

AD-A145 825

(21)

A TRIDENT SCHOLAR PROJECT REPORT

NO. 130

VARIATIONS WITH TIME OF THE CARBON DIOXIDE
PARTIAL PRESSURE IN CENTRAL AND SOUTH
ATLANTIC SURFACE WATERS



SEP 1 1984
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ANNAPOLIS, MARYLAND
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER U.S.N.A. - TSPR; no. 130 (1984)	2. GOVT ACCESSION NO. 4D-A145825	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) VARIATIONS WITH TIME OF THE CARBON DIOXIDE PARTIAL PRESSURE IN CENTRAL AND SOUTH ATLANTIC SURFACE WATERS.		5. TYPE OF REPORT & PERIOD COVERED Final: 1983/1984
7. AUTHOR(s) Lipphardt, Bruce		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS United States Naval Academy, Annapolis.		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS United States Naval Academy, Annapolis.		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE 25 May 1984
		13. NUMBER OF PAGES 23
		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) This document has been approved for public release; its distribution is UNLIMITED.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) This document has been approved for public release; its distribution is UNLIMITED.		
18. SUPPLEMENTARY NOTES Accepted by the U. S. Trident Scholar Committee.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Carbon dioxide Ocean-atmosphere interaction Chemical oceanography Oceanographic research		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Increasing levels of atmospheric carbon dioxide have been hypothesized to cause future global warming as a result of an enhanced "greenhouse effect." Man is responsible for the addition of carbon dioxide to the atmosphere through the burning of fossil fuels and the removal of vegetation from the continents. Future climatic changes caused by a global warming are of governmental concern because of their economic impact, and possible future restrictions on the use of fossil fuels are a likely result. (OVER)		

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S N 0102-LF-014-6601

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A study of time variations of surface ocean carbon dioxide levels is necessary to determine whether or not the oceans absorb significant quantities of atmospheric carbon dioxide. Three existing data sets are used to construct time variation studies covering 9 and 15 year intervals.

The resulting comparisons show that oceanic carbon dioxide levels do not consistently increase with time, although some significant increases are noted. One comparison suggests that the geographic location of local carbon dioxide sources and sinks may be changing with time. Studies covering a larger time interval are necessary to establish more clearly the response of the oceanic surface layer to increasing atmospheric carbon dioxide levels.

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Variations With Time of the Carbon Dioxide Partial Pressure in Central and South Atlantic Surface Waters

by

U. S. Naval Academy
Annapolis, Maryland

Accepted for Trident Scholar Committee

Chairman

May 25, 1984

Date _____



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Abstract

Increasing levels of atmospheric carbon dioxide have been hypothesized to cause future global warming as a result of an enhanced "greenhouse effect." Man is responsible for the addition of carbon dioxide to the atmosphere through the burning of fossil fuels and the removal of vegetation from the continents. Future climatic changes caused by a global warming are of governmental concern because of their economic impact, and possible future restrictions on the use of fossil fuels are a likely result.

It has been suggested that the carbonate system in the oceans may act as a carbon dioxide sink by converting excessive atmospheric carbon dioxide to dissolved ions. The role of the oceans as a carbon dioxide sink has not been clearly established, however.

A study of time variations of surface ocean carbon dioxide levels is necessary to determine whether or not the oceans absorb significant quantities of atmospheric carbon dioxide. Three existing data sets are used to construct time variation studies covering 9 and 15 year intervals.

The resulting comparisons show that oceanic carbon dioxide levels do not consistently increase with time, although some significant increases are noted. One comparison suggests that the geographic location of local carbon dioxide sources and sinks may be changing with time. Studies covering a larger time interval are necessary to establish more clearly the response of the oceanic surface layer to increasing atmospheric carbon dioxide levels.

Introduction

Man has been adding carbon dioxide to the atmosphere through fossil fuel burning and deforestation. Increased atmospheric carbon dioxide levels have been hypothesized to cause future warming of the earth's atmosphere. The role of the oceans with respect to carbon dioxide is not clear, although it seems logical that the oceanic carbonate system may act as a carbon dioxide sink for excessive atmospheric concentrations. This means that the oceans could act to lessen the climatic effects of man's increased output of carbon dioxide.

