

Will the Warming Speed the Warming?

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A significant body of experience, much of it summarized in the preceding chapters, suggests that there are mechanisms entrained by a change in global climate that tend to increase the trend of temperature change, whatever the trend and its original cause may be. In the case of a warming, there is a possibility that the warming itself may cause a series of further changes in the earth that will speed the warming. If so, what are the mechanisms involved and how seriously might our current appraisals of the speed and severity of the warming be in error? Will the warming speed the warming? If so, for how long and by how much?

The global climatic system involves a complicated array of primary and secondary causes that influence global temperature and many other climatic factors. The secondary effects are considered feedbacks insofar as they influence the primary effect. In the case of the warming of the earth, feedbacks are positive if they tend to enhance a warming trend and negative if they diminish the warming. Kellogg (1983) and Lashof (1989) explored this topic in detail for the climatic system as a whole, and M. Schlesinger and Mitchell (1985) discussed the physical atmospheric feedbacks. The general circulation models (GCMs) used in estimating the responses of climate to various disturbances usually contain various physical feedback systems (see J. T. Houghton et al. 1990, 1992).

The biotic feedbacks are complicated and have not commonly been incorporated into such models or into the general calculus of the warming of the earth, despite their potential for significant influence. The most widely recognized biotic feedback is the enhancement of photosynthesis by elevated levels of CO₂ in air, the so-called CO₂ fertilization effect. It has been incorporated for many years into carbon cycle models by Keeling and colleagues (Bacastow and Keeling 1973) as the β factor (see the discussion in Wullschlegel et al., Chapter 4) on the assumption that the increased photosynthesis results in increased carbon storage on land. The issue is complicated by the fact that carbon storage (net ecosystem production [NEP]) is determined by the balance between gross production (total photosynthesis) and total respiration of the ecosystem as defined by Woodwell and Whittaker (1968) and discussed in Chapter 1. Many factors apart from CO₂ concentration limit photosynthesis. Similarly, many factors influence the respiration of plants and also affect the rates of decay of organic matter in soils. NEP is

determined not only by net primary production (NPP) but also by the rates of respiration of the organisms that feed on plants and the organisms of decay in soils. These processes are influenced by the availability of water, nitrogen and other nutrient elements, and sunlight; temperature; the successional status of ecosystems; and other ecological factors, such as disturbance by fire, disease, toxins, and storms. NEP is always less than NPP, commonly by 50% or more (Woodwell and Whittaker 1968). It fluctuates around zero in a quasi-stable climax vegetation and may become negative under chronic disturbance.

Any of the factors just mentioned may have an influence on NEP that may vary from time to time and may be considerably greater than the direct effects observed so far from changes in the concentration of CO₂ in the atmosphere. The topic has been examined in detail by R. A. Houghton in Chapter 19 and by Woodwell (1983, 1989). Wullschlegel et al. in Chapter 4 and Allen and Amthor in Chapter 3 show that although there may be a stimulation of photosynthesis due to the increase in CO₂ concentration in the atmosphere, there will not necessarily be an equivalent increase in the storage of carbon in terrestrial ecosystems. The major reason is the sensitivity of respiration to temperature: a warming increases rates of respiration, including the rate of decay of organic matter in soils. In addition the loss of carbon due to disturbance is commonly much more rapid than its accumulation through regrowth of the disturbed ecosystems, as outlined by Kurz et al. in Chapter 6 in a discussion of the implications of fire and other past disturbances for NEP in forests.

Direct experience with global biotic feedbacks is limited and will remain so until the warming progresses over the next several years. Even then we shall have no basis for experimentation with the earth as a whole, and analyses will have to be based, then as now, on observation, on knowledge of present and past climate and vegetation, and on local experience with natural ecosystems. Modeling offers clear advantages, and progress in the development of models in support of such analyses is evident (see Section III, especially Chapters 16 by Luxmoore and Baldocchi and 17 by Prentice and Sykes). The models offer apparent detail and the possibility of exploring mechanisms. They are, however, only a tool; they offer a system of record keeping, a never-ending series of new questions about how nature works, and insights into the logic of current evaluations. They do not offer new data, nor do they offer answers to all questions. They depend heavily on assumptions of a new stability of climate and interpretations of the next years as "transient" periods, but it is instability that is the dominant characteristic of the next decades and the subject of the analysis. Although progress in modeling remains impressive, it does not yet reflect the experience of the Vostok Core, the Little Ice Age, and the contemporary correlations of CO₂ level with temperature outlined in Chapter 1 by Woodwell and later in this chapter. These data appear to establish a set of limits within which we must assume that the world operates. We must further assume that these limits are of primary importance in determining the course of the response to the warming now underway.

CRITICAL CONSTRAINTS ON THIS ANALYSIS

Time and Stability

Our interest is in the next several years to a century, not millennia. During this period of the span of our lives and those of our children, we expect profound changes in the human

circumstance quite apart from the warming of the earth. We seek the best appraisal possible of the implications of the warming for the earthly habitat while the human population is involved in yet another doubling beyond the nearly six billion humans that now crowd the planet and scramble for access to as wide a variety of earthly resources as possible.

We observe that the mean global warming over two decades, 1970–1990, has been about 0.2°C per decade. In the mid-high latitudes the future warming is expected to be greater, as much as twice the global average. A 1°C change in temperature is equivalent to a latitudinal migration in the midlatitudes of 60–100 miles or 100–160 km. It is reasonable to consider the possibility of a warming in the middle and higher latitudes of 0.5°C or more per decade or a migration of climatic zones on the order of 30–50 miles per decade. Such a change in the prairie-forest border in Minnesota or Wisconsin would be rapid by any standard. The difficulty is, however, that the climatic change is universal and affects the entire landscape and its vegetation, not simply the prairie-forest border. Each individual of each perennial species finds itself progressively maladapted to its environment under conditions of rapidly changing climate.

