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UPTAKE OF ANTHROPOGENIC CO_2 BY LATERAL TRANSPORT MODELS OF THE OCEAN BASED ON THE DISTRIBUTION OF BOMB-PRODUCED ^{14}C

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ABSTRACT. The pattern of global water column inventories of bomb-produced ^{14}C suggests that a sizeable portion of bomb ^{14}C that entered the Antarctic, northern Pacific, and tropical oceans has been transported to adjacent temperate regions. Models of lateral transport of surface water in the Atlantic, Indian, and Pacific Oceans are based on this distribution pattern. Upwelling of bomb-^{14}C-free water from below takes place in the Antarctic, northern Pacific, and tropical regions; downwelling of surface water occurs in the temperate oceans and northern Atlantic. Uptake of excess CO_2 by these models is calculated using the observed Mauna Loa pCO_2 record as an input function. Results indicate that 35% of fossil fuel CO_2 is taken up by these model oceans during the period 1958–1980. Considering the observed airborne fraction of 0.55, it appears that ca 10% of the global fossil fuel CO_2 is still missing.

INTRODUCTION

The world ocean is a major carbon reservoir in the global carbon cycle. To estimate the effect of ocean circulation on the partial pressure of CO_2 in the atmosphere after a wide-scale perturbation, we need a geochemical model of the world ocean circulation. The distribution of bomb-produced ^{14}C in the ocean, measured during the survey of Geochemical Ocean Sections (GEOSECS), can be used as constraints on these global ocean circulation models. Broecker *et al* (1985) summarized the water column inventories of bomb ^{14}C for all the stations for which the ^{14}C profiles were taken. The pattern of global inventories that emerged from their summary suggests that a sizeable portion of the bomb ^{14}C that entered the Antarctic, northern Pacific, and tropical oceans has been transported to adjacent temperate zones. Lateral surface water transport models for the three major oceans could be constructed to simulate the distribution of ^{14}C.

The major perturbation in the distribution of carbon in the ocean-atmosphere system is the release of fossil-fuel-produced CO_2 into the atmosphere since the early 19th century. Numerous ocean models were developed to estimate the uptake of fossil fuel CO_2 by the ocean in order to account for the observed changes in CO_2 content in the atmosphere. Except for outcrop-diffusion model of Siegenthaler (1983), most of these geochemical models do not take up enough excess CO_2 (Peng, 1984) to match the airborne fraction of fossil fuel CO_2 derived from the measured Mauna Loa atmospheric CO_2 records (Bacastow & Keeling, 1981).

In this paper, we address the question of whether models of lateral surface water transport in the three major oceans (derived from the distribution of bomb ^{14}C) will modify the CO_2 uptake of the oceans to account for the excess CO_2 and thereby balance the carbon budget in the system. The distribution of bomb ^{14}C in the ocean will be described, and the surface water transport models for the Atlantic, Indian, and Pacific Oceans will be discussed. The total CO_2 uptake by these transport models is compared with the uptake calculated using other one-dimensional ocean models.

