

MULTI-PROPERTY MODELING OF OCEAN BASIN
CARBON FLUXES

FINAL REPORT

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Final Report to NASA:

GRANT NAGW-850, Multi-Property Modeling of Ocean Basin Carbon Fluxes

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The scientific objectives of this project were to elucidate the causal mechanisms in some of the most important features of the global ocean/atmosphere carbon system. These included the interaction of physical and biological processes that produce the distinct large-scale patterns of surface water pCO₂, the quantification and effects of processes in the seasonal cycle of surface water pCO₂, and links between productivity, surface chlorophyll, and the carbon cycle that would aid global modeling efforts. In addition to work discussed below that fulfilled these objectives, several other areas of critical scientific interest involving links between the marine biosphere and the global carbon cycle were successfully pursued; specifically, a possible relation between phytoplankton⁹ emitted DMS and climate, and a relation between the location of calcium carbonate burial in the ocean and metamorphic source fluxes of CO₂ to the atmosphere. Most of this report consists of six scientific papers published in the open scientific literature between 1987 and 1989; these papers resulted from work supported by this grant and they acknowledge this support. The papers are discussed below, and their order for discussion and inclusion in this report is:

Rampino, M. R., and T. Volk, Mass extinctions, atmospheric sulphur and climatic warming at the K/T boundary, *Nature*, Vol. 332, pp. 63-65, 1988.

Volk, T., Sensitivity of climate and atmospheric CO₂ to deep-ocean and shallow-ocean carbonate burial, in press, *Nature*, (Feb. 12) 1989.

Volk, T., and Z. Liu, Controls on CO₂ sources and sinks in the earthscale surface ocean: temperature, nutrients, *Global Biogeochemical Cycles*, Vol. 2, pp. 73-89, 1988.

Volk, T., How well can we know the pre-anthropogenic, earth scale patterns of $\Delta p\text{CO}_2$ between ocean and atmosphere?, submitted to *Global Biogeochemical Cycles*, 1989.

Volk, T., Effect on atmospheric CO₂ from seasonal variations in the high latitude ocean, *Advances in Space Research*, in press, 1989.

Volk, T., Limitations on relating ocean surface chlorophyll to productivity, *Advances in Space Research*, Vol. 7, No. 2, pp.(2)137-(2)140, 1987. (this paper was re-set and reprinted in *Modeling in the Global Ocean Flux Study*, U.S. GOFS Planning Report Number 4, July, 1987, U.S. GOFS Planning Office, Woods Hole)

The first two papers I will discuss follow significant new lines of scientific investigation regarding the influence of the marine biosphere on global climate. Quantifying links between biota and climate is essential to the NASA's new trust into Earth Systems Science, and as such these papers represent an important expansion of the scope of the original project.

A key turning point came with a paper by Charleson et al. (1987). They proposed a connection between cloud albedo over the oceans and the release of dimethyl sulphide (DMS) by marine algae. This was an important reversal in direction of global ocean fluxes, which are usually considered as downward transports from the surface ocean to deep waters. DMS is a biological flux upwards from the ocean's surface into the atmosphere. While the downward fluxes of products from surface photosynthesis can affect climate via altering the carbon cycle of the ocean and hence atmospheric CO₂, the upward flux of DMS may alter climate by changing the reflective properties of clouds. My colleague, Michael Rampino, and I were familiar with the anomalous geochemistry at the mass extinction horizon of the K/T boundary and the previously-unexplained evidence for warming immediately following the boundary. If DMS emission cools the climate by increasing the albedo of clouds, the cessation of DMS would create climate warming. The near-sterilization of the oceans at the K/T boundary, the well-established "Strangelove" ocean of minimal productivity from evidence of homogenization of carbon isotopes and lack of calcium carbonate deposition, is consistent with global warming due to near-cessation of DMS production (Rampino and Volk, 1988). This paper was cited in special articles in such magazines as Newsweek, Science News, New Scientist, and many newspapers.

I recognized the relevance of this new research in DMS and climate to NASA's programs in Ocean Productivity and Interdisciplinary Earth Sciences. Combining satellite data of ocean color and cloud albedo might be a way to test the theory. There already has been a counter to the Charleson et al. hypothesis (Schwartz, 1988), but Charleson is preparing a rebuttal (R. H. Gammon, personal communication). The importance of clouds in the Earth's climate has recently been given new impetus by Ramanathan et al. (1989) in evidence that clouds are net cooling forcings to the planet. A connection between global cloud cover and marine productivity is a perfect topic for future research by NASA, and I proposed such a program at the NASA Ocean Color workshop:

Volk, T., Ocean color, clouds, and climate—a new research front?, invited talk given at NASA workshop, Ocean Color in the GOF S Era, sponsored by NASA Headquarters, Sept. 29- Oct. 1, Annapolis, Maryland, 1987.

