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Table 1. Data for the determination of the turquoise bead source area; ppm, parts per million.

Element	Snaketown			Himalaya		Crescent
	Group A	Group B	Unclassified	Group A	Group B	
<i>Trace element data (ppm)</i>						
Co	1.67	1.78	1.95	1.30	1.78	1003.0
Cr	1.66	1.44	1.20	1.54	2.30	67.3
Eu	0.26	0.32	0.28	0.27	0.63	*
Sb	2.10	2.90	1.43	1.76	2.10	4.66
Sc	35.1	101.5	15.1	36.2	106.4	65.3
Ta	*	*	*	*	*	326.0
<i>Similarity coefficients</i>						
Snaketown						
Group A	1.000					
Group B	.825	1.000				
Unclassified	.544	.337	1.000			
Himalaya						
Group A	.946	.808	.613	1.000		
Group B	.861	.991	.565	.840	1.000	
Crescent	.143	.177	.092	.208	.101	1.000

\*Not detected.

limits for the Himalaya-Snaketown turquoise, but were present in many of the other samples. These basic differences served to distinguish the California source area from other localities by simple examination of the data.

The Snaketown beads fell into two groups of five and seven samples each, based on Sc contents of 35 ppm (group A) and 100 ppm (group B), with 1 sample unclassified. The data for samples from the Himalaya mine also fell into the same two groups, emphasizing the need for multiple samples from each geographic source area.

In order to characterize the mine areas statistically, it was necessary to compare the concentrations of all trace elements simultaneously. The multivariate statistic devised by Borchardt *et al.* (8), in which the ratio of each element concentration in a pair of samples is summed and divided by the number of elements, was found to be the most useful for these data (9). The coefficients thus obtained are representative of the degree of similarity, or dissimilarity, between two or more samples. That is, the coefficients are a means of quantifying the degree of correlation based on sample analytical data. Perfect similarity results in a value of 1.0, and large differences result in coefficients near zero. Borchardt *et al.* determined by replicate analyses that coefficients above .800 were indicative of an accurate correlation at the 95 percent confidence level. Conversely, values below .560 indicated that a pair of samples probably were not from the same site.

Table 1 shows the correlation coefficient matrix for the two Snaketown groups, the unclassified bead, the two Himalaya mine groups, and for the Crescent mine in Nevada. On the basis of Borchardt's criterion, there is good correlation between samples

from Snaketown A and Himalaya A, and between Snaketown B and Himalaya B. The Crescent sample is clearly unrelated.

The similarity coefficients, then, substantiated the conclusion that trace element patterns for the Snaketown beads correlated with that of turquoise from the Himalaya group of mines near Halloran Springs, but not with the data from the 23 other mines analyzed. The 13 turquoise beads, however, represent only a portion of the turquoise from the site. Since turquoise was widely traded in the Southwest, it is possible that other sources may be represented in other artifacts from Snaketown.

Cultures and cultural ties are constantly changing, and it is expected that trade pat-

terns will also change with time because of political and economic pressures, or the depletion of a resource procurement area. Chemical analysis of a commonly utilized material such as turquoise is one method of detecting, or monitoring, these changes. Further identification of source areas utilized by particular cultural groups should provide additional information on the nature of prehistoric resource acquisition and exchange routes.

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#### References and Notes

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9. The similarity coefficient

$$d_{ab} = \frac{\sum R_i}{n}$$

where  $R_i = X_{ia}/X_{ib}$  if  $X_{ib} \geq X_{ia}$ ; or  $X_{ib}/X_{ia}$  if  $X_{ia} > X_{ib}$ ;  $X_{ia}$  = the content of element  $i$  in sample a;  $X_{ib}$  = content of element  $i$  in sample b; and  $n$  = the number of elements.

10. I thank G. W. Nelson and M. E. Wacks for help with the analytical aspects of this research; the Arizona State Museum, Tucson, for the artifacts; Geodata Systems, Inc., for permission to collect turquoise samples on their property; and G. A. Borchardt for the use of his similarity coefficient program.

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## Climatic Change: Are We on the Brink of a Pronounced Global Warming?

