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WHAT IF INCREASES IN ATMOSPHERIC CO_2 HAVE AN *INVERSE* GREENHOUSE EFFECT? I. ENERGY BALANCE CONSIDERATIONS RELATED TO SURFACE ALBEDO

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ABSTRACT

An analysis of northern, low and southern latitude temperature trends of the past century, along with available atmospheric CO_2 concentration and industrial carbon production data, suggests that the true climatic effect of increasing the CO_2 content of the atmosphere may be to cool the Earth and not warm it, contrary to most past analyses of this phenomenon. A physical mechanism is thus proposed to explain how CO_2 may act as an *inverse* greenhouse gas in Earth's atmosphere. However, a negative feedback mechanism related to a lowering of the planet's mean surface albedo, due to the migration of more mesic-adapted vegetation onto arid and semi-arid lands as a result of the increased water use efficiency which most plants experience under high levels of atmospheric CO_2, acts to counter this inverse greenhouse effect. Quantitative estimates of the magnitudes of both phenomena are made, and it is shown that they are probably compensatory. This finding suggests that we will not suffer any great climatic catastrophe but will instead reap great agricultural benefits from the rapid increase in atmospheric CO_2 which we are currently experiencing and which is projected to continue for perhaps another century or two into the future.

KEY WORDS Arctic haze Climatic change Carbon dioxide Dimeric water vapour Greenhouse effect Surface energy balance Planetary albedo

INTRODUCTION

Since the dawning of the Industrial Revolution, there has been a gradual but inexorable increase in the CO_2 content of Earth's atmosphere with each passing year, due primarily to the burning of fossil fuels such as coal, gas and oil. Starting from an initial value estimated to be somewhere in the range of 260 to 290 ppm (parts per million), the mean annual value of the global CO_2 concentration has now surpassed 340 ppm and appears to be rising at an ever accelerating rate (Bolin *et al.*, 1979; Keeling, 1982).

Well over a century ago, Tyndall (1861) described how this phenomenon could significantly raise the mean surface air temperature of the planet by means of a thermal blanketing process that has come to be called the 'greenhouse effect'. His ideas were subsequently embellished over the years by a number of other investigators, including Arrhenius (1896), Chamberlin (1897, 1898, 1899), Callendar (1938, 1949, 1961) and Plass (1956, 1961), until today there are probably hundreds of articles produced on the subject every year (Clark, 1982).

The explosive interest which the greenhouse effect of atmospheric CO_2 has generated both within and without the scientific community has in recent years led the U.S. National Academy of Sciences to produce several reports designed to distill its salient features and arrive at a consensus evaluation of the most likely effects of enhanced atmospheric CO_2 on surface air temperature and, hence, agriculture (National Research Council, 1979, 1982). The latest effort of this group suggests that for a nominal doubling of the atmospheric CO_2 content from 300 to 600 ppm, the mean surface air temperature of the

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globe would increase by about 2 to 4°C. They additionally conclude that the warming in polar regions, particularly the Arctic, would be several times greater, and that the ultimate results would be devastating to agriculture.

If the U.S. National Academy of Sciences is correct in its assessment of the magnitude of the greenhouse effect of CO_2, it is indeed possible that agriculture could suffer significantly, although there is by no means universal agreement on this point (Wittwer, 1980; Rosenberg, 1982). However, substantial dissenting arguments against the establishment viewpoint on the climatic effects of enhanced atmospheric CO_2 have been presented in recent years by Newell and Dopplick (1979, 1981) and Idso (1980a,b, 1981a–e, 1982a,b,c), who contend that the predicted global warming has been over-estimated by a full order of magnitude. If these latter investigators are correct, agriculture faces no problems whatsoever. Indeed, the studies of Kimball (1982, 1983) and Kimball and Idso (1983) indicate that, for a CO_2 concentration doubling from 300 to 600 ppm, there will probably be a 33 per cent increase in global agricultural productivity along with a similar percentage decrease in vegetative transpiration; and the beneficient implications of the consequent doubling of plant water use efficiency are truly mind-boggling (Wittwer, 1982).

In the waning months of 1982, however, an even more complicating factor was introduced into the ongoing debate over these issues by the serious suggestion of Idso (1982d) that enhanced concentrations of atmospheric CO_2 may actually tend to cool the Earth instead of warm it.

