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CARBON DIOXIDE AND OTHER GREENHOUSE GASES IN OCEAN, ATMOSPHERE, AND BIOSPHERE, AND FUTURE CLIMATIC IMPACTS

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Recent Anthropogenic Changes in Carbon Dioxide and Other Radiatively Active Gases

The concentration of carbon dioxide in Earth's atmosphere is now about 340 ppm by volume; it is increasing at a rate in excess of 1ppmv/year. By the latter half of the next century, atmospheric CO_2 could be more than 600 ppmv, double the pre-Industrial values. Three-dimensional, general circulation models of the atmosphere indicate that, because of various feedhack effects, the rise in atmospheric CO_2 will probably result in an increase in Earth's average surface temperature of 2°-3°C (Manabe and Wetherald, 1975; Hansen *et al.*, 1981). The warming will be much greater at high latitudes — possibly 9°C in arctic regions during the winter-time.

Other so-called greenhouse gases, notably methane, nitrous oxide, and the chlorofluorocarbons are also increasing in the atmosphere at about the same percentage rate as carbon dioxide (Machta, 1983a). This should bring about a furtber rise in temperature, of the same order of magnitude as the carbon dioxide-induced increase (Lacis *et al.*, 1981) Because the upper layers of the ocean must warm if the atmosphere does, the expected rise in temperature will lag two or three decades behind the increasing levels of atmospheric CO_2 and the other greenhouse gases (Bryan *et al.*, 1982). Melting of methane hydrate in continental slope sediments as a consequence of the ocean warming is a potential major source of methane

which has not yet been taken into account by most workers in the field (Revelle, 1983a).

On a worldwide basis, the temperature rise will be accompanied by an increase in both evaporation and precipitation. But the dry climatic zones are likely to shift to higher latitudes. For example, the dry climatic zone which is now centered at 20°-30°N may move northward to 30°-40°N (Manabe and Wetherald, 1980).

Only about 40 percent of the carbon dioxide being released by fossil fuel combustion and forest clearing remains in the atmosphere (Brewer, 1983; Bacastow and Keeling, 1981). Between 30 and 40 percent enters the ocean, and the remainder is probably taken up by the land biosphere, mostly in forest trees and soil humus (Revelle and Munk, 1977). Carbon dioxide acts as a fertilizer for plant growth, and it also reduces the water required by plants; hence, plant growth should be greater in relatively dry seasons and regions when the CO_2 content of the air increases (Gifford, 1979).

There is little direct evidence of a biospheric uptake during the last few decades. However, indirect evidence exists. The amplitude of the seasonal swings in atmospheric CO_2 concentration appears to have increased during the past 25 years (Machta, 1983b; Keeling, 1983). These seasonal fluctuations are the result of differences in rates of photosynthesis and respiration during different seasons of the year, and it is inferred that increases in their amplitude in part reflect increases in the size of the biosphere in temperate and higher latitudes (Kohlmaier *et al.*, 1983).

On the whole, the effects of increased atmospheric carbon dioxide and expected climatic change may be beneficial for rain-fed agriculture (Waggoner, 1983; Rosenberg, 1982). Certainly, the growing season for crops will lengthen at high latitudes, and the overall increase in precipitation, as well as the CO_2 fertilizer effect, should be beneficial. However, some areas will be deleteriously affected by the shifts in climatic zones. The story may be far different for irrigated agriculture. In regions where rainfall does not increase, the rise in temperature will cause greater evaporation of soil moisture and snow cover and consequently less river run-off. For example, the flow of the Colorado River in the Western United States may be reduced by 30 percent, and this could have disastrous effects on irrigation farming in the Southwest (Revelle and Waggoner, 1983).

The warming of the ocean waters and probable increased ablation of the Greenland ice cap (Ambach, 1980) and of mountain glaciers will bring about a significant rise in sea level, estimated at between 60 and

100 centimeters, during the next 100 years (Revelle, 1983b). A further rise in sea level of about 5 meters could occur during subsequent centuries if the West Antarctic ice cap disintegrates (Bentley, 1983). Disintegration of the West Antarctic ice cap apparently occurred during the last interglacial period, but it is not certain how rapidly this took place (Figure 1) (Moore, 1982).

Past Changes in Atmospheric Carbon Dioxide - Evidence from Ice Cores

Development of techniques for analyzing air trapped at different depths in the ice sheets of Greenland and Antarctica has made it possible to reconstruct an accurate record of past atmospheric carbon dioxide concentrations, during the present interglacial and part of the last glacial period. This work has been done on ice cores from deep drill holes in the ice sheets, hy D. Raynaud and his co-workers at the Laboratoire de Glaciologie et Geophysique de l'Environnement at Grenoble, France, and by Oeschger and colleagues of the Physics Institute of the University of

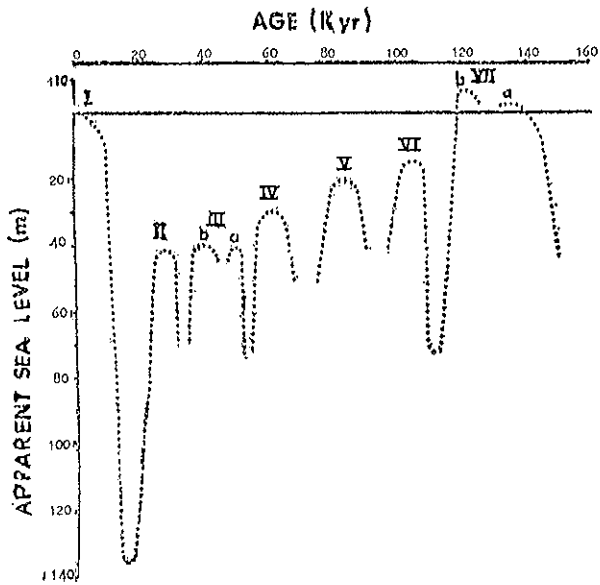

FIG. 1. High stands of sea level during the past 150,000 years. Note 6-meter terrace above present sea level, 120-125,000 years ago. This probably represents a rise in sea level resulting from the disintegration of the West Antarctic ice cap. (From Moore, 1982).

Bern, Switzerland (Neftel *et al.*, 1982). The experimental error of the gas analyses is of the order of ± 1% (3 ppmv of CO_2); the overall error, including errors in extracting air from the ice, and possibly sample variability, is about ± 3% (10 ppmv of CO_2). Measurements from the two laboratories agree within analytical errors. Although accurate dating of the samples remains difficult, several notable results have been achieved.