Some data exist that can be compared in a meaningful way as a first look at surface ocean carbon dioxide concentration variations with time. Two comparisons will be used to analyze the role of the oceans as a carbon dioxide sink, first between the years 1957 and 1972, and second, between the years 1963 and 1972.

Historical background

The question of possible climatic changes brought on by increasing levels of carbon dioxide in the atmosphere has received much attention in the past three decades. Man has been adding carbon to the atmosphere at an increasing rate since the beginning of the industrial revolution around 1860, through the burning of fossil fuels (coal, oil, and natural gas) and through the removal of trees and vegetation from the continents, called deforestation. Fossil fuel burning releases carbon dioxide

directly to the atmosphere, while deforestation removes an important carbon dioxide sink (photosynthesis), so that both have the same effect on atmospheric carbon dioxide levels.

The fact that atmospheric carbon dioxide is increasing became apparent in the early twentieth century, and it was soon hypothesized that the increase could result in a temperature rise at the earth's surface brought about by an enhanced "greenhouse effect" (Revelle, 1982). Carbon dioxide alters the earth's heat balance by increasing the amount of thermal radiation retained in the earth-atmosphere system. It acts as a one-way screen for solar radiation, allowing the incoming shortwave radiation to pass through to the surface, where it is absorbed and emitted as longwave, infrared radiation. Carbon dioxide molecules in the atmosphere absorb a portion of this longwave radiation that would otherwise freely escape to space. This absorbed thermal radiation is transferred to adjacent air molecules, which emit heat in all directions. A portion of this emitted heat returns to the earth's surface. The net result, then, is an increase in the total amount of radiation retained near the earth's surface, caused by the molecular carbon dioxide "screen" in the atmosphere. This process is known as the "greenhouse effect" (Revelle, 1982). Atmospheric trace gases such as ozone, carbon monoxide, nitrous oxide, and methane, as well as water vapor, could also contribute significantly to future climate changes, since they have thermal absorption properties similar to those of carbon dioxide (Clark, 1982, p. 257).

In the years 1957-1958, during the International Geophysical Year, a project was organized by Charles Keeling to monitor atmospheric carbon dioxide at two sites: Mauna Loa, Hawaii, and the South Pole. The data recorded at these sites since that time show an exponential increase in carbon dioxide levels, reaching an annual rate of increase of 1.4 ppm per year by the late 1970's. This increase provides convincing evidence of the influence of fossil fuel burning and deforestation on the chemistry of the atmosphere (Revelle, 1982).

The trend displayed by Keeling's data sparked a great deal of interest in predicting possible future climate changes. Mathematical models based on a variety of assumptions have been developed as prediction tools to estimate the average global temperature rise that can be expected from continued carbon dioxide increases. A recently emerging consensus estimates that the average atmospheric surface temperature will increase by 2 to 3 degrees C due to a doubling of current carbon dioxide concentrations (Clark, 1982, p. 4). The hypothesized effects of this predicted increase include changes in regional agricultural patterns, changes in rainfall, and a rise in the global average sea level brought about by a combination of partial melting of the ice caps and thermal expansion of ocean waters. It is apparent, then, that the effects of increasing carbon dioxide are economically significant and thus deserve careful attention to determine what can be done to lessen the severity of problems caused by a changing climate.

As more is learned about possible adverse effects of carbon dioxide on climate, government policy will attempt to limit the use of fossil fuels and promote alternative energy sources. The U. S. Navy is a major consumer of fossil fuels and will be affected by policies limiting their use in the future. Navy vessels and shore installations world-wide are currently dependent on fossil fuels as a primary energy source, and this dependency illustrates the need for advanced research to discover alternative sources for the Navy of the future. The adverse effects of fossil fuels on the environment make continued development of ships, aircraft, and shore facilities powered by these fuels unwise. New systems using alternative energy sources must be explored and developed in order to maintain the operational flexibility that the Navy requires. Government regulation of the Navy's fossil fuel systems could result in reduced defense capabilities. Proper planning for the energy requirements of the future will enable the Navy to maintain its current level of operational readiness.

