

Models for Changes in Atmospheric Carbon Dioxide, Ocean Geochemistry and Circulation during the Late Pleistocene

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ABSTRACT

This report provides a review of various hypotheses put forward so far as to the role of the oceans in controlling the glacial-interglacial climatic cycles through controls on the atmospheric carbon dioxide. The available paleochemical data appear to provide little support for the hypotheses involving changes in the overall oceanic nutrient inventory, but there are definite indications of substantial differences in the water mass distribution during the glacial and interglacial times. A shift in the vertical chemical structure (greater accumulation of the labile nutrients and metabolic CO_2 in the deep ocean at the expense of the intermediate layers during the ice ages), strongly suggested by the available data, could cause significant increases in oceanic alkalinity (and hence a decrease in atmospheric CO_2) due to CaCO_3 compensation. A likely mechanism for this rearrangement could be an orbital-forced insolation related increase in biological production in the Southern Ocean. This, coupled with greater production of the Antarctic Bottom Water (AABW) as compared to the North Atlantic Deep Water (NADW), seems to explain

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most of the observations. However, it is still not entirely clear how the system actually works. For example, the role of the dissolved organic matter (DOM) is being appreciated just now, but the factors which constrain the size of the oceanic DOM pool remain hitherto unknown.

One of the major shortcomings of the models proposed so far is that they do not take into consideration the regionally varying responses of primary productivity and water circulation to the climatic changes. For example, given the unique seasonally varying circulation pattern and an acute deficiency in dissolved oxygen at mid-depth, the feedback mechanisms operating in the North Indian Ocean could substantially modify the magnitude of the global responses. However, very little data are presently available on the paleoceanography of this region to assess these effects.

INTRODUCTION

Analyses of the air trapped in polar ice have revealed rather large variations in the atmospheric CO_2 associated with the glacial-interglacial cycles (Delmas *et al.*, 1980; Neftel *et al.*, 1982; Barnola *et al.*, 1987). It appears that the atmospheric carbon dioxide partial pressure (pCO_2) during the last glacial maximum (LGM ~ 18,000 a B.P.) was lower by 80-90 ppm than the Holocene (pre-industrial) levels. These results generated enormous interest among marine biogeochemists as it was quickly realized that, since the bulk of the carbon in the atmosphere-ocean system resides in the oceans, the causes for the observed changes must be looked for in the sea. A strong case has since been mounting for an intimate connection between the ocean biology, physics and chemistry on one hand and the climate on the other. A number of hypotheses have been put forward involving readjustments in various oceanic processes to explain the lower glacial atmospheric pCO_2 . All of these have different degrees of plausibility, although none seems to be perfect. It is possible that more than one mechanisms are effective in regulating the atmospheric CO_2 levels and hence the climate. A review of the progress made on this problem is presented here along with some observations as to

the kind of work that should be undertaken in the Indian Ocean region which could lead to improvements in the existing global ocean-atmosphere climatic-biogeochemical models.

BOX MODELS

Broecker (1982 a,b) was the first to "pounce" on the ice core CO_2 data. He proposed two mechanisms for explaining the observed pCO_2 fluctuations, both involving changes in marine nutrient chemistry. The first postulated a glacial to interglacial change in the overall marine nutrient inventory through differential deposition/erosion of the organic-rich sediments on the continental shelves. The second mechanism was based on a possible change in the Redfield stoichiometry (a glacial increase in the C:N and C:P ratios in particulate matter). In addition to

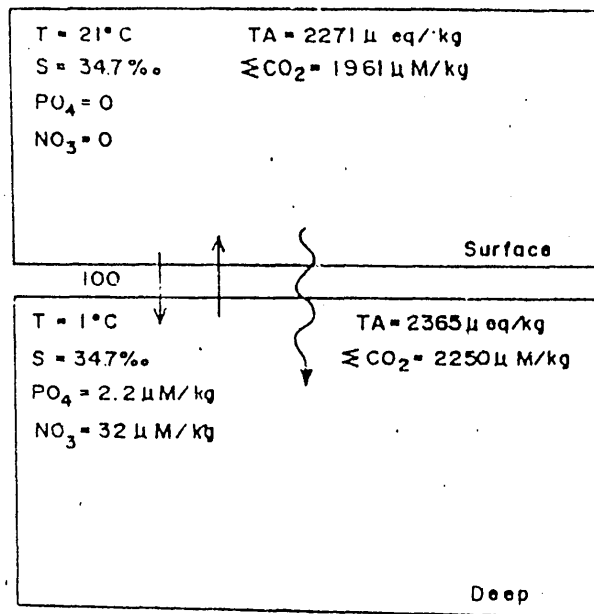


Fig. 1: A two box model of the oceans. The exchange between the surface and deep boxes (units sverdrup = $10^6 \text{ m}^3 \text{ s}^{-1}$) is effected through the formation and upwelling of deep waters. About 10.5% and 2.6% of the upwelled carbon are assumed to be carried by the sinking particles to the deep sea. Complete utilization of the upwelled phosphate within the surface box is assumed (after Broecker, 1982a).