This work had a role in forming the most recent new group of research topics for NASA's Interdisciplinary Program in Earth Sciences. In Research Announcement NRA-88-OSSA-11 of 31 August 1988, under Research Topic 2, Trace Gas Fluxes from Ecosystems and their Fate in the Troposphere, further work is requested to investigate connections between DMS, global productivity, cloud albedo, and climate, and to support this line of research the request uses the findings of Rampino and Volk (1988): "...an 80 percent reduction in cloud condensation nuclei caused by mass extinctions of calcareous plankton at the Cretaceous-Tertiary boundary could have produced a 6 °C global warming." If the global productivity of phytoplankton has the net effect of cooling the Earth, the implications are profound and will create lasting effects on the scientific research undertaken by NASA and NSF's GOFS.

The search for mechanisms by which marine life may not only influence the distribution of carbon dioxide and nutrients within the ocean, but exert continuous forcing on the background level of the climate itself led to another work (Volk, 1989a). This focuses on calcium carbonate precipitation by organisms along the continental margins (such as corals) vs. organisms of the open ocean (such as foraminifera and coccolithophores). I have demonstrated that this contrast between the shallow-ocean vs. deep-ocean burial of carbonates has profound implications for the average long-term level of atmospheric CO₂. The mechanism resides in the different rates of metamorphic recycling of the carbonates back to CO₂ in the carbonate-silicate geochemical cycle. This paper is in press in Nature, and is the first to show effects from the processes in the geochemical cycle involving carbonates. Previous work only established effects upon atmospheric CO₂ from silicate weathering. The key idea is that because marine life buries carbonates both in shallow-water and deep-water regimes, the buried carbonates become either a part of the continental masses or part of the deep sea sediments of the ocean floor. Metamorphic recycling on the continents is slow compared to the entry of all ocean carbonates into the metamorphic regimes of the subduction zones. I have been able to show that the evolution of the open-ocean habitats of the foraminifera and coccolithophores over the last several hundred million years would now be producing a higher flux of CO₂ to the atmosphere than would otherwise exist, perhaps maintaining the Earth from being locked in permanent glacial conditions. The relevance to NASA is that when satellites are able to provide detailed mappings of calcium carbonate precipitating organisms (already partially available, for example, see Holligan et al., 1983), new interpretations of the distribution of these organisms that influence the overall climate of Earth will be possible.

An important topic of this overall project on ocean basin carbon fluxes has been the relative roles that physical and biological processes exert on the distribution of large-scale and well-established patterns in the ocean/atmosphere carbon cycle, the so-called sources and sinks. Sources are regions where the pCO₂ of the ocean surface is greater than that of the atmosphere ($\Delta p\text{CO}_2 > 0$),

and sinks are the opposite ($\Delta p\text{CO}_2 < 0$). The ocean has prominent sources, such as the equatorial Pacific, and major sinks, such as the Antarctic Circumpolar Sink Zone and the far north Atlantic. The coupling of sources and sinks on a global scale results in great cycles of CO_2 passing out of the ocean into the atmosphere and back into the ocean thousands or tens of thousands of kilometers away. These cycles link the ocean and atmosphere as a global dynamic system, and changes in the intensity of these cycles can affect atmospheric CO_2 and therefore climate. In Volk and Liu (1988), we have constructed a series of models for studying in detail the fundamental reasons behind the distribution of the major sources and sink regions of the global ocean. The models contain water fluxes and biological particulate fluxes from the ocean surfaces. These particulate fluxes can be calculated by specifying the known nutrient concentrations at the ocean surface. With reasonable water fluxes, particulate fluxes in line with present day estimates for their magnitudes were established in the models.

A key step on the way to several findings was the discovery that the relative roles of surface temperature and nutrient distributions on $\Delta p\text{CO}_2$ could be isolated using placing models into new steady-state systems whose surface properties were alternately isothermal and isonutrient. Since the models had been calibrated to produce today's $\Delta p\text{CO}_2$'s for specific surface regions, how temperature and nutrients individually contribute to the $\Delta p\text{CO}_2$ could be isolated. This means the relative contributions to the outgassing and ingassing of CO_2 between ocean and atmosphere can be quantified. In the global, seasonally-averaged patterns, temperature was found to be dominant. This new finding is proving useful in the modeling hierarchy, because these the finding can serve as an hypothesis to take into more complex models. For example, already the 3-D circulation model of Bacastow and Maier-Reimer (1989) has generated steady-state global distributions of $\Delta p\text{CO}_2$ both with and without the presence of a marine biosphere. The persistence of the patterns verifies the dominance of temperature in these patterns.