Carbon in the environment

The carbon cycle utilizes four major reservoirs: the atmosphere, the oceans, land and aquatic biota, and the rocks and sediments. The cycle describes the distribution of carbon in the environment and the processes affecting its transfer between the various reservoirs. An increase in the atmospheric concentration of carbon dioxide will necessarily affect carbon distribution in

the other reservoirs as well, although the exact relationships are not well understood. It has been hypothesized that, over a long period of time, the carbonate system in the oceans will act as a sink for carbon dioxide (SCOR Working Group 62, 1980).

The role of the oceans as a sink for fossil fuel carbon dioxide has not been clearly established, and there is a need for additional surface ocean water carbon dioxide concentration data on a global scale. Charles Keeling (1968) provides a list of all sources of carbon dioxide partial pressure ($p\text{CO}_2$) data available at that time. Since then, the GEOSECS program (1972-1973) has provided a large volume of additional data (Bainbridge, 1981), and other isolated research vessels have made measurements as well.

Currently, very little work has been done in studying time variations of surface water $p\text{CO}_2$ values. Louis Gordon and his colleagues (1973) studied $p\text{CO}_2$ variations in the north Pacific Ocean over a period of 5 months, from October 1968 to March 1969. Matthias Buchen (1971) compared data collected along 30 degrees west longitude in the Atlantic Ocean in 1933, 1968, and 1969. Generally, this comparison shows an increase of $p\text{CO}_2$ with time, although the comparability of the data is questionable, since the measurement techniques used in 1968-1969 were not available in 1933, so that the data sets not only vary in time but also in analytical method.

It would be of interest to compare $p\text{CO}_2$ data collected over a period of several years, so that long-term variations for a

specific region could be determined. Several factors affect $p\text{CO}_2$ of surface waters, including temperature, barometric pressure, biological activity, and geographic location. All of these factors should be considered in a time comparison of $p\text{CO}_2$ data.

In order to study time variations of surface water carbon dioxide levels, two data sets spanning an interval of at least 8 to 10 years must be collected for the same geographic location. Although the data coverage of the world's surface waters is currently not extensive, there are some data that overlap geographically and facilitate a meaningful study of changes in surface water carbon dioxide concentrations with time. Data from the Lusiad Expedition in 1963 (Keeling and Waterman, 1968) and from the Vema cruise in 1957-1958 (Takahashi, 1961) can be compared with GEOSECS data collected in 1972 (Bainbridge, 1981) for certain regions of the central and south Atlantic Ocean. A comparison of this type would offer valuable insight into the role of the oceans in the global carbon cycle. It would also provide physical evidence to help determine whether or not the oceans act as a sink for excess atmospheric carbon dioxide. This paper will attempt to provide such a comparison.