providing an alternate explanation of the carbon isotopic compositional changes in deep-sea benthic foraminifera, previously believed to be related entirely to the size of the soil-forest carbon reservoir (Shackleton, 1977), Broecker demonstrated the importance of the "biological pump" in controlling the atmospheric chemistry. His results, based on a simple two-box model of the oceans (Fig. 1), suggested a decrease in the deep-sea phosphate content by approximately 1/3 through losses to the shelf sediments during deglaciation. The shelf deposition hypothesis, however, did not find much favour for several reasons. First, the magnitude of the decrease in the deep-sea PO_4 required would be 50% for a glacial to interglacial transition (Broecker and Peng, 1986), but the available data on the PO_4 proxy Cd in benthic foraminifera suggest little change in the overall PO_4 inventory (Boyle and Keigwin, 1985; Boyle, 1988 a). Secondly, since the deposition/erosion is facilitated by the changes in sea level, the latter (as recorded by $\delta^{18}\text{O}$ in fossil carbonates) should lead the $\delta^{13}\text{C}$ changes. Actually, this is against the observations (Shackleton and Pisias, 1985). Finally, the limited area of the continental shelves places severe physical constraints on the amount of sediments they can hold. Although Broecker did not deal with the other possibility in detail, computations by Broecker and Peng (1986) showed that a 50% glacial to interglacial decrease in the Redfield ratios is required to account for the observed pCO_2 change. Such an abrupt change in the elemental composition of marine organic matter seems rather unlikely.

Three-box models

The two-box representation of the oceans (Fig. 1) suffers from two major flaws. First, it does not take into consideration the circulation within the oceans; and, second, it does not differentiate between the low- and high-latitude waters. The chemical characteristics of the surface box (i.e., complete depletion of nutrients) are assumed to be those of the warm surface waters at low latitudes. Sarmiento and Toggweiler (1984) pointed out that the bulk of the ocean volume interacts with the atmosphere through very small (<5%) oceanic surface area at high latitudes. And since the surface waters in these regions

have vastly different chemical characteristics, this reservoir must be treated as a separate box. The next generation box models, developed independently by three groups of workers (Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Knox and McElroy, 1984), highlighted the potential role of the copious nutrients in the polar surface waters and of the oceanic circulation pattern in regulating the atmospheric $p\text{CO}_2$ levels. In these models, as also in the subsequent models described below, a particular type of circulation has been assumed, and the transport and exchange rates have been computed for the present (interglacial) oceanic conditions from a steady-state distribution of chemical tracers. Modifications of these interglacial models according to various possible scenarios (Table 1) help in identifying the parameters to which the atmospheric CO_2 content is most sensitive. Obviously, the most plausible scenario should be the one that is consistent with all the paleo-oceanographic data presently available.

The three-box models showed that the lower glacial atmospheric $p\text{CO}_2$ could result from a more effective functioning of the biological pump at high latitudes where the primary production is not limited by the availability of the nutrient salts. This might occur through either an enhanced biological production owing to greater insolation (Knox and McElroy, 1984) or changes in circulation (Siegenthaler and Wenk, 1984) or both (Sarmiento and Toggweiler, 1984). Although these hypotheses

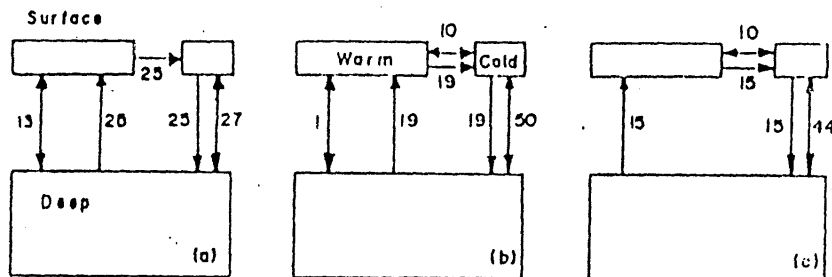


Fig. 2: Three-box models of present oceans: (a) Knox and McElroy (1984); (b) Toggweiler and Sarmiento (1985); and (c) Siegenthaler and Wenk (1984). Different particle fluxes are assumed out of the low- and high-latitude surface boxes. Numbers show transport exchange rates in sv in this and other figures (after Keir, 1989).

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Table 1

Role of the Oceans in Regulating the Glacial to Interglacial Atmospheric Carbon Dioxide Oscillations – A Summary of the Proposed Hypotheses

<i>Proposed</i>	<i>Model changes envisaged during glacial time</i>	<i>Model used</i>	<i>Predicted atm.pCO₂ (ppm)</i>	<i>Reference</i>
<i>erosion/erosion of deep sea sediments continental shelves</i>	41% increase in deep sea phosphate concentration	Two-box	231(G) 311 (II)	Broecker (1982 a,b)
<i>changes in the C:N and C:P ratios</i>	100% increase in the C:N and C:P ratios in particulate matter	–	200 (G) 275 (II)	Broecker (1982 a, b); Broecker and Peng (1986)
<i>changes in the pre-glacial nutrient contents high latitude surface</i>	Biological pump to be 100% efficient due to greater high latitude insolation in returning upwelled nutrients to deep water	Three-box Five-box	161(G) 282 (H) 216(G) 288(H)	Knox and McElroy (1984)
	4.5 fold increase in the vertical organic detrital flux/upto 80% decrease in exchange rate between cold surface and deep reservoirs and > 50% decrease in the low-latitude upwelling rate	Three-box	200(G) 265(II)	Sarmiento and Toggweiler (1984)