The chief impetus for this suggestion comes from an examination of real-world carbon dioxide and temperature data. In Figure 1, for instance, we see that the increasing concentration of CO_2 in the atmosphere has closely followed the increasing trend of its primary precursor—the rate of production of industrial CO_2 carbon—over the entire quarter century for which continuous high-quality atmospheric CO_2 measurements are available. Assuming that this same relationship has applied over the entire 100-year time span, it can be seen that the past century has been characterized by two distinctly different eras of atmospheric CO_2 increase: a period of gradual, linear increase lasting until about 1945 and a period of rapid, exponential increase subsequent to that time. Thus, it is logical to expect that, if enhanced concentrations of atmospheric CO_2 do indeed have an effect on surface air temperature, that

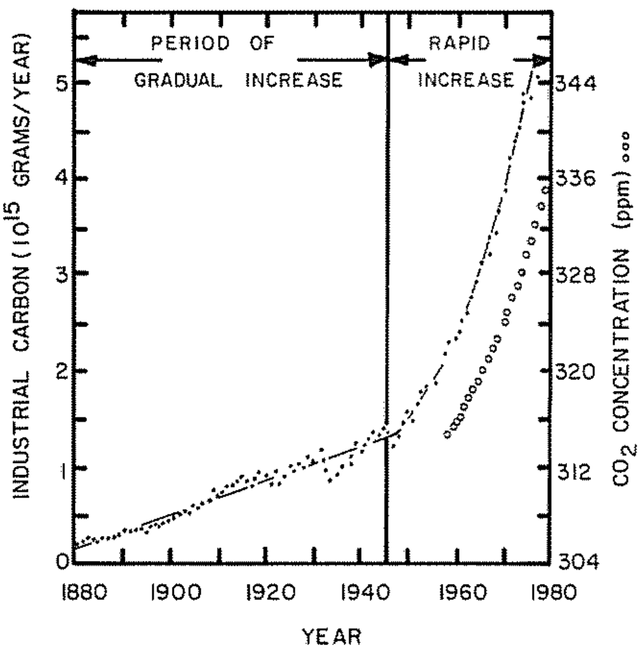

Figure 1. The global rate of production of industrial CO_2-carbon (from fuel production data of the United Nations) and the mean global atmospheric CO_2 concentration (from measurements at Mauna Loa, Hawaii and the South Pole) as functions of time. Adapted from Keeling (1982)