The warming would be especially rapid by comparison with the life cycle of most trees and the time required for terrestrial ecosystems, especially forests, to attain equilibrium with climate. Changes of tenths of a degree centigrade per decade can be expected to outrun the capacity of forest trees to respond in very few decades. This point has been made in various forms by Woodwell (1983, 1989), Davis and Zabinski (1992), and Solomon and Cramer (1993) among others. The effect is a transition from forest to shrublands or grasslands, or to more severe impoverishment (Woodwell 1990). Such transitions in the structure and pattern of vegetation will be accelerated, as warming progresses, by increased frequency and intensity of fires, the spread of diseases and pests into new ranges, and the increased frequency of human disturbance. The transitions in climate are not transitions to a new stability, but to continuous instability marked by a progressive, open-ended global warming in the patterns defined by the GCMs and summarized by the IPCC in J. T. Houghton et al. (1990, 1992).

Recent Glacial History: The Record from Ice

The glacial record over the past 160,000 years has provided important insights that are at once revealing and confusing (Barnola et al. 1987; Lorius et al. 1988; Raynaud et al. 1993). Throughout that period atmospheric CO₂ and CH₄ concentrations have been correlated with temperature. As temperature has risen, so have CO₂ and CH₄ concentrations; as temperature has dropped, CO₂ and CH₄ concentrations have also dropped. N₂O follows the same pattern (Khalil and Rasmussen 1989). Although the trends were reversed several times in that period and the causes of the reversals are not clear, the pattern is consistent with a positive feedback once the warming or cooling has begun. Temperature appears to have led the changes, especially during the cooling periods. The record suggests that a change of 1°C in this period was equivalent to a change of about 10 ppmv of CO₂ or 20 petagrams (Pg) (=10¹⁵ g) carbon in the global atmosphere (Table 23.1).

The topic has been addressed recently by Raynaud et al. (1993), who confirmed the correlation and explored the question of causes of the variations in temperature and atmospheric trace gases during the cycles of glaciation over the past 160,000 years.

Table 23.1. Changes in CO₂ and CH₄ Concentrations in the Atmosphere per Degree Centigrade Change in Temperature as Reported in Recent Data^a

Period	CO ₂ /°C (ppm)	Carbon as CO ₂ /°C (Pg)	CH ₄ /°C (ppb)	Reference
Glacial records (~160,000 years)	-10	-20	-60	Raynaud et al. 1993 (from Figure 5)
1940-1990		3.4-6.4		R. A. Houghton, Chapter 19
1958-1990	-2.9	5.8		Woodwell, Chapter 1 (from Figure 1.2)

^aData from the glacial record report what must be considered "equilibrium" conditions arrived at over a millennium or more. The data from this century report the short-term changes observed. Both sets, however, confirm an overall positive feedback that applies to CO₂ and CH₄. Although not shown here, N₂O concentrations follow the same pattern.

Their conclusion was that about 50% of the variation in temperature was controlled by the concentration of trace gases and that little is known of the factors determining the trace gas concentrations. Changes in trace gas concentrations involved not only changes in stocks of carbon on land, but also large changes in oceanic circulation and in the oceanic carbon cycle. It is possible that oceanic changes may be quite rapid, difficult to predict, and in themselves a feedback into climatic changes (Broecker 1987).

The Vostok and Byrd ice cores record what may have been equilibrium conditions, achieved over centuries to millennia. The resolution of time in these cores is, unfortunately, not fine enough to feed our need for addressing the global warming anticipated over the next several decades. More recent data from ice cores taken in Greenland bring the resolution down to a few years (Alley et al. 1993). These records in ice were established in periods when the CO₂, CH₄, and N₂O concentrations in the atmosphere were substantially lower than those in the postindustrial world. The Greenland records establish that, even during interglacial periods, the climatic system has been open to rapid changes. There is no reason to assume either that the correlations that occurred at that time are less valid now or that the rapid changes that marked earlier periods could not occur again in this interglacial period.

The Little Ice Age

The temperature-trace gas correlation holds, at least crudely, during the shorter-term cooling of the Little Ice Age, although details of the data and the correlation are less precise. The temperature decline began during the 14th century in Europe, replaced a medieval warm period of about 300 years, and lasted, with fluctuations, well into the 19th century. The data on CO₂ concentrations have been obtained from various ice cores and tabulated by Enting (Chapter 18, page 319). The concentrations follow the same pattern observed in the Vostok Core: the decline in temperature corresponds to a decline in the concentration of CO₂ in the atmosphere, and the late-19th-century warming is reflected in the familiar increase in CO₂ concentration that has now continued and become the focus of our concern.

Contemporary Observations of Temperature and Trace Gases

Limited contemporary local or regional data, summarized here by Woodwell (Chapter 1, page 7) from Kuo et al. (1990), Keeling et al. (1989), and Marston et al. (1991), show a similar pattern with temperature leading changes in the CO₂ concentrations by weeks to

a few months. The data of Keeling et al. (1989), which are the basis of all the analyses, suggest that a change of approximately 3 ppm in CO_2 concentration occurs per degree centigrade change in temperature, equal to about 6 Pg carbon in the atmosphere if the data can be interpreted globally (Table 23.1). The pattern is consistent both with a release of CO_2 from surface water of the ocean in response to warming and with a release from land through increases in rates of respiration of plants and in the rate of decay of organic matter in soils. Increases in temperature speed respiration, including the respiration of decay, and speed the release of both CO_2 and CH_4 .