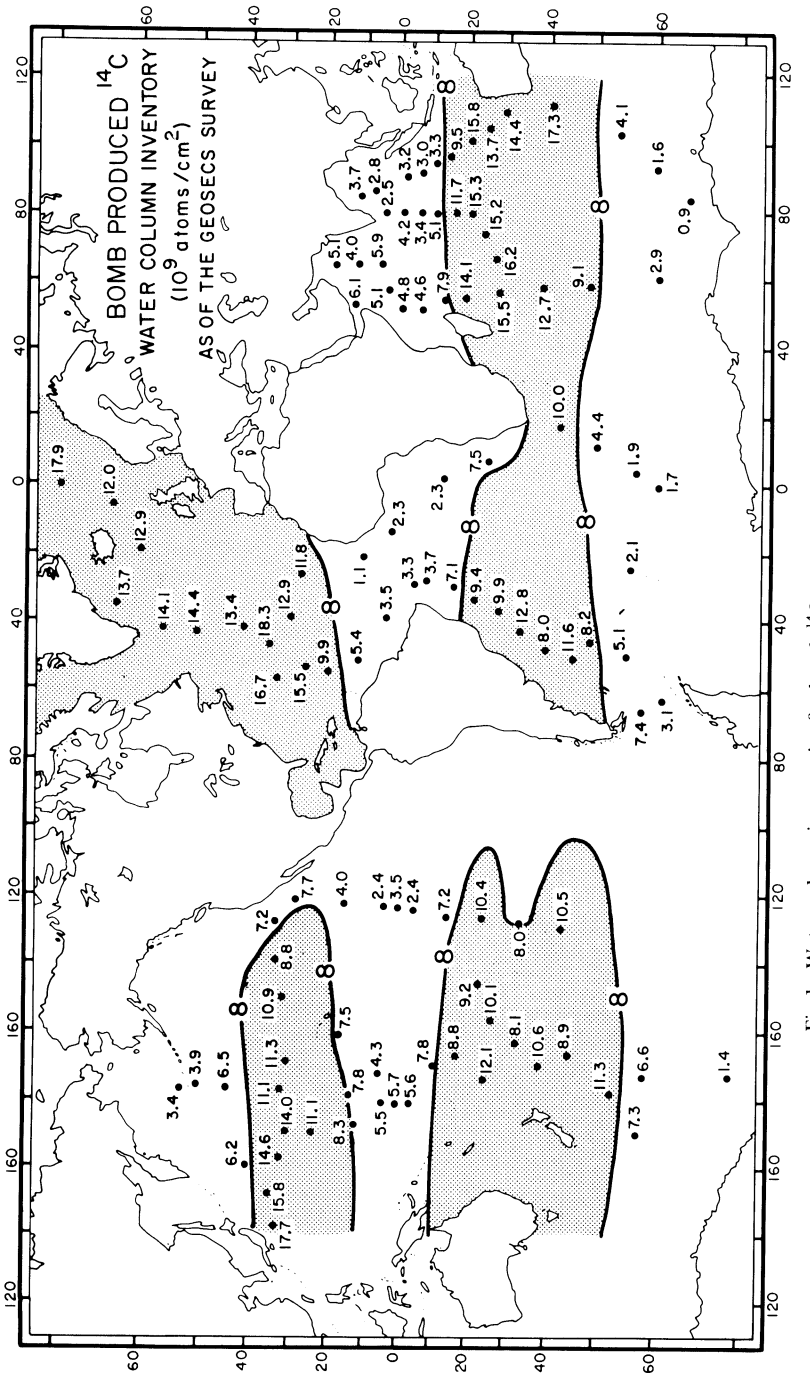

Fig 1. Water column inventories for bomb ^{14}C at the GEOSECS stations

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The water column inventories of bomb ^{14}C were obtained from the $\Delta^{14}C$ *vs* depth, ^{3}H *vs* depth, and total CO_2 concentration *vs* depth profiles measured during the GEOSECS program. The ^{3}H profile is used as a guide in reconstructing the prebomb $\Delta^{14}C$ profile because it can be assumed that both bomb-produced ^{3}H and ^{14}C have penetrated to approximately the same depth in the oceans. The total CO_2 data allow the $\Delta^{14}C$ excess (over the prebomb value) to be converted to the number of excess

TABLE 1

Summary for individual ocean regions showing either excess or deficient bomb ^{14}C inventories relative to the amount expected if the CO_2 invasion rate were uniform over the ocean

Latitude belt	Area (10^{16} cm^2)	Inventory (10^{26} atoms)	Input (10^{26} atoms)	Inv–Inp
Atlantic Ocean		[I = 22.3 mol/(m^2·yr)]		
80°N to 40°N	18.6	26.6	19.7	+6.9
40°N to 20°N	15.8	23.0	14.5	+8.5
20°N to 20°S	26.7	10.8	23.1	−12.3
20°S to 45°S	18.4	18.5	14.2	+4.3
45°S to 80°S	15.1	5.2	12.6	−7.4
80°N to 80°S	94.6	84.1	84.1	0.0
Indian Ocean		[I = 19.4 mol/(m^2·yr)]		
25°N to 15°S	27.0	13.2	24.1	−10.9
15°S to 45°S	29.8	40.5	20.3	+20.2
45°S to 70°S	20.7	15.9	25.2	−9.3
25°N to 70°S	77.5	69.6	69.6	0.0
Pacific Ocean		[I = 19.2 mol/(m^2·yr)]		
65°N to 40°N	15.1	7.3	13.4	−6.1
40°N to 15°N	35.0	35.9	27.8	+8.1
15°N to 10°S	50.0	23.7	39.1	−15.4
10°S to 55°S	63.0	61.3	43.6	+17.7
55°S to 80°S	13.8	6.6	10.9	−4.3
65°N to 80°S	176.9	134.8	134.8	0.0
World ocean	349.0	288.5		

