

# Ocean Carbon Cycle and Climate Change—An Introduction to the Interdisciplinary Union Symposium

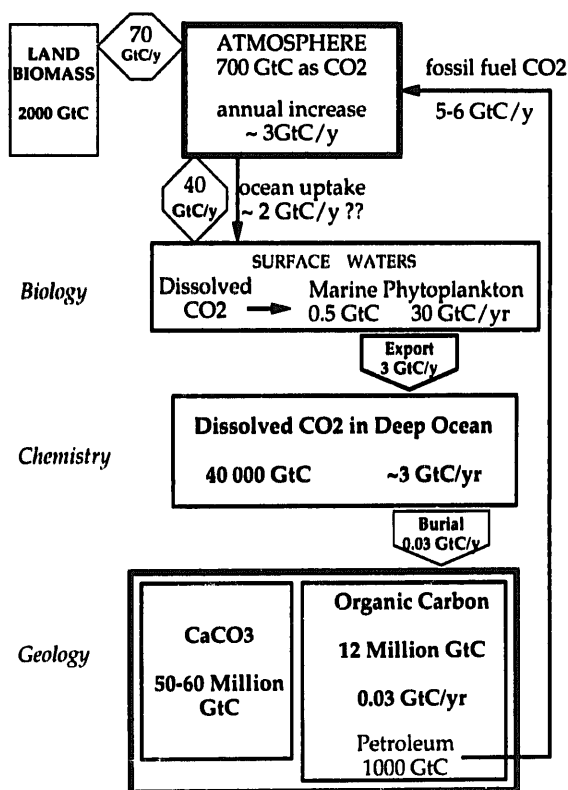
Hein J.W. de Baar <sup>a</sup> and Erwin Suess <sup>b</sup>

<sup>a</sup> Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, The Netherlands

<sup>b</sup> GEOMAR, Forschungszentrum für Marine Geowissenschaften an der Christian-Albrechts-Universität zu Kiel, Kiel, Germany

The large inventories of carbon in the oceanic reservoirs (Fig. 1) influence the atmospheric level of CO<sub>2</sub>, hence global climate, through various mechanisms. Exchange between the reservoirs takes place at vastly different rates. For example the annual exchange between ocean and atmosphere has been estimated to be in the order of  $\sim 40 \times 10^{15}$  g C/yr or  $\sim 40$  Gt C/yr (Goudriaan, 1990), i.e. the entire atmospheric CO<sub>2</sub> content passes through the surface ocean once every  $\sim 20$  years. Primary productivity by marine photosynthesizing algae fixes about  $\sim 30$  Gt C/yr but only a small part of this is involved in the annual ocean/atmosphere exchange. Even though most newly produced organic matter is recycled again within the surface ocean, the relatively small amount of  $\sim 3$  Gt C/yr of settling biogenic debris, which escapes as export production, serves to sequester carbon into the deep ocean. Only a minute fraction of carbon arriving at the deep ocean is in turn buried in marine sediments. Nevertheless over a long geological time scale, some  $\sim 12$  million Gt C organic matter has accumulated in deep-sea sediments, another  $\sim 50$  million Gt C of biogenic calcareous skeletons are fixed as marine limestone. By storing all this carbon into marine deposits the marine biota have been able to achieve a very low level of CO<sub>2</sub> (about  $\sim 0.03\%$ ) in the atmosphere of planet Earth. This is anomalously low compared with the CO<sub>2</sub>-dominated atmospheres of abiotic planets Mars and Venus.

During the past the small amount of CO<sub>2</sub> in the atmosphere has varied, likely preceded by orbital forcing (Shackleton and Pisias, 1985) and closely related to global changes of temperature

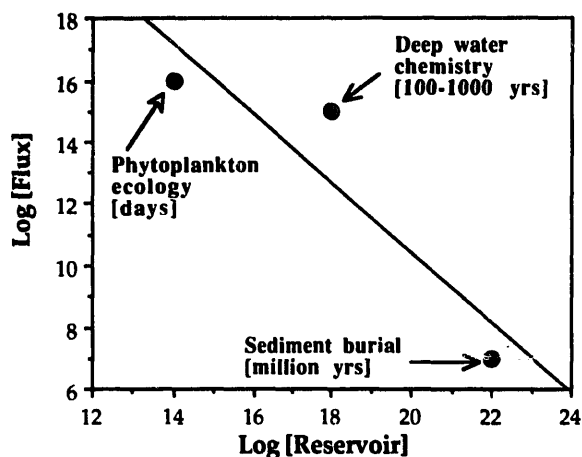


15  
 INVENTORIES 1 Gigaton C = 1 GtC = 10<sup>9</sup> gram C

FLUXES Giga ton C per year

Fig. 1. Simplified scheme of major reservoirs and fluxes of the ocean carbon cycle. After De Baar (1992).