CH_4 concentrations in the glacial record follow CO_2 concentrations closely (Raynaud et al. 1993), a relationship that seems to tie the fluctuations to the land as opposed to the sea because of the low solubility of CH_4 in water. CH_4 is produced principally through anaerobic decay in wetlands. Production and emission are heavily influenced by the moisture content of soils and peats (see Gorham, Chapter 9, and Nisbet and Ingham, Chapter 10). Large quantities of CH_4 occur as clathrates in coastal oceans, are vulnerable to release through warming, may have been large (perhaps major) sources of carbon for the atmosphere in the past, and may be such sources for the future (MacDonald 1990). Because CH_4 has very low solubility in seawater, the major sink is oxidation to CO_2 in the atmosphere. The uncertainties concerning the magnitude of the effects of the decomposition of clathrates through warming simply add to the potential for an accentuation of the positive feedback systems already identified.

The combination of the glacial record and the contemporary data appears to set overall limits on the patterns of responses possible. There is no basis for an assumption that the combination of changes inherent in a greenhouse gas-driven warming will stop the warming through accelerated storage of carbon on land in much-enriched forests and other terrestrial ecosystems, as suggested by some (see Idso et al. 1991 and discussions by Allen and Amthor in Chapter 3 and Wulfschleger et al. in Chapter 4). On the contrary, the data provide an envelope of experience that seems to limit the overall response of temperature and trace gases to a positive feedback in which a warming, however caused, results in the further accumulation of CO_2 and CH_4 (and probably N_2O) in the atmosphere within weeks to a few months. The net effect must be a further contribution to the warming. Within that context, there are undoubtedly a host of interactions, some of which add to the positive feedback while others, as negative feedbacks, reduce it.

The factors that initiated the periods of glacial advance and retreat are not known. The reversals of trends capped periods of warming and cooling that lasted many thousands of years. During those millennia the climate appeared to be under the influence of a positive feedback. We cannot say whether that feedback system has limits that caused the reversals. The probability seems greater that other outside factors, such as the amount of energy reaching the surface of the earth, changed at those times. Our interest is in the next years to decades, when we expect the earth to continue in its most recent postglacial warming as heat-trapping gases accumulate further in the atmosphere.

THE "MISSING CARBON" PROBLEM

The factors that determine the CO_2 and CH_4 content of the atmosphere would appear to be few, easily measured, and open to control by deliberate interference. There are but

two large reservoirs of carbon in addition to the atmosphere: the oceans and the terrestrial biota, especially forests and soils, including peat. The imbalance that has resulted in an unprecedented accumulation of CO₂ in the atmosphere has been caused by the combustion of fossil deposits of hydrocarbons as fuels for industrialization and by long-continued and accelerating deforestation associated with human activities.

Measurement of the stocks and flows of carbon among these major pools has proven unsatisfactory, at least from the standpoint of providing a global accounting for the carbon cycle. The difficulty lies in reconciling the major flows. We know, or think we know, with considerable accuracy the amount of carbon released through burning fossil fuels. In 1992 it is thought to have been about 6 Pg. To that we have added the release from deforestation globally, estimated most recently by R. A. Houghton as 1.6 ± 1 Pg. This release is the net release from changes in land uses. It includes the direct release from deforestation, burning, and the decay of organic matter in soils stimulated by changes in land use, as well as the storage of carbon resulting from the successional recovery of vegetation after human disturbance. It does not include a correction for any stimulation of carbon storage on land caused by a stimulation of photosynthesis from additional CO₂ in the atmosphere or of NEP from fertilization by atmospheric deposition of nitrogen mobilized by human activities, as discussed later in this chapter. These feedbacks are cited by several authors as factors that resolve the "missing carbon" problem. Nor does it include any assumption concerning forests or other vegetation globally beyond the basic assumption that undisturbed forests globally are late successional and approximately stable, and therefore have a net ecosystem production of zero.

Some of the carbon released into the atmosphere accumulates by an amount that varies from year to year. Between 1988 and 1991 the accumulation ranged between about 5 and 2 Pg carbon annually and averaged about 3. In the 1990s the rate of accumulation has been dropping abruptly. The difference between what is released (a sum commonly thought to include the 6.0 Pg carbon from fossil fuels plus 1.6 Pg carbon from changes in land use, plus any further increment from the warming itself) and the amount accumulating in the atmosphere would be expected to be the amount absorbed into the oceans, more than 4.5 Pg carbon. The difficulty is that the amount accumulating in the oceans, as estimated by several techniques, seems to be limited to about 2 ± 1 Pg (see Mackenzie, Chapter 2; Sarmiento and Sundquist 1992 and Sarmiento 1993). The difference has been called "missing carbon," as discussed by Woodwell (Chapter 1) and R. A. Houghton (Chapter 19).

The possibilities for explaining the discrepancy are limited. One possibility, of course, is that the appraisals of oceanic absorption are too low. The difficulty is that several techniques for appraising the absorption have been applied and all come to approximately the same magnitude for the current annual absorption (Woodwell, Chapter 1, and Mackenzie, Chapter 2). Broecker and Peng (1992) call attention to evidence of the magnitude of the transfer of carbon in cold oceanic currents from the Northern Hemisphere to the Southern Hemisphere as confirming the analyses of Tans et al. (1990) discussed later in this chapter. The overall appraisal of oceanic absorption and transport of carbon seems well established, although not at all beyond the need for continued scrutiny. It is also possible that the absorption varies significantly from year to year in response to temperature and other factors.