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^{14}C atoms. The prebomb surface water $\Delta^{14}C$ values for each locality can be adequately estimated from existing measurements (Broecker *et al,* 1960; Bien, Rakestraw & Suess, 1960, 1965; Rafter & O'Brien, 1970). The GEOSECS ^{14}C data were from Stuiver and Ostlund (1980) for the Atlantic, from Ostlund and Stuiver (1980) for the Pacific, and from Stuiver and Ostlund (1983) for the Indian Ocean. A detailed description of how the inventories were obtained was given by Broecker *et al* (1985).

The global distribution of the water column inventory values is shown in Figure 1. A striking feature of the bomb ^{14}C inventory is the zonal pattern of distribution. Temperate regions of the world oceans contain higher amounts of bomb ^{14}C than the neighboring tropical and Antarctic regions. In the Pacific, the northern high-latitude region contains less bomb ^{14}C than the north temperate region. In the Atlantic, however, the northern high-latitude zone contains as high a level of bomb ^{14}C as found in the neighboring temperate region.

To eliminate the variations resulting from differences in sampling dates (1972–1978), from geographic differences in the history of atmospheric $\Delta^{14}C$, and from differences in the ocean-to-atmosphere back-flux, the ratios of water column inventory to net atmospheric input should be used. To calculate the input of bomb ^{14}C to any given ocean locale, the following information is needed: 1) the history of the atmospheric $\Delta^{14}C$ excess (over the prebomb value) for the latitude of the site, 2) the history of the surface ocean $\Delta^{14}C$ excess (over the prebomb value) at the site, and 3) the average CO_2 invasion rate for the site. The time trend of the $^{14}C/C$ ratio in atmospheric CO_2 at various latitudes is obtained from a large number of direct measurements of CO_2 extracted from the air (Nydal & Lovseth, 1983). Detailed histories for the $\Delta^{14}C$ values in surface ocean water are available for only a few places in the ocean. They are based on the analyses of dated growth rings of living coral heads (Nozaki *et al,* 1978; Druffel & Linick, 1978). Thus, for virtually all the stations of interest, we have only the surface water $\Delta^{14}C$ value at the time the station was occupied and the estimate of the prebomb surface water value. However, as the surface water $\Delta^{14}C$ history is needed to correct for only a small back-flux of bomb ^{14}C from the ocean to the atmosphere, approximations based on these two points are adequate.

In the absence of reliable estimates for the regional variations in the CO_2 invasion rate, a single average CO_2 invasion rate for each ocean is adopted for initial calculation. These averages were obtained by demanding that the bomb ^{14}C inventory in a given ocean match the bomb ^{14}C input to that ocean. By changing this invasion rate for each ocean until the above condition is met (see summary in the last column of Table 1), we obtain 22.3 mol/(m^2 · yr) for the Atlantic, 19.4 mol/(m^2 · yr) for the Indian, and 19.2 mol/(m^2 · yr) for the Pacific. These values lie within the range of those obtained previously from bomb ^{14}C data (Stuiver, 1980; Stuiver, Ostlund & McConnaughey, 1981).

Ratios of water column inventory to net input are shown in Figure 2. The pattern of zonal distribution is similar to that shown in Figure 1. Latitudinal zones where this ratio is higher than 1.0 are located in the temper-