The early measurements suggested that the "preindustrial concentration" of atmospheric CO_2 during the middle of the 19th century was 260-270 ppmv. More recent analyses of larger ice samples indicate that a better estimate of this concentration is 280 ppmv, about 60 ppmv (corresponding to 125 gigatons of carbon) below the 1980 value at Mauna Loa, Hawaii, of 340 ppmv (Oeschger and Stauffer, 1985). Thus, atmospheric CO_2 has increased by 20% in the last 120 years. Depending on the value of the "Airborne Fraction" (the proportion of CO_2 added to the air by human activities which has remained in the air) the total quantity of carbon entering the air from fossil fuel combustion and clearing of forests was probably between 250 and 310 gigatons. Of this amount, fossil fuels contributed around 180 gigatons (Rotty, 1981) and forest clearing most of the remaining 70 to 130 gigatons (Richards *et al.* 1983). Depending on the time required to approach air-ocean temperature equilibrium, and on estimates of the magnitude of a possible CO_2-induced global temperature rise during the last 120 years, the estimated 20% increase in atmospheric CO_2 provides an indication of the sensitivity of global surface air temperatures to rising CO_2 (Hansen *et al.*, 1981).

A second result from the ice-cores is that the atmospheric carbon dioxide concentration near the coldest time of the Wisconsin glaciation, about 18,000 years ago, was much lower than in post-glacial times, the minimum value being about 175 ppmv. This low atmospheric CO_2 content may have played a major role in bringing about the extremely low temperatures which prevailed 18,000 years ago. These are reflected in very low values of the O^{18}/O^{16} ratio measured in the same cores. The atmospheric CO_2 content rose during the Bølling-Allerøyd warm phase about 12,000 years ago, and then fell slightly during the final Dryas cold period 10,000-11,000 years ago (Figure 2).

The most startling result of the ice-core analyses is that atmospheric CO_2 concentrations 30 to 40 thousand years ago apparently varied by nearly a factor of 2 over periods of less than a few hundred years (Figures 3 and 4) (Oeschger and Stauffer, 1985). That these apparent fluctuations are real is indicated by measurements of oxygen isotopes which reflect the

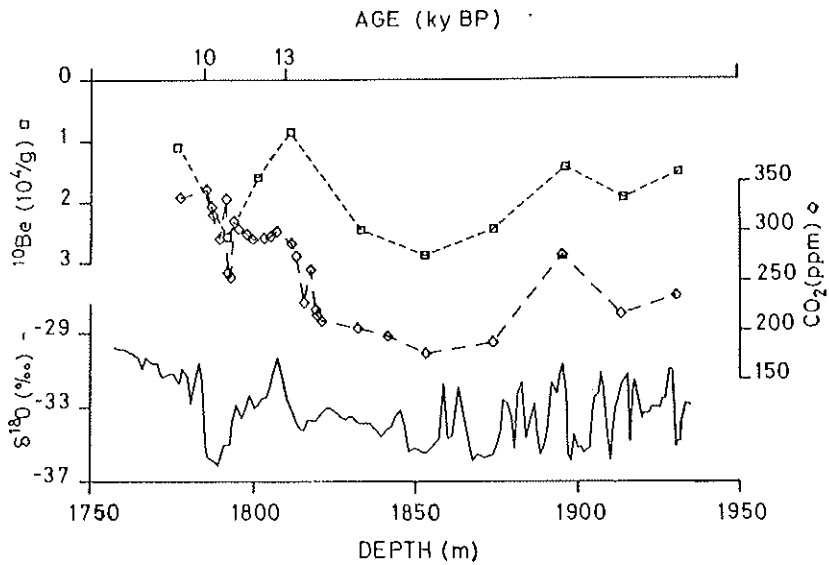

FIG. 2. CO_2 concentrations (ppmv) and $\delta\,0^{18}$ (‰) in air trapped in an ice-core (Dye 3) from Greenland. The tentative time marks at 10 and 13,000 years BP are suggested by comparison with European lake sediments dated by carbon 14. Also shown is the $Be/^{10}$ concentration (10^4 atoms per g of ice) in the core. The approximate parallelism with the $\delta\,0^{18}$ and the carbon dioxide concentration indicates that when the climate became colder the rate of snowfall on Greenland diminished. (From Neftel *et al.*, 1982).

expected atmospheric temperature change corresponding to the CO_2 variations. Rapid climatic variations during the Wisconsin glacial period are also suggested by the sea-level record inferred from ancient terraces (Figure 1) (Moore, 1982).

It is hard to see how the observed differences in atmospheric CO_2 between late glacial and post-glacial times, let alone the likely variations over a few hundred years, could occur without the existence of some kind of feedback process between the ocean and the atmosphere. One such process could be changes in the level or character of biological productivity in the upper ocean waters.

During late glacial times, the "fixed" nitrogen and phosphorus contents of ocean waters may have markedly increased through weathering and release of nutrients from the vast areas of continental shelf sediments that were exposed to the atmosphere by falling sea level (Broecker, 1982a, b). Destruction of boreal forests and other high latitude biomes by the