Could the appraisals of terrestrial releases be too high? Those involved in studies of forests and land use do not believe so. They call attention to the host of changes currently underway in forests, including the toxification of extensive areas by industrial wastes, ozone, and acid rain; the continued rapid deforestation and impoverishment of land in the tropics; the increasing rates of deforestation or harvesting of primary forests and their replacement by young, secondary forests with low carbon stocks in the Northern Hemisphere; and the increasing frequency of forest fires over the past decade in northern forests (see discussions by Woodwell in Chapter 1 and by Kurz et al. in Chapter 6). Warming over the past century may also have increased the decay of soil organic matter, releasing CO₂ into the atmosphere in a positive feedback, as suggested by Woodwell (1983 and Chapter 1) and Jenkinson et al. (1991) among others (see, for example, W. H. Schlesinger 1986). The direct experience with land use leads to the conclusion that releases from forests are increasing, not diminishing. If midlatitude forests are accumulating 1–2 Pg carbon annually above the amounts allowed for successional recovery in the models used for terrestrial systems, as suggested by Tans et al. (1990) (see Tans et al., Chapter 20, and Fung, Chapter 21), that accumulation would be expected to be conspicuous and measurable over a few years, as shown by R. A. Houghton (Chapter 19).

The data of Wofsy et al. (1993) showing that a forest in central Massachusetts is successional and accumulating carbon (has a positive NEP) do not change the earlier interpretations, which accommodated this successional storage, according to R. A. Houghton's discussion in Chapter 19. Houghton has also shown that the analysis of carbon storage in European forests by Kauppi et al. (1992) is incomplete and, if corrected for the decay of organic matter, confirms earlier analyses and offers no evidence that the forests are accumulating carbon at a rate sufficient to resolve the issue of imbalance in current accounts.

No part of this discussion of the global carbon budget suggests that errors or oversights are not possible or have not occurred. These claims of a solution, however, have been based on partial analyses and have brought no insight or data not considered in the earlier global estimates that defined the problem. A forested region with an NEP of 500 g carbon per year requires about 2×10^6 km² of midsuccessional forest to store 1 Pg carbon annually. A change of 1–2 Pg carbon per year in the storage of carbon in forests is a large change and difficult to effect in a way that will not be conspicuous. Recent analyses provide reason to examine the topic further.

Schindler and Bayley (1993), for instance, have presented an analysis that suggests that enough nitrogen is being mobilized by human activities in the Northern Hemisphere over land to account on a stoichiometric basis for an additional carbon storage of 1–2 Pg annually in the midlatitudes. This possibility, taken with the conclusions of physiological ecologists (Chapters 3 and 4) and other modeling efforts such as that of Post et al. (1992), provides a basis for a significant increase in carbon storage on land but does not reverse or negate the overall correlation between CO₂ concentration and temperature. Moreover, other fates of mineral nitrogen, such as immobilization by microbial biomass and loss via leaching and denitrification, as outlined by Davidson in Chapter 11, may prevent realization of the full potential of the increased carbon storage in plant biomass from the excess of nitrogen now circulating. The suggestions of Lugo and Brown (1986) that forests do not in fact reach an equilibrium but continue to store carbon indefinitely are not consistent with the pattern of carbon flows that must have occurred prior to

human intervention in global cycles (see Chapter 2 and Meybeck 1981). It is possible that the mechanism advanced by Schindler and Bayley (1993)—alone or in combination with other adjustments, such as the high NEP observed for the stand examined by Wofsy et al. (1993) and an adjustment for large areas of suburban forests hitherto overlooked—will prove significant. If so, improved field measurements should soon resolve the issue.

The fact is that the global carbon budget is “balanced” in nature, which knows nothing of our problems in maintaining global accounts. The contemporary cycle is novel, the product of human tinkering, in ignorance, with global cycles on a grand scale. In postglacial time there was probably a net transfer of carbon from the seas to the land as forests were restored on land exposed from under glacial ice and as peat deposits accumulated (Gorham 1991; Gorham and Janssens 1992). More recently, prior to the period of human tinkering, the last two centuries, there was probably a net movement of carbon from the atmosphere to the land and into the seas (as particulate and dissolved organic matter) and a net release of that carbon back into the atmosphere from the oceans, as outlined by Mackenzie in Chapter 2 (see also Meybeck 1981). Otherwise the atmosphere would have been depleted rapidly of carbon to levels far below those recorded in glacial ice.

Human intervention released a total of about 220 Pg carbon into the atmosphere from fossil fuels between 1860 and 1990, an amount equal to about one-third of the total in the atmosphere in 1860. Additional carbon has been released from destruction of forests (about 120 Pg according to R. A. Houghton in Chapter 19), from drainage of wetlands, and from the accelerated decay of organic matter in soils. Enough CO₂ has accumulated in the atmosphere to raise its partial pressure of CO₂ significantly above that in the surface layer of the ocean. The oceans have shifted to become a net accumulator of carbon. Their capacity for accumulating atmospheric carbon at any time, however, appears limited because of the slow exchange of CO₂ between surface water and abyssal waters. As warming progresses, the capacity of the surface water for absorbing CO₂ will decline, a process that amplifies the positive feedbacks outlined here.

