River discharges of carbon to the world's oceans: determining local inputs of alkalinity and of dissolved and particulate organic carbon

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Abstract An empirical modelling that allows a prediction the amount of atmospheric CO_2 consumed by continental erosion is combined with a river-routing file in order to determine the spatial distribution of river carbon inputs to the world's oceans. The total fluvial carbon input is calculated to be 710 teragrams of carbon per year (TgC/yr). 205 TgC/yr are discharged as dissolved organic carbon, 185 TgC/yr as particulate organic carbon, and 320 TgC/yr as bicarbonate ions. Of the latter figure, 230 TgC/yr stem from the atmosphere, while the remainder 90 TgC/yr originate from carbonate mineral dissolution. The Atlantic Ocean receives the greatest amount of river carbon, followed by the Pacific Ocean, the Indian Ocean, and the Arctic Ocean. The spatial distribution of the predicted river carbon inputs may be included in further modelling studies in order to better understand the lateral transports of carbon in the present-day global carbon cycle.

Keywords: Rivers, Alkalinity, Organic carbon, Atmospheric CO_2, Global carbon cycle.

Résumé **Transports de carbone par les fleuves aux océans : régionalisation des apports d'alcalinité et de carbone organique dissous et particulaire**

Une modélisation empirique qui permet de prédire la quantité de CO_2 atmosphérique consommée par l'érosion continentale a été couplée à une procédure de routage des eaux continentales vers les océans. Ainsi, le flux total de carbone apporté annuellement à l'ensemble des océans peut être estimé à 710 teragrammes de carbone (TgC/an), dont 205 TgC/an sous forme de carbone organique dissous, 185 TgC/an sous forme de carbone organique particulaire et 320 TgC/an sous forme de bicarbonates. L'océan Atlantique reçoit la majorité des apports fluviaux de carbone, suivi par l'océan Pacifique, l'océan Indien et l'océan Arctique. La distribution spatiale des apports de carbone aux océans, telle qu'elle a été déterminée dans cette étude peut être utilisée dans des modèles du cycle global du carbone, pour mieux comprendre les transports latéraux de carbone dans le cycle global du carbone.

Mots-clés : Fleuves, Alcalinité, Carbone organique, CO_2 atmosphérique, Cycle global du carbone.

Version française abrégée

INTRODUCTION

Les apports de carbone par les fleuves aux océans constituent un flux important dans le cycle

sphérique est consommé à la fois par la formation et l'érosion de la matière organique et par l'altération chimique des roches. Ce carbone est ensuite transféré par les fleuves sous forme de carbone organique dissous (COD), de carbone organique particulaire (COP) et de carbone inorganique dissous (HCO_3^-), des sols vers les océans. Ce flux constitue environ un tiers du flux net de CO_2 atmosphérique absorbé par les océans (Sarmiento et Sundquist, 1992).

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Tenir compte des apports fluviaux de carbone dans la modélisation du cycle du carbone nécessite de connaître localement l'intensité de ces apports dans les différents océans. L'objectif de ce travail est de combler ce manque, en couplant un modèle simulant la distribution spatiale des flux de CO_2 consommé par l'érosion continentale à une procédure de routage des eaux continentales vers les océans.

MATÉRIEL ET MÉTHODES

La distribution spatiale du CO_2 atmosphérique consommé par l'érosion continentale a été calculée par des modèles globaux d'érosion pour simuler les flux de HCO_3^- (Amiotte-Suchet et Probst, 1993 *a, b* ; 1995 *a, b* ; Amiotte-Suchet, 1995 ; Ludwig *et al.*, sous presse) et de carbone organique dissous et particulaire (Ludwig *et al.*, 1996 ; Ludwig *et al.*, sous presse) libérés par l'érosion et transportés par les fleuves. A partir de ces modèles, les flux moyens annuels de carbone apportés aux océans ont été déterminés en utilisant deux plans de
tales sur la base d'un réseau hydrographique global simplifié (Miller *et al.*, 1994), l'un à une résolution 2° latitude par 2,5° longitude et l'autre à 4° latitude par 5° longitude. Les flux de carbone ainsi calculés sont disponibles auprès des auteurs.

