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CARBON DIOXIDE AND ENVIRONMENT

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Abstract

There are six major impacts of rising CO_2: on climate, on natural ecosystems, on agriculture (and the supporting technology), on continental and oceanic ice conditions, and on the stability of the desert margin. A rise of sea-level is also probable, but major effects are likely to be deferred for a few centuries. Several uncertainties remain in the budget of the carbon cycle. Of these, the suggestion that the temperate and boreal forests act as a major sink for atmospheric carbon is queried, based on recent studies in Canada. The impact on agriculture is examined. Benefits as well as losses may result from CO_2 increase. These need to be foreseen, so that useful adaptation can be worked towards. Other economic impacts may include altered power consumption, northern navigation and perhaps forest yield. Analysis of overall ecosystem impact continues to be difficult. The CO_2 effect should remain high on the scientific agenda, so that governments may have the chance of preparing for the consequences.

Introduction

The rapid increase in the atmospheric reservoir of carbon dioxide (CO_2) is one of the dramatic realities of our times. Equivalent today to over 720 gigatonnes (Gt) of carbon, the reservoir is increasing at almost 3 Gt per annum (*), or about 0.4 per cent per annum. Since carbon dioxide is a raw material for photosynthesis and a radiatively significant gas, this increase has major implications for climatologists and biologists. It also

(*) 3 gigatonnes (10^{12} kilograms) per annum.

implies important economic effects, which are as yet imperfectly specified. I shall speak mainly from the perspective of impacts due to climate change, but shall try to identify interactions in other domains; an interdisciplinary approach is needed in dealing with this issue. Elsewhere Revelle will address the primary characteristics of the carbon dioxide effect. I shall hence lay most emphasis on higher order problems. My outlook is influenced by the fact that I come from a northern country, as my treatment will show.

In broad outline, the following appear likely to be the six main consequences of the increase:

(i) the direct impact of CO_2 increase (and of associated infrared absorbers such as nitrous oxide, N_2O, methane, CH_4 and various synthetic pollutants) on climate is expected to be large, exceeding anything observed in the whole course of civilization;

(ii) indirect potential effects on natural ecosystems may include possible fertilization of plant growth, altered soil moisture and structural effects, and, in general, disequilibria in many aspects of ecosystem dynamics;

(iii) major challenges will be posed to farmers, pastoralists, foresters and agricultural scientists as the result of altered climate and soil conditions, especially along the dry and cold margins of agriculture;

(iv) other economic changes will include altered water régimes, domestic and industrial energy budgets, and probably fish catches;

(v) big changes are most likely in high latitudes, most notably drastic alterations in river, lake and sea ice conditions, and hence ease of navigation. Permafrost, snowcover and the tundra ecosystems will also be affected;

(vi) along desert margins the increased heat-stress and increase in potential evapotranspiration imply a worsening of desertification, already critical in many populated areas.

There is already in progress a rise of sea-level (see Revelle's chapter) due to glacial melting and the warming and hence expansion of the ocean water column. The rise over the past century is believed to be about 15 cm, with some uncertainty. A further rise of 70-100 cm is probable in the next century from the same processes. Much larger rises are possible over the next few centuries if the effect persists. In this paper emphasis is placed on the next century, and the sea-level rise is hence not stressed, though its effects may well be serious in estuarine, deltaic and floodplain environments.

Whether any or all of these things happen depends crucially on the reality of the predicted temperature change. For doubled CO_2, possible in the latter half of the 21st century, and with some allowance for the rôle of other infrared absorbers, an increase in equilibrium mean annual surface temperatures of from 2° to 3° C is likely in lower latitudes, with sharply higher values (4° to 8° C) possible in higher northern latitudes. These changes may be retarded by the heat capacity of the intermediate layers of the ocean, possibly by two to three decades (the so-called *transient effect*). There are sceptics who go further, and maintain that the ocean must warm first, because the so-called CO_2 effect depends mainly on the associated increase in water vapour shielding. These dissenting opinions are well covered in recent reviews, and will be disregarded here (Clark, 1982; N.A.S., 1982). But one must keep in mind that air-ocean interactions may well be the key to this problem, and that present generation models incorporate them only crudely.

It is my intention to stress two aspects of the problem that are of special interest in middle and high latitudes. These are (i) the possible rôle of the biota in these zones as a sink for CO_2; and (ii) the economic impacts special to such latitudes, because of their importance to the world economy.

Some Major Uncertainties

Carbon moves between the following reservoirs at rates that are variously understood:

(i) a large but almost balanced flow occurs between living terrestrial biota and the atmosphere, where both photosynthetic absorption and respiratory release of carbon exceed 50 Gt a^{-1}, and may exceed 70 Gt a^{-1}. A recent conservative estimate of phytomass on land is 560 ± 100 Gt C (Olson, 1982), which implies an exchange between land vegetation and atmosphere about every ten years;

(ii) very large but unbalanced exchanges take place between atmosphere and ocean surface layers, coupled with some flux of carbon into the intermediate waters. These exchanges have been extensively modelled by a SCOPE project (Bolin, 1981) and others. A net downward flux is agreed, but its precise size and geographic distribution remain unspecified;

(iii) losses of carbon to the atmosphere arise from the oxidation of litter and soil humus (whose total storage of carbon is now usually estimated as close to 1,500 Gt) due to forest clearance and more intensive land use;

(iv) net transfers of carbon occur in streamflow to the continental shelf; and

(v) a well-monitored flux of 5 to 6 Gt a^{-1} C from fossil fuel burning is added annually to the atmosphere.