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Model	Model changes envisaged during glacial time	Model used	Predicted atm.pCO ₂ (ppm)	Reference
Model description description of salinity and CO ₂ model structure description of salinity and CO ₂ model structure	Factor of 2 changes in deep water formation-low latitude upwelling, and cold surface deep sea exchange rate	Three-box	230-257 (G) 282 (H)	Siegenthaler and Wenk (1984)
	Factor of 10 changes in rates of exchange between surface and intermediate; and between intermediate and deep waters	Three-stacked	265-20,000	Sarmiento <i>et al.</i> (1988)
	Increase in oceanic alkalinity due to carbonate compensation resulting from 100% more organic decomposition in the deep sea*	Five-box	235 (G) 281 (H)	Boyle (1988c)
	A factor of 2-3 increase in the Antarctic biological production and a decrease in the NADW:AAIW source ratio from 3:1 to 1:2	Thirteen-box	185-205 (G) 295 (H)	Keir (1988)
	50% of the surface production put into DOM (regeneration time 166 years)**	Three-dimensional	308 (DOM considered) 620 (DOM not considered)	Sarmiento <i>et al.</i> (1988)

* Chassignol, H - Holocene

** Only one case (low intermediate-deep mixing, low deep CaCO₃ regeneration) considered.

*** As a glacial change, it only shows how the atmospheric pCO₂ is sensitive to the size of the DOM pool.

did not call upon an overall increase in the global oceanic nutrient inventory, the effect on the deep-sea oxygen levels is not expected to be very different. That is, parts of the deep and intermediate waters would become anoxic due to a larger oxygen demand during the ice ages. The available evidence, however, does not support the occurrence of widespread anoxia during the glacials. In addition to this, as pointed out by Boyle (1988 c), the Holocene increase in $\Delta\delta^{13}\text{C}$ (Planktonic-Benthic), which has not been accompanied by corresponding changes in the atmospheric pCO_2 , is also inconsistent with these theories.

In the models described so far, the ocean is assumed to consist of only two layers vertically. This, of course, is a gross oversimplification, not only because it does not take into account the vertical stratification of water masses, but also due to the fact that the regenerations of hard parts (opal and CaCO_3) and soft tissues (organic matter) occur principally in different

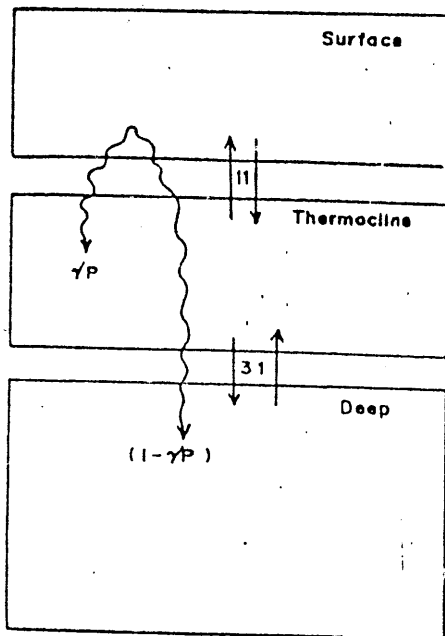


Fig. 3: A three-stacked box model of the oceans. A proportion (γ) of the surface particle flux (P) is taken to regenerate within the intermediate box and the rest within the deep box (after Sarmiento *et al.*, 1988).

depth zones. While the former occurs predominantly in the deep-sea, the latter is most intense in the upper ocean. As pCO_2 is a function of both alkalinity (which is dominantly controlled by the removal/solution of CaCO_3) and total CO_2 (which is equally affected by the production/destruction of both the soft tissues and hardparts), the atmospheric pCO_2 will be influenced by the extent of separation of the regeneration of alkalinity and total carbon dioxide. Using a three-stacked box model (Fig. 3), Sarmiento *et al.* (1988) showed that a higher productivity or a stag-

nation of deep waters could lead to trapping of alkalinity in the deep waters and large increases in atmospheric $p\text{CO}_2$. However, the reverse of this process probably might not be very effective in lowering the atmospheric CO_2 levels because the vertical stagnation in the present-day ocean is relatively small.