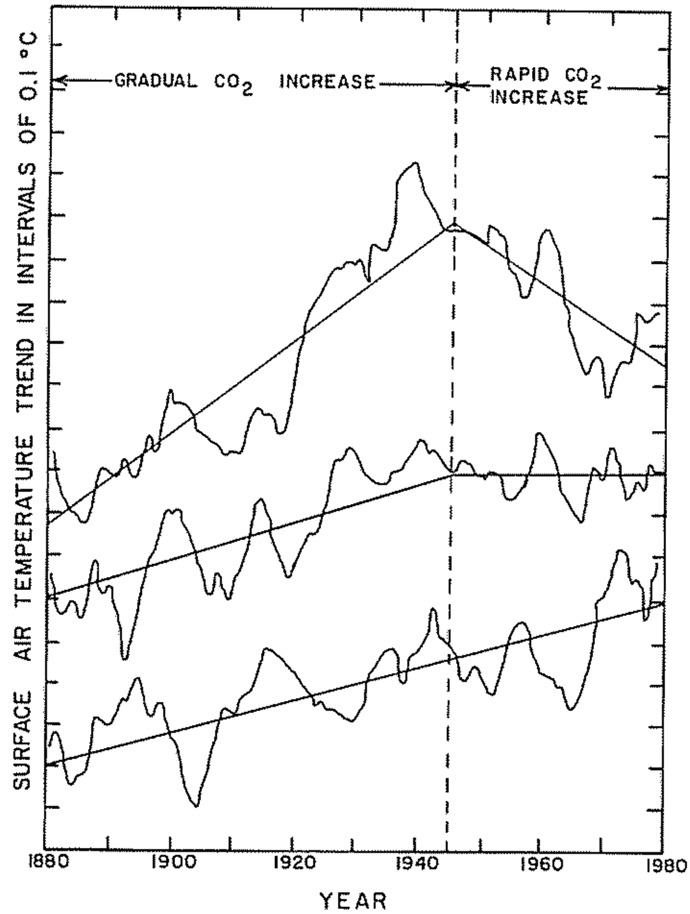

Figure 2. Observed trends of mean surface air temperature for: top—northern latitudes (90°N–23·6°N), middle—low latitudes (23·6°N–23·6°S), and bottom—southern latitudes (23·6°S–90°S), as reported by Hansen *et al.* (1981). I have added the straight lines, drawn by eye, to depict general trends before and after the pivotal year of 1945

effect may manifest itself as a change in global or subglobal temperature trends at that approximate time.

In seeking evidence for such an expression of CO_2 effects on climate, the data of Figure 2 are most useful for several reasons. First, they cover the same 100-year time span as the industrial CO_2 carbon production data of Figure 1. Secondly, they are of good quality and are in no way biased to portray cooling, as they were developed by a group of scientists intent on trying to substantiate predictions of a significant CO_2-induced warming (Hansen *et al.*, 1981). Thirdly, they pertain primarily to land surfaces, where CO_2 effects can be expected to be manifest without the ten to twenty year time lag induced by the large thermal inertia of the oceans (Paltridge and Woodruff, 1981; Fletcher *et al.*, 1982). And fourthly, they are divided into the three categories of northern, low and southern latitudes, where CO_2 effects are predicted to be greatest, less, and possibly least, respectively (Flohn, 1981; Revelle, 1982).

So what do the data tell us? In the case of southern latitudes, where CO_2 effects are expected to be small, we see that that portion of the planet has been under the influence of a consistent warming tendency throughout the entire century of record. But since virtually everyone who has studied the problem in detail admits that the global warming prior to 1945 could not have been due to CO_2, there is no reason to attribute the continuation of this trend beyond 1945 to it. Thus, the cause of the steady, century-long warming trend in southern latitudes remains unidentified.

In the case of low latitudes, however, it is evident that the pervasive global warming began to be counterbalanced by some other factor in the vicinity of 1945, so that temperatures there have remained essentially constant since that time; and in the case of northern latitudes, where CO_2 effects are universally predicted to be several times greater than anywhere else on the face of the globe, the initial warming has been completely reversed, with a dramatic cooling established in its place—commencing again at about 1945. The only logical conclusion to be drawn from these observations would seem to be that the significant acceleration in the rate of build-up of atmospheric CO_2 which began about that time is the cause of the observed changes in temperature trend, although, of course, there is no way of absolutely proving that supposition.

Nevertheless, there are other impressive empirical observations which lend credence to this conclusion. For one thing, Kukla and Gavin's (1981) satellite study of sea ice coverage in southern latitudes clearly shows continued warming, whereas Dewey and Heim's (1981) satellite study of snow cover in northern latitudes shows dramatic cooling. Not only has the areal extent of snow coverage there increased dramatically over the period 1966 to 1980, but, as they report, 'there has also been a trend toward earlier, more extensive snow cover in the fall and slower ablation in the spring'.

This finding is in complete harmony with the predictions of the one model of CO_2 effects on climate that considers in detail the role of enhanced atmospheric CO_2 concentrations in reducing the short-wave energy from the sun that is available for absorption at snow and ice surfaces (Choudhury and Kukla, 1979). Indeed, in that study it was shown that this interaction would 'contribute to an extension of snow and ice seasons . . . marked by delayed snowmelt in spring, and early snow deposition in autumn'—precisely what Dewey and Heim documented to be occurring fully two years later.

Since these observations are exactly the opposite of what the U.S. National Academy of Sciences suggests should be the result of a CO_2-induced warming (National Research Council, 1982), there is consequently no alternative but to seriously explore the possibility that the true effect of enhanced concentrations of atmospheric CO_2 may actually be to cool the Earth and not warm it. But what atmospheric properties or processes could possibly cause CO_2 to act as an *inverse* greenhouse gas?