Major efforts have been made to sharpen this sketch of the global carbon cycle. In part such work consists of quantitative system modelling (e.g., Bolin, 1981), where the chief gains derive from the need to grasp and quantify the nature of the various exchange processes. For the rest, the effort is directed primarily towards actual measurement of the fluxes, or of reservoir content (e.g., Woodwell *et al.*, 1978; Ajtay *et al.*, 1979; Olson, 1982).

In this short space I can discuss only one of the uncertainties in the balance. This concerns the phytomass-soil-atmosphere exchange. Most recent estimates imply that clearance of tropical forests for agriculture or pasture, together with deterioration of tropical dryland ecosystems, have produced a large transfer of carbon. Olson (1982) gives a net transfer of 1.6 ± 1 Gt C per annum to the atmosphere from this source. Myers (1980) prefers a substantially larger figure. Olson and others have suggested, however, that temperate and boreal forests may actually accumulate carbon. A recent modelling exercise by Higuchi (1982) suggests that the magnitude of this sink may be about 2 Gt per annum. If this is true, then it may justify the belief of some ocean scientists that a net transfer *to* the biota *from* the atmosphere is essential to a balanced cycle.

For several years various Canadian groups, my own among them, have been trying to quantify the capacity of the sub-arctic — the Boreal forest biome — to remove carbon from the atmosphere. There is little sign of any increase in standing biomass. If anything the forest industries are cutting more trees than regrowth can replace. But the soils and wetlands of the Boreal biome can and do absorb carbon, and then retain it under poorly aerated conditions that inhibit oxidation.

Table I summarizes the estimated level of storage, and of annual accumulation rates, in Canada (Boville *et al.*, 1982). The data refer to dead organic carbon. They do not include living biomass, nor the litter of forest soils. Since the Wisconsin glaciers (i.e. the final Pleistocene ice sheets) covered all Canada (except for small areas in the Yukon), it can be assumed that all the carbon shown in Table I has accumulated in post-glacial (i.e., Holocene) times. The following points can be made:

(i) total net post-glacial withdrawals from the atmosphere in wet-

TABLE I - *Summary results of Non-living Organic Carbon Reservoirs and Rates of Change* (excluding crops and major forest areas).

	Area × (100 km)^2	Error estimate	Organic Carbon Gt	Error estimate
Major Bogs	85	> ±15	85	> ±20
Shallow Peatlands	20		10	
Other Organic Soils	145	±45	35	factor 2
Accumulation Rate	14 M tonnes per year			range 8 - 20
Lakes	80	±10	50	factor 2
Accumulation Rate	6 M tonnes per year			range 3 - 10

After Boville, Kwizak and Davies (1982)

lands, organic soils and lakes amount to 180 Gt of carbon (within a factor of 2), equivalent to a quarter of present atmospheric content;

(ii) withdrawals were slow in early Holocene times, especially in wetlands and organic soils. Most rapid accumulation appears to have been about 5,000 B.P. in all reservoirs, but rates remained high throughout the late Holocene;

(iii) present day annual withdrawals amount to 14×10^6 t per annum on land, and 6×10^6 t per annum on lakes, or a total of 20×10^6 t per annum, again with large potential error.

Canada has about 36 per cent of the world peat area, and at least 50 per cent of the lake surfaces within the Boreal and Arctic biomes. If the figures of Table I are weighted with these areas, on the assumption that conditions have been similar in Eurasia it can be estimated that world post-glacial carbon accumulation in high latitude bogs, peats, soils and lakes may have been close to 500 Gt, equivalent to 70 per cent of present atmospheric storage. Present annual rates of withdrawal may be close to 80×10^6 t a^{-1} ($\sim$ 0.1 Gt per annum).

This last figure is far short of what Higuchi's model estimate calls for ($\sim$ 2 Gt per annum). Nevertheless, if sustained it would be fully capable of yielding the 500 Gt of storage during post-glacial time. Moreover, withdrawals from other reservoirs must have been considerable. To the 500 Gt of dead organic carbon must be added a figure for the living biomass and litter now occupying the formerly glaciated areas. We do not yet have a Canadian estimate for this addition, but other studies (e.g., Pollard, 1982, citing Armentano and Hatt, 1979, in Canada, 1982) suggest that on a world basis it exceeds 50 Gt. Atmospheric increases since late Wisconsin times have been about 250 Gt. The post-glacial millennia have thus seen transfers of order 800 Gt into the atmosphere and into Boreal terrestrial storage.

The uncertainties in these estimates are very great. Large disparities exist between the figures adopted by the groups studying the overall carbon cycle (e.g., Olson, 1982; Rodin and Bazilevich, 1967; Woodwell, 1978). Anyone who works on carbon storage at once comes up against the immense complexity and heterogeneity of the biotic, edaphic and oceanic reservoirs. Only the atmosphere is reasonably well-mixed, and yields fairly firm answers when monitored.

Impacts on Agriculture

Revelle has spoken of the plant fertilizing effect, at least on the C-3 photosynthesizers, of rising ambient CO_2 levels. This favourable impact, inferred largely from laboratory experiments, may be enhanced by the fact (Wittwer, 1980) that some plants use water more efficiently at high CO_2 concentrations. Hence it is easy to conclude that rising CO_2 may raise agricultural productivity.

It is likely, however, that the main impact on agriculture will be via the induced climatic changes. Two obvious effects have been widely discussed:

(i) several major modelling exercises suggest that rising CO_2 concentrations may induce lower soil moisture availability in mid-latitude cereal growing areas (e.g., Manabe and Stouffer, 1980. See also Kellogg and Schware, 1981).

(ii) most such exercises predict a rise of summer temperatures of order 2° to 4° C during the growing season, and a lengthening of the latter by several weeks at either end (in middle and high latitude areas).