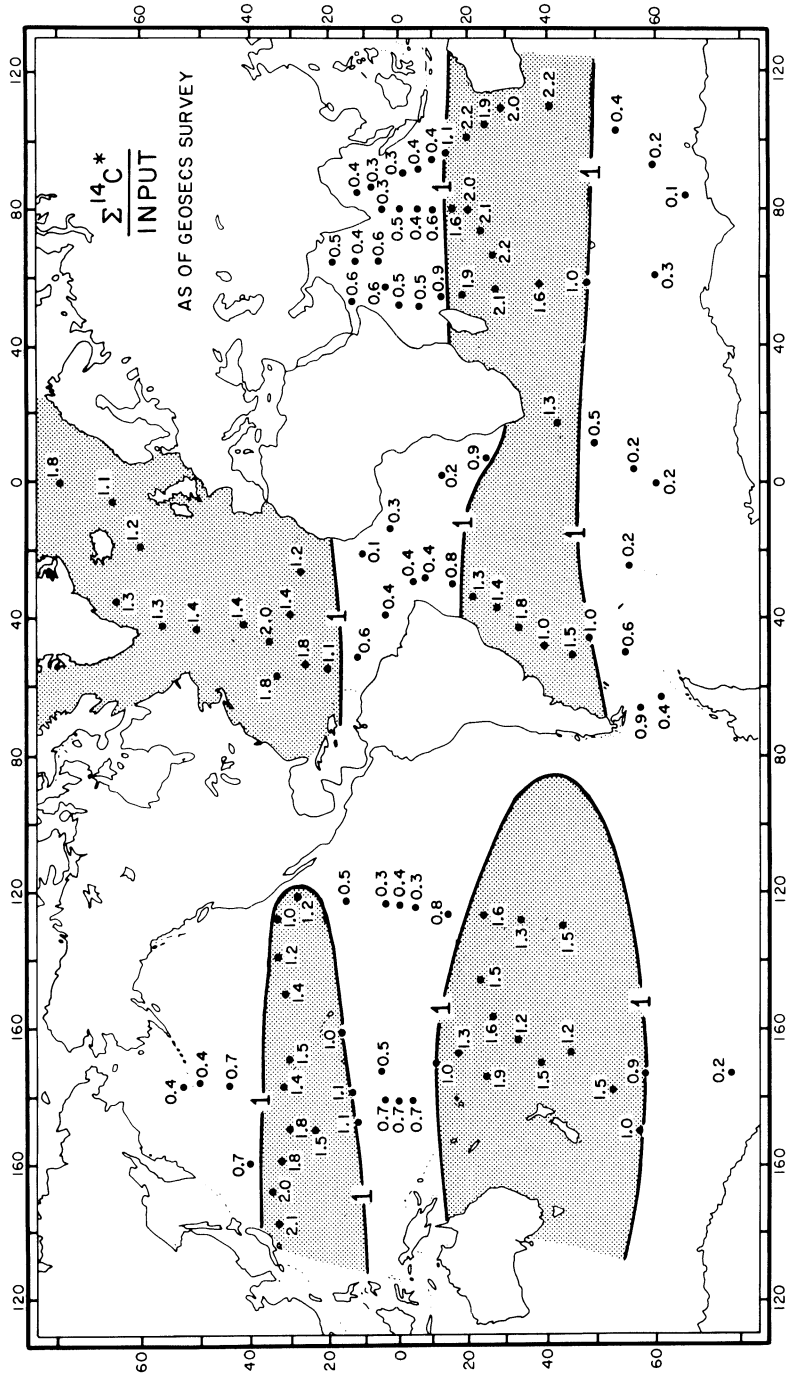

Fig 2. Ratios of water column inventory to net input of bomb ^{14}C for the GEOSECS stations