A MECHANISM FOR AN INVERSE CO_2 GREENHOUSE EFFECT

Consider what has always been my primary complaint about the computer models, i.e. that they are not basically wrong, but that they do not incorporate all of the relevant processes which occur in the real world (Idso, 1983a, 1984). Recently, Kiehl and Ramanathan (1982) investigated one such process which had never before been included in any model study of CO_2 effects on climate. This process was the radiative participation of the so-called continuum absorption of water vapour, which I had previously linked with the equilibrium concentration of water dimers in the atmosphere and had shown to be the chief determinant of atmospheric window thermal emission variability (Idso, 1981b,c, 1983b).

Figure 3 shows the results and ramifications of the inclusion of this *one* previously omitted process. Whereas originally, and up until the work of Kiehl and Ramanathan, a doubling of the atmospheric CO_2 concentration had been calculated to increase the flux of thermal radiation to the surface of the earth by about 1·5–1·6 Wm^{-2}, the new calculations indicate that, between latitudes 23·6°S and 23·6°N, this flux is now a full order of magnitude less.

The significance of this reduction in the thermal blanketing capacity of CO_2 is further highlighted by comparing it with the reduction in the flux of solar radiation to the Earth's surface which is also calculated to accompany a doubling of the atmospheric CO_2 content (Newell and Dopplick, 1979). Over the 40 per cent of the Earth's surface located between latitudes 23·6°N and 23·6°S, it can be seen that the increase in thermal radiation to the Earth's surface is not sufficient to offset the reduction in solar radiation experienced there, for a net *inverse* greenhouse effect. Indeed, one must move poleward of 40°N and 40°S, covering fully 65 per cent of the Earth's surface, before the integrals of the two opposing effects become equivalent.

Let us next consider a phenomenon which is currently being investigated by a multinational team of scientists from the United States, Canada, Norway and Sweden, i.e. Arctic haze. Although there were