These predictions have caused much concern in North America. Sharp decreases of corn and wheat yield from the major granaries of the mid-west and Great Plains (Abrahamson, 1983) have been seen as a likely outcome, because these crops are already grown at temperatures above their optima, and because the maintenance of adequate soil moisture is already a problem. On the drier Great Plains, corn cultivation is dependent on irrigation from the Ogallala aquifer, whose water is being rapidly depleted. A reversion to ranching, low-yield dry (rainfed) farming, or possibly land abandonment has been predicted for these areas, even without the CO_2 effect.

The summer of 1983 provided a rehearsal for the potential doubled CO_2 effect. Temperature was above normal and precipitation below normal on scales not unlike those predicted by models of the doubled CO_2 effect, or of conditions typical of mid-twenty-first century if other absorbers are included. In 1983 corn yields were halved (by reference to the previous crop year). About half this reduction was probably due to the hostile climate. Winter wheat was adversely affected in some areas, but escaped the worst effects of the summer drought, because of early harvesting dates. Spring wheat was badly affected in many areas. Thus a natural rehearsal of future events appeared to confirm the pessimistic estimates of the Abrahamson forum.

In Canada (and by inference Scandinavia and the Soviet Union) these concerns appear in a different light. Our agriculture is circumscribed by the short, cool growing season. Rises of temperature imply for us the possibility of a more diverse, productive and profitable system of cropping. We are, of course, worried about the possibility of reduced soil-water availability — and in many areas a switch to an irrigated system is not possible. Nevertheless we foresee gains.

I recently calculated that in my home province of Ontario growing degree days may increase by 10 to 25 per cent by 2050 AD, with a net increase in the growing season of five to seven weeks (Hare, 1982). This would allow the penetration of typical corn belt agriculture into southern areas of Ontario. On the Canadian Prairies, now dominated by spring wheat-barley-oilseeds cultivation, winter wheat might become the dominant crop. These gains would, however, be lost if rainfall failed to make up for the increased water demands that are implied.

Projected temperature and precipitation changes for the tropical countries are more worrisome. Though some model calculations predict strengthened summer monsoonal circulations over Africa, Asia and Australasia, and hence enhanced rainfall in the areas covered, there is as yet no reliable prediction of specific regional changes. What is certain is that a rise of temperature of 2° to 3° C year-round is the last thing that tropical agriculture and pastoralism need; the absence of strong seasonal changes means that the entire annual temperature curve is lifted by this amount. The deterioration of the tropical drylands, already a grim reality, may well accelerate (Hare, 1983).

How will such changes affect world issues, and how can they be coped with? The world's food system is already stressed, more by disparity of income and increase in human numbers than by adverse climate. The major implication of the above sketch is that some countries may gain from the impending changes, but many will lose. Fundamental strategic issues will arise. Africa, already facing intolerable losses of productivity from protracted drought, is unlikely to be rescued from the decline in food supply experienced in the past two decades. South America — especially north-eastern Brazil — faces some of the same problems.

Over the largely self-sufficient countries in the humid tropics and sub-tropics, the CO_2 issue hangs as a cloud of uncertainty. There are many regions where a small rise in rainfall — predicted by some models — might greatly improve the prospects for agriculture. There are others — notably the great alluvial deltas of the east — where the small rises in sea-level predicted from the CO_2 effect (70-100 cm in the next century) might imperil precious land. And for food-importing countries everywhere lies the possibility that the productivity of the major exporting granary — inland North America — may be significantly reduced. No-one can doubt the seriousness of the strategic issues.

Yet it is a mistake to assume, as many have done, that an adverse outcome is inevitable. Western agriculture, at least, is highly adaptable, and is supported by first rate science and technology. The big crop losses of 1983 in the U.S. came because the heat and drought were unpredicted. If such climate became the norm, a variety of responses would be possible:

(i) New crops, or new genetic varieties of existing crops, might be introduced. This process already has a long record of success.

(ii) Altered field-techniques and farm calendars (dates of seeding, harvesting, *et cetera*) might make possible better use of available soil water.

(iii) Extension of irrigation might be possible in some areas.

It is highly improbable that the western farmer, confronted with a slow shift towards warmer, dryer conditions, would sit back and allow the changes to bankrupt him. Instead he would respond in one or more of these ways. On the agricultural map of the world the integrated response would appear both as a change in characteristics of the major agricultural regions (such as the U.S.S.R. and North American spring wheat belts), and also as a migration of the region following the climate. In Canada, for example, the climates of the Prairies and south-western Ontario *after* the CO_2 warming would be similar to those *now* experienced in parts of the U.S. mid-west and Great Plains, where profitable agriculture is already practiced. In other words there is already experience of future climates — in other places. And years like 1983 give us a useful foretaste of what may happen.

Nevertheless there are limits to adaptation. Over the Canadian Prairies, and in Soviet Asia, for example, a northward migration of spring wheat cultivation may be difficult or impossible, because of adverse soil conditions. In fact there will everywhere be a protracted delay in bringing climate, soil and vegetation into a new equilibrium. The resulting misfit may have adverse economic consequences in many places.

Nor can one simply dismiss the problems of the desert margin. Africa is at this moment in the grip of widespread drought that has compounded the problems of over-population and bad land use so widespread in tbe continent (WMO, 1983). It is conceivable that a CO_2 enriched atmosphere will ultimately bring more adequate rainfall to the savannah and semi-arid lands that sustain so much of the continent's burgeoning population. But the trend of rainfall in the past fifteen years has been downward over most of the continent. There is little sign that nature is about to come to the aid of the faltering national economies of the world's most distressed continent.

The domain of agriculture is undoubtedly where the CO_2 effects will be most dramatic. If they are not negative, it will be necessary to foresee them, and to plan world wide responses. This calls for major efforts by scientists, economists and engineers on the technical side, and for political foresight. I am much surer of the former than of the latter.