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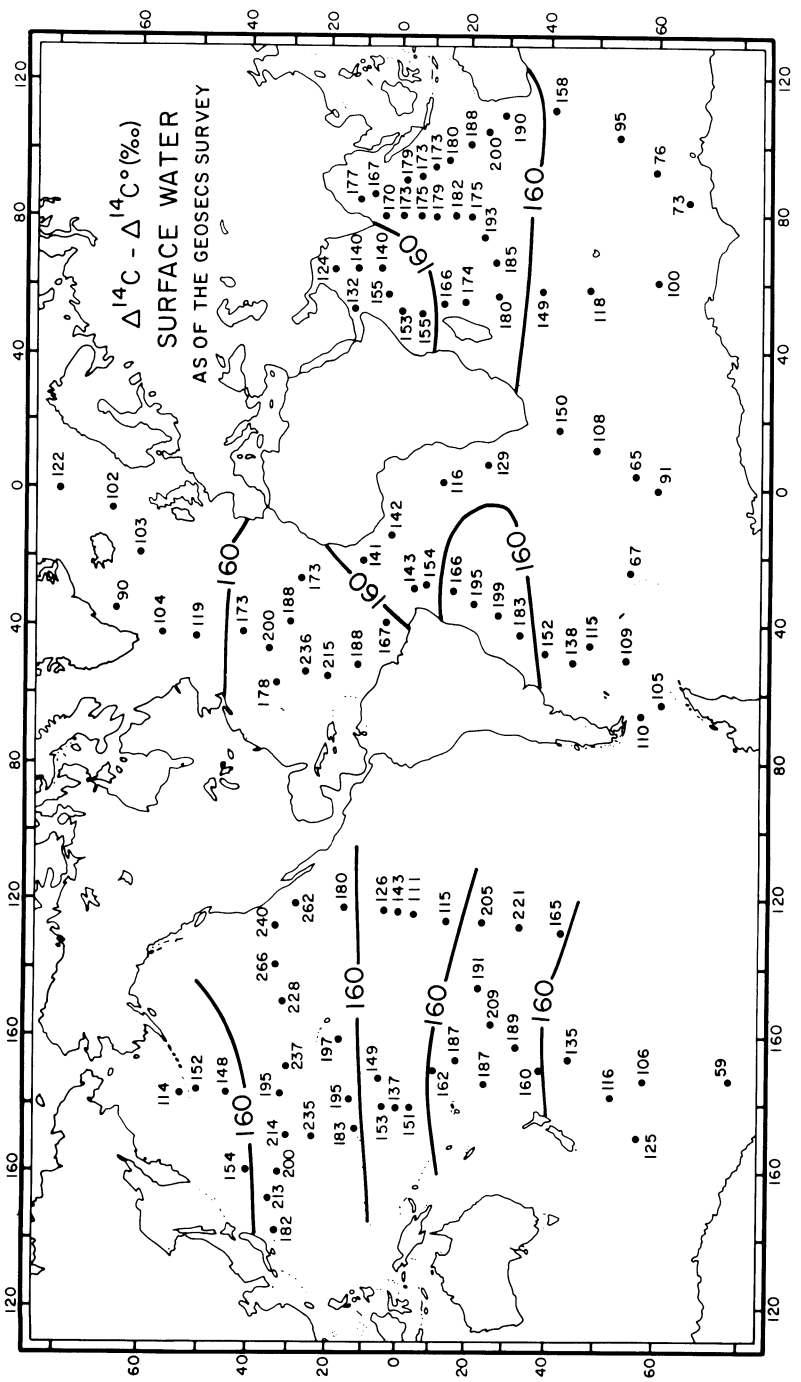

Fig 3. Distribution of $\Delta^{14}C$ excesses (over the prebomb values) for surface waters at the time of the GEOSECS surveys

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ate regions of each ocean and in the northern Atlantic. This geographic pattern of bomb ^{14}C inventories is also to some extent, reflected by the $\Delta^{14}C$ increase in surface waters (over the prebomb value) at the time of the GEOSECS surveys (see Fig 3). However, the correspondence between the water column inventory and the surface water increase pattern would be perfect only if the depth distribution of the bomb ^{14}C anomaly was the same everywhere. This is not the case. The most prominent difference between the texture of the water column inventory and that of the surface water excess is for the northern Atlantic. Here very deep penetration of the bomb tracer holds down the surface water $\Delta^{14}C$ value despite large water column inventories.

Table 1 summarizes the regional difference between the bomb ^{14}C inventory and the net input in each of the three oceans. The boundaries of the individual regions are taken to be the latitude where the sign of the inventory anomaly changes. The only exception to this is in the north Atlantic where a boundary is placed at 40° N. Since the water column inventories exceed the calculated input everywhere north of 20° N in the Atlantic, this division is somewhat arbitrary. The other boundaries are drawn to separate the zones which appear to have gained bomb ^{14}C through lateral transport from those which appear to have lost bomb ^{14}C through lateral transport.

