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How strong is the Harvardton-Bear constraint?

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Abstract. We compare the sensitivity of the partial pressure of CO_2 in the warm surface ocean and atmosphere to the influence of the ocean's cold water outcrops in a wide spectrum of models. While in simple box models the cold ocean dominates, in three-dimensional ocean general circulation models, this influence is considerably smaller, suggesting that exchange processes between the warm and cold regime in the real ocean are extremely important in determining the distribution of chemical properties.

1. Introduction

More than a decade ago, three groups [*Knox and McElroy*, 1984; *Sarmiento and Toggweiler*, 1984; *Siegenthaler and Wenk*, 1984] pointed out a very important aspect of the marine carbon cycle. Using simple three-box models, each group independently demonstrated that despite their limited area, surface waters in the cold high-latitude surface box dictated the CO_2 content of the warm surface ocean and hence also of the atmosphere. This dominance stems from the direct connection between polar surface waters and those in the deep ocean reservoir and the fact that transport of CO_2 via the atmosphere between the warm and cold regions of the ocean is sufficiently rapid to bring the carbon dioxide partial pressure (pCO_2) of the warm surface ocean close to that of the cold surface ocean. This dominance of the cold surface ocean is often referred to as the Harvardton-Bear effect after the three institutions housing the authors of the original papers (i.e., Harvard, Princeton, and Bern).

This finding has very important implications with regard to scenarios designed to account for the lower CO_2 content of the glacial atmosphere [*Neftel et al.*, 1985; *Barnola et al.*, 1987]. The reason is that if the Harvardton-Bear constraint applies to the real ocean, it eliminates from contention all but one scenario involving changes in the strength of the biologic pump for the temperate and tropical surface ocean. Only for the *Archer and Maier-Reimer* [1994] hypothesis, which calls for an increase in the rain ratio of organic matter to $CaCO_3$ to the sea floor, can changes in conditions in the warm surface be of consequence. Thus, as the Southern Ocean dominates the cold regions, it is changes in its surface waters that have played a key role in the reduction in the CO_2 content of the glacial atmosphere. Further, the minuscule dust fall onto today's Southern Ocean gave rise to the idea that the inefficient utilization of nutrients in this oceanic region is the result of a dearth of the element iron. Thus *Martin* [1990] called on the far higher dust fall of glacial time documented in ice cores [*Petit et al.*, 1999] to account for a strengthening of the biologic pump in this region.

2. Concept

Shown in Figure 1 is a simple way to understand this constraint. Consider a hypothetical abiotic ocean consisting of a warm reservoir covering 80% of the surface and a cold reservoir with an outcrop occupying the remaining 20% of the surface. The volume of the deep reservoir is taken to be very much larger than that of the warm reservoir. Hence the carbon chemistry of the deep reservoir can be taken to be immutable (i.e., the pCO_2 in the cold reservoir is fixed at 280 µatm). We assume that differences in carbon chemistry between the warm and cold reservoir relate entirely to the temperature difference between these reservoirs (25°C for the warm and 0°C for the cold). In the situation where the transport of CO_2 through the atmosphere from the warm to the cold reservoir is far slower than the rate of transfer of water (and hence ΣCO_2) between these reservoirs, the CO_2 partial pressure in the warm surface reservoir would be 790 µatm. In this case, the partial pressure of CO_2 in the atmosphere would be as follows:

$$pCO_2^{(atm)} = 0.8x790 + 0.2x280 = 688\mu atm \qquad (1)$$

At the other extreme where the rate of CO_2 transfer between atmosphere and ocean far outstrips the rate of water circulation, the CO_2 partial pressure in both the warm reservoir and the atmosphere would be 280 µatm.