Other Economic Impacts

I cannot deal in detail with the many other impacts of CO_2 increase on the economy. They are very numerous. In Canada, for example, we have thought extensively about these possibilities:

(i) Rising air temperatures will lessen space-heating costs, and increase air conditioning costs. Calculations suggest that by 2050 winter space-heating costs in Ontario might, with strong economic growth, be decreased by 15 to 30 per cent, and that this would exceed air conditioning increases

(Hare, 1982). The reverse will hold in the United States, where peak loads already come in summer to meet this latter need.

(ii) Also by 2050 it is conceivable that ice will cease to impede winter navigation on the Great Lakes and St. Lawrence River, one of the world's great waterways. Little ice formed in the winter of 1982-83, when temperatures were about 3 °C above normal.

(iii) By the same date there should be a marked improvement in summer ice conditions in Hudson's Bay and Strait, and in the complex channels of the Arctic Archipelago. A similar improvement can be foreseen along the Siberian coast (benefiting the U.S.S.R.'s Northern Sea Route) and in the Beaufort Sea, where submarine oil exploration is now under way.

(iv) Northern forests should show some improvement in yield per unit area, as CO_2 fertilization and rise of soil temperatures encourage tree growth. On the other hand forest fire losses, already high in warm, dry summers, would become even more significant — as might insect infestation.

These and other considerations make it difficult for Canadians to take a wholly pessimistic view of the potential CO_2 impact. As a major trading nation, however, Canada depends crucially on the health of the world economy. Hence the overall CO_2 impact on her welfare — and that on the northern countries — may well be determined by what happens elsewhere. More than any other issue the CO_2 effect is truly global in character. Every country should at this moment be preparing a check-list of possible consequences for itself and its trading partners. And world organizations should prepare for constructive action, when the reality of the effect is firmly established, which should happen quite soon, almost certainly within the next two decades.

Ecosystem Impact

Though one can consider the effect of CO_2 increase on individual plants, animals and human beings, it is next to impossible to say anything meaningful about the effect on entire ecosystems. This is because it is hard to express in functional terms the present relations between ecosystem composition, function and dynamics and either CO_2 levels or the existing climate. By pure chance I happened to be present when Tansley first used the term "ecosystem". In the ensuing half-century I have seen it become a household word, and the central notion in the theory of the human environment. Yet it is an elusive idea, and one that is hard to fit in to the methodology of research. The interdisciplinary teams who laboured during the International Biological Programme to unravel the structure of sample ecosystems did so essentially by analyses, *inter alia*, of the carbon and energy exchanges within the systems, including that between vegetation and atmosphere. Highly successful analyses were made in my own country, for example, of the tundra and grassland biomes. But neither of these analyses answers the question: what would doubled CO_2 concentration do to the functions revealed?

Instead one must still grope towards qualitative, spatial coincidences. The forest and tundra biomes of Canada coincide fairly well with certain climatic distributions. The southern limit of the boreal coniferous forest is close to a specific isoline of net radiant energy input from Alaska to Newfoundland. The arctic treeline is close to a specific isotherm for mean daily July temperature. These climatic isolines will be shifted northwards by 150 to 400 km at equilibrium with doubled CO_2. Will the vegetation follow them? There is scattered evidence that the dryer, warmer conditions of early mid-Holocene times did indeed see northward shifts of individual species, and that temperatures were then about as much above present levels as one would infer from the vegetational shifts. Closer than this one cannot go. The science of linking climatic variation to ecosystem structure, function and dynamics is still in a primitive state.

Elsewhere (Hare, 1976) I have pointed out, for example, the fallacy of assuming that the displaced Boreal forest of late Wisconsin times ($\sim$ 18,000 B.P.) had a bioclimate like that of the modern forest. The temperature régime *may* have been a close analogue, but the radiation climate could not have been similar. And there is evidence that the specific composition of the forest was different.

The pessimism of these remarks needs qualification. Many attempts are in progress to prove them wrong. There are several large modelling exercises under way aimed at answering the question: how will CO_2 change alter ecosystems? I am supportive of such work, but still doubtful that reliable answers are just around the corner. It is one thing to work out the system whereby carbon, energy and materials cycle through existing ecosystems. It is another and more formidable thing to work out all the first and second derivatives — the rates of change, and of accelerated change, that will follow the imposed change of CO_2.

Conclusions

In common with many colleagues elsewhere, I regard the rise of CO_2 concentration as a central environmental question of our day. It transcends in importance the acid rain issue now so predominant in Europe and North America. It is a truly global issue on two grounds: first, that the atmosphere carries added CO_2 to every part of the globe within a year or two; and second, because CO_2 concentration touches on life itself, and on the central life-support systems.

In this review I have stressed the many uncertainties that persist. Most notably we are far from understanding how the biota interacts with the atmosphere as a functioning community. We are very unsure of the transfers of carbon between air and biota, as we are of the transfers and transformations of carbon within the ocean (as Revelle has stressed). Standing out in contrast is the upward march of atmospheric CO_2, which is firmly established. Increasingly there is also consensus as to the climatic change that may flow from the increase. Presumably one can also rely on the estimate of fossil fuel consumption, though the future course of this consumption is uncertain.

I have suggested that the economic consequences of the CO_2 increase will be complex and many-sided. There will be economic gains for some countries, most probably those of the north. Others will lose. There is a threat to the productivity of the world's most important source of grain exports, inland North America. There is also a hazard, in my judgement, for the arid zone, and for the deltaic and flood plain cultivators of the eastern countries. It is nevertheless misleading to see the CO_2 issue as an unmitigated threat to human well-being. It also a challenge to ingenuity.

