed problem, but, although it is clear that an improved general circulation model will yield a superior ten-day forecast, it still does not seem possible that several hundred years of climate can be evolved by integrating weather in 10-minute steps.

The most promising direction would seem to be the development of hybrid models that couple the improved general circulation model with a simpler hydrostatic model. In this sort of scheme the general circulation routine is given realistic input conditions and is made to generate a consistent set of climate statistics complete with appropriate values of parameters such as lateral energy transport, surface albedo, amount and type of cloud cover. Using these values the hydrostatic model takes over and evolves climate for an extended period of say six months, taking into account increased atmospheric concentration of carbon dioxide, increased energy consumption in industrial activities, etc. The ball is then passed back to the general circulation routine, which updates the various parameterizations before the simpler hydrostatic routine is allowed to take the next giant step forward. In this proposal, the spectre of intransitivity rears its ugly head. There is no defense, except to suggest that operation of the hybrid model be tried with a variety of similar initial conditions and rates of introduction of pollutants in the hope that wildly different final states were not generated.

The next generation of predictions of climate change will probably be less spectacular than those we now have from the simpler models, but on the other hand, they will be much more credible and therefore much more compelling. It is clear that if the industrial revolution continues at the present rate, it is only a question of time until man's activities begin to change the earth's climate. We must try to understand the limits this imposes upon us and act accordingly.

Acknowledgments

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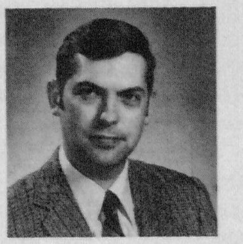

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The Environmental Context

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Secure as we may feel in the conviction that a better understanding of the physical universe in which we live, and a deeper knowledge of the processes of plant and animal life in that universe, have the potential for improving rather than degrading the lot of mankind, not all of our fellow beings share this belief. One of our challenges during the balance of this century is to demonstrate that in their pure and applied forms the physical sciences, the life sciences, and the social sciences–properly developed and orchestrated in the services of mankind–do constitute forces for good rather than evil. We must endeavor to bring these disciplines together, to extend and to strengthen our knowledge, and to perfect the use of that knowledge in the service of mankind.

If that purpose is to be achieved, we must be sensitively conscious of the larger context within which we go about our tasks. We can cast that context within the framework of time over which the earth has evolved and the opportunity and problem that recently evolving knowledge has thrust into prominence.

It is useful to recall that our Spaceship Earth was launched nearly five billion years ago. A primitive form of living organism made its appearance a little more than three billion years ago, and the first signs of animal life go back about half a billion years. The nature and form of life was determined to a large extent by an environment that was evolving in response to an array of natural forces, including those arising from the presence of life itself. Most species sought, with varying degrees of success, to adapt to their environment and to live in harmony with it. The reign of the dinosaurs began 200 million years ago and lasted for 140 million years. The age of mammals began 60 million years ago. Human life seems to have appeared within the past three million years. What has come to be designated as modern man emerged as the delicately balanced product of the human species and its environment less than 50 thousand years ago.

As a footnote to this telescoped account of man and his environment, it may be noted that the prospects appear to be good that the natural environment of Spaceship Earth *should* be capable of sustaining human life for at least another ten million years. We should keep this time scale in mind as we go about either conscious or inadvertent modifications of ecosystems. One of the questions we must ask ourselves is: Can man, who has characteristically had hundreds of thousands of years to adapt biologically to a sharply changed physical environment, and hundreds of years to adapt to new social environments, respond to the kind of environmental changes that can now take place over a period of a few decades? What could–or should –we do to prevent these changes from being traumatic?

Several notable developments that have a bearing on the human environment have taken place during the last couple of centuries:

- In the first place, our comparatively recently acquired ability to manipulate matter and energy has lifted the constraints imposed by the physical limitations of the human muscle to perform work.

- In the second place, the constraints imposed by the limitations of the human mind to perceive, to receive, to store, to utilize, and to retrieve information have been shattered by very recent advances in sensing systems, communications technology, and computer capabil-

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