Carbon dioxide partial pressure data

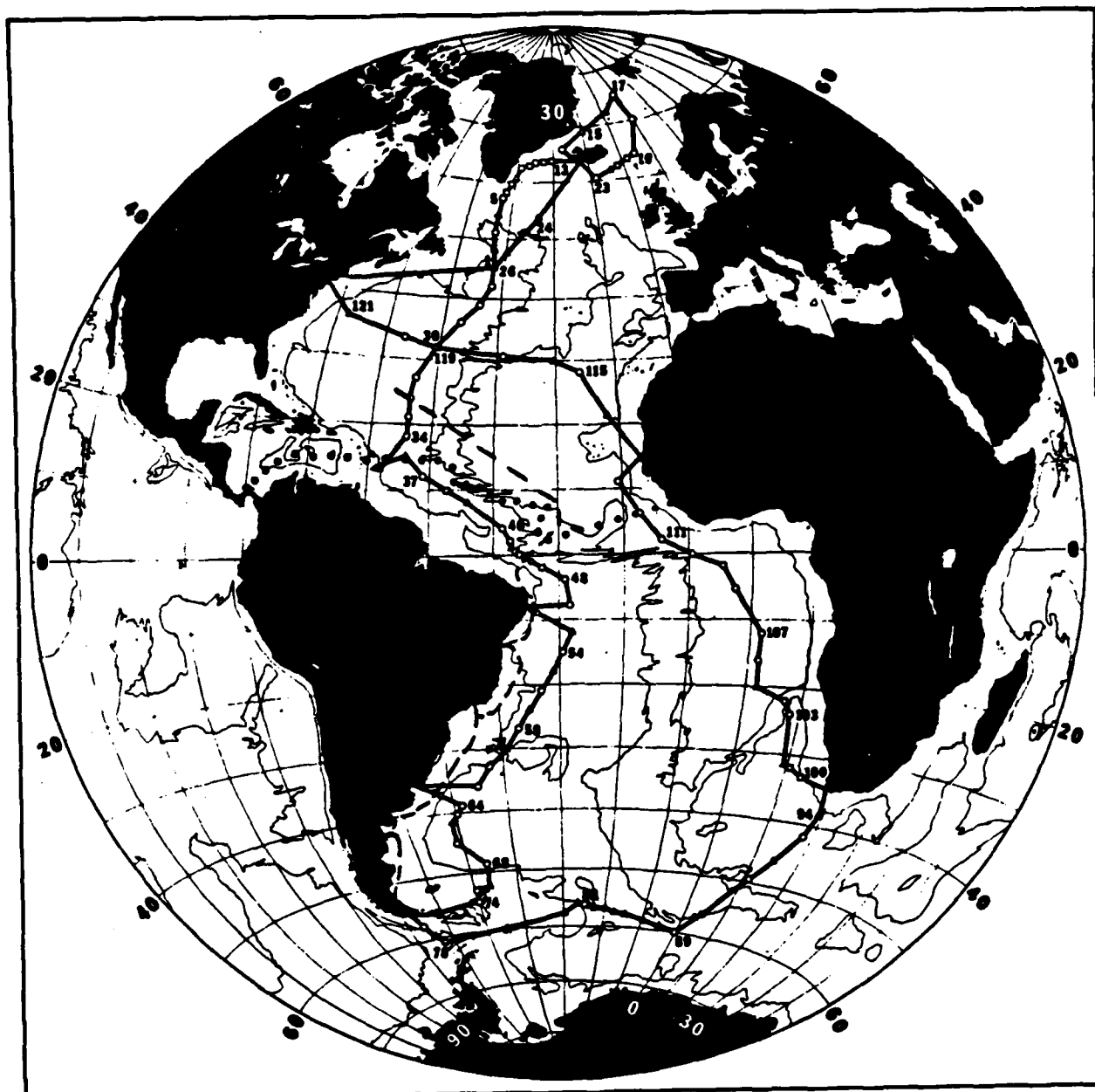
The research vessel Vema collected $p\text{CO}_2$ data in the Atlantic Ocean region as part of an International Geophysical Year program in December-February, 1957-58. A portion of the vessel's track

off the eastern coast of South America is represented by a dashed line in Figure 1.

Takahashi (1961) presented the data collected by the Vema along the track shown in Figure 1. His work gives detailed explanation of the measurement and calibration techniques used. Continuous $p\text{CO}_2$ measurements were made using an infrared gas analyzer, which detects carbon dioxide through its absorption of infrared energy. Water samples are allowed to equilibrate with a volume of air which is free from other infrared absorbers. The CO_2 concentration of the air is then measured with the infrared analyzer. After equilibration, this measurement also represents the $p\text{CO}_2$ value of the water sample.

In October-December 1972, as part of the Geochemical Ocean Sections Study (GEOSECS), carbon dioxide partial pressure data were collected along a track that was geographically very close to the 1957-58 Vema track discussed above. Continuous $p\text{CO}_2$ measurements were again made using infrared analysis. The GEOSECS track is represented by a solid line in Figure 1, and the resulting data are presented in atlas form by Arnold Bainbridge (1981).