In this very simple model, the actual CO_2 partial pressures for the atmosphere and the warm surface ocean reservoir depend on the ratio of the rate of gas exchange between ocean and atmosphere to the rate of thermohaline circulation. If the transport rate of water around the thermohaline circuit is set at 30 Sv and the rate of CO_2 exchange at 6 x 10^{-2} mol/µatm m^2 yr, then the CO_2 partial pressure in the warm reservoir stabilizes at 335 µatm and that in the atmosphere stabilizes at 324 µatm. This result can be expressed as the Harvardton Bear Equilibration Index (HBEI) which is defined as follows:

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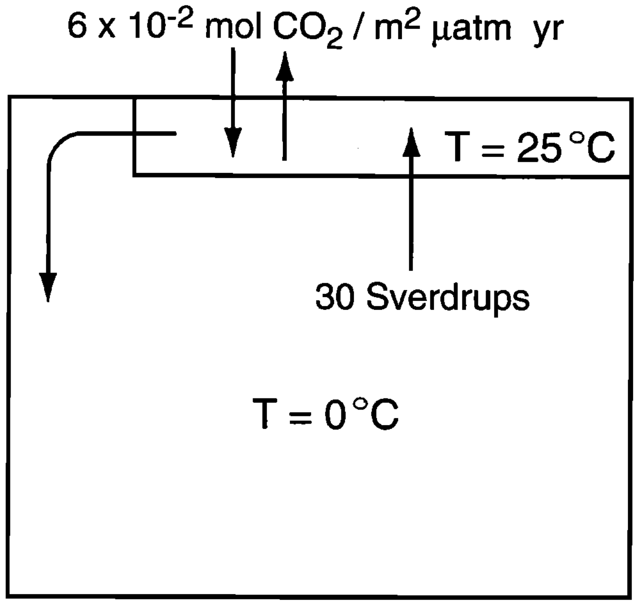

Figure 1. Simple abiotic two-box model [*Broecker and Peng*, 1998].

$$\mathrm{HBEI} = \frac{324-280}{688-280} = 0.11 \text{ (atmosphere)} \tag{2}$$

$$\mathrm{HBEI} = \frac{335-280}{790-280} = 0.10 \text{ (warm ocean)} \tag{3}$$

For an ocean where gas exchange dominates thermohaline circulation, the index would approach zero. In this case, rule by the cold surface ocean would dominate, and hence changes in the strength of the biological pump or in the temperature of the warm ocean would be of no consequence. The reason is that any tendency to change the CO_2 partial pressure of the warm surface ocean would be compensated by transport of CO_2 from cold surface ocean. For an ocean where the opposite was true, the index would approach unity. In this case, the changes in the strength of the biological pump or temperature of the warm surface ocean would impact the atmosphere in proportion to the fraction of the ocean area they cover. If the HBEI for the real ocean is as low as that in this simple example, then indeed no scenario dependent on changes in the temperature or biologic pumping strength for the warm surface ocean could be invoked to explain the low-CO_2 content of the glacial atmosphere.

3. Application of the Index

The question then is whether full-scale dynamic models of the ocean designed to replicate the observed oceanic density, radiocarbon, and nutrient distributions yield similarly low-equilibration indices. We have designed a simple test to determine whether or not this is the case. It is carried out as follows. After the model's carbon cycle has reached steady, a change is made in the solubility coefficient relating the partial pressure of CO_2 to the concentration of CO_2 in the surface waters between 40°N and 40°S. The coefficient for these waters is arbitrarily changed by a fixed factor while its value is left unchanged poleward of 40° latitude. The equilibration index is then determined by comparing the partial pressure calculated for the model atmosphere or warm surface ocean were no readjustment to occur with that which the model achieves after it is run to steady state with the new solubility coefficient. The ratio of these two changes yields the equilibration index

$$\mathrm{HBEI} = \frac{p^F - p^o}{p^I - p^o} \tag{4}$$

where p^o is the model's initial steady state pCO_2, p^I is the pCO_2 immediately after the change of the solubility coefficient, and p^F is the pCO_2 after steady state has been reestablished. The index can be calculated either using the atmospheric partial pressures or using the warm surface ocean's partial pressures (averaged from 40°N to 40°S). However, it must be kept in mind that in the case of the atmosphere, the CO_2 partial pressure immediately after the coefficient change is that which would exist if an amount of CO_2 were instantaneously added (or subtracted) to bring it to steady state with the CO_2 pressures in the underlying surface ocean. As already stated, the impact of changes in the warm surface ocean biological pump or temperature are directly proportional to the value of the index. If the index is 1, then the full impact of the change is felt by the atmosphere. If the index is 0, then such changes have no impact.