**Abstract.** *If man-made dust is unimportant as a major cause of climatic change, then a strong case can be made that the present cooling trend will, within a decade or so, give way to a pronounced warming induced by carbon dioxide. By analogy with similar events in the past, the natural climatic cooling which, since 1940, has more than compensated for the carbon dioxide effect, will soon bottom out. Once this happens, the exponential rise in the atmospheric carbon dioxide content will tend to become a significant factor and by early in the next century will have driven the mean planetary temperature beyond the limits experienced during the last 1000 years.*

The fact that the mean global temperature has been falling over the past several decades has led observers to discount the warming effect of the  $\text{CO}_2$  produced by the burning of chemical fuels. In this report I present an argument to show that this complacency may not be warranted. It is possible that we are on the brink of a several-decades-long period of rapid warming. Briefly, the argument runs as follows. The

$^{18}\text{O}$  record in the Greenland ice core (1) strongly suggests that the present cooling is one of a long series of similar natural climatic fluctuations. This cooling has, over the last three decades, more than compensated for the warming effect produced by the  $\text{CO}_2$  released into the atmosphere as a by-product of chemical fuel combustion. By analogy with similar events in the past, the present natural cooling will, however,

bottom out during the next decade or so. Once this happens, the CO<sub>2</sub> effect will tend to become a significant factor and by the first decade of the next century we may experience global temperatures warmer than any in the last 1000 years. The remainder of this report will be devoted to the elaboration of the assumptions used in constructing the curves shown in Fig. 1 which displays this projection.

Of the climatic effects induced by man, only that for CO<sub>2</sub> can be conclusively demonstrated to be globally significant. It is difficult to determine the significance of the next most important climatic effect induced by man, "dust," because of uncertainties with regard to the amount, the optical properties, and the distribution of man-made particles (2, 3). Man-made heat currently runs a poor third to CO<sub>2</sub> and dust. Its effects will, for at least a few decades, remain entirely local (4). In this report only the interaction of the CO<sub>2</sub> effect and natural climatic change is considered. As other anthropogenic effects are shown to be significant and as means to quantitatively predict their future influence on global temperatures are developed, they can be included in models such as this. Meanwhile it is important to consider the potential impact of the two causes of change for which we do have quantitative information.

A number of people have made estimates of the change in global temperature that would result if the atmospheric CO<sub>2</sub> content were to double. These estimates range from 0.8° to 3.6°C. Manabe and Wetherald's value (5) of 2.4°C, based on a model assuming fixed relative humidity and cloudiness, is the most widely used. The difference between this estimate and that of 0.8°C by Rasool and Schneider (3) has been largely resolved. When an improved infrared radiation scheme is introduced into the Manabe-Wetherald calculation, the result drops to 1.9°C (6). However, Manabe and Wetherald (6) have suggested, on the basis of some preliminary three-dimensional calculations, that the effect in polar regions is much larger than for the "typical" atmospheric column. This polar amplification leads to an enhancement of the global effect, bringing the value up to somewhat above 2.4°C. Although surprises may yet be in store for us when larger computers and a better knowledge of cloud physics allow the next stage of the modeling to be accomplished, the magnitude of the CO<sub>2</sub> effect has probably been pinned down to within a factor of 2 to 4 (7).

The response of the global temperature to the atmospheric CO<sub>2</sub> content is not linear. As the CO<sub>2</sub> content of the atmosphere rises, the absorption of infrared radiation

Table 1. Reconstruction and prediction of atmospheric CO<sub>2</sub> contents based on fuel consumption data.