A comparison of the Vema cruise data and the GEOSECS data is presented in Figure 2. Each curve represents the variation of surface ocean carbon dioxide partial pressure (in parts per million) with latitude. The Vema cruise data are presented as average values for ten degree latitude bands, and the bracket notation is used to represent error ranges expressed by Takahashi



- R/V Vema (1957-1958)
- R/V Argo, Lusiad Expedition (1963)
- GEOSECS (1972)

Figure 1 - Tracks of vessels involved in surface ocean pCO_2 data collection

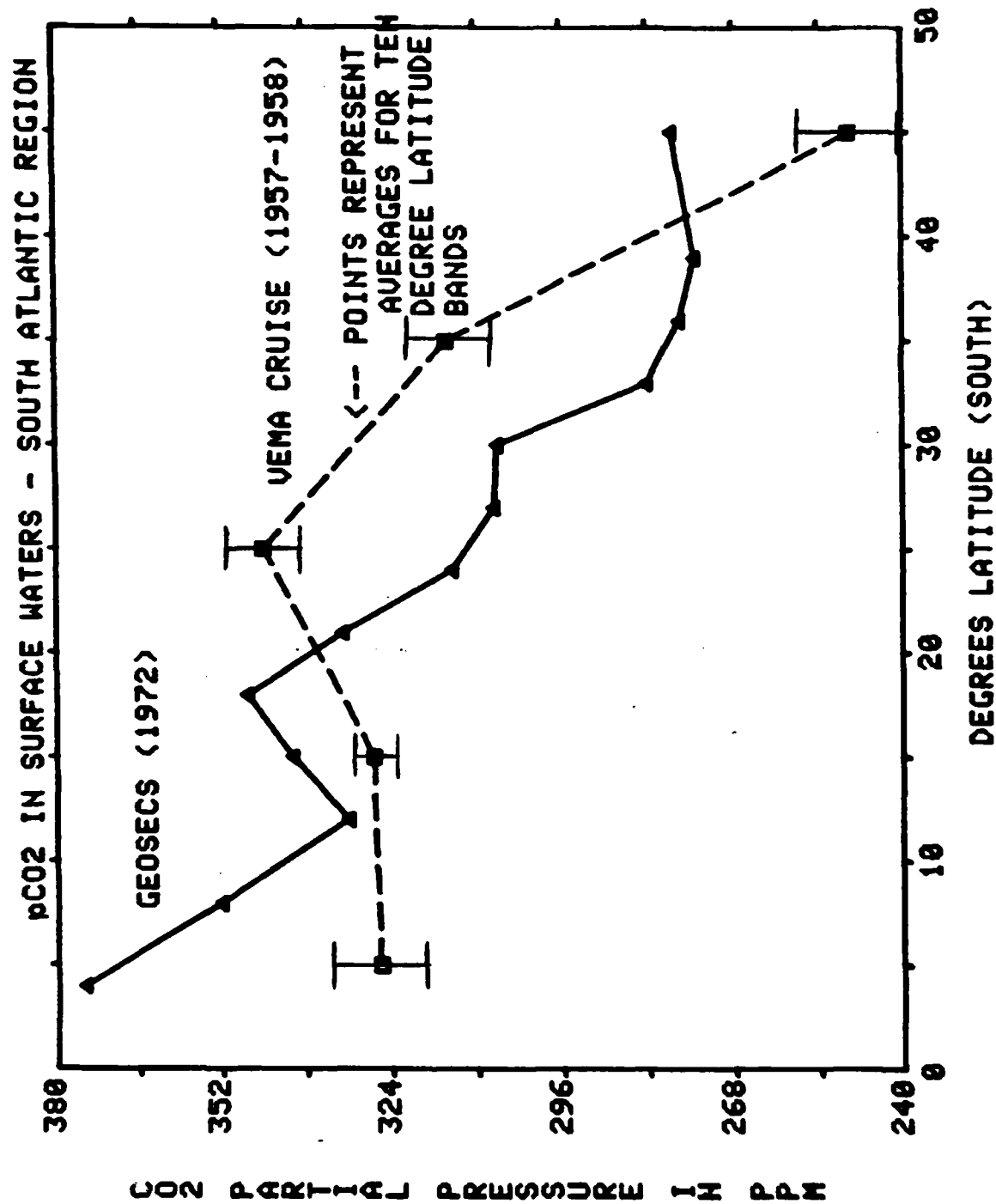


Figure 2 - Comparison of surface ocean pCO₂ data collected in 1957 and 1972 - south Atlantic Ocean