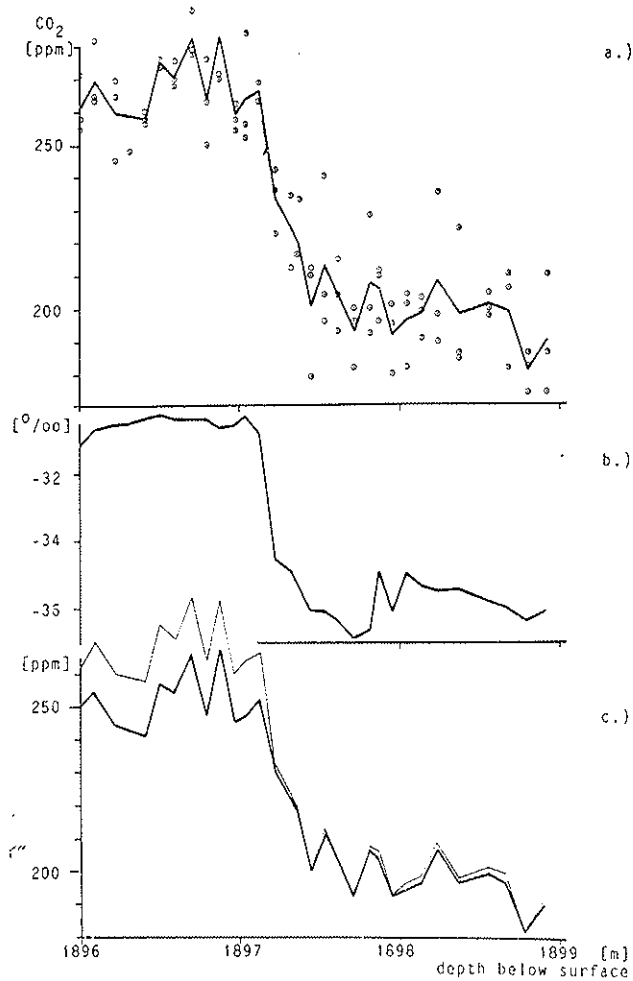

FIG. 3. CO_2 and $\delta\, 0^{18}$ measured on ice samples from the Dye 3 core in Greenland. The 30 m increment in the core corresponds to about 10,000 years, between about 30 and 40,000 years BP. (From Oeschger and Stauffer, 1985).

a) Circles indicate single measurements of the CO_2 concentration of air extracted from ice samples. The solid line connects the mean values for each depth.

b) The solid line connects the $\delta\, 0^{18}$ measurements done on 0.1 m core increments.

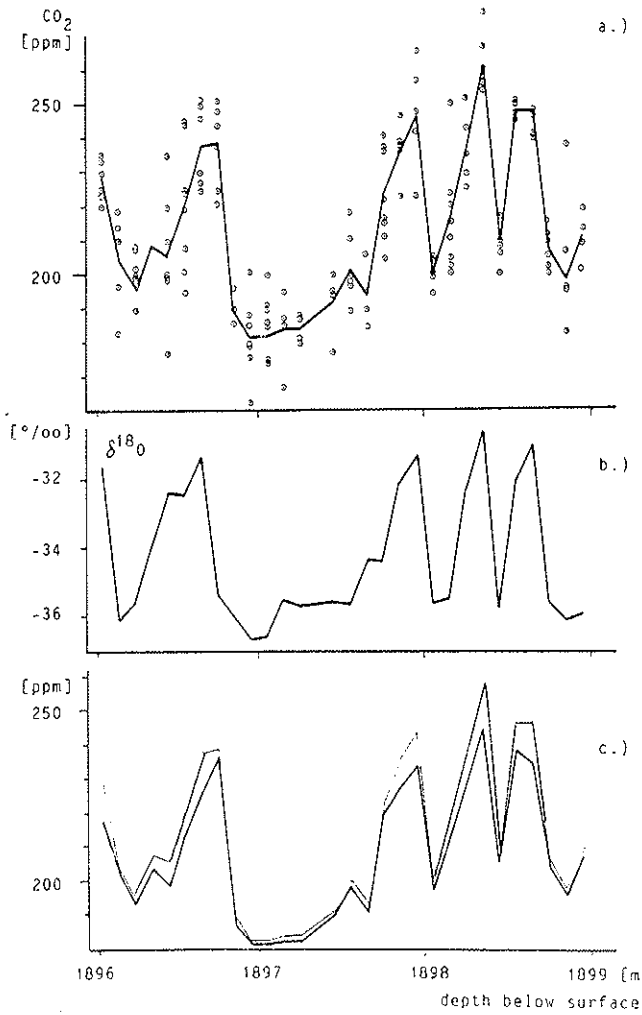

FIG. 4. CO_2 and $\delta\,0^{18}$ values measured on ice samples from Dye 3 at a somewhat greater depth than in fig. 3. The 3 m increment corresponds to about 1000 years. (From Oeschger and Stauffer, 1985).

a) Circles indicate single measurements of the CO_2 concentration of air extracted from ice samples. The solid line connects the mean values calculated for increments of about 0.1 m.

b) The solid line connects the $\delta\,0^{18}$ measurements done on 0.1 m core increments.

advancing ice sheets could also have resulted in a discharge of nutrients to the oceans. Plankton production in the oceans should have been markedly stimulated by this increase in oceanic nutrient content. If the resulting organic materials were sequestered for some time in hottom sediments on the continental slopes or in the deep sea, large quantities of CO_2 could have been extracted from the atmosphere.

Over time, this process would be self-limiting as nitrogen and phosphorus were also sequestered in the organic matter of the sediments and the deep waters and, consequently, smaller quantities of nutrients entered the sunlit upper layers of the sea where phytoplankton production occurs. The removal of nutrients from the ocean waters and the diminution of the supply of nutrients from the land could have been accelerated at the end of the Ice Age, when active biological production was reestablished in previously ice-covered areas and the continental shelves were again covered by rising sea level. Because of the lower level of phytoplankton production, there should have been a net flux of CO_2 from the sea to the air and a corresponding rise in the atmospheric content of carbon dioxide. The abruptness of the rise in atmospheric CO_2 at the end of the Ice Age 13,000 years ago is hard to explain with this hypothesis, however. It may be necessary to appeal to changes in ocean circulation accompanying the climatic change, which resulted in a markedly lower rate of upwelling of deeper nutrient-rich waters into the sunlit zone of phytoplankton production.

The short-term changes in atmospheric CO_2 occurring over a few hundred years, observed in the Greenland ice cores, may be a local phenomenon related in some way to the processes of ice deposition and air entrapment in the ice. However, if they represent worldwide changes in atmospheric CO_2, these changes must almost certainly be related to changes in oceanic circulation which resulted in large scale changes in biological production that, in turn, affected the net flux of CO_2 between the sea and the air.