(Barnola et al., 1987; Berner, 1991). Currently the atmospheric CO<sub>2</sub> level is rising rapidly due to combustion of fossil fuels, however production records show that only about ~ 60% of fossil fuel CO<sub>2</sub> remains in the atmosphere, the other ~ 40% apparently is taken up by the oceans (in this scenario additional terrestrial sources and sinks are not explicitly considered because they roughly cancel each other out; Goudriaan, 1990; Houghton et al., 1990). The exact assessment and underlying processes of ocean uptake are the subject of further investigations and debate (e.g. this volume; see also Tans et al., 1990; Quay, Tilbrook and Wong, 1992; Sarmiento and Siegenthaler, 1992; Sundquist, 1993). Therefore, the ocean carbon cycle and climate change is a truly multidisciplinary issue. Yet when following the recent debate on alleged "false advertising about global change" one wonders whether the viewpoints of conventional fields of science biology, chemistry or geology are more important in ocean climate studies than the multidisciplinary approach. There appears to be a risk of inadvertently valuing one's own field of expertise higher than another one (e.g. Smith and Mackenzie, 1991; Broecker, 1991; Banse, 1991; Sarmiento, 1991; Longhurst, 1991). We think that the discussion can be focussed in a constructive manner, because in reality *climate change is a matter of dynamics* (Sundquist, 1986). How fast can the surface ocean take up extra CO<sub>2</sub>, how rapidly is it transferred downwards, which parameters determine burial, what is the time constant for calcite dissolution, when does enhanced weathering of continents become apparent? The time scales of interest for a given question determine the importance of one expertise versus the other (Fig. 2). Over very short time scales the biological fluxes, e.g. primary and export production are quite significant, despite the relatively small size of the plankton reservoir. Over long geological time scales the sheer size of sedimentary reservoirs is impressive, as opposed to the very slow rate of burial. Geochemical processes and remineralization in the deep water column appear to be intermediate with respect to inventories and fluxes. In combination with ocean circulation and mixing, the deep ocean geochemistry, however,



*Which field of research is most important ?  
(Give me your time scale and I tell who you are)*

Fig. 2. The apparent inverse relation between reservoir size (Gt C) and turnover rate or flux [Gt C/yr]. Different mass balances prevail dependent on the selected time scale, e.g. a mass balance of the surface ocean at short time scales may well neglect the final burial term, whereas at long time scales phytoplankton turnover is trivial for a mass balance of the sedimentary reservoirs. Depending partly on the time frame of interest different processes and related scientific disciplines prevail.

dominates the predicted atmospheric CO<sub>2</sub> level for the next centuries.

For the Interdisciplinary Union Symposium "Ocean Carbon Cycle and Climate Change" (European Union of Geosciences, Strasbourg, 8 April 1993) the intention was to bring together speakers and topics spanning the above range of disciplines and time constants. Each paper was to provide its own mix of original research findings with an overview of the topic area. Here we attempt to highlight the important findings and tie them together under the view-point of time scales. Raven et al. (1993) unravel the physical-chemical transport of CO<sub>2</sub> into phytoplankton cells with attention towards understanding the relationship between <sup>13</sup>C/<sup>12</sup>C fractionations, CO<sub>2</sub>-availability and temperature. Such relations have been suggested from field observations (Rau et al., 1989). Their understanding is of prime importance for the reconstruction of past pCO<sub>2</sub>. Several approaches have been taken towards this task, all of which implicitly or explicitly assume that the isotopic composition of photosynthetically fixed marine organic carbon reflects the

$p\text{CO}_2$  of surface seawater for a given temperature. For the application to the geological record, the marine source of the organic matter has to be ascertained as well as the temperature of carbon fixation (Jasper and Hayes, 1990). Recently  $\text{CO}_2$ -availability, i.e.  $\text{CO}_2$ -limitation of growth rate, has also been found significant in the laboratory (Riebesell et al., 1993), where in the real ocean there may conceivably, but not necessarily, be a positive relation between  $\text{CO}_2$ -availability and export production. The important point of these experiments is, that under different concentrations of  $[\text{CO}_2]$  different optimal growth potential of phytoplankton assemblages are realized.