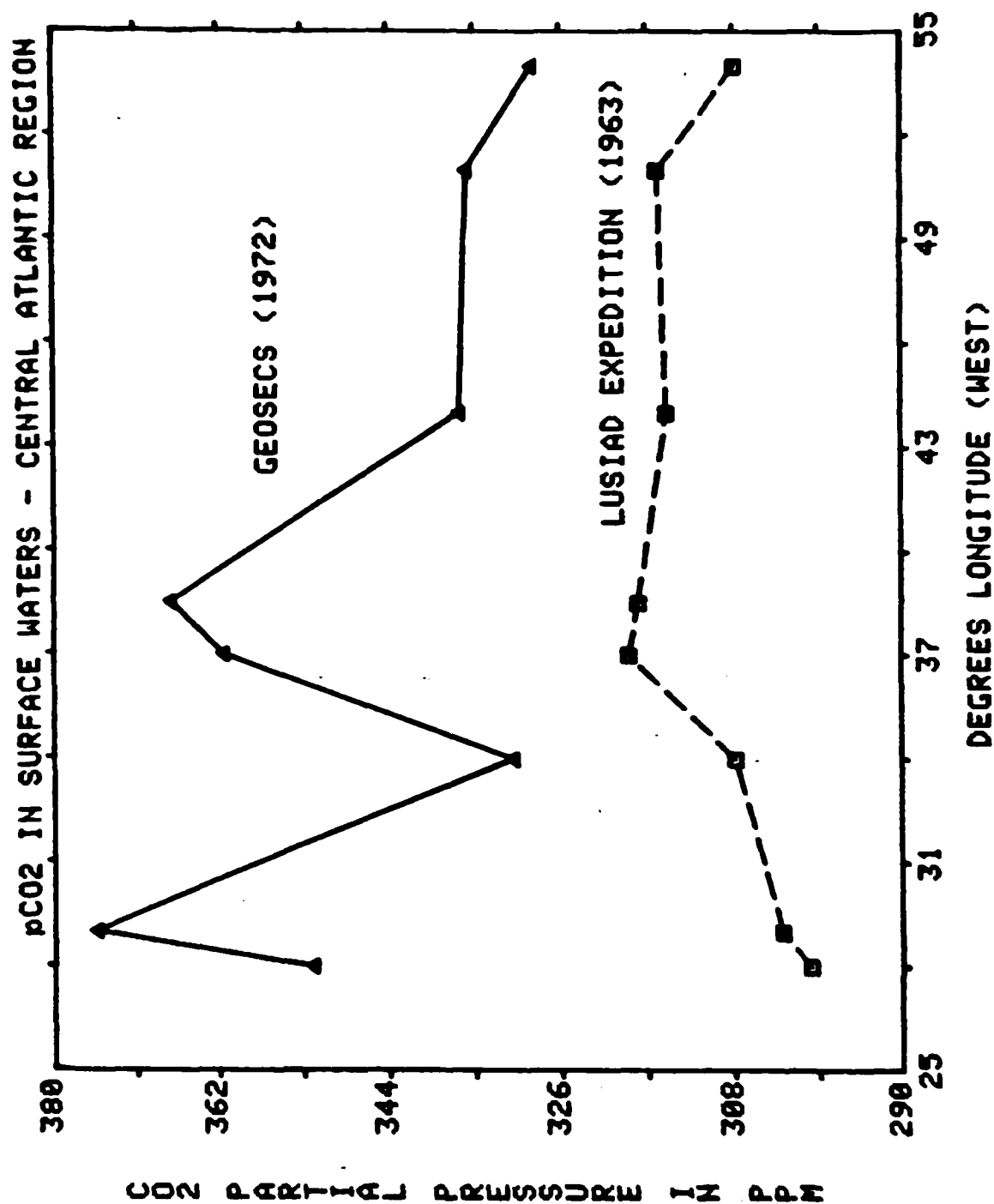
in his report of the data. The resulting comparison shows the variation of $p\text{CO}_2$ in the surface ocean water for this geographic location between 1957-58 and 1972.