Although significant effort has gone to measure the details of the $p\text{CO}_2$ distribution in the earth scale surface ocean, little has gone into asking to what extent these patterns of sources and sinks represent the ocean/atmosphere flux cycle in its state prior to the release of anthropogenic CO_2 from deforestation and fossil fuel combustion. This question is important because although there has been a net flux of this anthropogenic CO_2 from the atmosphere to the ocean for several hundred years, much of the overall chemical structure of the ocean is usually assumed to be in its pre-anthropogenic state. We would therefore like to know what the pre-anthropogenic patterns of $\Delta p\text{CO}_2$ were in order to further understanding of the source/sink patterns and as an aid in calibrating models of the carbon cycle. I have accomplished some modeling studies of possible changes in $\Delta p\text{CO}_2$ during the anthropogenic transient (Volk, 1989b). This work contributes a quantitative focus on the issue and first look at ways of estimating the pre-anthropogenic values, given only knowledge of today's ocean conditions. I have also estimated the pre-anthropogenic outgassing of the equatorial Pacific as 30% higher than this flux today.

Another area that previously has been little investigated involves the dramatic seasonality in the $\Delta p\text{CO}_2$ of the surface ocean in the high latitudes. Biological productivity has been pointed to as causing the low summer and high winter $p\text{CO}_2$'s of the high latitudes in the north Atlantic (Peng et al., 1987). Can this seasonality affect the average global value of atmospheric CO_2 ? The possibility exists because of well-established effects of the steady-state chemical properties of the high latitude ocean on atmospheric CO_2 . In Volk (1989c), I have examined potential effects of seasonality, in particular, the contributions from the rates at which the summer and winter conditions equilibrate with the atmosphere. This paper shows that differences in these rates can shift the atmosphere's average value of $p\text{CO}_2$. The finding indicates that winter values can dominate over the summer values; in other words, the atmosphere's $p\text{CO}_2$ can, on average, be closer to the winter equilibrium values than the summer equilibrium values. This work establishes a new direction for future studies.

Finally, in Volk (1987), we have examined some relations between productivity and chlorophyll, with a specific focus on how phytoplankton/zooplankton relations contribute to explaining the Eppley et al. (1985) empirical relation between productivity and chlorophyll. In this relation between chlorophyll (C) and primary productivity (P), $P \propto C^\beta$, and $\beta < 1$. My work with nutrients, phytoplankton, and zooplankton shows that ecological dynamics alone creates $\beta > 1$. In other words, in a system determined by ecological dynamics and driven by nutrients alone, productivity increases at a rate proportionally faster than chlorophyll. This implies that the relation of Eppley et al. is probably dominated by the effect of phytoplankton and water absorption of light; this light/depth effect overpowers the food-web forcing of $\beta > 1$ to give a net system property of $\beta < 1$. Other models (see for example, Wroblewski et al., 1988) have been developed to look at such relations on basin scales and the future looks promising for this work.

I would also like to mention several meetings that were germane to this project. Ones that were partially supported by this grant are marked with (*).

Volk, T., Controls on seasonality of $p\text{CO}_2$ in high latitude surface waters: temperature, nutrients, presented with published abstract for Topical Meeting F9, Carbon Cycling: Global and Local Biosphere, Atmosphere, and Hydrosphere Interactions, at the 27th International Congress of the Committee on Space Research (COSPAR), July 18-29, Espoo, Finland, 1988.

Chairman of Topical Meeting F9, Carbon Cycling: Global and Local Biosphere, Atmosphere, and Hydrosphere Interactions, at the 27th International Congress of the Committee on Space Research (COSPAR), July 18-29, Espoo, Finland, 1988.

Invited expert to the State Hydrological Institute in Leningrad, U. S. S. R., July 23 - Aug. 1, 1988, to discuss collaboration with Soviet scientists on carbon cycle and climate, under the February, 1988 Memorandum of the US-USSR Joint Committee on Cooperation in the Field of Environmental Protection.

*Volk, T., Ocean color, clouds, and climate—a new research front?, invited talk given at NASA workshop, Ocean Color in the GOF S Era, sponsored by NASA Headquarters, Sept. 29- Oct. 1, Annapolis, Maryland, 1987.

*Volk, T., Limitations on relating ocean surface chlorophyll to productivity, presented with published abstract (p. 252) at Topical Meeting A.3, Satellite observations of ocean color for dynamic and biological studies, at the 26th International Congress of the Committee on Space Research (COSPAR), June 30- July 11, Toulouse, France, 1986.

Invited participant in Global Ocean Flux Study (NSF) Modeling Workshop, Dept. of Oceanography, U. of Wash., Seattle, Sept. 1986.

*Invited participant and speaker at Ocean Color Workshop, sponsored by NASA, Sterling Forest, NY, May, 1986.

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