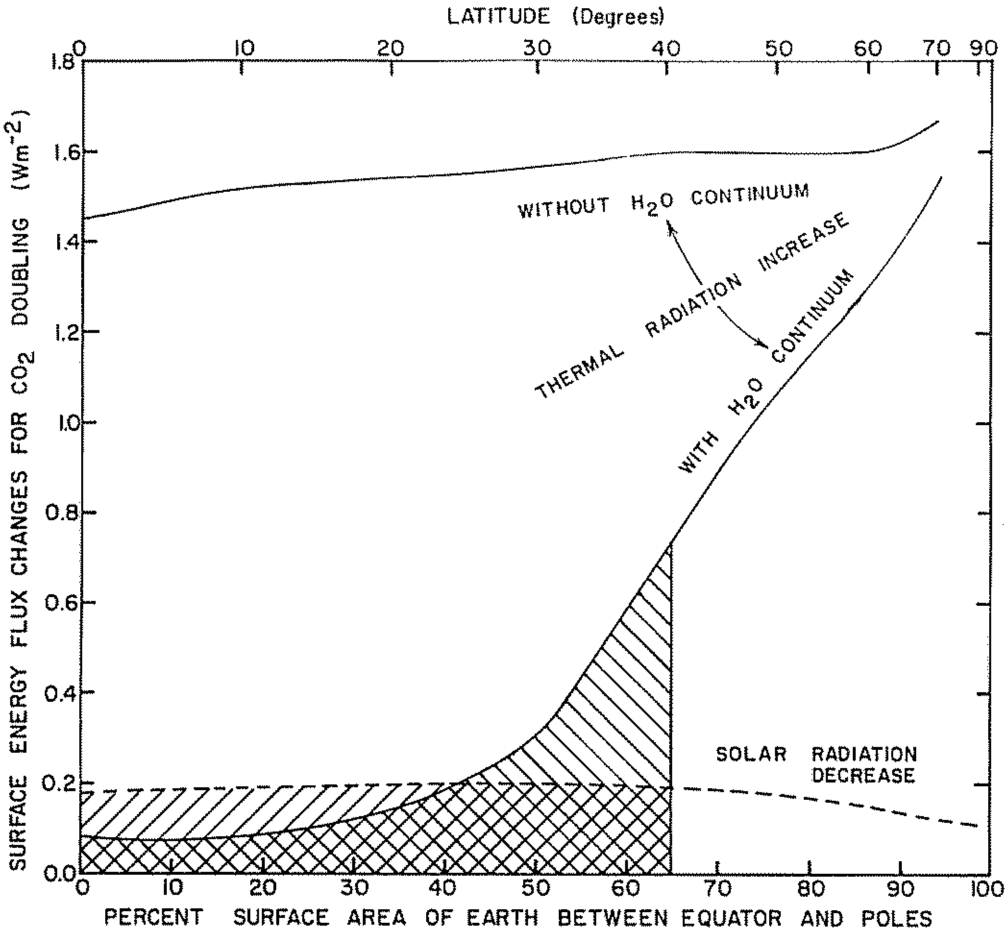

Figure 3. Calculated changes in fluxes of solar and thermal radiation to the surface of the Earth for a doubling of the atmospheric CO_2 concentration as functions of latitude and percent surface area of the Earth between the equator and the poles

no reports of haze in the Arctic before 1950, it has probably existed for decades; and there is good reason to believe that it has built up gradually ever since the inception of the Industrial Revolution (Hileman, 1983). Composed of sooty, particulate pollution advected into the Arctic from Northern Hemispheric industrial activity, Arctic haze begins to appear in late autumn and peaks in March and April to play a major role in the region's winter and spring weather—but just how major a role we are only just now beginning to appreciate.

For instance, in spring 1983, when scientists first flew into the haze for intensive study, they noted (Hileman, 1983) that 'the pollution was not only thick, but amazingly thick'. Indeed, they found it to persist continuously up to 10,000 feet (over 3000 m) and to occur in layers above that to at least 28,000 feet (over 8500 m), which was as high as their plane could fly. Additionally, they found that the haze completely covered the Arctic ice cap with a characteristic dimension of about 3000 miles (almost 5000 km), shrouding a region comparable in size to the entire North American continent.

What are the climatic effects of such a mass of particulate pollution? Although it reduces the flux of solar radiation to the Earth's surface (reductions as great as 10 per cent were recorded in the studies in spring 1983), such particulates also increase the downward flux of thermal radiation. And in a number of studies of similar particulate pollution of the air at Phoenix, Arizona and elsewhere (Idso, 1972, 1974, 1976, 1980c, 1981d,e; Idso and Brazel, 1977, 1978a,b), which I have carried out over the past dozen or so years, I have invariably found that on a climatological basis (averaged over entire 24-hour periods), the increase in thermal radiation to the Earth's surface has always been greater than the reduction in solar radiation. Two studies of special note in this regard were one time when a thick tropospheric dust suspension hung in the air all day long and essentially saturated the entire thermal spectrum (Idso, 1973), and another time when the pollution was so thin that it did not reduce the incoming solar radiation by any detectable amount, although it increased the flux of thermal radiation to the ground by over 10 per cent (Idso, 1975). Years of field experience of this nature lead me to believe that the Arctic haze will not be found to be any different in these respects, and that it thus acts as an effective 'greenhouse gas' itself.

If this is so, and considering the great extent, thickness and persistence of the phenomenon, Arctic haze should have exerted a strong greenhouse effect in northern latitudes over the past century, which probably well before now attained a capacity in this region, more than equivalent to that of dimeric water vapour in low latidudes, to pre-empt the greenhouse properties of CO_2. Consequently, over more than 80 per cent of the globe (from at least 40°S to 90°N), CO_2 should now act as an *inverse* greenhouse gas.

The temperature data of Figure 2 present strong evidence for the validity of this hypothesis. We see that initially the temperature of the entire globe was increasing (for some unspecified reason), but that the temperatures of northern latitudes were increasing at a rate almost 2·5 times greater than the common rate of low and southern latitudes. This greater rate of temperature rise in northern latitudes is postulated to be the response of that region to the increasing greenhouse properties of Arctic haze. Then, at about 1945, when CO_2 began to dramatically increase, its *inverse* greenhouse properties began to be felt. Low latitudes ceased warming, as CO_2 began to counter the influence (unspecified) which allowed the warming of southern latitudes to continue unabated; while northern latitudes began to dramatically cool, as Choudhury and Kukla (1979) have shown should occur in that region in the absence of a CO_2-induced thermal blanketing effect.