4. Model Intercomparisons

One of us (D.A.) has calculated the HBEI for the box models in common use (i.e., the Harvardton Bears three-box models and the Pandora and Cyclops multibox models). As summarized in Table 1, these indices range upward from the index value of 0.11 obtained from the very simple to two-box model to 0.28 for Pandora.

The zonally averaged model of *Wright and Stocker* [1991] has been programmed to include the ocean carbon cycle [*Marchal et al.*, 1998]. This model yields an index value of 0.16 for the atmosphere and 0.14 for the warm surface ocean.

Runs were made in two ocean general circulation models (OGCMs) programmed to include the biological cycling. The indices obtained using the Hamburg model are 0.41 for the atmosphere and 0.32 for the warm surface ocean. The indices obtained for the Princeton model are 0.37 and 0.24, respectively.

5. Discussion

The result of this exercise is clear. The full OGCMs have indices considerably higher than those for the simpler box models. We suspect that the higher indices for the OGCM reflect a greater extent of exchange between the warm and cold waters of the ocean than those included in the simpler box models. In an independent study of model behavior, one of us (D.A.) has shown that vertical diffusion in the OGCMs is responsible for their muted high-latitude sensitivity. This statement is in no sense derogatory but rather indicates that these models have horizontal variations in the flow that cancel in the global average and hence act in some aspects similarly to diffusion. If, indeed, these models replicate the real ocean in this regard, then, as already shown by *Bacastow* [1995], it is clear that results from simple box models can be misleading.

There exists a second difference that is important in determining the HBEI indices. It is the size of the water masses ventilated

Table 1. Summary of Harvardton Bears Equilibration Indices Obtained in a Series of Ever More Complex Ocean Models

Model	Description	HBEI Atmosphere	HBEI Warm Surface
Two box	*Broecker and Peng* [1998]	0.11	0.10
Three box	*Knox and McElroy* [1984]	0.11	0.13
	Sarmiento and Toggweiler [1984]		
	Siegenthaler and Wenk [1984]		
Pandora multibox	*Broecker and Peng* [1989]	0.28	0.22
Cyclops multibox	*Keir* [1988]	0.17	0.19
Bern 2D GCM	*Wright and Stocker* [1991]	0.16	0.14
	Stocker and Wright [1991]		
Hamburg 3D GCM	*Maier-Reimer* [1993]	0.41	0.32
	Maier-Reimer et al. [1993]		
Princeton 3D GCM	*Murnane et al.* [1998]	0.37	0.24
	Sarmiento et al. [1995]		

from 40°S to 40°N relative to those that are ventilated at more poleward latitudes. In the Harvardton-Bear models, the volume of the low-latitude surface box is very small compared to the volume of the deep box, and therefore the concentration in the deep box hardly changes at all. The situation in OGCMs is quite different. In the Princeton OGCM the signal propagates down to more than 1500 m; that is, the concentration of total dissolved inorganic carbon (TCO_2) was reduced above about 1700 m and increased below this depth. This indicates that the relative size of the two water masses is very different in OGCMs, of the order of 3 to 1, instead of something like 30 to 1 in the simplest box models.

So where does this leave us with regard to the Harvardton-Bear constraint? The answer is that while the simple box models suggest that the reduction of the impacts of changes in the warm ocean biological pumping and temperature by factors as high as 9 (i.e., 1/0.11), the three-dimensional OGCMs suggest a factor as small as 2.5 (i.e., 1/0.41). This opens the door a bit for changes in the temperature and nutrient dynamics of the warm ocean to play a role in the drawdown of CO_2 in the glacial atmosphere. This study also points out the importance of coming to grips with the reliability of water transports simulated in OGCMs. To what extent are they true to the real ocean?

6. Conclusions

Various drafts of this paper were circulated to a number of scientists outside the author group. Jorge Sarmiento and Robert Bacastow picked up on it and made comments which initiated a vigorous debate. This debate forced us to think more deeply about the role of exchange terms in the models and also about the exact definition of the HBEI. Among other things, the value of this index depends on the sign and magnitude of the perturbation. Clearly, other papers will be forthcoming which delve into the issues left unanswered by this one. However, the bottom line will remain unchanged; simple box models significantly overestimate the importance of the cold surface ocean in setting the CO_2 partial pressure of the atmosphere.

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