Multiple-box models

The potential effect of the alkalinity changes resulting from the dissolution/deposition of CaCO_3 on the atmospheric CO_2 invoked in the three-stacked model, has also been considered in some other recent studies (Broecker and Peng, 1987; Boyle, 1988 b,c; Keir, 1988). Broecker and Peng (1987) showed that the CaCO_3 compensation, which could result from rapid changes in the deep-sea carbonate ion concentration due to the variations in oceanic nutrient chemistry, might substantially increase the magnitude of the nutrient-forced $p\text{CO}_2$ fluctuations. However, they suggested that this compensation occurred over time scales of a few thousand years. This implies a lag between the atmospheric $p\text{CO}_2$ response and the polar warming which is not seen in the paleochemical records. Boyle (1988 b,c) pointed out that the hypothesis of an elevated primary production at high latitudes during the glacials is not entirely supported by the paleochemical data which suggest a phase lead of $\Delta\delta^{13}\text{C}$ (P-11) over $p\text{CO}_2$ and $\delta^{18}\text{O}$. He proposed that the deep-water alkalinity changes caused by a vertical re-arrangement of the products of chemical solution and bacterial decomposition of biogenic material could be more important in controlling the atmospheric $p\text{CO}_2$. This hypothesis envisages a glacial to interglacial shift in the sites of the regeneration of biogenic debris—much more of such regeneration, especially of soft tissues, is supposed to occur in the deep ocean at the cost of intermediate layers during glacial time, with the overall nutrient inventory remaining more or less the same. Such a concentration of the products of regenerative processes in the glacial deep ocean is supported by $\delta^{13}\text{C}$ and Cd/Ca in the benthic foraminifera (e.g., Boyle and Keigwin, 1987; Kallel *et al.*, 1988; Curry *et al.*, 1988). Various mechanisms have been proposed to explain this re-arrangement (cf. Boyle, 1988 c). These include (a) an enhanced glacial production of the inter-

mediate waters at the expense of deep waters; (b) an elevated biological productivity of the low-latitude ocean; (c) a decrease in the preformed nutrient content of the intermediate waters due to more primary production in their formation zones; and (d) an ecological change that would result in greater fraction of the organic matter reaching the deep sea. Boyle (1988 c) used a five-box equilibrium model (Fig. 4) to evaluate the various possibilities. He found the largest decrease (46 ppm corresponding to an assumed mid-depth phosphate change of $0.4 \mu\text{M kg}^{-1}$) when more organic matter was assumed to decompose in the deep box. On the other hand, a reduction in the rate of formation of the NADW' to facilitate the formation of intermediate water produced negligible (8 ppm) change. Boyle's model suggests that the variations in alkalinity and atmospheric CO_2 may lag behind changes in the chemical structure by several thousand years, in accordance with the observations. However, this model does not explain why the oceans alternate

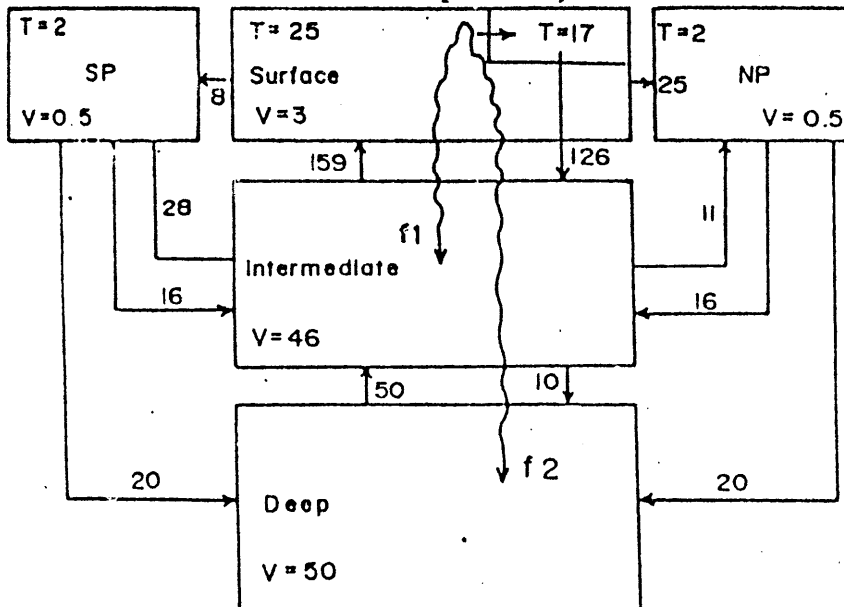


Fig. 4: A five box model of present oceans. The high-latitude surface box has been split into the north polar (NP) and South polar (SP) boxes. Fractions of surface fluxes regenerating within the intermediate and deep boxes are f_1 and f_2 , respectively: $f_2 = 0.13$ (organic carbon) and 0.27 (CaCO_3) for the case shown here (after Boyle, 1988c).

between the "preglacial" and "deglacial" modes. Boyle (1988 c) considered the insolation variations brought about by the orbital changes to be responsible for driving the ocean in between the two modes.