A FEEDBACK MECHANISM TO INHIBIT CO_2-INDUCED COOLING

In my recent book which points out the inadequacies of the U.S. National Academy of Sciences' approach to the CO_2-climate question and where I first presented the detailed evidence for the likelihood of an inverse CO_2 greenhouse effect, I also stressed the great beneficial effects of enhanced concentrations of atmospheric CO_2 on agriculture and suggested that the current upward trend in atmospheric CO_2 was a phenomenon to be encouraged and not suppressed (Idso, 1982d). However, if the cooling effect of enhanced atmospheric CO_2 is as great as that suggested by the data in Figures 1 and 2, humanity could be in just as much danger due to dramatic global cooling as the National Academy of Sciences suggests we may experience due to their predicted warming. But just as the Academy's ultimate climate-trend prediction derives primarily not from the direct effects of CO_2 but rather from various feedback mechanisms which greatly amplify its supposed initial positive perturbation, so it can be shown that there are important negative feedbacks which should operate to inhibit any global cooling trend which CO_2 may tend to produce.

Consider, for instance, the findings of Kimball (1982, 1983) and Kimball and Idso (1983). They show that for a CO_2 concentration doubling from 300 to 600 ppm, plant productivity will increase and transpiration decrease by such amounts what the water use efficiencies of most plants could well double. This vastly increased capacity for survival implies that plants the world over will be able to successfully migrate into regions of much greater aridity where they are at present unable to grow and reproduce (see Idso and Quinn (1983) for a case study of Arizona and New Mexico). Owing to increasing pressures of population growth in developing countries, this natural transition will additionally be augmented by the bringing into production of lands not now suitable for agriculture (Wittwer, 1982). As a result, great areas of the globe that previously reflected a high percentage of the solar radiation incident upon them, due to the high albedos of their barren soil and sand, will in the future reflect considerably less solar radiation, as a result of their being covered by various types and densities of vegetation of lower albedo.

In addition, not only will the vegetation of desert fringes migrate beyond its current bounds, forest areas too will increase for the same reason. Indeed, there will be a general tendency the world over for vegetation zones of all types to shift, with the net result that as grasses encroach upon the deserts at one extreme, forests will encroach upon grasslands at the other. And, as is pointed out in the following section, forests absorb much more solar radiation than do grasslands.

The ultimate consequence of this enhanced capture of solar radiation at the Earth's surface should be a significant tendency for global warming. Indeed, Hummel and Reck (1979) note that many general circulation models of the atmosphere typically show a 1°C rise in surface air temperature for a 0·01 decrease in surface albedo, whereas Sagan *et al.* (1979) contend that such an albedo decrease should raise surface air temperature by about 2°C. The primary question to be answered in the analysis of this effect, then, is how great a change in the mean global albedo of the Earth may be expected for a doubling of the atmospheric CO_2 content, due to the proliferation of vegetation over presently unvegetated or sparsely vegetated arid and semi-arid lands and the replacement of short vegetation such as grasses by taller vegetation such as trees.

GLOBAL ALBEDO REDUCTION DUE TO VEGETATIVE PROLIFERATION

Over the years there have been many attempts to characterize the mean global albedo of the Earth's surface, but the most comprehensive study published to date is probably that of Hummel and Reck (1979). They arrived at their final answer (0·154) by dividing the globe into 77,040 separate sections and then assigning each area one of 49 different land type (and, hence, albedo) classifications for each quarter of the year. Predating them by two years, however, was an even more useful study for the purposes of the present analysis. This earlier paper was an investigation by Otterman (1977) into the possible effects of man's impact on surface albedo over the past 6000 years. He, in turn, was building upon the work of Flohn (1975), who calculated a mean global albedo of 0·134 by dividing the Earth into but five surface types: open and ice-covered oceans, open and ice-covered land, and snow. Otterman pointed out that the albedo value used by Flohn for open land (0·12) was much too low for the arid and semi-arid land areas of the globe which account for a third of this category (Amiran, 1966). Based upon field measurements of Otterman *et al.* (1975) and Otterman and Fraser (1976), as well as laboratory measurements of Hovis (1966) and Gates (1970), he thus changed the albedo value of one-third of the open land area from 0·12 to 0·42, which then led to a mean global albedo of 0·154, exactly the same number which Hummel and Reck (1979) obtained from their much more detailed analysis two years later.