This issue must be kept very high on the agenda of the scientific community. The Pontifical Academy of Sciences is to be congratulated on recognizing this before our arrival in Rome. It is also vital that the world political system prepare for what may be a huge strategic issue within a few decades. This is a potential environmental crisis that science has, for once, foreseen. If that foresight is confirmed by events, there will still be time for the nations and their international institutions to work for solutions.

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DISCUSSION

REVELLE

I am part of a team with Professor Hare, and we are going to try to put on a joint act. So it might be a good idea to postpone the discussion until after his turn and then we will have a kind of dialogue between us.

One thing we did not say much about is how long this effect is going to last. Estimates are that we are going to have a warm world for at least 1000 years after it warms up. CO_2 will eventually get into the ocean; that will take a very long time and it depends on overturning this thing which we might call the time constant of the circulation of the deep water. It is probably of the order of 500 to 1000 years, so that the maximum warming will be at the time carbon dioxide reaches its maximum value. There will be a slow decline after that for many centuries.

MARINI-BETTÒLO

I believe that you have pointed out one of the most important points, and that is the equilibrium between CO_2 and the water of the oceans. That is the main thing out of the photosynthesis by chlorophyll. Oceans should therefore be protected against excessive oil spills and other contaminants because although they can metabolize hydrocarbons, in some areas the formation of layers of hydrocarbons can make more difficult the interchange between the atmospheric CO_2 and the surface waters.

REVELLE

I guess it is clear that the equilibration with the ocean will delay predicted warming, we do not know by how many decades. It is also true that, as you say, the interchange between the surface layers of the ocean and the atmosphere in some way determines the CO_2 content of the atmosphere, that is quite right. We have a very good illustration of that in the analyses of the ice cores. The carbon dioxide content of the air has risen fairly rapidly in the last 100 years, and before that it was more or lesse constant. Then about 120,000 years ago there was a marked decrease in carbon dioxide, with a minimum — that was the time of the maximum deglaciation. It apparently went up again over the previous time, but it went down and up again, the top figure being about 250 and the bottom figure about 125 parts per million. What is interesting here I think is the very abrupt transitions between the 250 parts per million and the 125 parts per million. Now what is the real cause of these abrupt transitions? Perhaps it must be something to do with the sources and sinks in the ocean. When at high latitudes there were large areas where the CO_2 in the water was higher than in the air, carbon was released to the air. At other times when there were large areas where the ocean was a sink, carbon was washed out of the air, and you have some kind of a feedback in fact, so that once you get some carbon going into the air it keeps on going in that direction, up to some kind of a maximum — or when some comes out of the air it keeps on going to a minimum. This may very well be due to changes in biological productivity. If the biological productivity is high, you have in effect a pump operating in the ocean, in which a lot of organic carbon settles out of the mixed layer into deep water where it cannot get back as much as one gigaton a year, year after year, so that after 100 years you have a change of about 100 parts per million.

MARINI-BETTÒLO

What is the nature of the feedback effect?

REVELLE

It keeps on going in the same direction. We just really do not understand this at all. And this could happen now, but in the future this could have happened 20,000 or 30,000 years ago, I think, which would be a very large perturbation of the total atmospheric CO_2 content, having nothing to do with human activities at all. And this is something which I think we need to really understand a lot better than we do now. This will require certainly satellite observations of the color of the ocean, to establish the chlorophyll content of the ocean, and it will involve contrast with the U shift, which will measure the areas of high CO_2 in the surface layers and of low CO_2 in surface areas in high level, particularly in the north Pacific, the northeast Pacific, northwest and north Atlantic and all around Antarctica up to 40 degrees of latitude. I am very enthusiastic about Tom Malone's geosphere-biosphere program and it must show from this particular standpoint what bappens to the carbon dioxide.

MARINI-BETTÒLO

What you are saying is very interesting. I was just wondering if this is not possible with the presence of the extra activity in this period of algae or other phytoplankton, which can under particular conditions have increased the photosynthesis in water, in the oceans.

REVELLE

That is exactly what I think it is: phytoplankton productivity. In the northwest Atlantic, for example, one finds right now a fairly large area of high phytoplankton production in springtime. The ocean becomes green over many square kilometers, due to high chlorophyll content. That disappears in about two weeks, and if you can calculate the changes in phosphorus content of about 2 grams per square meter to zero grams per square meter, that implies a productivity of about 100 grams per square meter of carbon, all of which settles out very quickly.

SALATI

There is a possible negative feedback to control the increase in CO_2 in the atmosphere by increasing the partition rate after you reach some concentration of the CO_2 in the atmosphere.

REVELLE

You are talking about the CO_2 fertilizer effect? I think that is a real process, that the CO_2 will act as a fertilizer and will cause a biotic accumulation of carbon, but this is very controversial and many colleagues do not believe this.

HARE

I really do not believe it either as far as natural vegetation is concerned, because there will also be under these conditions an increased respiratory loss. Respiration is a temperature-sensitive process, so to do any good you would have to be able to increase the standing biomass by probably something of the order of 7 gigatons a year. Such a figure boggles the mind. To keep the biotic regulator on, you would have to take in photosynthetically an extra 7 gigatons a year.

REVELLE

I do not think that is possible at all. But I think there is some fertilizer effect.

CANUTO

If, going back to the question of the sea, the fact that the ocean is so difficult to quantify, to understand actually, how reliable are those numbers that predict a working of 1.8 to 2° C or the number you quoted this morning and that were able to show that they change the physics or the understanding of clouds, etc.? But this is such a large uncertainty as you say; then what reliability do those numbers have? or do they take into account some kind of model of the ocean? How do they do that?