The role of high-latitude insolation changes is more obvious in the model designed by Keir (1988), which reinvokes an enhanced glacial primary production rate at high latitudes (the Antarctic) as the key parameter for regulating the atmospheric CO_2 . In this model (CYCLOPS), the ocean is partitioned into 13 compartments to resolve the geochemical changes on a coarse regional basis. A comparison of the circulation assumed in this model with two other multiple-box models with similar configurations (BBIM of Bolin *et al.*, 1983; and PANDORA of Broecker and Peng, 1986) is made in Fig. 5, where the number of boxes have been reduced to 10 by lumping some boxes, wherever necessary (such as the Indian, N. Pacific and S. Pacific in the CYCLOPS). The CYCLOPS model assumes an estuarine circulation for the Antarctic (in contrast with the Mediterranean-type circulation assumed for the "cold" box in the three-box models) and a Mediterranean-type circulation for the Arctic. Consequently, an increase in Antarctic primary production is expected to lead to a decrease in the preformed nutrient contents of the intermediate waters globally. Keir proposed that this could account for the observed decreases in nutrient contents of the glacial intermediate waters. As the net effect would be to pump more organic matter to the deep sea, this could be a possible mechanism for the vertical re-arrangement envisaged by Boyle (1988 b,c). Lower nutrient concentrations in the glacial intermediate waters are expected to have another important implication: these would cause the low latitude biological production to diminish. This would imply a smaller flux of CaCO_3 to the deep sea, and therefore better preservation of carbonates during most part of the glacials following an initial increase in dissolution globally. These features are indeed recorded in the sediments (Keir, 1988).

Examining various possible scenarios, Keir concluded that the postulated increase in the Antarctic primary production (by a factor of 2 or 3) should combine with an increase in the AABW to NADW source ratio from 1:3 (present) to 2:1 (glacial) for the

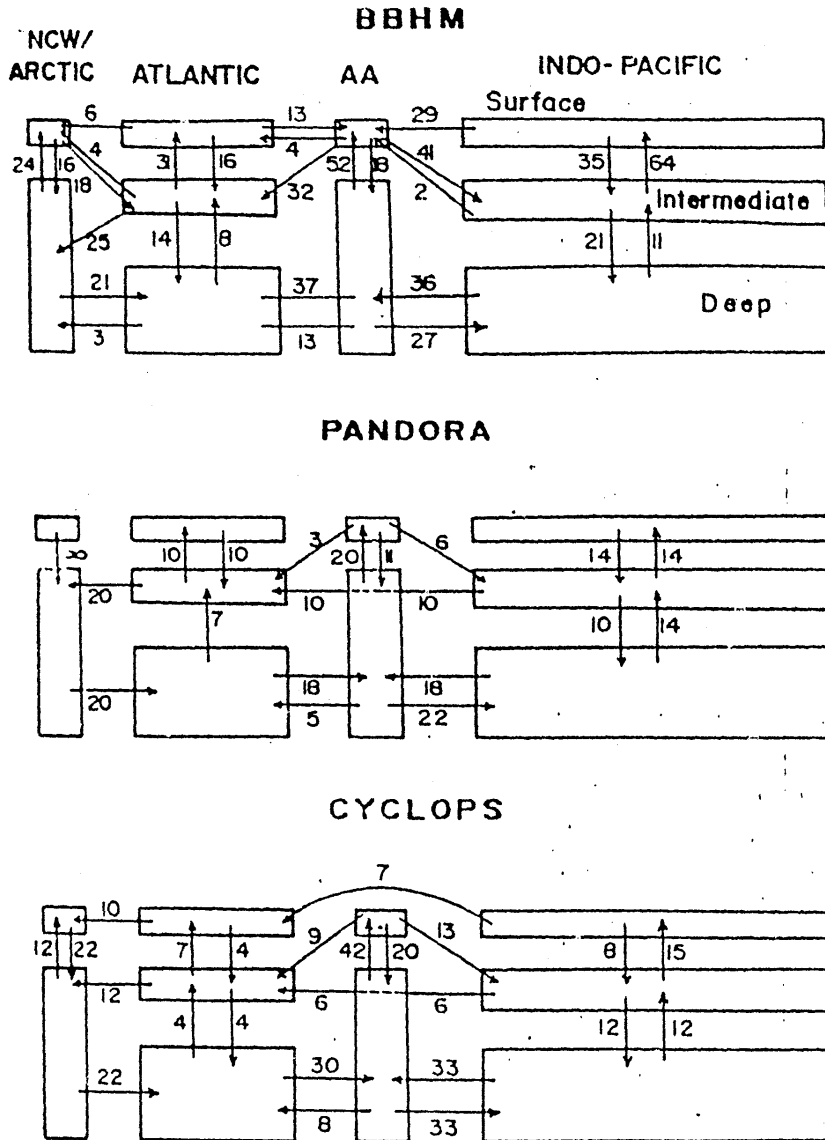


Fig. 5: A comparison of the multiple-box models of present oceans (BBHM of *et al.*, 1983; PANDORA of Broecker and Peng, 1986; and CYCLOPS of Keir, 1988). Some boxes have been lumped, whenever necessary, to present similar (10-box) configuration (after Keir, 1988).

Bolin /

best model simulations of the atmospheric $p\text{CO}_2$ changes and regional distributions of CaCO_3 dissolution $\delta^{13}\text{C}$ and PO_4 contents of the intermediate and deep waters as inferred from the Cd/Ca record in benthic foraminifera. The question, however, is that in view of what has been said about the not-so-higher-than-the-present Antarctic productivity during the LGM, which seems to be supported by more recent results on Cd/Ca in the planktonic foraminifera from the Southern Ocean (Boyle, 1988 a), whether one could still allow room for a factor of 2 or 3 changes? Keir argues that an increase in the total particulate carbon transport could result from an expansion of the high-productivity zones rather than an increase in the actual flux. However, it is difficult to assess such expansion, if any, with the available data.