Now the primary purpose of Otterman's study was to investigate the effects of anthropogenic pressures arising from overgrazing of arid and semi-arid lands by cattle, sheep, goats and camels. Based upon both satellite and ground-based measurements, he concluded that such activities could raise the surface albedo of these areas from a value of about 0·22 to 0·42, and, hence, that their cessation could thus return the albedo of such land from 0·42 to 0·22. Indeed, Otterman cites several experiments which verify this point, as do Sagan *et al.* (1979). Thus, making this adjustment in his calculation of the mean global albedo, he then obtained a value of 0·141, which he suggested may have been characteristic of the Earth about 6000 years ago when such anthropogenic pressures were negligible.

In the light of Otterman's analysis, let us consider what could happen with a doubling of the Earth's atmospheric CO_2 concentration that will significantly increase plant water use efficiency, possibly even doubling it. For one thing, the Earth's arid and semi-arid lands would be dramatically transformed by an advancing wave of vegetation characteristic of more mesic conditions. And since merely reducing grazing pressure has been demonstrated to bring back a vegetative cover sufficient to reduce the surface albedo of these areas from 0·42 to 0·22, it is highly likely that the CO_2-induced proliferation of vegetation would do at least as well, if not better, leading to a reduction in mean global albedo of at least 0·013, obtained by subtracting 0·141 from 0·154. What is more, the resultant lower albedo would probably be capable of being maintained indefinitely, even in the face of significant grazing pressure; for

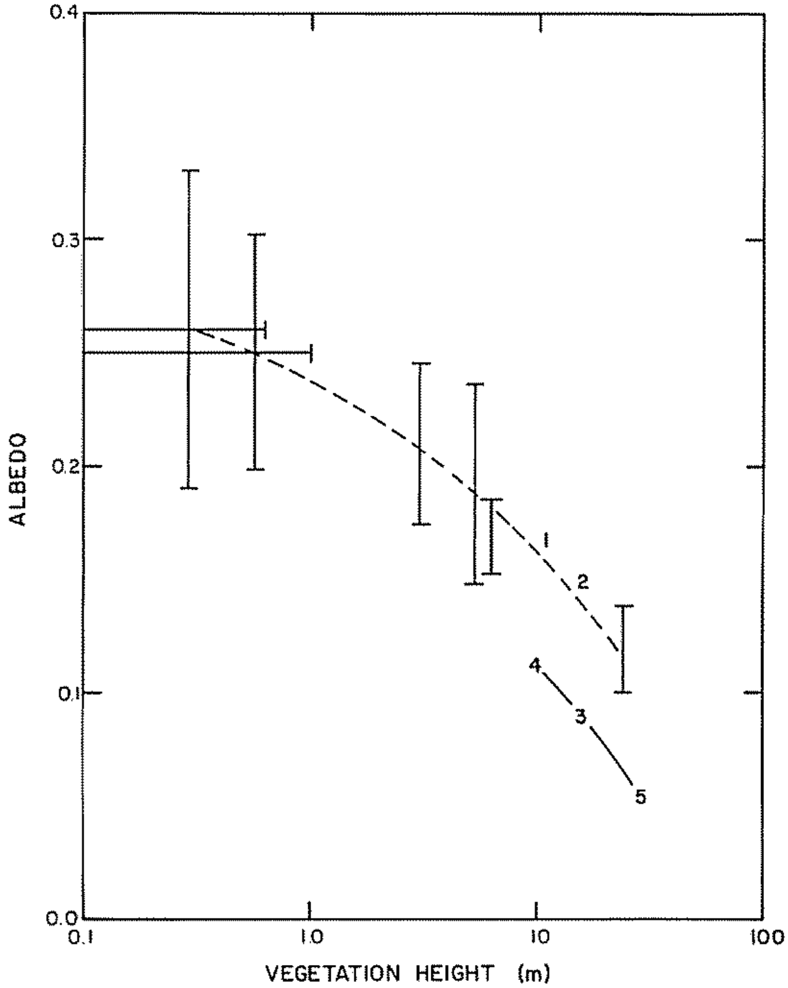

Figure 4. Surface albedo as a function of vegetation height. Bar data and dashed line from Standhill (1970). Points 1 and 2 attributed to Federer (1968) and Grulois (1968) by Stanhill. New points 3, 4 and 5 from Stewart (1971) for Scots and Corsican pine, from Pinker *et al.* (1980) for a tropical evergreen forest, and from Tajchman (1971) for a Norway spruce forest, respectively