These processes do not necessarily proceed in a simple linear fashion (see Chapter 6 by Kurz et al.). Temperature changes, so important in determining climatic features and the responses of biotic systems, have not followed closely the accumulation of heat-trapping gases over the past century. Presumably, in due course, the accumulation of these gases will reach a point at which their effect will become conspicuous. In the interim, we may expect the diversity of responses outlined in the various chapters of this book. Nevertheless, if the earth warms at the rates projected (tenths of a degree centigrade per decade), we can expect the capacity of existing terrestrial ecosystems for storing carbon to diminish; they can be expected ultimately to release carbon into the atmosphere as the warming proceeds. The pool of carbon is large, about 2200 Pg (Table 23.2D), with a little more than two-thirds of it in soils and peats. This stock is maintained by a continuous flow from the gross production of plant communities that are vulnerable to any disturbance.

It is at this point of rapid change that the longer-lived species, and the communities of which they are a part, become vulnerable. Species have an intrinsic genetic variability that is usually higher near the margin of the distribution of the species (Cain 1944). Environment works on that variability to select combinations of genes that are appropriate for the particular circumstances of any place. The selection occurs over generations,

but few generations are required to refine ecotypes to specificity for any place. There are many spectacular examples of such selection. Its importance and the generality of the phenomenon are not in question (Woodwell, Chapter 1). Each individual, including each tree or herb of the forest and each animal, carries a set of genes selected over generations for the particular environment of that place. A rapid, continuous, and persistent change in the environment moves it out from under the species, which becomes progressively maladapted to the new environment and vulnerable to disease and other disturbances. The process can, if the disturbance is sudden and severe, lead to the progressive impoverishment of the forest, with an immediate and probably continuing release of carbon into the atmosphere. At the prairie-forest margin, for example, forest is transformed first into savanna and then into grassland by the combination of drought, fire, and disease.

If the transition were to a newly stable climate, there would be a new selection of ecotypes adapted to the new environment, and carbon storage might again increase. But if the changes are continuous, the selection is for species that survive under chronic disturbance. These are small-bodied organisms with short life cycles and rapid reproduction. The carbon stocks drop as forests make the transition to grasslands. Such transitions can be rapid, far more rapid than the development of forests in tundra or other regions where climate is ameliorated. Woodwell (Chapter 1) calls attention to the sharp, genetically fixed differences in ecotypes within larch of the forests of northern Siberia. Although forest trees may invade bog and tundra under a warming climate, the rate of invasion is likely to be far slower than that required by current estimates of global warming (Gear and Huntley 1991; MacDonald et al. 1993). Such invasions will usually require a selection of ecotypes appropriate for the new environment; the assumption that such ecotypes are uniformly available is clearly false. Continuous change is the enemy of such developments.

The "missing carbon" problem is indicative of the frailty of our understanding of the interactions between climate and the terrestrial vegetation and its soils. Although a solution to the conundrum is clearly desirable, the solution is not necessary to an appraisal of biotic feedbacks and their potential for affecting the course of a warming. What is clear is that the potential for a positive feedback is large enough to be of significant concern. The seriousness of the problem grows rapidly with the speed of the warming.

TEMPERATURE AND ATMOSPHERIC TRACE GASES DURING THE LAST FEW HUNDRED YEARS: A REINTERPRETATION

Since the late 1700s atmospheric CO₂ levels have increased by nearly 30%, from 280 to about 360 ppmv. If we estimate the total effect of all heat-trapping gases (except water vapor) as though it were due to CO₂, the CO₂ levels would have risen 40%, from 310 ppmv 100 years ago to 430 ppmv in 1992. With this increase in heat-trapping capacity the GCMs predict several changes in climate. The changes include an average warming globally of at least 1°C with a reduction in the range of diurnal temperature, an increase in precipitation and cloud cover; a slight decrease in stratospheric temperatures; a small decrease in the area of snow, glacial ice, and sea ice; and a slight rise in sea level. To some degree, all these changes are present in the observational record of climate and sea level.

Climate is not regulated by the concentration of heat-trapping gases alone. The amount of warming of the planet globally is less than that predicted for an increase in

CO₂ concentration equivalent to 120 ppmv. In addition, much of the warming took place prior to the 1940s, before the most substantial increase in atmospheric trace gas concentrations. Between 1940 and the mid-1970s the observational record shows a very small decrease in temperature. This trend has been followed by increasing global temperatures with eight of the warmest years on record in the 1980s and 1990s. Furthermore, in contrast to most model calculations, the Southern Hemisphere has warmed more than the Northern Hemisphere, particularly since 1950. These observations suggest that the temperature of the earth over the past century and more has been influenced heavily, possibly controlled, by factors other than the accumulation of trace gases in the atmosphere.

One interpretation of the temperature history of the earth since the late 1800s is that the early part of the record still represents in part a recovery from the Little Ice Age of the 15th through mid-19th centuries. Temperatures during this cold period at times were 0.5°C cooler than a global average of 15°C. It should be recalled that recovery from the last glacial stage of the Wisconsin has not been continuous and unidirectional. The recovery has involved a series of temperature fluctuations, including the cool periods of the Younger Dryas and Little Ice Age and the warm intervals of the Holocene Climatic Optimum and the Medieval Warm Period. Of special interest here is the observation that during the Little Ice Age, when temperatures fell, atmospheric CO₂ levels also appear to have fallen, as summarized by Enting in Chapter 18. Furthermore, it appears that the decline in temperature may have preceded the decline in atmospheric CO₂ concentration. The observation is consistent with the Vostok Core, which shows that during cooling phases changes in atmospheric CO₂ and CH₄ concentrations lagged behind changes in temperature (see the discussion in Chapter 1). The point is that the recovery from the Little Ice Age, whatever its cause, clearly extended into the latter part of the 19th century and perhaps into part of the 20th. As CO₂ and other heat-trapping gases accumulated with the warming, their contribution to the warming increased as well. Nevertheless, although they contributed to the increase of about 0.34°C in global mean temperature between the late 1800s and 1940, they probably did not dominate that change.