Year	Chemical fuel CO <sub>2</sub> (× 10 <sup>16</sup> g)	Excess atmospheric CO <sub>2</sub> * (× 10 <sup>16</sup> g)	Excess atmospheric CO <sub>2</sub> (%)	Excess atmospheric CO <sub>2</sub> (ppm)	CO <sub>2</sub> content of the atmosphere† (ppm)	Global temperature increase‡ (°C)
1900	3.8	1.9	0.9	2	295	0.02
1910	6.3	3.1	1.4	4	297	.04
1920	9.7	4.8	2.2	6	299	.07
1930	13.6	6.8	3.1	9	302	.09
1940	17.9	8.9	4.1	12	305	.11
1950	23.3	11.6	5.3	16	309	.15
1960	31.2	15.6	7.2	21	314§	.21
1970	44.0	22.0	10.2	29	322§	.29
1980	63	31	14	42	335	.42
1990	88	44	20	58	351	.58
2000	121	60	28	80	373	.80
2010	167	83	38	110	403	1.10

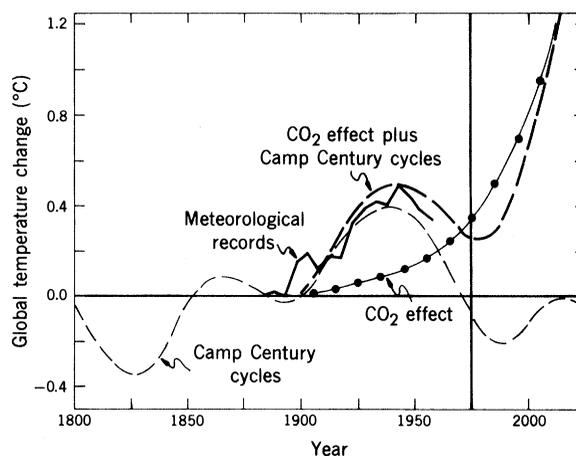
\*On the assumption that 50 percent of the CO<sub>2</sub> produced by the burning of fuel remains in the atmosphere. †The preindustrial atmospheric partial pressure of CO<sub>2</sub> is assumed to be 293 ppm. ‡Assumes a 0.3°C global temperature increase for each 10 percent rise in the atmospheric CO<sub>2</sub> content. §Value observed on Hawaii for 1960, 314 ppm; value for 1970, 322 ppm (8). ||Post-1972 growth rate taken to be 3 percent per year.

will "saturate" over an ever greater portion of the band. Rasool and Schneider (3) point out that the temperature increases as the logarithm of the atmospheric CO<sub>2</sub> content. Thus, if doubling of the CO<sub>2</sub> content raises the temperature by 2.4°C, then a 10 percent increase in the CO<sub>2</sub> content will raise the temperature by 0.32°C.

With respect to the amounts of CO<sub>2</sub> to be expected in the atmosphere, we are in a position to make fairly accurate estimates. Measurements carried out by Keeling and his co-workers on the island of Hawaii over the past 15 years suggest that the CO<sub>2</sub> content of the atmosphere rose an average of 0.7 part per million (ppm) per year from 1958 to 1972 (8). Had all the CO<sub>2</sub> generated by the burning of chemical fuels remained in the atmosphere, the rate of increase in the atmospheric CO<sub>2</sub> content should have been about 1.5 ppm/year. Thus, about half of the CO<sub>2</sub> added to the atmosphere is seemingly being removed to the sea (through combination with the CO<sub>3</sub><sup>2-</sup> ion) and to the terrestrial biosphere (through enhanced photosynthesis). Calculations based on the model of Broecker *et*

*al.* suggest that uptake by the sea can account for the removal of 35 ± 10 percent of the CO<sub>2</sub> produced (9). Other investigators (10), using oceanic mixing models which neglect short-term transfer between the surface ocean and the main oceanic thermocline, conclude that considerably smaller fractions of the CO<sub>2</sub> have gone into the ocean. In order to match the observed rate of increase in the atmospheric CO<sub>2</sub> content, these authors are required to put what I consider to be an inordinately large part of the CO<sub>2</sub> into the terrestrial biosphere. If the ocean is currently the main sink for the "missing" CO<sub>2</sub>, the models suggest that, if our CO<sub>2</sub> production continues to increase at the rate of several percent per year, the fraction of this CO<sub>2</sub> remaining in the atmosphere will remain nearly constant over the next several decades (9). If, on the other hand, a major fraction of the chemical fuel CO<sub>2</sub> is being removed to the terrestrial biosphere, we are not in as good a position to state how the distribution coefficient between the atmosphere and other reservoirs will change with time. On the time scale of a few dec-

Fig. 1. Curves for the global temperature change due to chemical fuel CO<sub>2</sub>, natural climatic cycles, and the sum of the two effects. The measured temperature anomaly for successive 5-year means from meteorological records over the last century is given for comparison.