Figure 5 shows, on a global basis, estimated differences in the partial pressure of CO_2 between the surface ocean waters and the ovetlying atmosphere (Keeling, 1968). During most years, in the equatorial Pacific and the eastern equatorial Atlantic, oceanic CO_2 is 30-90 micro-atmospheres higher than the atmospheric value, and hence in these regions the ocean is a net source of CO_2 to the atmosphere. Higher oceanic than atmospheric values are also found in the ocean areas of upwelling off the west coasts of North and South America and Africa, in the region of the Somali Cur-

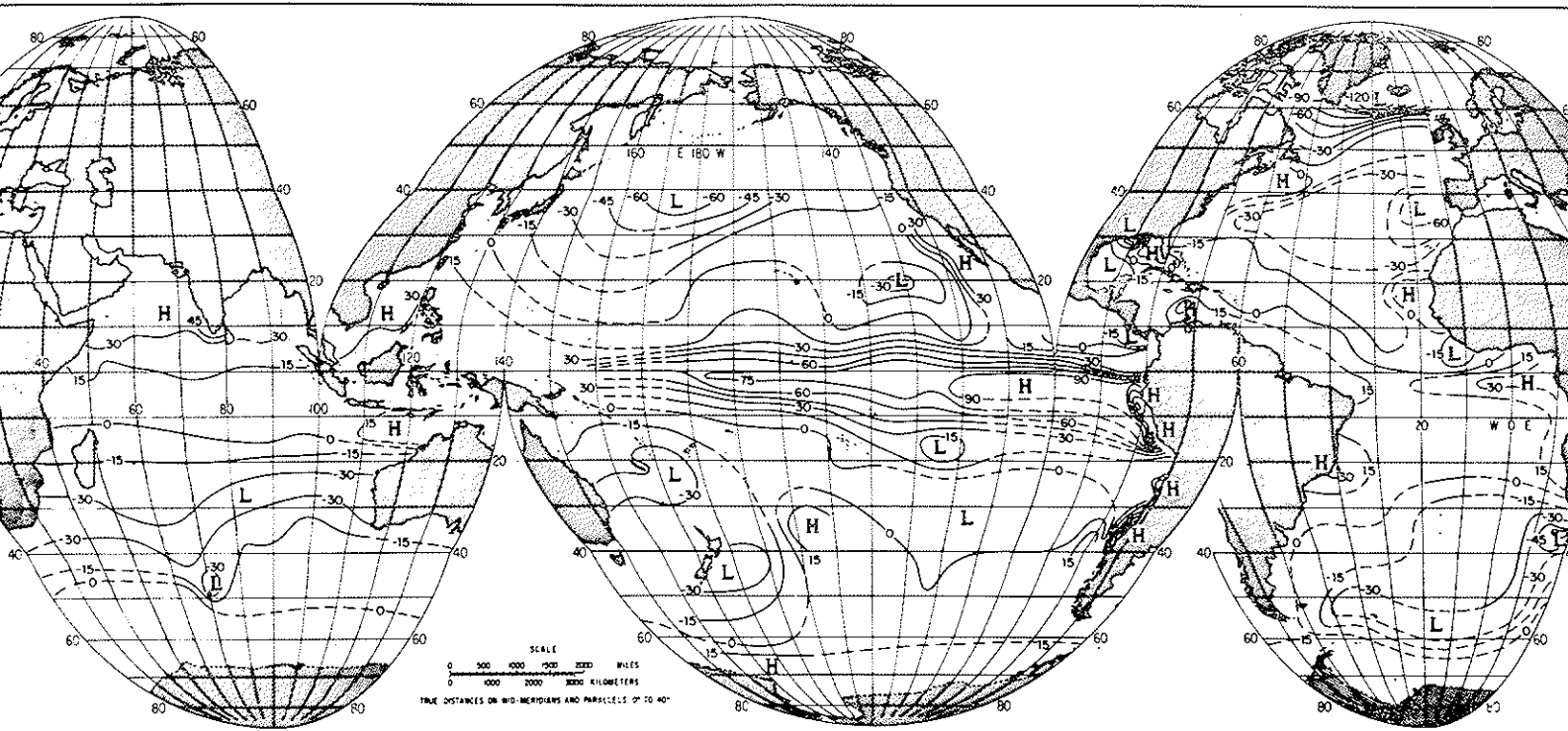

FIG. 5. Estimated approximate differences between the CO_2 partial pressure in near surface ocean waters in the overlying atmosphere, about 1965. Positive values indicate that oceanic PCO_2 is higher than in the atmosphere. Negative values indicate the reverse. (From Keeling, 1968).

rent off East Africa, in the Arabian Sea, the western limb of the Gulf Stream, and off Central Brazil. In mid latitudes of both the Pacific and the Atlantic and in high latitudes of the North Atlantic, CO_2 in the surface ocean is lower than in the atmosphere; and these ocean areas act as a net sink for CO_2. The reverse is true in high latitudes around Antarctica and in the South Pacific as far north as 40 degrees south.

The regional differences between oceanic and atmospheric CO_2 result in annual fluxes between the sea and the air of approximately 5 gigatons of carbon, corresponding to 2.5 parts per million by volume of atmospheric CO_2. This is just about equal to the present annual input of 5 gigatons of carbon to the atmosphere from combustion of fossil fuels. Roughly half tbis quantity of CO_2 from fossil fuel combustion, i.e. between 2 and 3 gigatons, enters the ocean, probably largely in mid-latitudes. This is in addition to the mid-latitude flux into the ocean of about 2.5 gigatons that would exist in the absence of fossil fuel CO_2.

The map shown in Figure 5 is based on relatively sparse data. It is at best a rough, schematic presentation of summer conditions in both hemispheres, and does not take into account either seasonal or interannual variations. These could result in marked differences in the areal extent and intensity of the regions in which there is a net flux of CO_2 from the sea to the air, and vice-versa.

As an example of possible seasonal variations, observations from an ocean-color scanning satellite indicate that in the northwest Atlantic there is a short, intense late-spring phytoplankton bloom in which a high chlorophyll content exists for a few weeks and then disappears. The phosphate content in the top 100 meters is known to decrease by about 2 grams m^{-2} between spring and summer in areas of high productivity. If this occurs over 3 percent of the ocean area, about one gigaton of carbon could settle gravitationally into the deep water after such blooms. This process is in effect a "biological pump", by which carbon is transferred from one water mass to a completely different one.

The phospborus and "fixed" nitrogen contents could be replaced annually by upwelling from a different water mass than that into wbich the carbon has settled. Over a few hundred years, the process could extract several hundred gigatons of carbon from the atmosphere. Conversely, if the spring blooms ceased or were sharply reduced in intensity and extent, one would expect carbon dioxide to accumulate in the atmospbere.

The Effect of the El Niño - Southern Oscillation on Atmospheric Carbon Dioxide

The flux from the sea to the air along the equatorial belt varies markedly from year to year, depending on the presence or absence of the phenomenon known as the Southern Oscillation - El Niño. During "normal" years total CO_2 is high at 160° west along a narrow band centered on the equator (Figure 6). Phosphate and nitrate are also high along the equator and the surface temperature is relatively low. Further east, along longitude 120° west, the belt of high CO_2, phosphate and nitrate extends from near the equator to about 20° south latitude. These are the regions of upwelling in which relatively cold water is brought near the surface from depths of several hundred meters. The dissolved CO_2, phosphate, and nitrate, remain high throughout the year. This indicates that for reasons that are not entirely clear phytoplankton production is not able to keep up with the influx of nutrients and CO_2 from the deeper water, and the upwelling CO_2 is continually released into the atmosphere (Figure 7).