A similar time variation comparison can be made between the GEOSECS data and data collected during the Lusiad Expedition in July, 1963. A partial track of the research vessel Argo, assigned to the Lusiad Expedition, is shown as a dotted line in Figure 1. The GEOSECS and Lusiad tracks cover the same geographic region of the central Atlantic, although the two are offset slightly. The Argo collected continuous $p\text{CO}_2$ data along the track using an infrared analysis technique similar to the one discussed above. The Lusiad Expedition's data were published by Keeling and Waterman (1968).

Figure 3 represents a comparison of the Lusiad Expedition data with the GEOSECS data for the central Atlantic Ocean. Each data curve represents the variation of surface ocean carbon dioxide partial pressure (in parts per million) with longitude. By comparing the data curves, the variation of $p\text{CO}_2$ in the surface ocean water for this region of the Atlantic between 1963 and 1972 can be determined.

Analysis of the comparisons

In comparing surface ocean carbon dioxide concentration data, it is important to keep in mind the factors that affect $p\text{CO}_2$ in sea water. These factors are variables that directly influence the local carbon dioxide concentration in surface



waters, and they must be considered in making a time interval analysis of different data sets.

The complexity of the carbonate system in the oceans makes it impossible to consider all possible factors that influence carbon dioxide levels in the oceans. There are, however, five significant variables that must be considered in studying time variations of surface ocean $p\text{CO}_2$. Since these factors are primarily seasonal in their variation, they become important in comparing data sets that were collected during different months of the year.

The five factors to be considered are surface water temperature, barometric pressure, vertical mixing, biological activity, and local atmospheric carbon dioxide concentrations. Since information about the effects of these factors was not published with the data, an assumption must be made about their influence on $p\text{CO}_2$ values over the time interval studied. It is logical to assume that the variation of these factors is seasonally dependent, so that some consideration of their relative effects on $p\text{CO}_2$ values can be made by noting the month or months over which the data were collected. This will facilitate a generalized consideration of the effects of environmental changes that occur in the atmosphere and in the surface ocean water with time.

In addition to considering environmental changes with time, three assumptions must be made concerning differences in the collection of the three data sets being compared.

First, it is assumed that the measurement techniques used to collect each data set are directly comparable. Since Keeling was consulted by Takahashi prior to the Vema cruise, the infrared analysis procedures used by the Vema and the Lusiad Expedition are similar. Takahashi was involved in the GEOSECS data collection as well, so that Keeling's influence is present in all three data sets, and the measurement systems all use the infrared technique.

Second, it must be assumed that the surface layer is well-mixed with respect to dissolved carbon dioxide between 1 meter and 15 meters of depth. This assumption is necessary because there is no control over the sample depths used in collecting each data set. Some of the GEOSECS data were collected at a depth of 15 meters, so that a direct comparison between the data sets suggests a homogenous surface layer extending to this depth. No data were collected above a depth of 1 meter, where the greatest vertical variation in pCO_2 exists (due to contact with the atmosphere and wave action), so that this assumption is at least plausible.

Third, it is assumed that the ship's tracks being used for data comparison represent the same geographic location. Figure 1 shows that this is not exactly the case, since both comparisons use tracks that are slightly offset from each other. The comparisons were constructed so as to minimize the amount of offset in order to get as much overlapping data as possible.

Currently, no exact geographic overlapping exists among $p\text{CO}_2$ data sets, so that this is a necessary assumption.