Maier-Reimer (1993) shows the results of first runs with the biological pump (i.e. export production) incorporated in the well known Hamburg carbon cycle model. At first glance the predicted atmospheric  $\text{CO}_2$  trend is remarkably similar with or without the biological pump. The inclusion of an interactive sediment-pool modifies the uptake characteristics substantially after a few centuries. One would be anxious to see the inclusion of aforementioned newly found  $\text{CO}_2$  growth-rate limitations into the models.

Ittekkot (1993) advances the notion that higher input of mineral matter into the sea would enhance the sequestration of organic matter into the deep ocean, the mineral matter with higher density acting as ballast in settling mineral-organic assemblages such as fecal pellets. Higher wind velocities such as commonly assumed for glacial periods would bring more mineral aerosol particles into the oceans, i.e. would enhance the effectiveness of the biological pump. Since Ittekkot (1991) has previously drawn attention to the fact that increased wind speed and resulting surface turbulence also increase biological production, a perfect positive feedback between production and flux exists here. The relationship between mineral matter flux and carbon flux to the deep sea creates another interesting feedback on carbon burial v. carbon remineralization. The author shows that the ratio of recycled organic carbon to buried carbon decreases roughly by 2/3 when the mineral matter flux increases 2-fold.

Westbroek et al. (1993) provide an overview of recent findings about the calcifying algae *Emilia-*

*nia huxleyi*, which may serve as a model organism for studying carbon pathways from the molecular to the global scale. The relevance to the theme of the EUG-7 Symposium is the non-linear relationship between particle organic carbon (POC) and particulate inorganic carbon (PIC), here exemplified by *E. huxleyi*, in different oceanographic settings. At present, for global models of the carbonate pump, the coupling between POC and PIC is of the "Redfield-type" and does not consider ecological and environmental factors. The authors develop this issue in great detail as well as the strategy of using *E. huxleyi* as a proxy for PIC in the global ocean. Another aspect of their concern is that in the surface ocean, although being supersaturated with respect to crystallization of  $\text{CaCO}_3$ , the expected inorganic precipitation of  $\text{CaCO}_3$  apparently is hindered by slow kinetics or otherwise. The sites for  $\text{CaCO}_3$  crystallization of *Emiliana huxleyi* are controlled by polysaccharide coating, Westbroek et al. suggest that similar coatings on the outside of *E. huxleyi* may exist as a defence against precipitation of  $\text{CaCO}_3$ . Latter mechanism is derived from the early interpretation of Chave (1965) about the role of organic coatings in maintaining the supersaturation of most oceanic waters with respect to calcite.

Middelburg et al. (1993) lucidly review the important development in modelling the rates of mineralization of organic matter, with special attention towards assessing the validity of kinetic equations. Organic matter mineralization is the "mother of all deep-sea processes". The question about rate constants involved in this process has a long history. The authors now settle on the "continuum models" of which two types are in use. The one (Middelburg, 1989) asserts that the remineralization rate changes with time following a power function, the other (Boudreau and Rudnick, 1991) assumes a continuum of reactivities which follows a decay law. The second issue which the authors address is that of oxic versus anoxic mineralization. Even though data suggest that anoxic conditions favor a higher carbon burial efficiency than oxic conditions do, they imply that this may be an artefact due to considering  $\text{SO}_4^-$  reduction as the only mechanism of mineraliza-

tion. It is clear from their contribution that it was time to consolidate some view-points on carbon mineralization rates but that for a long time to come organic matter mineralization will be an active research topic.

Keir (1993) envisions that the higher wind speeds common for the glacial climate would enhance the uptake rate of  $\text{CO}_2$  in cooling surface waters flowing polewards. This process may conceivably accommodate the apparent discrepancy between the actually observed Vostok  $\text{CO}_2$  record (Barnola et al., 1987) and the reconstructed  $\text{CO}_2$  record based on the oceanic  $\Delta\delta^{13}\text{C}$ -signal (Shackleton and Pisias, 1985). Not only does the more efficient solubility pump, as hypothesized by Keir (1993), cause less  $^{13}\text{C}/^{12}\text{C}$  fractionation than nutrient forcing does, it also predicts correctly a lowering of  $\text{CO}_2$  by  $\sim 50$  ppm during glacial stages. Compared to the previously published scenario of cold surface ocean ventilation (Keir, 1993b), the author now demonstrates how this process might have operated in the past. The crucial link is that marine  $\text{Na}$  in the ice record may be used as a proxy for relative wind speed, which in turn accelerates the solubility pump.