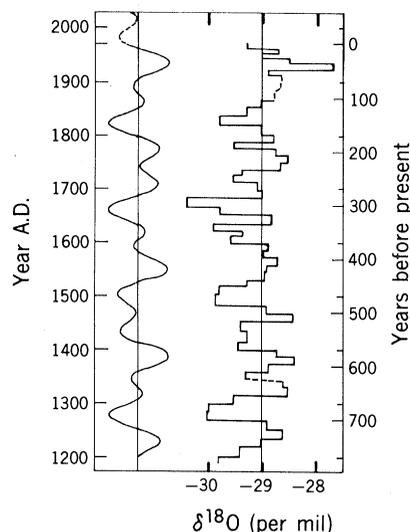


Fig. 2. Difference (per mil) between the  $^{18}\text{O}/^{16}\text{O}$  ratio in decade composites of Greenland ice from the Camp Century site and mean ocean water as obtained by Dansgaard and his co-workers (1). A decrease of 1 per mil in the  $^{18}\text{O}$  content corresponds to a  $1.5^\circ\text{C}$  drop in air temperature. The curve on the left is the simulation of the isotope curve obtained by combining sinusoidal curves with periods of 80 and 180 years.

ades, however, there is no reason to believe that it will change greatly.

The global temperature increase due to  $\text{CO}_2$  in Fig. 1 is calculated on the basis of the following assumptions: (i) 50 percent of the  $\text{CO}_2$  generated by the burning of chemical fuels has in the past and will in the near future remain in the atmosphere; (ii) the United Nations fuel consumption estimates are used to 1960 (11); between 1960 and 1975 a growth rate of 4.5 percent per year is used, and from 1975 on a 3 percent growth rate is predicted; (iii) for each 10 percent increase in the atmospheric  $\text{CO}_2$  content the mean global temperature increases by  $0.3^\circ\text{C}$ . These calculations are summarized in Table 1.

Meteorological records of the mean global temperature are adequate only over the last century. The mean global temperature (successive 5-year means) obtained from these records by Mitchell (12) is given in Fig. 1. From this record alone little can be said about the causes of climatic fluctuations. It is too short and may be influenced by pollution. Obtaining comparable information from historic and natural records for previous centuries has proved very difficult. There is no simple relation between the indices used and the temperature, and regional noise tends to mask the global picture. In my estimation the only existing record which may give a picture of the natural fluctuations in global temperature over the last 1000 years is that from the ice core taken at Camp Century in northwestern Greenland. The air temperature over this site is being recorded in

terms of the ratio of  $^{18}\text{O}$  to  $^{16}\text{O}$  in the snow which falls. Because of the polar amplification of global climatic changes [noted both in this century's meteorological records (12) and in models (6)], a strong signal emerges from the regional noise. Measurements on snow generated over a range of polar temperatures show that for each  $1^\circ\text{C}$  of cooling the  $^{18}\text{O}$  content of the precipitation drops by about 0.7 per mil (13). The time scale is obtained by extrapolation of the accumulation rates established by counting seasonal couplets (14). The widely quoted results of Dansgaard and his co-workers of measurements on the Camp Century core (1) are reproduced in Fig. 2. Clearly the fluctuation in global temperature documented by meteorological observations over the last century is not unique; similar changes have occurred in a more or less regular fashion throughout the last 1000 years. Dansgaard and his co-workers have shown by power spectral techniques that cycles of 80 and 180 years appear in this record. The model curve to the left of the isotopic curve (Fig. 2) is their best fit to the data based on the use of only 80- and 180-year cycles.

The amplitude of the last half "cycle" in Greenland (1900 to 1940) as recorded by meteorological observations (both give about  $1.5^\circ\text{C}$  warming) (2, 3). Also the ice core record is roughly in phase with the global change recorded meteorologically. Consistent with the Manabe-Wetherald model (6), the amplitude of the temperature change in the polar region is several times larger than the global average.