Consequently, under "normal" trade wind conditions there is a secondary maximum of atmospheric CO_2 in the neighborhood of the equator in the eastern Tropical Pacific (Figure 8). That this is due to an influx of oceanic CO_2 to the atmosphere and not to tropical deforestation is clearly shown by the isotopic ratio of carbon 13 to carbon 12, which increases continuously from high northern latitudes where fossil fuel CO_2 which, like the CO_2 of the land biota, is low in carbon 13, enters the atmosphere, to about 20° south latitude.

At intervals of 2 to 10 years the trade winds in the eastern Tropical Pacific die down or even reverse direction, and warm low CO_2 water from the western Pacific flows over the eastern equatorial waters. Upwelling ceases, the phosphate, nitrate, and inorganic carbon contents markedly diminish, while the temperature rises by as much as 4 or 5 degrees (Figure 9) (Bacastow, 1976; Newell and Weare, 1977).

In principle, the equatorial maximum in CO_2 should diminish during an El Niño, and the secular increase of atmospheric CO_2 from fossil fuel combustion should be counterbalanced by the diminution of the equatorial oceanic flux. That this did not occur during the strong El Niño of 1972-73 is shown in Figure 10. During 1982-83 the secular increase in CO_2 likewise appears not to have been affected by the diminution of the equatorial oceanic flux (Keeling and Revelle, 1985). A possible explanation is given

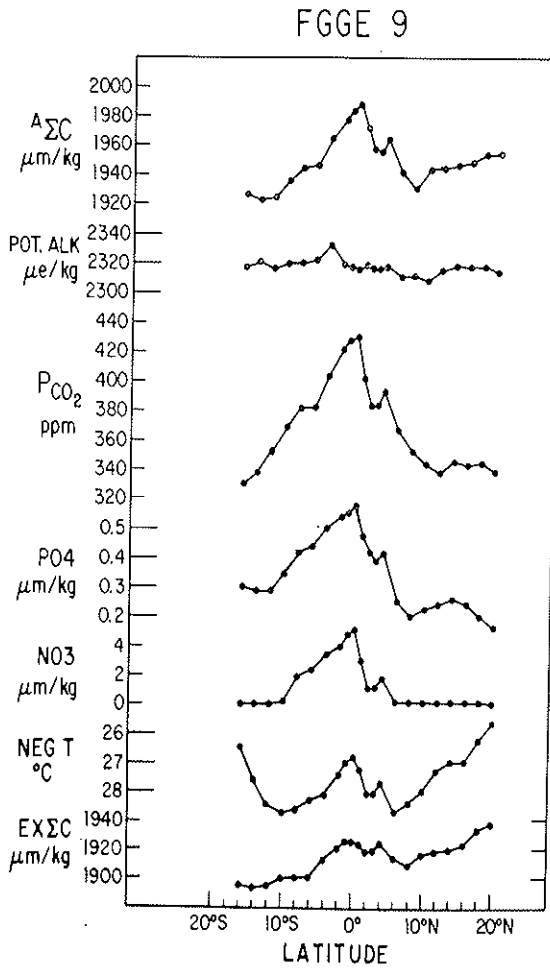

FIG. 6. CO_2 components, nutrients and temperature in a north-south section along 150° west in 1979. Note the high PCO_2, phosphate and nitrate concentrations along the Equator, and the relatively low temperature. Measurements by C. D. Keeling and others during the "First Garp Global Experiment" (FGGE).

by the C13/C12 ratios during the 1982-83 El Niño at both Mauna Loa and the South Pole. These ratios appear to have become more negative during 1982-83, indicating an increased flux of CO_2 from the land biosphere (Figure 11). We know that during this period severe droughts occurred in Australia, Indonesia, Southern India, Northeast Brazil, and West Africa. Presumably heterotrophic respiration remained constant or

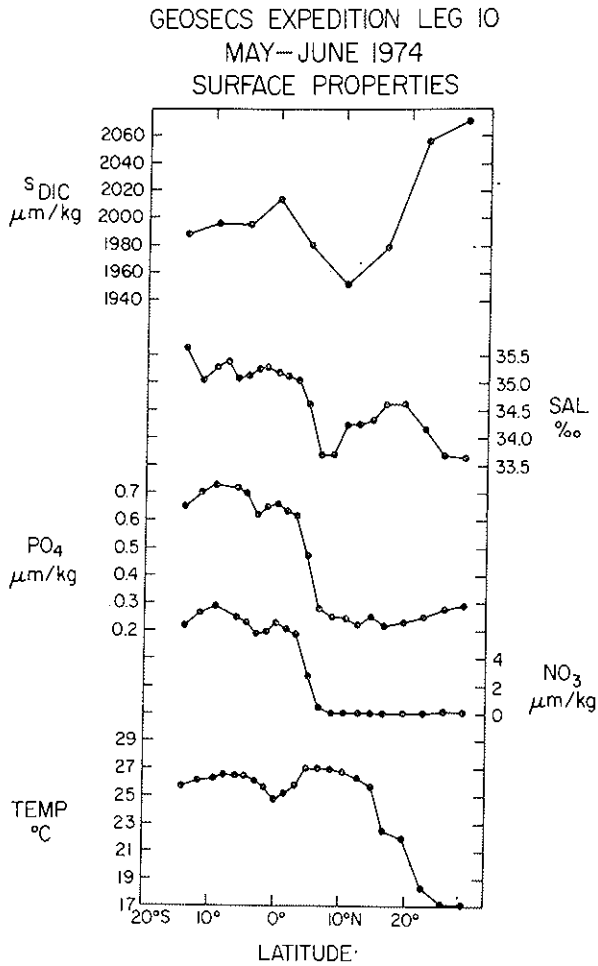

FIG. 7. Dissolved inorganic carbon, salinity, phosphate, nitrate and temperature along an approximate north-south line at 90° west longitude, in 1974. Note that high CO_2 and nutrients extend southward at least 15° from the equator in this section, which is closer to the South American coast than that shown in Fig 6. (From GEOSECS Atlas, vol. 4).

increased while net primary production markedly diminished, hence several gigatons of CO_2 may have been released from the biota and the soil, compensating for the cessation of the CO_2 flux from the equatorial ocean.