Beginning in 1940 and through the mid-1970s there was an erratic cooling of about 0.1°C. The cause of this cooling is uncertain. Several mechanisms have been suggested, including decreased solar activity, increased levels of stratospheric volcanic dust and sulfate aerosol in the high atmosphere, and, most recently, increased tropospheric sulfate aerosol, particularly in the Northern Hemisphere, derived from anthropogenic SO₂ emissions (see the discussion by Charlson in Chapter 14). The last mechanism is most appealing because of the increased global rate of emission of anthropogenic SO₂ that has occurred in the years after World War II, primarily in the Northern Hemisphere. This SO₂ forms sulfate aerosol in the troposphere that can trigger a cooling by stimulating the formation of brighter clouds that reflect solar radiation back to space, and by particulate backscattering of incoming solar radiation. Whatever the actual mechanism, the effect of greenhouse gases on temperature was masked by other factors for the period between 1940 and the mid-1970s.

Between 1974 and 1990 global mean surface temperature rose at a rate of 0.02°C per year, or 0.32°C for the period. For comparison, the rate between 1910 and 1939 was 0.014°C per year, or 0.41°C for this period of time. The rate of temperature increase

between 1974 and 1990 was about 1.3 times the rate prior to the midcentury cooling that began in 1940.

The recent rate of increase in temperature leads to concern that we are entering a new phase in climate, one in which the enhanced greenhouse effect is emerging as the dominant influence on the temperature of the earth. A host of observational and theoretical arguments support the conclusion that the accelerated warming will have important effects on the NEP of terrestrial ecosystems. R. A. Houghton's analysis (Chapter 19) suggests that the recent warming coincided with a release (or a reduced uptake) of carbon from land, whereas the earlier, more gradual warming before 1940 did not. Before 1940 temperature had no apparent relationship to terrestrial carbon storage. Since 1940, however, Houghton's analysis suggests that the accumulation of carbon in terrestrial ecosystems has been negatively correlated with global temperature; that is, a warming has released carbon from storage on land. The correlation shows a 3.4- to 6.4-Pg carbon release (or reduced uptake) per degree centigrade, with the release lagging behind temperature by up to 7 years. There may be several factors involved in explaining the difference in response during these two periods, but the observation is consistent with the recognition, on the basis of experience with studies of vegetation (Chapters 1 and 19 above), that the carbon balance of terrestrial ecosystems is sensitive to rates of change in temperature.

The terrestrial ecosystems that are most vulnerable to the changes in global climate are forests and peatlands of the middle and higher latitudes of the Northern Hemisphere, where the climatic changes will be most abrupt. The midlatitude forests of the temperate zone have been considered on the basis of modeling studies to be absorbing a large amount of the otherwise unaccounted-for carbon being released by human activities. These forests, already heavily stressed by exposures to ozone, acid deposition, and photochemical smog, can be expected to respond rapidly to further temperature changes. The probability is high that the response will be an increase in total respiration relative to gross photosynthesis, a change that will produce rapid, further impoverishment with the release of additional carbon as CO_2 and, if soils are sufficiently wet, CH_4 (see Chapters 8, 9, and 10) into the atmosphere. If this region has been serving as a net sink for atmospheric CO_2 , as suggested by Tans et al. (1990) (see Chapters 20 and 21), the strength of that sink can be expected to weaken rapidly and the region can be expected to become a source of additional CO_2 .

Support for this analysis comes from the global record of temperature and the record of temperature and CO_2 anomalies following the Mt. Pinatubo eruption in June and July, 1991. Its emissions of volcanic dust and sulfur aerosols have reduced the temperature of the earth by approximately 0.5°C , and the rate of CO_2 accumulation in the atmosphere has declined abruptly as well (see Figure 1.2). Such triggering events as the Pinatubo eruption may have caused the abrupt reversals of climatic trends observed in records such as that of the Vostok Core (Figure 1.1). The assumption at present is that concentrations of the heat-trapping gases, including especially CO_2 , have reached the point at which their influence, despite the feedback effect of the drop in temperature, will remain large as the atmosphere clears and the temperature will return to its global upward trend. Evidence of the emergence of dominance by heat-trapping gases is especially important because of the positive feedback now recognized as characteristic of past climatic changes. The feedback has always existed. When temperature was dominated by other

factors, such as dust in the upper atmosphere, the feedback was present but the influence of heat-trapping gases was not strong enough to dominate in modulating temperature globally. Now that these gases are emerging as the dominant influence, the importance of the feedback becomes conspicuous and the potential exists for a far more rapid and significant excursion of global temperature.

HOW LARGE A BIOTIC FEEDBACK?