LATERAL TRANSPORT MODEL

Broecker *et al* (1985) suggested lateral transport within the ocean to explain the pattern of bomb ^{14}C inventories. This transport model calls for upwelling coupled with a divergence in surface water flow for the tropical zones, for the Antarctic regions, and for the northern Pacific. Correspondingly, it would be necessary to call for a convergence of surface water flow coupled with downwelling in the temperate regions of the ocean and in the northern Atlantic. The model structure is shown in Figure 4. In these models each of the regions of the ocean listed in Table 1 is treated as laterally homogeneous. For those regions showing a bomb ^{14}C deficiency, the assumption is made that water free of bomb ^{14}C upwells from below. For those regions showing a bomb ^{14}C excess, the assumption is made that surface water downwells. Water is conserved by requiring that the upwelling in any given region be matched by the flow of surface waters to adjacent regions. In addition to the vertical fluxes in each region, the pattern of horizontal divergence and vertical mixing coefficients for each region are considered variable parameters in the model.

Based on the transport pattern described, sets of reasonable advective fluxes and vertical mixing coefficients are given for each ocean. Adjustments of these parameters are made until the observed water column inventory and the observed surface water excess $\Delta^{14}C$ are as closely reproduced as possible. In the model calculations, water and bomb ^{14}C are conserved. Because of lack of knowledge of the pattern of wind speed over the ocean and the wind speed dependence of the rate of gas exchange between the atmosphere and the ocean, the assumption is made that the CO_2 invasion rate is uniform from region to region in a given ocean and that the magnitudes are the same as those used earlier for computation of bomb ^{14}C

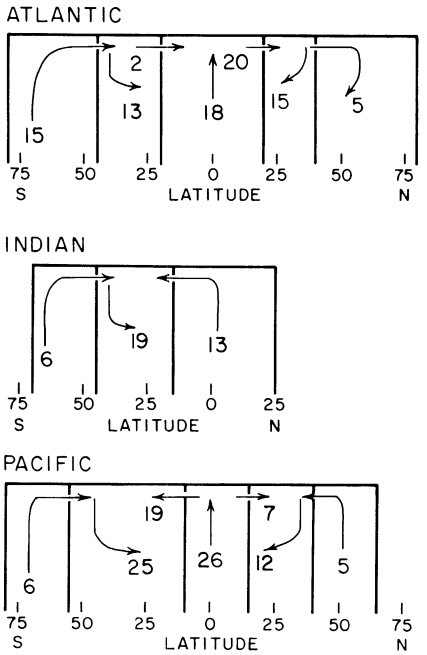

Fig 4. Diagram of lateral transport model designed to explain the distribution of bomb ^{14}C in the ocean. The water fluxes are given in sverdrups (10^6 m^3/s).

input (see Table 1). Also, it is assumed that there is no transport of bomb ^{14}C from region to region via the deep water. The model flow velocities and vertical diffusivities obtained in this way are given in Table 2. These values are by no means the unique solutions to this transport pattern, but are considered to be the most appropriate sets of values. In fact, the magnitudes of these fluxes are reasonable and consistent with estimates obtained in other ways. The vertical diffusivities also agree with those derived from tritium distributions (Li *et al,* 1984). Also listed in Table 2 are the calculated bomb ^{14}C water column inventories and the calculated surface water $\Delta^{14}C$ excesses. Averages of these quantities based on measurements are shown for comparison. The agreements are satisfactory.

CARBON DIOXIDE UPTAKE

The lateral transport models derived from the distribution of bomb ^{14}C cover the global oceans, but the linkage between the major oceans is not included. For example, the bomb ^{14}C which invades one sector of the Antarctic ocean will move with the circumpolar current to adjacent sectors. However, it would be instructive to compute the CO_2 uptake using these models and to compare it with the uptakes by other geochemical models of the ocean. The lateral transport model described here is, in fact, an extension and improvement of regional ocean models presented by Broecker, Peng & Engh (1980).

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TABLE 2

Summary of model parameter and model results.* The observed bomb ^{14}C excesses for surface water (in $\Delta^{14}C$ units) and the observed water column inventories are given in parentheses for comparison.