For reconstruction of nutrient-forcing it has been suggested that the remarkable  $\text{Cd}/\text{Ca}$  record of fossil foraminifera may serve as a proxy for paleonutrient distributions. One inherent assumption here is the assumed constant relation between  $\text{Cd}$  and nutrient phosphate in seawater over geological time. With a simulation model Saager and De Baar (1993) demonstrate such relation unlikely to be constant. This, along with uncertainty of the distribution coefficient of  $\text{Cd}$  between seawater and calcite, renders the sedimentary  $\text{Cd}/\text{Ca}$  record to be a qualitative indicator at best of paleonutrients.

At the symposium Suess (1993) provided a regional pattern on the relationship between  $\text{Ba}$  and organic productivity for the equatorial and high latitude areas of the Pacific. This relationship is based on a transfer equation by Dymond et al. (1992) linking the carbon export flux to bio-barite accumulation, water depth, and the regional pattern of dissolved  $\text{Ba}$  in the water column. The new information provided by the

author showed a much more detailed pattern of carbon export flux than that predicted from the carbon accumulation rate alone, for the eastern equatorial productivity belt and a segment of the polar front between New Zealand and Antarctica. The multiple tracer approach, employing here  $\text{Ba}$  and  $\text{C}_{\text{org}}$ , is just one illustration of how more accurate reconstructions of carbon export fluxes may be achieved. Unfortunately, at this stage reconciling these estimates with those based solely on carbon (Müller and Suess, 1979; Sarnthein et al., 1988) is difficult and hence publication of these results in the context of the EUG-7 conference proceedings seems premature.

Bard (1993) presented the Outstanding Young Scientist Lecture interpreting the reconstruction of sea surface  $^{14}\text{C}$  during the younger Dryas event. The various novel insights of this presentation are also subject to further investigations such that rapid publication in this volume would have been premature.

The seven articles assembled in this volume together present both new concepts on the role of carbon and climate change as well as their assessment by simulation modeling. Overviews of some general topics of linking oceans, climate, and carbon provide state-of-the-art evaluations. While yielding some new insights, this volume does by no means pretend to provide final answers on a subject which undoubtedly will be continually debated well into the next century.