REVELLE

You are talking about the temperature increase with the carbon dioxide increase? (Yes) I would not like to comment on the validity of those model predictions. That is really a question of atmosphere physics, — which I do not understand that well — these climatic models. But I will say that if you can rely on authority, it looks pretty good, in the sense that all of the modelers agree, and all of the people who understand radiating balance, the behavior of radiators, like carbon dioxide, they all agree that the temperature increase for a doubling of CO_2 will be between one and a half and perhaps 4, or 5 degrees over all. There is a man named Sherwood Idso in Arizona who says that this is not so, but the modelers tell me that Idso's data in fact infer what they are saying — if they are interpreted correctly.

CRUTZEN

The origin of the methane clathrates interests me. How are they formed in the sediments? Do they come from below, or above? If they would come from above, I cannot see how they ever could form there in such high concentrations because they first go through a higher temperature régime. It is something that I do not understand, I am afraid.

REVELLE

Well, I think that there are two possibilities. One very simple and straightforward possibility is that the amount of organic carbon in those sediments is of the order of 1-1/2 percent, between 1 and 2%. These are anaerobic conditions which prevail. Right at the surface you get reduction of sulphate, so that within the top meter some organic matter is reduced, or rather some organic matter is oxidized and inorganic sulphate is reduced to provide the electronic exchange for that process. But that is a very small effect. Within a half minute or so all the sulphate is reduced. Below that point you have methane production instead, and if you just make the analogy of one of these biogas producers that they use in China and India — where about a third to a half of the organic matter is turned into methane — you get plenty of methane by that process. That will go down, it will keep on going for a long time; the rate of deposition of those continental slope sediments is of the order of 10 to 27 centimeters per thousand years. The deep-sea drilling cores show that you go down maybe 200 meters and you get plyocene sediments on the slope. You have essentially an infinity of time for these anaerobic processes to go on.

Now there is a man named Gordon Erdman of the Philips Petroleum Company — there are companies of course very much interested in these methane deposits — and he has looked into this process with more sophistication than I was able to, but he thinks that there is another process that may be responsible for the methane rather than simply microbial fermentation, and that is pyrolysis, at great depths where the thermogradient is quite high. Remember I said that there was a thermogradient of around 30° per kilometer. Within a few kilometers you get to the boiling point, above the boiling point of water. And he thinks that it is because of these high temperatures that methane is formed. In this case the methane will rise up to a point where clathrate is stable. So he thinks that the production is from below and that methane rises until it finally freezes in the clathrate. He estimates, as I do too, that the total quantity is of the order of 10,000 gigatons. That is about twice the entire fossil fuel reserves.

WANDIGA

I would like to pose the question differently. I know that something unusual happened in North America this season. How do we know it is a permanent feature? Because I know at the same time that in Africa we have these seasonal variations. And we have a very unusual high rain pattern in some areas and very dry, rainy or both seasons in some other areas. The two of you have painted a picture which tends to indicate that we are sure we are going to get warming up. Is it a reflection of what has happened this year? Because there is also a trend of cooling that we studied in the 40's. How do we know this is not going to balance the warming up? Finally, how do we know, with the increased particulate input into the air, whether the cooling off will overcome the warming up and therefore we will have a permanent cooling?

HARE

I would like to make it clear that I use 1983 as an example, not because I think it is a permanent effect — I am quite sure it is not — but because it is a marvelous, cheap experiment that nature has provided for us to get some broad numerical estimates from the economic domain. Surely we ought to say scientifically that the CO_2, effect is not yet in the bank; we have not, in my personal opinion — this is highly controversial — unmistakably seen the CO_2 signal. Equally well I am persuaded that we shall see the signal, if it is real, by the end of the century. In other words, the enormous noise, as you very rightly say, affects this record. Inter-annual variations of rainfall and temperature are extremely high. The differences year to year of mean annual hemispheric temperature are as great as that which corresponds to something like a 50-year period in relationship to the carbon dioxide effect. It will be a long time before we can say for sure we have seen the signal through that noise. Now there are people in the United States and the USSR — I am thinking of Budyko in the USSR and Hanson in the USA — who persuade themselves they can see it, because if you take the last century, it is warmer now than it was in 1885; but it still is colder than it was in 1940. Well, things have really broken out all over in the last two or three years; but it is a great mistake to be misled by short-period variations. I appreciate your point, because in using '83 there I may have conveyed the impression that I thought the CO_2 warming had finally emerged; I must make it clear I thought no such thing.

REVELLE

I think what Wandiga is saying is something different, that there may be countervailing factors like the growth of particulates in the air. I do not think that is so. Particulates are not increasing without limit. Sometimes they are high and sometimes they are not. It is only when you have a lot of volcanism that you get much effect on the climate. You do not get it from man-made, from anthropogenic causes.

HARE

That is the point I was trying to make in those last two slides. Anthropogenic low-level haze, large particle haze, is very photogenic; hut I do not think it has a lot of significance for the solar radiation level.

WANDIGA

May I add something? I think the experience you may be having in North America and in other developed countries might be totally different from the experience in the tropical regions because we have or we have seen a very high rate of vegetation destruction, and the amount of particulates being put up into the atmosphere by wind is much higher than you will see anywhere in your country. And we are also worried about this, but we might be seeing something different.

MARINI-BETTÒLO

I think that another point that was stressed yesterday is that there are certain cultivars like rice that give a considerable amount of gases and methane which can modify the atmosphere.

ARNOLD

I am just wondering about your statement that aerosols may have an effect on climate only during periods of strong volcanic activity by increasing the albedo. I am no expert in cloud physics, but I am wondering if increased aerosol burnings in the troposphere could affect cloud processes and thereby have an impact on climate.