The curve of natural fluctuations drawn in Fig. 1 was obtained as follows. The pattern of the fluctuations is that obtained by Dansgaard and his co-workers (1), assuming that the 80- and 180-year periods dominate the natural record. The amplitude of the curve is reduced so that, when summed with the  $\text{CO}_2$  effect, it yields a reasonable

Table 2. Projections based on an analogy to individual Camp Century cycles over the last 800 years.

Warm peak No.*	Years to next cold minimum*	Projected date for next cold minimum
1	40	1980
2	25	1965
3	40	1980
4	35	1975
5	55	1995
6	30	1970
7	25	1965
8	35	1975
9	35	1975
Mean	35	1975
Simulation†	50	1990

\*See Fig. 3.

†See Fig. 2.

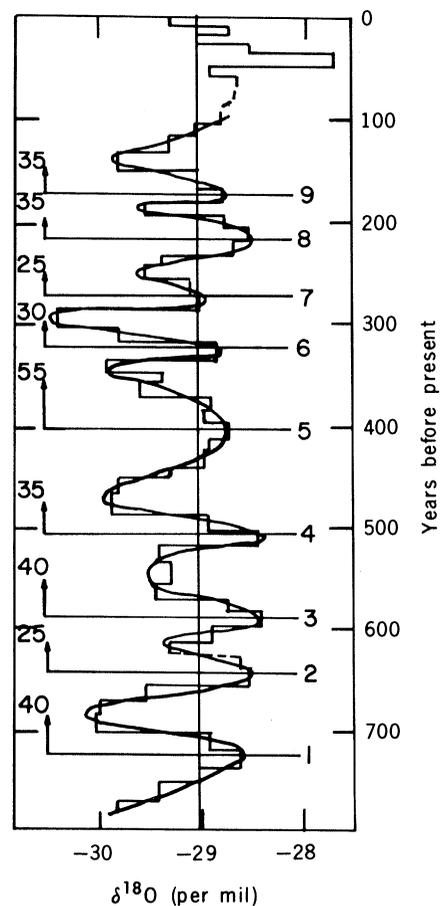


Fig. 3. Spacings between warm maxima and cold minima for the "smoothed" Camp Century ice core  $^{18}\text{O}$  curve.

match to the global temperature curve for the last century (that is, a fourfold reduction due to polar amplification is made).

The resultant curve obtained by combining the  $\text{CO}_2$  effect with the simulated natural curve shows dramatically what will happen if the natural cooling trend bottoms out and swings into the next warming phase according to the schedule postulated here. Global temperature would begin a dramatic rise which would continue for about four decades (that is, half the 80-year cycle). This warming would by the year 2000 bring average global temperatures beyond the range experienced during the last 1000 years. Until chemical fuel consumption is dramatically reduced, global temperatures would continue to rise. Future natural cycles would merely modulate this ever-steepening rise (40-year periods of more rapid increase followed by 40-year periods of less rapid increase).

Although the details of the argument presented here depend largely on the results of Dansgaard *et al.* (1), simulation of the Camp Century cycles, the sense of the argument, is not dependent on these results. As shown in Fig. 3 and Table 2, a similar conclusion with regard to the timing of the forthcoming natural minima would be reached by analogy with almost

any portion of the Greenland record over the last 700 years. If anything, the simulation puts the next minimum farther into the future than would estimates based strictly on analogies with previous "cycles." Thus, whereas the exact date of the minimum shown in the extended natural climate curve (Fig. 1) is uncertain, its occurrence in the next decade is probable. The rate of warming beyond the minimum is also open to question. As the CO<sub>2</sub> effect will dominate, the uncertainty here lies mainly in the estimates of future chemical fuel use and in the magnitude of the warming per unit of excess atmospheric CO<sub>2</sub>. The major point of the argument is that over the past 30 years the warming trend due to CO<sub>2</sub> has been more than countered by a natural cooling. This compensation cannot long continue both because of the rapid growth of the CO<sub>2</sub> effect and because the natural cooling will almost certainly soon bottom out. We may be in for a climatic surprise. The onset of the era of CO<sub>2</sub>-induced warming may be much more dramatic than in the absence of natural climatic variations.