Howard (1971) has found that grazing of more mesic vegetation does not necessarily lead to albedo increases, and in some cases it actually produces a further slight decrease.

Consider next the experimentally derived relationship between albedo and vegetation height depicted in Figure 4. It indicates that in going from grassland to forest the mean surface albedo is essentially halved, dropping from about 0·25 to about 0·12. Thus, if we merely assume that forests would replace an area of grassland equivalent to the area of desert replaced by grassland, there would be an additional mean global albedo reduction of 0·008, obtained as (0·25 − 0·12)/(0·42 − 0·22) × (0·154 − 0·141).

As a reasonable first-order approximation, then, we may conclude that a doubling of the Earth's atmospheric CO_2 concentration will lead to about a 0·02 reduction in the planet's mean surface albedo, as obtained from the sum of the two decreases calculated above: 0·013 + 0·008.

COMPARISON OF WARMING AND COOLING TENDENCIES

As indicated earlier, Hummel and Reck (1979) note that a 0·01 drop in the mean surface albedo of the Earth is predicted by many general circulation models of the atmosphere to lead to a global mean surface air temperature increase of about 1°C, whereas Sagan *et al.* (1979) suggest an increase of 2°C for a 0·01 albedo drop. For lack of any good criterion to judge between these two estimates, I will adopt their mean in what follows. Thus, for a doubling of the Earth's atmospheric CO_2 content that is estimated above to reduce the mean global albedo by about 0·02, we may expect a mean surface air temperature increase of about 3°C, obtained as (0·02) (1·5°C/0·01). How does this warming tendency compare with the direct cooling tendency of CO_2 described in the Introduction?

To begin with, we note that the 30 per cent of the Earth's surface represented by the southern latitude data set of Figure 2 shows no cooling whatsoever. For the 40 per cent of the Earth's surface represented by the low latitude data set, however, we may postulate a cooling tendency of equivalent absolute magnitude to the natural warming tendency of southern latitudes, in order to obtain the cancellation of effects needed to reproduce the observed steady temperature trend of low latitudes since 1945. This cooling tendency is evaluated over the period 1945 to 1980 from the data of Figures 1 and 2 to be about −0·135°C/26 ppm or −0·0052°C/ppm CO_2. For the final 30 per cent of the Earth's surface represented by the northern latitude data set, we similarly calculate a cooling tendency of −0·0280°C/ppm CO_2, composed of a −0·0149°C/ppm CO_2 component required to cancel the extension of the warming tendency that existed there prior to 1945 and a −0·0131°C/ppm CO_2 component required to produce the cooling trend observed since that time.

The mean global cooling tendency of enhanced atmospheric CO_2 is thus calculated to be 0·30 (0·0000°C/ppm CO_2) + 0·40 (−0·0052°C/ppm CO_2) + 0·30 (−0·0280°C/ppm CO_2) or about −0·010°C/ppm CO_2. Thus, for a doubling of the CO_2 content of the atmosphere from 300 to 600 ppm, we may expect a direct CO_2-induced cooling of about 3°C, obtained as (300 ppm) (−0·010°C/ppm).

CONCLUDING DISCUSSION

Although it must be acknowledged there is probably considerable uncertainty associated with the analyses that led to both the warming and cooling tendency evaluations of the preceding section, the identical absolute values of the two evaluations indicates that there is probably no significant net effect. This observation engenders confidence in the thermoregulatory powers of the planet to maintain its surface air temperature within the same range of variability it has experienced over the past several centuries. And that is good news for agriculture, for it means that we will probably reap the great positive benefits of increased productivity and water use efficiency that come from enhanced atmospheric CO_2 without fear of a catastrophic climatic change.

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