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## References

- Banse, K., 1991. False advertising in the greenhouse. *Global Biogeochem. Cycles*, 5(4): 305–307.
- Bard, E., Arnold, M., Mangerud, J., Paterno, M., Labeyrie, L. and Duprat, J., 1993. Past variations of the atmosphere–sea surface  $^{14}\text{C}$  gradient. Example of the North Atlantic during the younger Dryas climatic event. Paper presented at the 7th Meet. EUG, Strasbourg, 8 April 1993.
- Barnola, J.M., Raynaud, D., Korotkevich, Y.S. and Lorius, C., 1987. Vostok ice core provides 160,000-year record of atmospheric  $\text{CO}_2$ . *Nature*, 329: 408–414.
- Berner, R.A., 1991. A model for atmospheric  $\text{CO}_2$  over Phanerozoic time. *Am. J. Sci.*, 291: 339–376.
- Broecker, W.S., 1991. Keeping global change honest. *Global Biogeochem. Cycles*, 5(3): 191–192.
- Chave, K.E., 1965. Calcium carbonate: association with organic matter in surface seawater. *Science*, 148: 1723–1724.
- De Baar, H.J.W., 1992. Options for enhancing the storage of carbon dioxide in the oceans: a review. *Energy Conserv. Manage.*, 22 (5–8): 635–642.
- Dymond, J., Suess, E. and Lyle, M., 1992. Barium in deep-sea sediment: a geochemical proxy for paleoproductivity. *Paleoceanography*, 7: 163–181.
- Goudriaan, J., 1990. Atmospheric  $\text{CO}_2$ , global carbon fluxes and the biosphere. In: R. Rabbinge et al. (Editors), *Theoretical Production Ecology: Reflections and Prospects*. PUDOC, Wageningen, pp. 17–40.
- Houghton, J.T., Jenkins, G.J. and Ephraïms, J.J., 1990. *Climate Change—the IPCC Scientific Assessment*. Cambridge Univ. Press, Cambridge, pp. 366.
- Ittekkot, V., 1993. Organic mineral interactions in the sea: implications for atmospheric  $\text{CO}_2$  removal. *Global Planet. Change*, 8: 17–25.
- Jasper, J.P., and Hayes, J.M., 1990. A carbon isotope record of  $\text{CO}_2$  levels during the late Quaternary. *Nature*, 347: 462–464.
- Keir, R.A., 1993. Are atmospheric  $\text{CO}_2$  content and Pleistocene climate connected by the wind speed over polar mediterranean seas? *Global Planet. Change*, 8: 59–68.
- Keir, R.A., 1993b. Cold surface ocean ventilation and its effect on atmospheric  $\text{CO}_2$ . *J. Geophys. Res.*, 98: 849–856.
- Longhurst, X., 1991. A reply to Broecker's charges. *Global Biogeochem. Cycles*, 5(4): 315–316.
- Maier-Reimer, E., 1993. The biological pump in the fossil fuel  $\text{CO}_2$  uptake by the ocean. *Global Planet. Change*, 8: 13–15.
- Middelburg, J.J., Vlug, T. and Van der Nat, J.W.A., 1993. Organic matter mineralization in marine systems. *Global Planet. Change*, 8: 47–58.
- Müller, P.J. and Suess, E., 1979. Productivity, sedimentation rate, and sedimentary organic matter in the oceans. I. Organic carbon preservation. *Deep-Sea Res.*, 26: 1347–1362.
- Quay, P.D., Tilbrook, B. and Wong, C.S., 1992. Oceanic uptake of fossil fuel  $\text{CO}_2$ : carbon-13 evidence. *Science*, 256: 74–79.
- Raven, J.A., Johnston, A.M. and Turpin, D.H., 1993. The influence of changes in  $\text{CO}_2$  concentration and temperature on marine phytoplankton  $^{13}\text{C}/^{12}\text{C}$  ratios: an analysis of possible mechanisms. *Global Planet. Change*, 8: 1–12.
- Rau, G.H., Takahashi, T. and Des Marais, D.J., 1989. Latitudinal variations in plankton  $\delta^{13}\text{C}$ : implications for  $\text{CO}_2$  and productivity in past oceans. *Nature*, 341: 516–518.
- Riebesell, U., Wolf-Gladrow, D.A. and Smetacek, V., 1993. Carbon dioxide limitation of marine phytoplankton growth rates. *Nature*, 361: 249–251.
- Saager, P.M. and De Baar, H.J.W., 1993. Limitations to the quantitative applications of Cd as a paleoceanographic tracer, based on results of a multi-box model (MENU) and statistical considerations. *Global Planet. Change*, 8: 69–92.
- Sarmiento, J.L., 1991. Oceanic uptake of anthropogenic  $\text{CO}_2$ : the major uncertainties. *Global Biogeochem. Cycles*, 5(4): 309–314.
- Sarmiento, J.L. and Sundquist, E.T., 1992. Revised budget for the oceanic uptake of anthropogenic carbon dioxide. *Nature*, 356: 589–593.
- Sarnthein, M., Winn, K., Duplessy, J.C. and Fontugen, M.R., 1988. Global variations of surface ocean productivity in low and mid latitudes: influence on  $\text{CO}_2$  reservoirs of the deep ocean and atmosphere during the last 21,000 years. *Paleoceanography*, 3: 361–399.
- Shackleton, N.J. and Pisias, N.G., 1985. Atmospheric carbon dioxide, orbital forcing and climate. In: E.T. Sundquist and W.S. Broecker (Editors), *The Carbon Cycle and Atmospheric  $\text{CO}_2$ : Natural Variations Archean to Present* (Geophys. Monogr., 32) Am. Geophys. Union, Washington, DC, pp. 303–317.
- Smith, S.V. and Mackenzie, F.T., 1991. Comments on the role of biota as a sink for anthropogenic  $\text{CO}_2$  emissions. *Global Biogeochem. Cycles*, 5(3): 189–190.
- Suess, E., 1993. The new barium–organic-carbon-productivity algorithm for the prediction of carbon burial and recycling in the ocean. Paper presented at 7th Meet. EUG, Strasbourg, 8 April 1993.
- Sundquist, E.T., 1986. Geological analogs: their value and limitations in carbon dioxide research. In: J.R. Trabalka and D.E. Reichle (Editors), *The Changing Carbon Cycle*. Springer, New York, pp. 371–402.
- Sundquist, E.T., 1993. The global carbon dioxide budget. *Science*, 259: 934–941.
- Tans, P., Fung, Y.I. and Takahashi, T., 1990. Observational constraints on the global atmospheric  $\text{CO}_2$  budget. *Science*, 247: 1431–1438.
- Westbroek, P., Brown, C.W., Van Bleijswijk, J., Brownlee, C., Brummer, G.J., Conte, M., Egge, J., Fernández, E., Jordan, R., Knappertsbusch, M., Smith, M., Stefels, J., Veldhuis, M., Van der Wal, P. and Young, J., 1993. A model system approach to biological climate forcing. The example of *Emiliania huxleyi*. *Global Planet. Change*, 8: 27–46.