Latitude belt	Area (10^{12} m^2)	W (m/yr)	Flux (sverdrups)	K (cm^2/s)	Z (m)	$\Delta^{14}C-\Delta^{14}C°$ (‰)	Bomb ^{14}C input (10^{26} atoms)	Bomb ^{14}C inventory (10^{26} atoms)
				Atlantic [I = 22.3 mol/(m^2·yr)]				
80°N-40°N	18.6	-8.5	-5	9.9	710	130 (120)	20	26 (26)
40°N-20°N	15.8	-30.0	-15	0.5	470	215 (195)	14	24 (23)
20°N-20°S	26.7	+21.2	+18	1.0	190	146 (150)	25	11 (10)
20°S-45°S	18.4	-22.3	-13	1.0	400	185 (170)	14	20 (18)
45°S-80°S	15.1	+31.2	+15	3.0	270	100 (100)	14	6 (7)
				Indian [I = 19.4 mol/(m^2·yr)]				
25°N-15°S	27.0	+15.2	+13	1.0	215	130 (160)	26	11 (12)
15°S-45°S	29.8	-20.1	-19	1.0	510	190 (180)	23	43 (42)
45°S-70°S	20.7	+9.1	+6	3.0	410	115 (100)	19	14 (13)
				Pacific [(I = 19.2 mol/m^2·yr)]				
65°N-40°N	15.1	+10.4	+5	1.5	260	152 (145)	13	9 (8)
40°N-15°N	35.0	-10.8	-12	1.0	365	206 (210)	30	39 (37)
15°N-10°S	50.0	+16.4	+26	1.0	255	134 (150)	44	25 (25)
10°S-55°S	63.0	-12.5	-25	2.0	410	166 (170)	48	64 (60)
55°S-80°S	13.8	+13.7	+6	3.0	335	111 (100)	11	8 (7)

* W = mean advective flow rate (minus represents downwelling), K = vertical diffusivity, Z = mean penetration depth, and $\Delta^{14}C°$ = prebomb $\Delta^{14}C$ value.

The production of fossil fuels since 1860 was compiled by Keeling (1973) and later by Rotty (1981, 1983). The partial pressure of CO_2 in the atmosphere before the release of anthropogenic carbon and from the first release up to 1958 is not known. Although the atmospheric pCO_2 recorded in the ice cores at the polar regions could be recovered (Neftel *et al,* 1985; Raynaud & Barnola, 1985), the results are subject to some uncertainties, and the implications, with regard to the input of carbon from terrestrial biosphere to the atmosphere, are subject to debate. To compare the oceanic uptake by various geochemical models, the pCO_2 increase observed at Mauna Loa since 1958 will be used in the model computations. The pCO_2 variations prior to 1958 are reconstructed on the basis of fossil fuel production records using a modified box-diffusion model (Peng *et al,* 1983; Peng, 1984). The atmospheric pCO_2 value was forced through the 1958 value of 315.5ppm. The pre-industrial pCO_2 in the atmosphere is estimated to be ca 295.2ppm. The model ocean will simulate the CO_2 uptake starting

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in 1860, assuming that the atmospheric pCO_2 is prescribed according to this pCO_2 time history. The net uptake between 1958 and 1980 is then calculated. Results of fossil fuel CO_2 uptake by lateral transport models are summarized in Table 3. Surface ocean temperatures, salinity (assumed to be 35‰), and salinity-normalized alkalinity are also given (Takahashi, Broecker & Bainbridge, 1981).

As expected, areas where the water downwells take up more CO_2 than areas where the water upwells. The oceanic excess CO_2 is mainly distributed

TABLE 3

Summary of fossil fuel CO_2 uptake by lateral transport models (in 10^{12} mol)*

Latitude belt	1958	1980	Net 1958 to 1980
Atlantic (T = 22.6°C, S = 35.0°/₀₀, Alk)s = 2309.7 μeq/kg)			
80°N–40°N	252	498	246
40°N–20°N	228	461	233
20°N–20°S	63	128	65
20°S–45°S	220	444	224
45°S–80°S	48	97	49
Subtotal	811	1628	817
Indian (T = 26.5°C, S = 35.0°/₀₀, Alk)s = 2298.9 μeq/kg)			
25°N–15°S	69	139	70
15°S–45°S	349	706	357
45°S–70°S	120	239	119
Subtotal	538	1084	546
Pacific (T = 23.5°C, S = 35.0°/₀₀, Alk)s = 2323.2 μeq/kg)			
65°N–40°N	58	115	57
40°N–15°N	300	603	303
15°N–10°N	164	330	166
10°S–55°S	637	1278	641
55°S–80°S	69	137	68
Subtotal	1228	2463	1235
Global sum	2577	5175	2598