The question of the amount of carbon that might be mobilized as CO_2 and CH_4 is the key to the scale of the net feedback. Although the feedback may be positive overall, as indicated previously, it is far from clear that the negative feedbacks are insignificant. There is a considerable body of evidence to suggest that at present the world carbon budget is being influenced by the combination of successional changes in forests and a stimulation of net primary production from increased concentrations of CO_2 in the atmosphere (Chapters 3, 4 and 6). What does seem clear is that as the total warming increases and environmental conditions drift farther from the slower changes of recent centuries, the effectiveness of the negative relative to the positive feedbacks will diminish. A 10% decrease in the total pool of carbon held on land in plants, soils, and peats (Table 23.2) seems possible over a few decades. Such a change could involve the release of as much as 200 Pg carbon at a rate of 4 Pg/year over 50 years. Using similar logic and the assumption that a 1°C increase in temperature might increase rates of respiration by 10%, Woodwell (1989) suggested that a warming of forests and tundra in northern latitudes could produce from that source alone as much as 3 Pg carbon per year as CO_2 and, under certain circumstances, CH_4 , through the increased decay of organic matter in soils.

Models of changes in vegetation in response to a warming of the earth often, but not uniformly, predict increased carbon storage in terrestrial ecosystems under future, warmer climates (see Prentice and Sykes, Chapter 17, for a discussion; see also Solomon and Shugart 1993). The predictions generally assume a new equilibrium climate; the increased storage of carbon results from an increased area of forest, especially in the far north. Will this transition occur in a time of human interest? At least two factors work against such an expectation. First, as outlined previously in several ways, accommodation of existing forests to the changes in climate is not likely to provide negative feedbacks in most instances. Second, the changes in ecosystem structure that must accompany the establishment of forest over large regions will proceed on time scales of centuries to millennia. Existing forests, adapted to present conditions, must disappear and be replaced in toto by new forests, complete with stocks of soil carbon and nutrients and with trees from other regions selected anew for a climatic and photoperiodic regime that is novel for them. If increased storage of carbon can be anticipated in such forests in a new "equilibrium," it is unlikely that the pathways by which the earth reaches this state will be marked by negative feedbacks of significance in the global carbon cycle in the next 100 years. Rates of forest development are too slow.

At the same time it is important to observe that a warmer ocean absorbs and holds less CO_2 from the atmosphere simply because the solubility of CO_2 in seawater declines as the temperature rises (Sarmiento 1993).

Table 23.2A. Estimates of Total Carbon (Pg) Held in Plants, Including Roots, Globally^a

Estimate	Reference	Comment
450	Bolin (1970)	
833	Reiners (1973)	
1081	Bazilevich (1974)	Assuming carbon equals 45% dry mass
592	Duvigneaud (1972)	In Bolin et al. (1979)
827	Whittaker and Likens (1975)	
760	Baes et al. (1976)	
700	Bolin et al. (1979)	
560	Atjay et al. (1979)	
500	Brown and Lugo (1981)	
558	Olson et al. (1983)	
830	Bolin (1983)	
734	Manhews (1984)	Mean of four estimates
594	Goudriaan and Ketner (1984)	
657	Esser 1987	
737	Smith et al. (1992)	

^aMean \pm standard deviation, coefficient of variation 23%: 694 \pm 162. Median: 700.

Table 23.2B. Estimates of Total Carbon (Pg) Held in Soil Organic Matter Globally^a

Estimate	Reference	Comment
700	Bolin (1970)	
1080	Yakushevskaya (1971)	Seen in Baes et al. (1976)
1051	Keeling (1973)	
1407 ^b	Bazilevich (1974)	Assuming carbon equals 50% dry mass
1000	Baes et al. (1976)	
2946 ^b	Bohn (1976)	
1456	W. H. Schlesinger (1977)	
2840	Duvigneaud (1979)	In Bolin et al. (1979)
1672 ^b	Bolin et al. (1979)	
1636 ^b	Atjay et al. (1979)	
2070	Atjay et al. (1979)	Alternate estimate
1457	Meentemeyer et al. (1981)	
1380	Brown and Lugo (1981)	
1395	Post et al. (1982)	
2200 ^b	Bohn (1982)	
1900 ^b	Bolin (1983)	
1532	Goudriaan and Ketner (1984)	
1551	W. H. Schlesinger (1984)	
1477	Buringh (1984)	
1272	Post et al. (1985)	
1576	Eswaran et al. (1993)	

^aMean \pm standard deviation, coefficient of variation 35%: 1601 \pm 565. Median: 1467.

^bIncludes a specific estimate for peat.

Table 23.2C. Estimates of Total Carbon (Pg) Held in Peat Globally^a

Estimate	Reference	Comment
114	Bazilevich (1974)	Assuming carbon equals 51.7% dry mass (Gorham 1991)
862	Bohn (1976)	From histosol maps
882	Bolin et al. (1979)	
225	Atjay et al. (1979)	Including swamp and marsh
150	Bramryd (1980)	
300	Sjörs (1980)	
124	Kivinen and Pakarinen (1981)	Calculated by E. Gorham
377	Bohn (1982)	From histosol maps
500	Bolin (1983)	
557	Gorham, new ^b	
446	Gorham, new ^c	
357	Eswaran et al. (1993)	For histosols from global soil data bases

^aMean \pm deviation, coefficient of variation 66%: 412 ± 272 . Median: 377.

^bThis new estimate is based on $133 \text{ kg carbon m}^{-2}$ in 342 million ha of northern peatlands (Gorham 1991), multiplied by a new total area of world peatlands, 419 million ha, in which the world area estimated by Kivinen and Pakarinen (1981), 450 million ha, is reduced by a correction for Canada, where the area estimate of Gorham (1991) is substituted.

^cThis new estimate is calculated as above but using a different total area of world peatlands (bogs and fens), estimated by Aselmann and Crutzen (1989) at 335 million ha.