As stated earlier, the CaCO_3 compensation increases the magnitude of a CO_2 change per unit of nutrient forcing (Broecker and Peng, 1987). Since this compensation takes several thousand years, it should delay the CO_2 response for which there is no evidence. However, Keir (1988) demonstrated that 92% of the CO_2 change has a time constant of about 200 years, while the remaining 8% change occurs with a time constant of about 3,000 years. Thus the lack of a delay in the CO_2 response due to CaCO_3 compensation may not be inconsistent with the nutrient-based scenarios. A vertical re-arrangement in the distribution of the products of regeneration of biogenic material, proposed by Boyle (1988 b,c) and supported by Keir (1988), also averts the "oxygen crisis" that represented a major shortcoming of the previous models. As more organic matter is believed to decompose during glacial time in the deep sea which is presently characterized by fairly high oxygen concentrations, widespread anoxia is unlikely, to develop, although the oxygen contents of the deep waters during glacial time are expected to be substantially lower than those observed today.

THREE-DIMENSIONAL MODEL

Although the box models described so far have shown how the various possible changes in the productivity and circulation could have affected the atmospheric $p\text{CO}_2$, and hence the

climate, they have not told us how these changes were brought about. The present efforts are aimed at developing models of the ocean carbon system which should integrate models of water circulation, upper-ocean ecology, water-column transformations and diagenetic processes (Toggweiler *et al.*, 1987; Sarmiento *et al.*, 1988). When combined with the models with a coupled ocean-atmosphere, these are expected to lead to an understanding of the overall response of the system to various external forcing functions.

As a part of these efforts, Sarmiento *et al.* (1988) utilized a 3-dimensional simulation of the ocean circulation to focus on some processes controlling the large-scale distributions and biogeochemical cycling of carbon and nutrients. Assuming that the organic matter is removed from the euphotic zone primarily as large particles, these authors made use of the sediment trap data to arrive at a scaling law for the regeneration of PO_4 in the water column. The production of CaCO_3 was assumed to be proportional to organic production; CaCO_3 was assumed to dissolve entirely within the deepest box (the ocean, 4-km deep, was partitioned vertically into 25 levels). As shown in Fig. 6, the model simulated the distributions of new production and PO_4 quite well qualitatively. However, the absolute values of both were much higher than those actually observed. As discussed by Sarmiento *et al.* (1988), the anomalously high PO_4 concentrations predicted by the model probably lead to the predicted high fluxes of carbon from the surface layer. The model-simulated PO_4 maximum was also found to be located at much shallower depths (~500 m at the equator). Sarmiento *et al.* suggested that these anomalies could arise from an incorrect characterization of the cycling of organic matter in the ocean. That is, the assumption that most of the downward transport of degradable organic matter occurred through large particles might not be actually valid. This could account for a smaller regeneration scale depth deduced from the sediment trap observations as compared to the estimates based on the oxygen profiles. This is also in conformity with the recent results of Sugimura and Suzuki (1988) and Kumar *et al.* (in press) which suggest that the dissolved organic matter (DOM) in the oceans could be much more labile than has been believed so far, and