* T = temperature, S = salinity, $Alk)_s$ = alkalinity normalized with 35‰ salinity

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in the temperate regions of the world oceans and in the source region of the North Atlantic Deep Water at high latitude northern Atlantic Ocean. The global net uptake during the period with a documented pCO_2 record of high precision is estimated to be 26×10^{14} mol, which is ca 35% of the net fossil fuel production during the same period. The average airborne fraction between 1959 and 1978 was calculated to be 55% of fossil fuel production, leaving 45% unaccounted for (Bacastow & Keeling, 1981). Apparently, the lateral transport models fail to account for the remaining 10% of the net release of fossil fuel carbon. This failure may be due either to the design of the ocean models or to the existence of other carbon sinks such as the terrestrial biosphere. Since the lateral transport models are based on the global distribution of bomb ^{14}C, one tends to accept the latter explanation. In contrast, however, there are suggestions (based on land-use data) that the terrestrial biota do not constitute a carbon sink but rather a significant and increasing source of atmospheric carbon (eg, Houghton *et al,* 1983). It is apparent that we have a problem.

A comparison of CO_2 uptake by the lateral transport models with that by box-diffusion models is given in Table 4. The structure of the box-diffusion model is taken from Oeschger *et al* (1975) with surface mixed layer of 75m, sea-air CO_2 exchange rate of 18 mol/(m^2 · yr), and vertical diffusivity in the diffusive subsurface layer of 1.25 cm^2/s. This model is originally calibrated with the distribution of natural ^{14}C in the ocean. If the distribution of bomb ^{14}C is used for the calibration instead, the CO_2 exchange rate becomes 20.6 mol/(m^2 · yr) and the vertical diffusivity becomes 2.44 cm^2/s (Siegenthaler, 1983). The fraction of net fossil fuel production in this period, taken up by the box-diffusion model calibrated with the natural ^{14}C, is 0.26 and that, by the same model calibrated with the bomb ^{14}C, is 0.34. A similar computation is made by using the modified box-diffusion model (Peng *et al,* 1983). The ocean uptake is 0.29 of the net production.

TABLE 4

Comparison of net fossil fuel CO_2 uptakes between 1958 and 1980 by various geochemical models of the ocean using Mauna Loa pCO_2 record as an input function*

Models	K (cm^2/s)	I (mol/m^2yr)	Net uptake (10^{14} mol)	Fraction uptake
Box-diffusion (1)	1.25	18.0	19.4	0.26
Box diffusion (2)	2.44	20.6	25.3	0.34
Modified box-diffusion (Peng et al 1983)	1.6	17.5	21.2	0.29
Lateral transport (This work)	--	--	26.0	0.35

* K = vertical diffusivity, I = CO_2 exchange rate. Box diffusion (1) is calibrated with natural ^{14}C and box diffusion (2) is calibrated with bomb-produced ^{14}C. The fraction of ocean uptake is calculated using the net production of fossil fuel carbon between 1958 and 1980 of 73.5×10^{14} moles.

Although the outcrop-diffusion model of Siegenthaler (1983) will take up more fossil fuel CO_2 during this period, its assumption of infinite mixing rate in the deep water isopycnal horizons causes an instantaneous transport of excess carbon to the deep ocean from the polar outcrop regions. As a result, it predicts only the unrealistic upper limit of oceanic CO_2 uptake.

The estimates of CO_2 uptake by the box-diffusion model calculated here appear to be slightly lower than those published by Siegenthaler (1983). The differences may be attributed to the assumption of CO_2 input function to the atmosphere. In this calculation, the partial pressure of CO_2 in the atmosphere is prescribed each year according to the time history of atmospheric pCO_2. The actual production history of fossil fuel is used in Siegenthaler's calculation.

In any case, it is apparent that all of these geochemical models for ocean uptake of CO_2 do not have the capacity to assimilate the portion of fossil fuel carbon which does not remain in the atmosphere after release. The lateral transport model based on the global distribution of bomb ^{14}C enhances this conclusion. We need to look for a potential carbon sink besides the ocean and atmosphere.

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