REVELLE

But how are these aerosols going to increase except by the process that Wandiga talks about, namely the destruction of tropical forests? We are going to run out of tropical forests pretty soon. There is no reason to believe that this is going to keep on going. The aerosols are not a permanent feature, tbey have a very short half-life in the air.

ROWLAND

I have both a technical question and also a sort of an intuitive comment. The technical question has to do with the analysis of the bases which have come out of what you are calling the methane clathrates as to the knowledge of what the actual composition is: whether it is pure methane, whether there are other hydrocarbons, etc. The intuitive comment I think has to do more with the questions; as I see the carbon dioxide effects, it is almost as if the changes are going to be a uniform increase of temperature. And I am sure that is not meant. The kind of feeling that I have is that the particular climatic circulation that we have is very much a characteristic of the particular set of temperature distributions that we have and the fact that living where I do we have 12 inches of rain a year. If I lived in San Francisco, which is 400 miles north, I would have 25 inches of rain a year; if I lived in Seattle I would have 150 inches of rain a year. I have a feeling that perhaps the major effects of the warming would be rather in large shifts in small regions as the whole climatic system adjusted again, such that the impacts that one could see on averages might not be depicting what would really be the major effects.

HARE

Of course I have simplified to a great extent the original model prediction that I put up to start the thing off with. That does show strong geographical differences in the impact; but I would be prepared to bet that the way the changes would be perceived will not be as a slow upward trend of temperature, but as different sequences of drought years, warm years and cold years. The variability of climate is great. The internal variability is part and parcel of the huge general circulation system itself. That includes the ocean, and such phenomena as the quasi-periodic el Niño. This variability is so much greater than the trends that we are talking about that we are generally unaware of the trend. It requires tremendous statistical sophistication to see any trend, and to be sure that we are seeing it. But what I think a warming means, Sherry, is that gradually there will be more years like 1983 and more stresses like those that we have just undergone. Therefore we shall see a greater tendency to adapt technology to sequences of extreme years, and not to perceived trends, because people do not notice this kind of slow trend.

KNABE

Maybe no professor is thinking of the challenge Dr. Hare mentioned. Couldn't we also say we should increase the production of beer and stop the consumption of beer to store all the CO_2 in bottles? But may I have really a question? I got two different figures — maybe I am wrong. One figure was the content of the atmosphere would amount to 100 gigatons in the first paper and this would be every year all would pass to the environment. And the other figure in the second paper was 750 gigatons of CO_2 in the atmosphere. Did I get the wrong figures? I would like to have an answer here. The other question: have the people who are concerned with CO_2 considered the possibility of depositing organic waste, or municipal waste for instance, in piles that exclude burning, to store some of the carbon under cover and avoid additional CO_2 emission?

REVELLE

As far as your first question is concerned, I think maybe you got confused between the past and the future. When we talk about a doubling of carbon dioxide in the atmosphere, we are talking in terms of the atmospheric content of carbon of something like 1200 gigatons in the atmosphere. A hundred years ago it was a little bit less than 600 gigatons — we are talking about an increase of 600 gigatons. That is a lot. You just cannot do much if I started carboning trees to countervail a hig effect like that. The only thing about trees is: if you are going to, go in that direction to try to overcome the CO_2 effect, the best thing to do with trees is to burn them as a source of energy, because you can recycle them and use nothing but biotic energy instead of using the bottled fuel energy. That would be a better way to utilize trees to countervail the CO_2 effect.

FIOCCO

Clouds are the main mechanism that affects the albedo of the earth, and the relationship of the cloud coverage to the CO_2 increase seems to be a rather difficult problem to treat in models. We have attempted some calculation two or three years ago, the result of which I do not even remember due to the difficulties we went through, but we could practically obtain positive or negative feedback according to various other parameters we had to include in the calculation, a sort of "off the hat" — how much is the humidity going to increase? How much is the radical transfer of water into the troposphere going to be affected by an increase in temperature? Where is the cloud going to be formed? In most models which have a radical definition, the cloud is assigned to a specific height, but the radiating effects are largely dependent on where in the atmosphere you are going to locate this cloud. We thought that this kind of problem would of course be dealt with with 2D or even 3D models, but that in this case the difficulties become immense and the question of the presence of clouds at high latitudes becomes really a major issue. Do you have any comments on that?

HARE

Of course I entirely agree that the whole business of clouds is worrisome. Various modelers have tried to look at this. We have even done a one-dimensional model of the same kind that you referred to quite recently in my own little backyard. But most of the answers you get are that the acceleration of the hydrologic cycle that is inherent in this does not seem to increase the total cloud amount. Actually it probably does; potentially it also increases the level at which that cloud will sit, in other words, alter its effective radiation temperature. As you know, it is very hard to find good English to express the greenhouse effect. Quite responsible scientists say that what happens is that the carbon dioxide traps heat and prevents it from escaping, which is a valid comment for the warming phase, but is no good for describing equilibrium. What the carbon dioxide effect does is not drastically to alter the radiative temperature of the earth, but to alter the level in the atmosphere where you find that effective radiative temperature. And that must mean ultimately a rise in the level of the cloud tops. But I know of no model that could do that, or will do it, and I think you do not have to parameterize it as we do now.

REVELLE

What these modeling people say is that if you retain a fixed cloud temperature rather than a fixed cloud altitude, that has a big feedback effect on the CO_2 — of warmth — as much of an effect as the reduction of the albedo by melting of snow and ice — they both have about a one degree feedback effect. There is a Russian climatologist by the name of Borisenkov, who is skeptical about the CO_2 warming because he thinks that the area of clouds will increase, not the height but the area. And I do not really know how to answer him. That is something which we really have to face at the present time, and we just have to wait and see, but if there were an increase in albedo due to larger area of cloud, that would certainly counteract the CO_2 radiative warming. Most of the modelers, however, do not think that is going to happen, for reasons that I do not understand. Do you understand it at all?