If "El Niño" conditions persisted for several years, however, this effect of drought-caused heterotrophic respiration of the land biota would disappear. The balance between the mid-latitude areas of net CO_2 flux

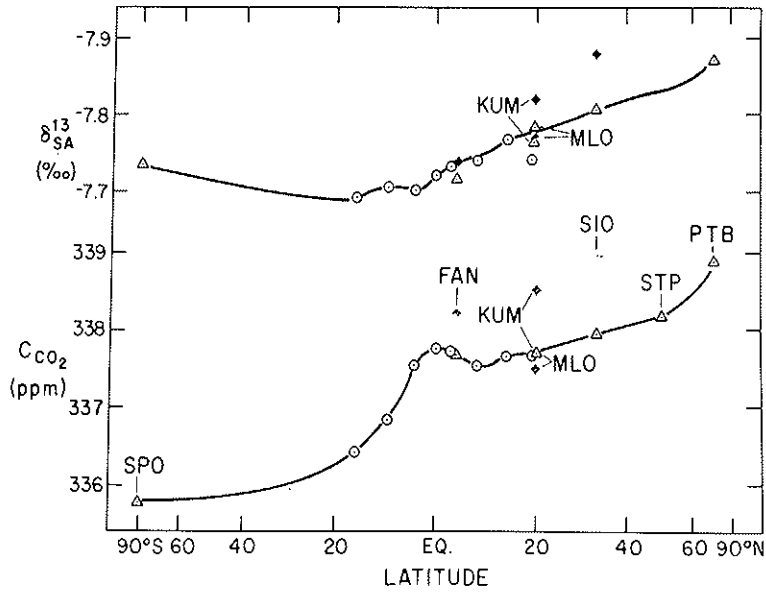

FIG. 8. The concentration of atmospheric CO_2 and an index of the carbon 13/carbon 12 ratio along an approximate north-south section from Point Barrow (PTB) weather station Papa (STP), the Scripps Institution of Oceanography (SIO), Mauna Loa (MLO) and Cape Kumakahi (KUM) on Hawaii, Fanning Island (FAN), near the equator, and the South Pole (SPO), about 1978. Circles indicate samples collected on shipboard. (From Keeling, 1983).

to the ocean and the equatorial regions of net flux to the atmosphere would shift and a net loss of atmospheric CO_2 would result. Conceivably such persistent "El Niño" conditions could have existed at intervals over periods of a century or more during glacial times.

Needed Observations

What measurements should be made to study these processes? Perhaps most important would be accurate ocean-wide time-series measurements of the inorganic CO_2 content of upper ocean waters and of the seasonal and interannual change in the difference between CO_2 partial pressure in the ocean and the atmosphere, particularly at high latitudes and in equatorial regions (Keeling, 1983).

A start on understanding large scale space and time changes in biological productivity might be made by satellite observation of chlorophyll content in the upper ocean waters. Provided difficulties of interpretation

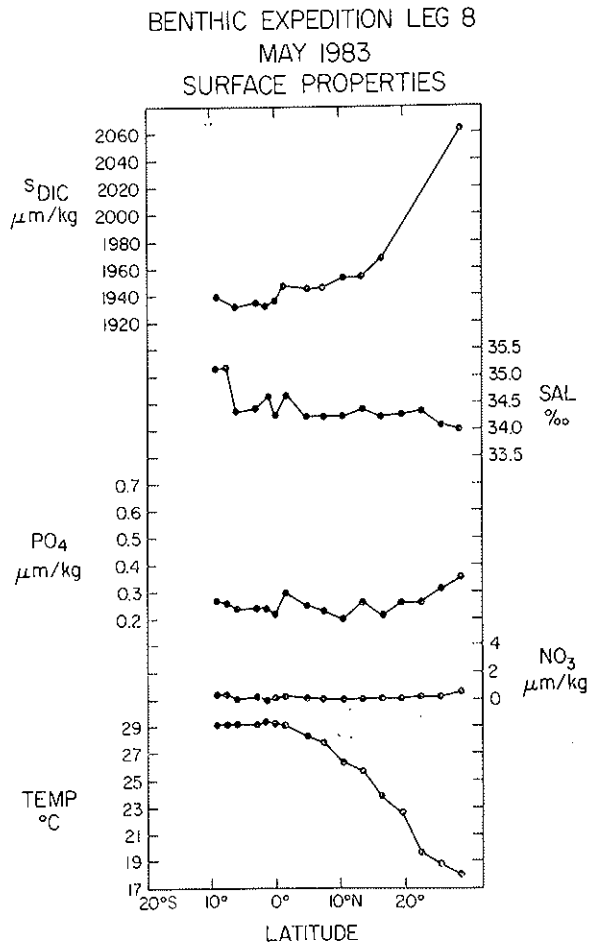

FIG. 9. Dissolved inorganic carbon, salinity, phosphate, nitrate, and temperature in surface ocean waters, during the 1982-83 El Nino, at the same longitude as in Fig. 7. Note that the high values for CO_2 and nutrients south from the equator have disappeared while the water temperature has become warmer as warm waters from the Western Pacific flooded over the region. Measurements by C. D. Keeling, R. F. Weiss and others.

can be overcome, these should be planned as a continuing program for many years, supplemented by studies of time variability in the efficiency of the "biological pump" referred to above; and of the biological processes that affect the opacity of sea water and hence the depth of penetration of sunlight into the upper ocean waters. The latter may profoundly affect mixed-layer thermocline processes.

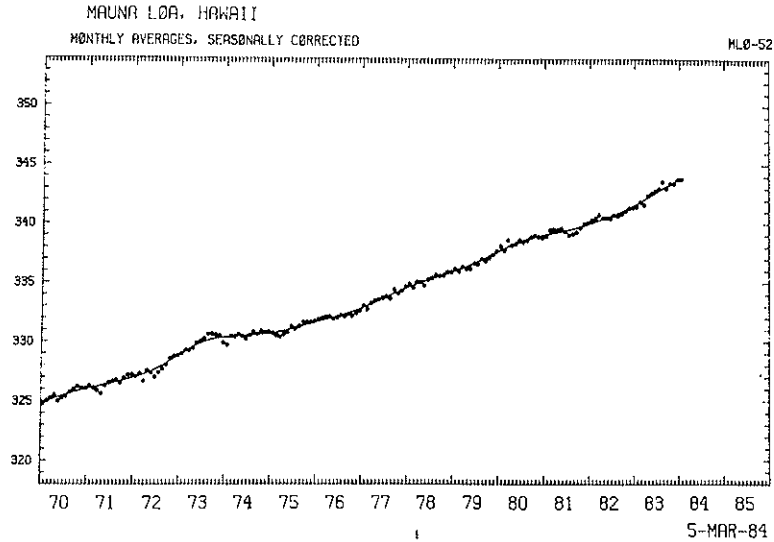

FIG. 10. Monthly averages of atmospheric CO_2 at Mauna Loa, corrected for the seasonal swing. Note that in the 1972-73 El Nino CO_2 apparently increased more rapidly than the normal secular increase, while in 1982-83 the normal secular increase was maintained. (From Keeling and Revelle, 1985).