APPORTS DE CARBONE AUX OCÉANS

La figure montre la distribution spatiale des apports fluviaux moyens annuels de carbone. Dans le tableau, ces flux sont détaillés pour chaque océan et pour chaque bande latitudinale de 4°. Nous avons pu estimer que le flux total de carbone apporté annuellement à l'ensemble des océans était de 710 TgC, dont 205 TgC de COD, 185 TgC de COP et 320 TgC de HCO_3^-. Ce dernier flux est lui-même constitué de 230 TgC provenant du CO_2 d'origine atmosphérique et de 90 TgC issus de la dissolution des minéraux carbonatés. 43 % des exportations totales de carbone se font vers l'océan Atlantique, 34 % vers l'océan Pacifique, 15 % vers l'océan Indien et 8 % vers l'océan Arctique.

A l'échelle globale, le flux de HCO_3^- est moins élevé que le flux de carbone organique (dissous et particulaire). Cependant, à l'échelle locale, le rapport entre le carbone inorganique et le carbone organique (R_{IO}) peut varier de façon importante (tableau). En effet, les flux de carbone organique sont plus liés à l'intensité du drainage que ne l'est le flux de HCO_3^- qui dépend, en plus, de la nature des roches affleurant sur les bassins
affleurements de roches carbonatées sont importants, R_{IO} peut atteindre 1,5 à 2, comme par exemple dans l'océan Atlantique entre 48 et 52° N (fleuve St. Laurent) et entre 40 et 44° N (fleuves européens tels que le Danube et le Rhône), ou dans l'océan Pacifique entre 28 et 32° N (fleuve Changjiang) et entre 20 et 24° N (fleuve Hungho). Les affleurements de roche carbonatées étant les plus abondants sur les continents de l'hémisphère Nord, R_{IO} des apports fluviaux de carbone aux océans est plus fort pour les régions situées au Nord de l'équateur.

Le rapport entre le COD et le COP (R_{DP}) montre que les apports de COD sont dominants dans l'océan Atlantique, alors que ceux de COP sont plus abondants dans les océans Pacifique et Indien. Dans la partie nord de l'océan Indien, R_{DP} est de 0,6 en moyenne, car les fleuves drainant le Sud et le SE de l'Himalaya (Ganges/ Brahmapoutre, Indus et Irrawaddy) sont caractérisés par des transports de sédiment très élevés.

DEVENIR DANS LES OCÉANS

Une fois dans l'océan, le carbone est éliminé par la sédimentation de la matière organique, par la sédimentation carbonatée, ainsi que par l'oxydation de la matière organique dans la colonne d'eau. Les deux derniers processus libèrent du CO_2 qui retourne à l'atmosphère, alors que les processus de sédimentation constituent un flux d'entrée dans le réservoir lithosphère. En considérant le réservoir océan à l'équilibre, Smith et Hollibaugh (1993) estiment d'après des données de la littérature, qu'environ un tiers de l'apport total de carbone organique par les fleuves est transféré vers la lithosphère, pendant que le reste dégaze vers l'atmosphère. En appliquant leurs résultats aux valeurs déterminées dans cette étude, on peut estimer que 265 TgC/an de carbone organique apporté par les fleuves retournent à l'atmosphère après oxydation, dans les zones côtières (30%) ou en océan ouvert (70%).

En ce qui concerne le carbone inorganique, la précipitation des minéraux carbonatés fixe une mole de HCO_3^- pour une mole de CO_2 dégazé vers l'atmosphère. En considérant le réservoir océan à l'équilibre, 160 TgC/an

de HCO_3^- sont sédimentés, alors qu'une quantité équivalente de CO_2 est dégazée.

CONCLUSIONS

Ainsi, sur les 620 TgC de CO_2 d'origine atmosphérique consommé chaque année par l'érosion, on estime que 425 TgC/an sont directement dégazés des océans vers l'atmosphère. Les 195 TgC/an restant devraient retourner à l'atmosphère à partir du réservoir lithosphère, par l'intermédiaire du volcanisme aérien (environ 70 TgC/an ; Berner *et al.*, 1983 ; Williams *et al.*, 1992) et de l'oxydation de la matière organique des roches sédimentaires sur les continents (environ 125 TgC/an ; Kramer, 1994 ; Sarmiento et Sundquist, 1992).

Cependant, le taux
nique fluviatile qui est oxydée ou sédimentée dans les estuaires et dans les zones côtières est toujours peu connu à l'échelle globale.