HARE

I do not understand everything, but I do know that empirically warm years are not cloudier than cold years, and vice versa.

MARINI-BETTÒLO

Have we considered sufficiently in all these the parameter due to particulates?

REVELLE

I think so. Hansen of the Goddard Institute for Space Science, as I said, has tried to parameterize the volcanic particulates, and he shows that they really are important, but of course it only lasts for a very short time. Anthropomorphic or anthropogenic particulates — I guess one thing to say about that is people are not going to stand for it, they are going to reduce them. Like the discussion we had of London the other day. London is cleaner now than it has been for a thousand years, and that is going on all over the world except in the developing countries, which are pretty smoggy. But they are not going to stay smoggy as they develop economically.

ANDERSON

Putting aside the question of the relationship between change in surface temperature and changes in CO_2 content and focusing on projections of CO_2 changes in the atmosphere over the next 100 years, could you summarize for us the three major uncertainties, two or three major uncertainties in that prediction and suggest research to eliminate those uncertainties? or reduce them?

REVELLE

As Nordhaus points out, the uncertainty is basically an economic uncertainty: mainly, how fast is economic growth going to occur? and what is going to he the cost of different sources of energy — nuclear energy or biomass energy versus fossil fuel energy? And that is the real cost, which includes the convenience of fossil fuel energy. Liquid fuels are absolutely essential in our modern industrial society, but primarily for transportation, and it is awfully hard to get any other source of liquid fuels than petroleum. You can make a lot out of coal and oil shale, but at a cost. You can make them sort of artificially in a big nuclear power plant, but the expense there is very high, and the uncertainty is really the uncertainty of predicting what the world is going to be like a hundred years from now from the standpoint of our industrial civilization, not really a scientific but a physical uncertainty.

ANDERSON

May I recast the question slightly: for a given release rate of CO_2 from fossil fuel, could you speak to the major uncertainties, given that input and research that could be directed toward reducing the uncertainties?

REVELLE

I gave a list of those uncertainties — let me see if I can find that. The only thing you might call scientific uncertainty is the airborne fraction — that is the basic problem of the carbon cycle. The evidence today is that it is about .4, in other words 40% of all CO_2 put into the atmosphere stays in the atmosphere for a considerable time. That quantity is probably going to go up as the CO_2 content increases, because of what is called the buffer factor; in sea water it could go up as high as 8 in the airborne fraction. That group of uncertainties really involves better understanding of the carbon cycle, the interchange between the sea and the air, than we have now, and the effect of the biosphere on the airborne fraction. All of the other uncertainties relate to the quantity of fossil fuels that will be burned, and those pretty much overwhelm this airborne fraction.

HARE

Could I add to that? There are two others, namely, the numbers of the human population, which I think is a scientific number, but we do not know it. Secondly, peace or war.

REVELLE

Of course all bets are off if you have a nuclear war.

CHAMEIDES

I have two questions. The first question concerns this airborne fraction. There must be some time scale associated with what you call the airborne fraction because presumably after a thousand years the airborne fraction is extremely small. So I would like to know whether you are talking about 5 years, 10 years or 100 years for that. The second question is one of clarification concerning the effect of particulates on climate. It was my understanding that the climatic impact of particulates in the atmosphere was not all that obvious whether it would be cooling or heating. Professor Fiocco told us yesterday, I thought, that the impact of volcanos on the surface temperature of the earth was not all that clear — we had a very warm winter in spite of the large volcano emissions. So is it established that the particulates lead to a cooling, or is that still an open question of itself?

REVELLE

Well, actually a lot is known about them, but they behave in a complicated way. Particulates over the ocean increase the albedos because the albedo of the ocean is only about 5%. Particulates over the land lead to warmth, because they in fact absorb and re-radiate radiation, and they reduce the albedo, they are less reflective than the land surface itself. So it is not by any means obvious that they would actually reduce the temperature. The other question about the airborne fraction, that depends on the rate of emission of CO_2 and the airborne fraction of 0.4, or rather the amount going into the ocean is about 40%. Remember I said that the entire atmosphere exchanges with the ocean in about 7 or 8 years.

CANUTO

Just a piece of information since Professor Fiocco bas brought up the cloud impact in centimeters and Prof. Bettòlo has brought out the particulates. In my Institute Hansen and two of his colleagues, are exactly working out the details for those two models, and they are working both on the volcanos and the clouds — there are a couple of people working on clouds — so I think that the next major piece of research that they are going to dedicate themselves to is precisely trying to solve this problem. I do not think the heads of NASA would be ready to bet on any direction of ΔT as far as Chameides is concerned, but having recognized the importance of that uncertainty, they are dedicated to that; and so I think that in the next year or so, with the care with which they usually work, we will have a rather reliable number.

ROWLAND

I want to repeat a question that I asked before and which got lost. But I will make a comment in connection with the comment that Professor Knabe made about varying organic matter, that one of the strongest point sources of methane that we have found is the city dump for the city of Irvine, where the air over that dump when we sampled it was 250 parts per million methane instead of 1.7 because of the methane that was coming off from the dump. So in the city of Long Beach they are taking the methane out of their dumps, covered biological areas, and enough methane is coming off that it is profitable to take the methane and use it to burn. But the question I just want to repeat because the answer got lost in the previous discussions. What is known about the composition of that gas?

REVELLE

There are some higher hydrocarbons. There is some pentane and I think some butane too, but I am not quite sure. It is rather small, but it is surprising how more or less pure the stuff is.

ROWLAND

Are there unsaturated hydrocarbons present?

REVELLE

Yes.