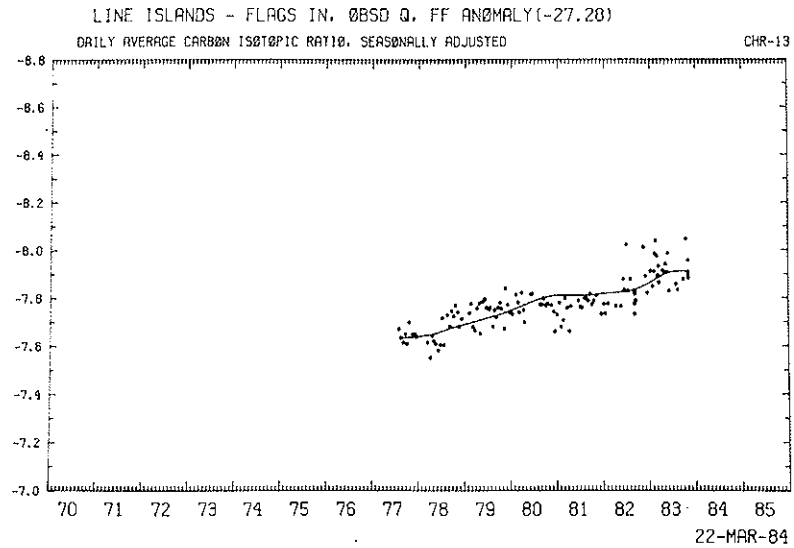

FIG. 11. Seasonally adjusted daily averages of δC^{13} near the equator between 1977 and Dec. 1983. Note that during the 1982-83 El Niño δC^{13} became more negative, indicating a flux of CO_2 to the air from the land biota. (From Keeling and Revelle, 1985).

TAB. I - *Some "trace" gases in the atmosphere and the estimated increase in global surface temperature for the indicated change in mixing ratio.*

Constituent	Mixing Ratio Change (ppb) From	To	Surface Temperature Change (°C)	Source[a]
Nitrous oxide (N_2O)	300	600	0.3-0.4	1,3
Methane (CH_4)	1500	3000	0.3	3,4
CFC-11 ($CFCl_3$)	0	1	0.15	1,5
CFC-12 (CF_2Cl_2)	0	1	0.13	1,5
CFC-22 (CF_2HCl)	0	1	0.04	7
Carbon tetrachloride (CCl_4)	0	1	0.14	1,5
Carbon tetrafluoride (CF_4)	0	1	0.07	2
Methyl chloride (CH_3Cl_3)	0	1	0.013	1,5
Methylene chloride (CH_2Cl_2)	0	1	0.05	1,5
Chloroform ($CHCl_3$)	0	1	0.1	1,5
Methyl chloroform (CH_3CCl_3)	0	1	0.02	7
Ethylene (C_2H_4)	0.2	0.4	0.01	1
Sulfur dioxide (SO_2)	2	4	0.02	1
Ammonia (NH_3)	6	12	0.09	1
Tropospheric ozone (O_3)	F (Lat, ht)	2F (Lat, ht)	0.9	4,6
Stratospheric water vapor (H_2O)	3000	6000	0.6	1

Sources: 1, Wang *et al.* (1976); 2, Wang *et al.* (1980); 3, Donner and Ramanathan (1980); 4, Hameed *et al.* (1980); 5, Ramanathan (1975); 6, Fishman *et al.* (1979); 7, Hummel and Reck (1981).

Other "Greenhouse" Gases in the Lower Atmosphere

As shown in Table I, a large number of "trace" gases in the atmosphere absorb and emit infrared radiation in a manner similar to carbon dioxide (Lacis *et. al.*, 1981). At the present time the concentrations of some of these gases, notably methane (CH_4), the chloro-fluoro carbons ($CFCl_3$, CF_2Cl_2, and CF_2HCl) and possibly tropospheric ozone (O_3), are rising at relatively rapid rates. A doubling of present concentrations of these gases, taken together, would have an effect on global air temperatures, of the same order as a doubling of CO_2. It should be noted that Table I does not take into account feedback effects of increased water vapor and lower snow-ice albedo, which are usually included in discussions of the CO_2 effect.

It is estimated that about 500 million tons of methane are being added to the air each year (Craig and Chou, 1982), largely by anaerobic production in rice paddies and wetlands as well as from the metabolism of ruminant domestic animals and, possibly, African termites (Rasmussen and Khalil, 1981; Zimmerman *et al.*, 1982). This gas is slowly oxidized by reactions with Hydroxyl free radical. Its atmospheric content is around 5 gigatons, indicating that the residence time in the atmosphere is about 10 years. As Figure 12 shows, since 1965 the atmospheric concentration of methane has increased by about 30%. If this rate continues, the methane concentration will have doubled early in the 21st century.