The agricultural consequences of this ensuing warming are not obvious (neither are the implications to global sea level). A knowledge of the mean global temperature tells us little about the rainfall patterns in the chief grain-producing regions. There is little doubt, however, that this gradual warming will lead to changes in the pattern of global precipitation. Our efforts to understand and eventually to predict these changes must be redoubled.

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10 March 1975; revised 7 May 1975

## Chlorinated Hydrocarbon Pollutants and Photosynthesis of Marine Phytoplankton: A Reassessment

**Abstract.** *The chlorinated hydrocarbons DDT and PCB's (polychlorinated biphenyls), ubiquitous pollutants of the marine environment, have been observed to reduce the cell division rate of marine phytoplankton, thereby indirectly reducing the total photosynthetic carbon fixation in treated cultures. The photosynthetic capacity of each cell was not affected. Total marine photosynthesis will likely remain undiminished by these compounds, although alterations in phytoplankton communities through selective toxicity could affect herbivore populations.*

Several persistent and ubiquitous chlorinated hydrocarbon pollutants of the marine environment, most notably PCB's (polychlorinated biphenyls) and DDT [1,1,1-trichloro-2,2-bis(p-chlorophenyl)ethane], can reduce the growth rate (1, 2) and have been reported to reduce photosynthesis (2-4) in some marine phytoplankton cultures. The decrease in carbon fixation observed in treated cultures (2-4), as measured by the incorporation of <sup>14</sup>C-labeled bicarbonate, could have resulted from an inhibition of the photosynthetic process itself, or it may have been due to a depressed growth rate, that is, fewer cells photosynthesizing in treated than in control cultures.

I conducted an experiment to determine whether algal photosynthesis on a per cell basis, as well as on a per culture basis, was affected by PCB's or DDT. The organochlorine concentrations used were above those found in natural waters (5); no attempt was made to determine the toxicity of environmentally realistic concentrations of these compounds, as was done elsewhere (6). The purpose of this study was to establish whether, in algae, photosynthetic carbon fixation itself is inhibited or whether just growth is affected by these chemicals.

The three algal species studied (7) were selected on the basis of their sensitivity to chlorinated hydrocarbons: the growth of *Thalassiosira pseudonana* and *Skeletonema costatum*, common marine diatoms, is affected by PCB's and DDT (1), and photosynthetic carbon fixation in cultures

of *Coccolithus huxleyi* and the two diatoms is reportedly reduced by DDT (2, 3). Culture conditions and procedures have been described elsewhere (8). Methanolic solutions of PCB's (Aroclor 1254) or DDT were injected (1) into the cell suspensions at time zero to give initial PCB concentrations of 10 µg/liter (parts per billion) and DDT concentrations of 50 ppb in the medium. Equal volumes of methanol were added to the control cultures (9). These organochlorine compounds, at similar concentrations (or doses per cell), have been reported to substantially depress the net carbon fixation in monocultures of these algal species (2, 3). At 48 hours, 1 ml of medium was removed from each tube so that cell counts could be determined (10), 0.2 µc of [<sup>14</sup>C]NaHCO<sub>3</sub> was added (11), and the cultures were incubated as before for about 5 hours. The same procedure was also carried out for dark controls. The cells were then gently filtered through 0.8-µm Millipore filters and washed with filtered seawater; the radioactivity of the filters was counted in a liquid scintillation counter (Tri-Carb, Packard). The entire experiment was repeated with the two diatom species.

Table 1 presents the 48-hour cell counts, photosynthetic carbon fixation per culture, and carbon uptake per cell (α). The dark uptake of <sup>14</sup>C, which varied with each species (being 2 percent of the illuminated *T. pseudonana* <sup>14</sup>C uptake, less than 1 percent with *S. costatum*, and 10 percent with *C. huxleyi*), was subtracted from the raw