CONCLUSIONS: WHAT WE KNOW . . . AND SOME OF WHAT WE NEED TO KNOW

Significant uncertainties continue to plague our knowledge of the global carbon cycle. There is little question that the atmospheric burdens of CO_2 , CH_4 , and other radiatively important trace gases are increasing as a result of human activities. There is also little question as to the importance of terrestrial ecosystems, especially forests, and oceans in modulating the atmospheric increase. Between 1988 and 1991 the increase varied between about 2 and 5 Pg carbon without an obvious anthropogenic cause. The modulating factors are obviously inconstant and the variability is high. The details, however important, are not known.

The most serious questions have to do with the potential for just such surprises, especially surprises that lead to positive feedbacks. The potential appears significant—

Table 23.2D. Estimates of Total Carbon (Pg) Held in Plants and Soil Globally^a

Total pool	Comment
2295	Mean phytomass + mean soil organic carbon
2167	Median phytomass + median soil organic carbon

^aIt is not always clear whether these estimates include carbon in standing dead biomass and forest litter. Bazilevich (1974) and Atjay et al. (1979) estimate the former at 75 and 30 Pg, respectively. Litter estimates by Bazilevich (1974), Whitaker (1975), and Atjay et al. (1979) are 97, 56, and 60 Pg, respectively. Bolin et al. (1979) estimate standing dead biomass and litter together at 150 Pg. Bolin (1983) estimates 60 Pg.

unfortunately more significant than the potential for surprises involving negative feedbacks. If, for instance, a sufficient decline in the water table occurs in the boreal and tundra peatlands, subterranean fires could speed oxidation of the peat in the vast, remote peatlands of Canada and Russia, spewing forth smoke, CO_2 , and CH_4 throughout the Northern Hemisphere for years. Alternatively, if water tables remain high, these peatlands might shift toward the production of CH_4 at high rates, as outlined by Gorham (Chapter 9). The issue is all the more serious because the positive feedbacks may be large enough to speed the warming and are coupled directly to some of the most difficult human problems, such as the growth of the human population and the expansion of demands for food, fiber, land, and energy. Urgency is attached to efforts to reduce the risks. Action hinges heavily on clear understanding of the problems and the consequences. The feedback issues, critical as they are, cannot be separated from basic understanding of the global climatic cycle. The following topics, slightly modified from the summary of the IPCC workshop, emerge at the moment as especially worthy of further consideration by the scientific community:

1. The implications of the feedbacks intrinsic in the data from the Vostok, Greenland, and other ice cores, which provide a record of atmospheric composition and climatic changes through glacial and interglacial periods. Do these data provide an envelope of experience within which the current world can be expected to operate? What are the causes of reversals of the trends of temperature change over glacial time?
2. The implications of the contemporary correlations between temperature and the CO_2 content of the atmosphere, in which changes in temperature precede changes in CO_2 level by about 5–7 months. Parallel correlations for CH_4 and N_2O raise additional questions worthy of detailed examination.
3. Improvement of the inventory of the carbon retained in terrestrial ecosystems globally. Satellite imagery offers the possibility of making direct measurements of changes in that inventory by quantifying changes in the area and distribution of forests and peatlands, changes in successional status, and changes in the structure of forests, all with continuously improving detail. Measurement of the frequency, area, and severity of fires bears heavily on calculation of carbon stocks on land. The data are to be used to define the role of the terrestrial vegetation, especially forests, in controlling the composition of the atmosphere. Satellite imagery and computer techniques (e.g., geographic information systems) for handling data make this realm a new frontier that offers great opportunities for innovations in scholarship and for improving management of resources in the public interest.
4. Improvement of global budgets of trace gases that affect climate, including CH_4 , N_2O , dimethyl sulfide, and ozone.
5. The implications for the composition of the atmosphere, the energy budget, and the temperature of the earth of the systematic impoverishment of the biosphere through the cumulative effects of progressive chronic disturbance.
6. The implications of the changes in climate—including changes in temperature, precipitation, fire, and composition of the atmosphere—for the growth, selection, and survival of plants and especially for the storage of carbon as net ecosystem production in terrestrial ecosystems.

7. The development of methods sensitive enough for the direct monitoring of flows of carbon in its various forms between the atmosphere and the land, with errors reduced to the order of 10% or less.
8. The refinement of analyses of the mass transport of atmospheric components, especially CO₂, through global circulation patterns as the basis for the testing of data and hypotheses on stocks and flows of carbon among the major reservoirs of land, air, and oceans. These techniques have been heavily dependent on isotopic data and on modeling.
9. Continued exploration of the role of the oceans in absorbing and sequestering carbon transferred as atmospheric CO₂ and as fixed carbon through terrestrial runoff. Have we overlooked an oceanic sink for carbon of significant size? How will the warming of the earth, or other changes now in process or probable, influence the role of the oceans and their currents in affecting the energy budget globally?
10. Exploration of the potential for an increase in UV-B or other human disturbance to affect the current biotic fluxes of organic carbon in the world oceans and thereby upset current projections of the course of the global energy budget over the next decades.
11. Continued examination of various suggestions for improving the storage of carbon on land or in the sea by nutrient fertilization or other manipulations of biogeochemical cycles.
12. Continued monitoring of atmospheric trace gases globally, with increased attention to terrestrial sites where the mobilization of large pools of carbon may become conspicuous as the warming gains momentum.

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Biotic Feedbacks IN THE Global Climatic System

Will the Warming Feed the Warming?

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