The causes of the increase in atmospheric methane are not clear. It is possible that the concentration of hydroxyl radical in the atmosphere is diminishing and consequently that the rate of oxidation of methane is decreasing, i.e., the residence time of methane in the atmosphere is becoming longer. Alternatively, with the growth in human population and the intensification of paddy rice production, the increase in methane may be due to larger populations of ruminants and to an increase in anaerobic

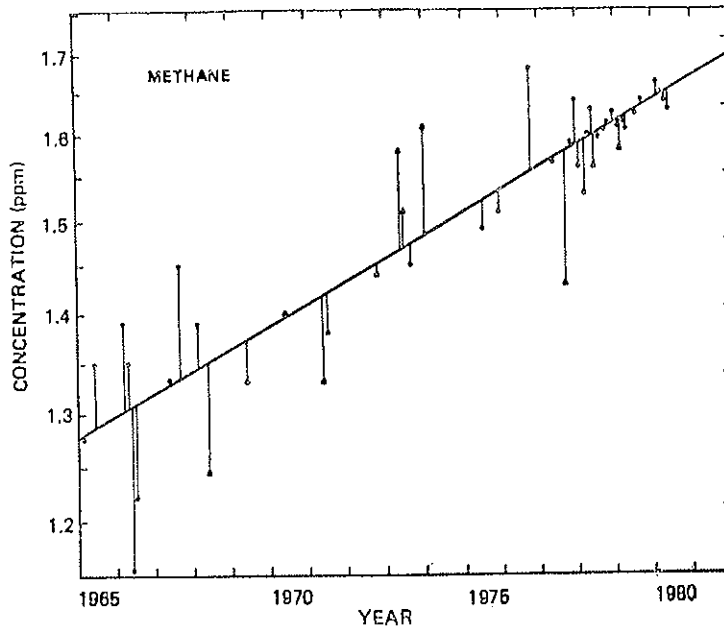

FIG. 12. Measurements of atmospheric methane (ppmv) between 1965 and 1980. The straight line is an approximate average of the data. (From Wang *et al.*, 1980).

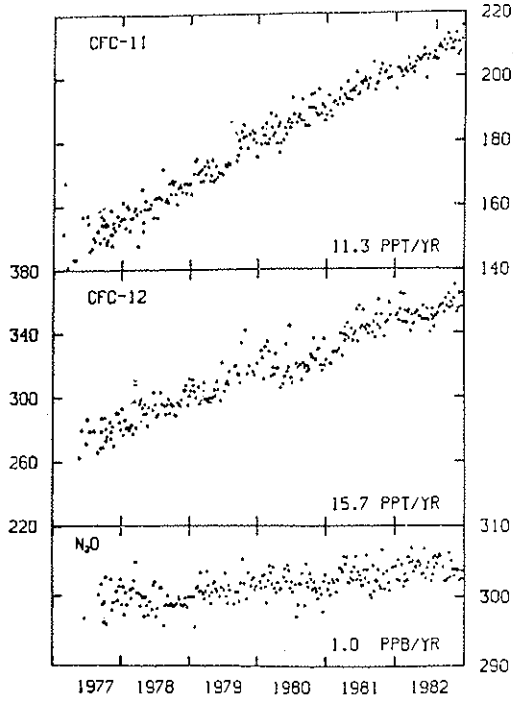

FIG. 13. Measurements of atmospheric $CFCl_3$ (CFC-11), and CF_2Cl_2 (CFS-12), in parts per trillion by volume between 1977 and 1982. Also shown are measurements of atmospheric nitrous oxide (N_2O) in parts per billion. (From U.S. Government, 1982).

production in rice paddies. Large quantities of methane (of the order of 10,000 gigatons) are believed to exist as methane hydrates (clathrates) in the sediments of continental slopes. Parts of these deposits will be released if the upper ocean and the underlying sediments become warmer under the influence of increased atmospheric CO_2. This could result in another doubling of atmospheric methane during the next 100 years and an enhanced greenhouse effect (Revelle, 1983a).

The chloro-fluoro carbons are increasing at relatively rapid rates, about 7% a year (Figure 13), and their concentrations in the lower atmosphere may reach one part per billion within the next century, bringing about a climatic warming of several tenths of a degree (Hummel and Reck, 1981; Ramanathan, 1975; Wang *et al.*, 1976). On the other hand, nitrous oxide (N_2O) appears to be increasing very slowly; several hundred years

would be required for a doubling at present rates of increase (U.S. Government, 1982).

Observations of trophospheric ozone (O_3) (Figure 14) (Angell, 1983), during the past 15 years give equivocal results. Ozone appears to be increasing significantly in the Northern hemisphere, but it is remaining relatively constant in Australia.

Early Detection of Climate Change

A lively debate exists with respect to the CO_2/Climate signal (Weller *et al.*, 1983). A minority of climatologists maintain that the CO_2 signal can already be detected in climatic data (Hansen *et al.*, 1981), while others feel that it would require CO_2 levels in the atmosphere predicted for the next century for a clear signal to emerge from background variability due to other causes (Revelle, 1982). The discrimination of long-term climatic

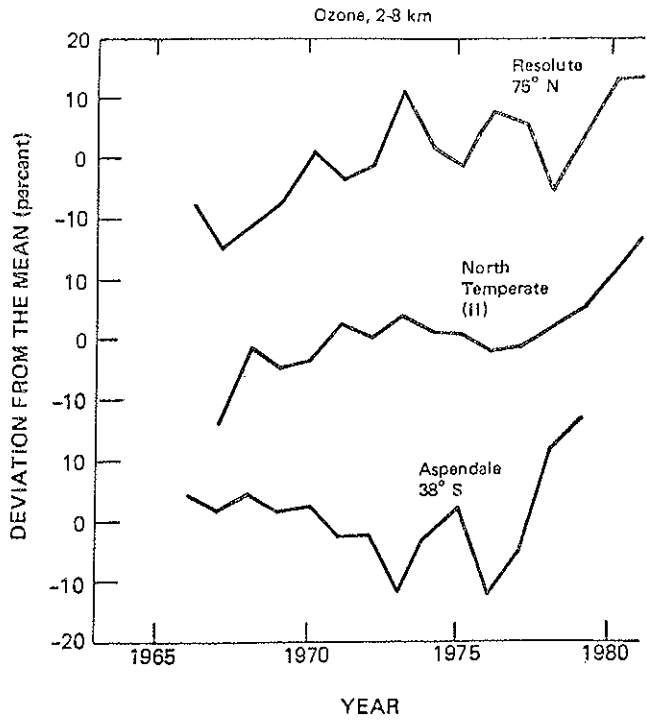

FIG. 14. Changes in tropospheric ozone at two stations in the Northern Hemisphere and one in Australia, 1965-1980. (From Angell, 1983).

trends from noisy historical data is extremely difficult. For example, surface measurements of temperature over land are difficult to interpret without corresponding measurements over the sea. Routine sea temperature measurements taken in different decades may not be comparable because of changing methods and size of the reporting vessels. Intercomparisons are very difficult between "bucket" temperatures, injection temperatures, bathy thermograph data, and microwave measurements of the "temperature" of the sea surface. The detection of long-term climatic trends requires the design of a measurement system which will overcome these difficulties of existing data sets. For this purpose measurements of water properties below the seasonal thermocline offer a possible approach to the detection problem.

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