The comparison shown in Figure 2 does not show a consistent increase in surface ocean $p\text{CO}_2$ with time. The Vema data were collected in December and January and the GEOSECS data were collected in November, so that little seasonal influence should be evident in the comparison. Environmental effects on $p\text{CO}_2$ should therefore be minimal in this case. The lower latitudes do reflect an increase in $p\text{CO}_2$ with time, but this trend shifts below 20 degrees South, where a decrease of $p\text{CO}_2$ with time is evident. This comparison suggests that the ocean does not act as a significant carbon dioxide sink, since carbon dioxide concentrations do not consistently increase with time.

It is interesting to note, however, that the data trends for each curve are the same below 20 degrees South. Each curve displays a decrease in $p\text{CO}_2$ with increasing latitude. The fact that the similar trends are offset by almost 7 degrees of latitude indicates that the location of the water masses may be shifting with time. Between 1957 and 1972, it is possible that water masses having similar chemical properties shifted northward by approximately 7 degrees, due to changes in ocean circulation. Figure 2 indicates that this may be the case when carbon dioxide concentrations are observed.

In contrast, Figure 3 shows a consistent increase in surface ocean $p\text{CO}_2$ with time. The Lusiad Expedition data were collected in July and the GEOSECS data were collected in November, so that

some seasonal influence could be displayed in a comparison of the data. The geographic location of the measurements, however, is predominantly equatorial, as shown in Figure 1, so that seasonal variations of the environmental factors in this region will be at a minimum. The significance of seasonal influence in a comparison of equatorial data is therefore reduced, since the impact of the seasons on the equatorial regions is comparatively smaller than that on the mid-latitude regions.

The consistent trend of increase in pCO_2 displayed by Figure 3 suggests that the oceans do act as a significant sink for excessive atmospheric carbon dioxide. The magnitude of the increase is not constant with respect to longitude, which indicates the patchy nature of carbon dioxide distribution in the surface layer. The comparison shows an approximate increase in pCO_2 of 10-20 ppm over a period of 9 years.

Conclusions

The two data comparisons presented do not provide convincing evidence to indicate that the oceans act as a sink for excessive atmospheric carbon dioxide. A consistent increase in surface ocean pCO_2 is not evident in both data comparisons, although Figure 3 does show such a trend. A greater number of time comparisons are necessary to clearly establish the role of the oceans in carbon dioxide uptake.

Since Keeling's atmospheric data show an annual increase in atmospheric carbon dioxide of only about 1 ppm per year for the decade being studied (Revelle, 1982), it may not be possible to

observe a definite trend of increase for such a short time period. Oceanic uptake of atmospheric carbon dioxide is a comparatively slow process, and a total atmospheric increase in carbon dioxide of 10-15 ppm for the interval studied may not be detectable in a comparison of surface ocean pCO_2 values.

It is possible that the geographic location of local carbon dioxide sources and sinks may be changing with time. Figure 2 shows an offset of approximately 7 degrees of latitude that indicates such a shift in pCO_2 distribution. If this is the case, time interval pCO_2 studies of the same geographic location may not be as meaningful as studies that compare pCO_2 values for the same water mass, regardless of its specific geographic location. If shifting water masses can be tracked and observed with time, a determination of their changing carbon dioxide concentrations can be made. This determination would provide information about the oceans role in the carbon cycle.

In order to more completely understand the response of the oceans to increasing atmospheric carbon dioxide levels, longer time-interval studies of surface water carbon dioxide concentration are necessary. The comparisons made here use a time interval of 9-15 years, which is not sufficient to indicate clear trends in oceanic response. As more data are collected, longer time-interval comparisons can be made.

Acknowledgements

I would like to gratefully acknowledge the Reference staff of the Nimitz Library, U. S. Naval Academy, Annapolis, Maryland

for their help in locating and obtaining a majority of my reference material. Also, I would like to acknowledge the Carbon Dioxide Information Center of the Oak Ridge National Laboratory for their valuable assistance in providing a computerized bibliography of applicable sourcework. Finally, I want to thank Professor Jerome Williams of the U. S. Naval Academy Department of Oceanography for his guidance and advice at every stage of the development of this work.

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