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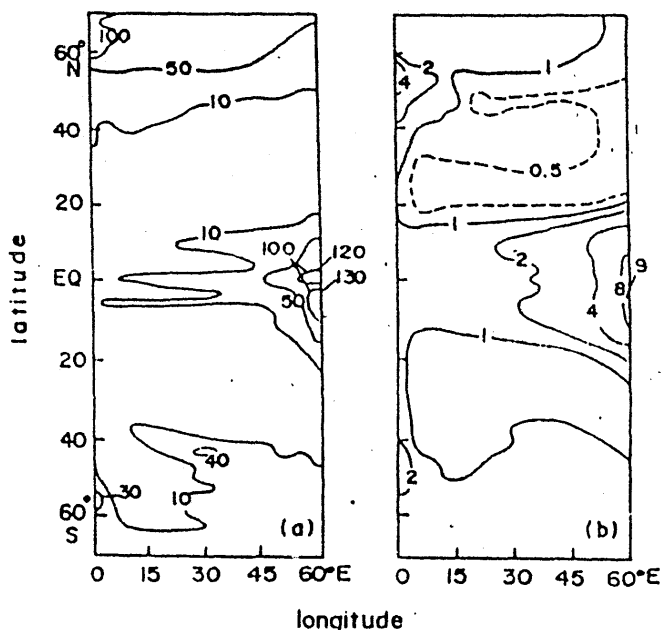
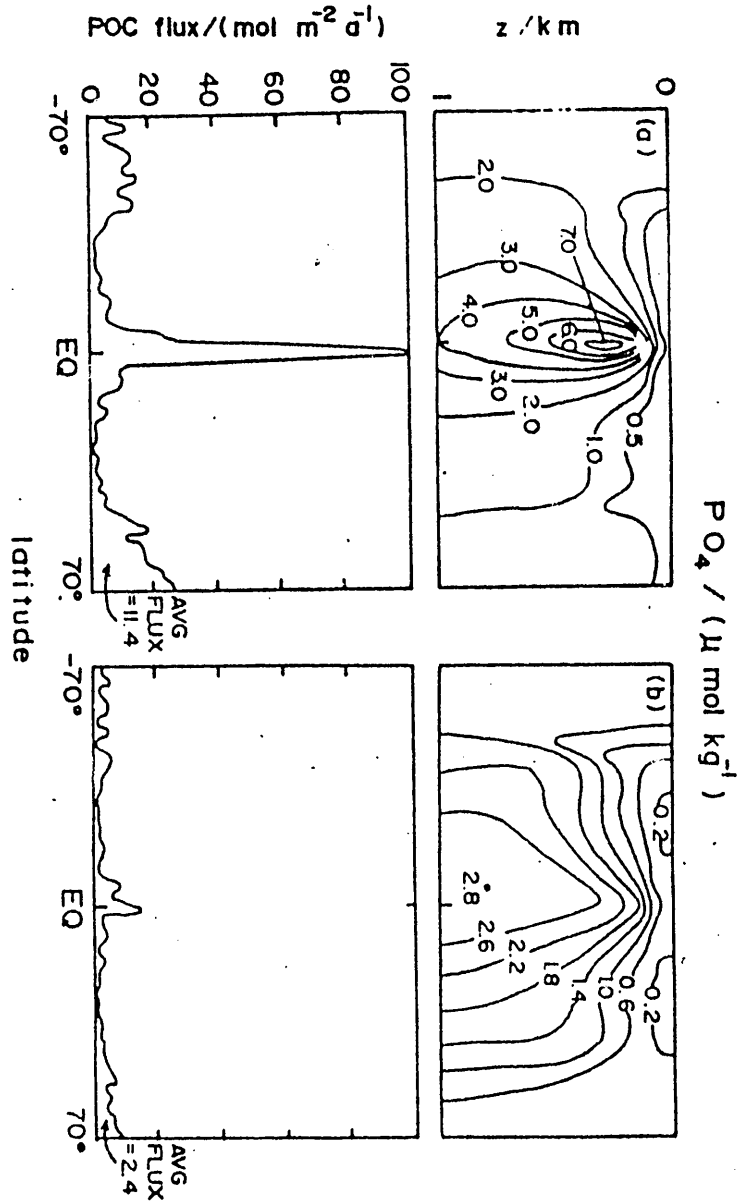


Fig. 6: (a) Carbon flux at 100 m ($\text{moles m}^{-2} \text{a}^{-1}$) and (b) phosphate at 180 m ($\mu\text{mole kg}^{-1}$) as predicted by the three-dimensional model (after Sarmiento *et al.*, 1988).

that the transfer of the large pool of DOM to the deep sea by advective processes might account for a considerable fraction of oxygen consumption in the subsurface layers. Sarmiento *et al.* showed that when half of the surface production was put into DOM with a regeneration time of 166 years, and was allowed to diffuse and advect, the model led to a much better match with the observations (Fig. 7).

The 3-dimensional model yields anomalously high (620 ppm) pCO_2 when the DOM contribution is not considered, ostensibly due to the higher production owing to shallow regeneration of PO_4 predicted by the model. This results in a large CaCO_3 flux to the deep sea which lowers the alkalinity in upper oceanic layers raising the atmospheric pCO_2 . Incorporation of DOM into model calculations lowers the pCO_2 to 308 ppm. Thus the changes in the oceanic DOM pool could cause large fluctuations in the atmospheric CO_2 content. However, at this stage it is not clear what constrains the size of the DOM pool in the sea (Toggweiler, 1988).



(a) Zonally-averaged phosphate ($\mu\text{mole kg}^{-1}$) distribution in the upper kilometer and carbon flux predicted by the three-dimensional model; and (b) the same as in (a) but with half of the organic carbon production put into DOM with a regeneration time of 166 years.

Fig. 7

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SCOPE OF FURTHER WORK WITH REFERENCE TO THE INDIAN OCEAN REGION

In all the models dealing with the long-term geochemical variability of the ocean and its relationship with the climate, the approaches taken so far have been rather general. This, of course, is to be expected since we are dealing with the global phenomena. These models have not taken into consideration the possible regionally varying responses of both the productivity and circulation to the climatic changes. This is particularly important for the Indian Ocean, where the atmospheric and surface oceanic circulations differ from those experienced by the other oceans in that these undergo unique reversals every six months in the region approximately north of the equator. The pollen and stable isotopic data suggest large changes in relative intensity of the monsoons associated with the glacial-interglacial cycles (Prell *et al.*, 1980; Duplessy, 1982; Van Campo *et al.*, 1982). This region also contains one of the three major sites in the open ocean—the Arabian Sea—where the oxygen content at mid-depth falls to vanishingly low levels, turning the environment reducing. Under such conditions large scale bacterial reduction of nitrate ions to molecular nitrogen (denitrification) takes place. Due to the precarious balance between the oxygen supply and its utilization that exists in the oxygen-deficient environments, these environments may respond more actively to the external perturbations than any other. The large short-term changes in the reducing conditions observed in these areas support this view (Codispoti *et al.*, 1986; Naqvi, 1987; Naqvi *et al.*, in press). Presently the Arabian Sea contributes about 1/3 (approx. 30 Tg N a⁻¹) of the total marine water-column denitrification (Naqvi, 1987). A 50% change in this rate maintained over a period of 1,000 years will increase or decrease the mean concentration of inorganic combined nitrogen by about 1 μM l⁻¹; the actual change will be much more in the more important upper ocean. This could lead to significant changes in productivity and this may represent an important feedback mechanism that could increase or decrease the magnitude of the global change.

