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HANSON, R. B., H. W. DUCKLOW, AND J. G. FIELD [EDS.] 1997. **The changing ocean carbon cycle—a midterm synthesis of the Joint Global Ocean Flux Study.** Cambridge Univ. Press. xiii + 514 p. US$54.95. ISBN 0-521-65199-6 (paperback).

The last 20 yr has seen nothing other than a revolution in our understanding of the ocean carbon cycle, and curiously, it has been rather like working at a giant jigsaw puzzle. When a critical piece has been found and fitted into place, it seems as if it had never been missing—so obvious is it that the fit is correct. It is hard to believe that before 1982 we knew nothing of the changes in atmospheric CO_2 concentrations during glacial periods, and that only 10 yr ago the limiting role of elemental Fe in open ocean photosynthesis was a matter of concern to just a few people. During the same period, we have learned that oceanic cyanobacteria and prochlorophytes existed in abundance and were responsible for perhaps one fifth of oceanic primary production. And so it goes: until the last year or two, we would have ascribed the termination of algal blooms to senescence, clumping, and accelerated sinking of cells. Now we know that this process may be the work of extraordinarily abundant, and previously uncounted, viral phytophages. These, along with phages responsible for the death and lysis of significant fractions of bacterial populations, require us to digest a quite new paradigm for the microbial loop.

But it all fits together beautifully and seems very simple if you stand back far enough. Consider fig. 5.5 of this volume, illustrating the ice- and sediment-core records back to 30,000 yr B.P. for atmospheric CO_2 and for proxies of sea surface temperature ($\delta^{18}O$), surface ocean productivity (total organic carbon, sediment), Fe in aerosol (Al), and for dimethyl sulfide. This evokes a mental model of glacial–interglacial transitions that seems to make perfect sense, even remembering the caveat that cores may render only regional glimpses of past atmospheres. The real problem is that the closer you stand to the dynamics of global carbon flux, the more these seem chaotic in the sense of representing a dynamical system in which the rates of change of important variables depend, in a nonlinear fashion, on the variables themselves (Gollub and Cross 2000).

It is the two sister programs of JGOFS (the Joint Global Ocean Flux Study) and the global CO_2 survey of WOCE (the World Ocean Circulation Experiment) that have made this explosion of knowledge possible, and what an explosion it is! By my count, there are >6,000 pages in special JGOFS numbers of Deep-Sea Research and, according to McCarthy in this book, 1,500 reviewed publications describe research done as part of JGOFS since 1987. If you are somewhat familiar with this literature, there is probably not a lot for you in ''The changing ocean carbon cycle,'' which is, after a too-long gestation, a revision of some of the invited plenary lectures at the first JGOFS Scientific Symposium, Villefranche-sur-Mer, 1995.

But if you are unfamiliar with JGOFS, it might be a good place to start. Seventeen chapters will introduce you to the two major JGOFS themes of regional studies (northwest Pacific, eastern tropical Pacific, north Atlantic, eastern tropical Atlantic, Arabian Sea, Southern Ocean) and of the time-series studies (at HOT, north of Oahu, and BATS, southeast of Bermuda). Special emphasis is given to the open-ocean Fe-limitation experiments IronEx I and II and associated in vitro work. Though peer-reviewed, the individual chapters are uneven: two, early on in the book, are repetitive, discursive, and appallingly badly written; when you find yourself wading gummily through a paragraph, you will know you have found one of them. Several chapters are revisions of papers already published, mostly in special numbers of Deep-Sea Research.

But to return to the subject matter. Lest you should think that my enthusiasm leads me to believe that JGOFS has solved the problem it posed for itself (''to understand the interactive physical–chemical–biological processes that regulate the earth system''), I had better emphasize a wise remark made by Denman and Peña, in their ''Beyond JGOFS'' chapter. They write ''Results from the process studies have not yet allowed us to develop better budgets for the pool sizes and fluxes of carbon . . . rather, the explosion of knowledge . . . has raised our awareness of previously poorly-known or unknown processes . . . yet to be assimilated into a revised paradigm for the ocean carbon cycle.'' Amen, in spades!

However, we should be in better shape to quantify global pools and fluxes now that the SeaWiFS radiometers are operational. It is a lament often repeated in this book that JGOFS was planned in the expectation of having global sea-surface chlorophyll coverage but lacked it because the process studies were mostly done in the interval between CZCS and SeaWiFS. Perhaps soon we shall be able to agree that the ''missing carbon sink,'' which is a moving target not yet hit, is no longer a matter of serious concern for modeling the future evolution of the global carbon system. At least we know now, after the JGOFS regional study in the Southern Ocean, that this is not a source for CO_2 but instead a complex and incompletely understood sink.

But the novel or newly understood biological nonlinearities that continue to come forward will probably continue to bedevil global modeling because they are so difficult to generalize. It is often characteristic of newly revealed biological processes that first calculations suggest that they are, or may be, non-negligible. An example is the import of new nitrogen to the photic zone of the central North Pacific by vertically migrating diatom mats (Villareal et al. 1999) that mediate a nitrate flux reaching 170 μmol N m^{-2} d^{-1} at individual stations, equivalent to about 60% of export production. Is this a local specialty or does it occur everywhere in oligotrophic seas? How do we extrapolate such novel information, emanating from just a handful of observations?

Even more importantly, how should we assimilate the clear new evidence that the cycling of carbon in photosynthesis and respiration cannot be linked to nitrogen by invariant Redfield stoichiometry? At BATS and HOT, the C : N ratio for export is higher than for uptake, and dissolved organic C and N may be even further out of Redfield balance. Michaels et al., in their chapter on these time-series studies, note that most current versions of global biogeochemical models require invariant Redfield ratios and go on to suggest that '' . . . either these simple assumptions are true and ocean biology is minimally important (in which case we can probably invest our global change effort elsewhere) or we have to study the biology of the ocean from a different perspective.''

Perhaps because these difficulties were foreseen, JGOFS—as McCarthy points out in his introduction—has until recently given lower priority to modeling than to observation and experiment. But models have, of course, been deployed, and Fasham reviews the performance of two examples that simulate the North Atlantic spring bloom, with special emphasis on the mathematical problems associated with validating models against observations that seems to me a second-order problem. For now, I prefer the more pragmatic approach of Taylor et al. (1993), whose highly compartmentalized model (four groups of phytoplankters, three groups of consumers plus mesograzers, four sources of nutrient) successfully reproduces the northward march of the bloom as observed during the JGOFS North Atlantic Bloom Experiment of 1989. As is now appropriate, the JGOFS data archivists of the 19 participating nations, advised by a JGOFS Data Management Task Team, are ensuring that all data shall be accessible for modeling. And, in its final years, JGOFS is entering into OCMIP (the Ocean Carbon-Cycle Model Intercomparison Project) that will enable phase II of that effort to include explicit biology in global geochemical simulations.

It is not possible to read this book without a great sense of gratitude for the existence of SCOR (the Scientific Committee for Oceanic Research) without which JGOFS could not have been accomplished. Rare among international agencies of whatever kind, SCOR officers have never (at least to my knowledge, and I have known SCOR a long time) confused form with substance and have never allowed political rectitude or current fashion to get in the way of proceeding sensibly with the job in hand. No other kind of agency could comfortably have served as home, simultaneously, for a highly centralized project like WOCE and a highly decentralized one like JGOFS—which is what both needed in order to succeed.

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