In order to incorporate these regionally varying responses into the global models, however, we must have a good under-

standing of the composition and circulation of the glacial subsurface waters. Unfortunately, while adequate paleo-oceanographic data have been generated from the Atlantic and more recently the Pacific Ocean, very little is known about the conditions that existed in the northern Indian Ocean during the ice ages. Even the limited data which are available pose more problems than the questions they answer.

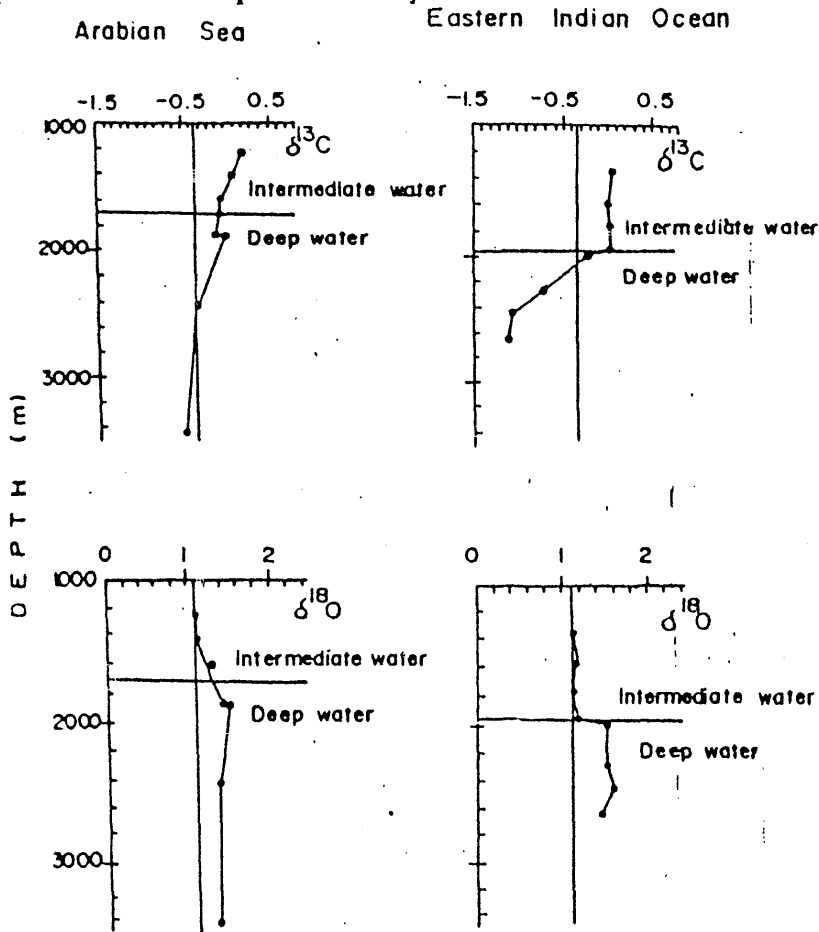


Fig. 8: Changes in the intermediate and deep sea $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ between the LGM and today in the North Indian Ocean as inferred from the analyses of foraminifera in sediment cores. The 0.32‰ $\delta^{13}\text{C}$ line represents the expected changes if the circulation were to remain unaltered; the 1.1‰ $\delta^{18}\text{O}$ line gives the expected change if the water temperature had not varied (modified from Kallel *et al.*, 1988).

The stable isotopic data of Kallel *et al.* (1988), reproduced in Fig. 8, suggest that a strong thermal discontinuity separating the deep and intermediate waters probably existed during the LGM with the deep waters being cooler than today; also they were more oxygen-depleted. These authors also suggested the glacial intermediate waters in the North Indian Ocean had more or less the same temperature as observed today. But they could have been more effectively ventilated as was probably the case with their counterparts in the Atlantic (Boyle and Keigwin, 1987). It must, however, be pointed out that there was little or no exchange, due to a lower sea level during glacial time, between the Arabian Sea with the Red Sea and the Persian Gulf, which presently supply warm, saline waters to the Arabian Sea at mid-depth. Consequently, one would expect the glacial intermediate waters in this region to be cooler than today unless the ventilation (supply from the south) was poor and/or the Arabian Sea itself was a source region of warm intermediate waters. In either case, the mid-depth oxygen balance, and consequently the intensity of the reducing conditions and nitrogen cycling, will be affected. More data are, therefore, required from various depth regimes on paleochemical tracers such as ^{13}C and Cd/Ca in benthic foraminifera to understand how the subsurface circulation in the North Indian Ocean changed with the glacial-interglacial cycles. In addition to providing valuable inputs to the global climatic models, these studies will also help in the development of predictive models for assessing the response of the mid-depth reducing conditions to anthropogenic perturbations.

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