INTRODUCTION

The discharge of fluvial carbon to the world's oceans represents an important component of the global carbon cycle. Atmospheric/soil CO_2 is consumed both by organic matter formation and chemical rock weathering, and subsequently transferred as dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (mainly bicarbonate ions, HCO_3^-) to the oceans by rivers. It has been estimated that there is a permanent flux of 700 to 800 teragrams (10^{12} g) of atmospheric carbon going to the oceans every year (TgC/yr), with about 200 to 220 TgC/yr being discharged as DOC (Meybeck, 1982; 1993; Spitzy and Leenheer, 1991; Ludwig *et al.*, 1996), 180 to 280 TgC as POC (Meybeck, 1982; 1993; Ittekkot, 1988; Ludwig *et al.*, 1996), and 260 to 300 TgC/yr as HCO_3^- (Berner *et al.*, 1983; Meybeck, 1987; Probst, 1992; Probst *et al.*, 1992; 1994 *a*; Amiotte-Suchet and Probst, 1995). This can account for about one third of the estimated net oceanic carbon uptake for present-day (Sarmiento and Sundquist, 1992).

Modelling the fate of the anthropogenic released CO_2 revealed an inconsistency of the observed latitudinal CO_2 gradient in the atmosphere with the modelled transport fields (Tans *et al.*, 1990). Up to now, it was difficult to evaluate the role of the fluvial transport pathway in this context because of the lack of sufficient river data world-wide. The purpose of this paper is to respond to this data need. We present a modelling approach to predict the fluxes of atmospheric CO_2 consumed by continental erosion, coupled to a river-routing scheme. This allows not only a refinement of global and regional budgets with respect to the amount of carbon that is taken out of the atmosphere, but also a prediction of the local inputs of this carbon to the oceans worldwide. It is mainly the latter aspect that is discussed here. The basic relationships to determine the atmospheric CO_2 consumption over the continents have been described elsewhere (*see* below).

DATA AND METHODS

This work is based upon previous studies on the river fluxes of inorganic carbon (Amiotte-Suchet and Probst, 1993 *a*, *b*; 1995 *a*, *b*; Amiotte-Suchet, 1995; Probst *et al.*, 1994 *b*; Ludwig *et al.*, in press), and on the river fluxes of organic carbon (Probst *et al.*, 1994 *b*; Ludwig *et al.*, 1996; Ludwig *et al.*, in press). HCO_3^- fluxes are calculated as a function of drainage intensity, and of the rock type that is drained by the surface waters. The relationships were established by Amiotte-Suchet and Probst (1993 *a*) using data published by Meybeck (1986) concerning runoff and HCO_3^- concentrations in small monolithologic watersheds in France. DOC fluxes are determined as a function of drainage intensity, surface slope, and of the organic carbon content in the soils. For POC, first a global map of sediment yields was derived by an extrapolation of observed river data, coupled to an empirical relationship between river sediment fluxes and a morphoclimatic index (Ludwig *et al.*, 1996; Ludwig and Probst, 1996). Then, POC fluxes are calculated as a function of sediment yield and of drainage intensity (Ludwig *et al.*, 1996). Most of the field data which were used to establish the empirical relationships for the fluxes of organic carbon have been collected within the SCOPE/ UNEP program *Transport of Carbon and Minerals in Major World Rivers* (*see* Degens *et al.*, 1991).

In this study, all fluxes were recalculated in a $0.5° \times 0.5°$ latitude/longitude grid point resolution on the basis of common data sets in order to determine the atmospheric CO_2 consumption over the continents. Carbon fluxes from the ice-covered parts of the continents are

considered to be negligible. For drainage intensity, we used the runoff data of the *Atlas of World Water Balance* of Korzoun *et al.* (1977) that was digitized and gridded at our institute. Mean organic carbon content in the soils was extracted from a global dataset developed at the Soil Conservation Service of the United States Department of Agriculture (USDA-SCS). Then, the annual carbon fluxes were brought to the oceans following two river-routing files (Miller *et al.*, 1994) in a 2° × 2.5° and in a 4° × 5° latitude/longitude grid point resolution, respectively. The proceeding results in data files for the global distribution of river carbon inputs to the oceans in the same resolutions as the river-routing files exist. These data files are available from the authors.

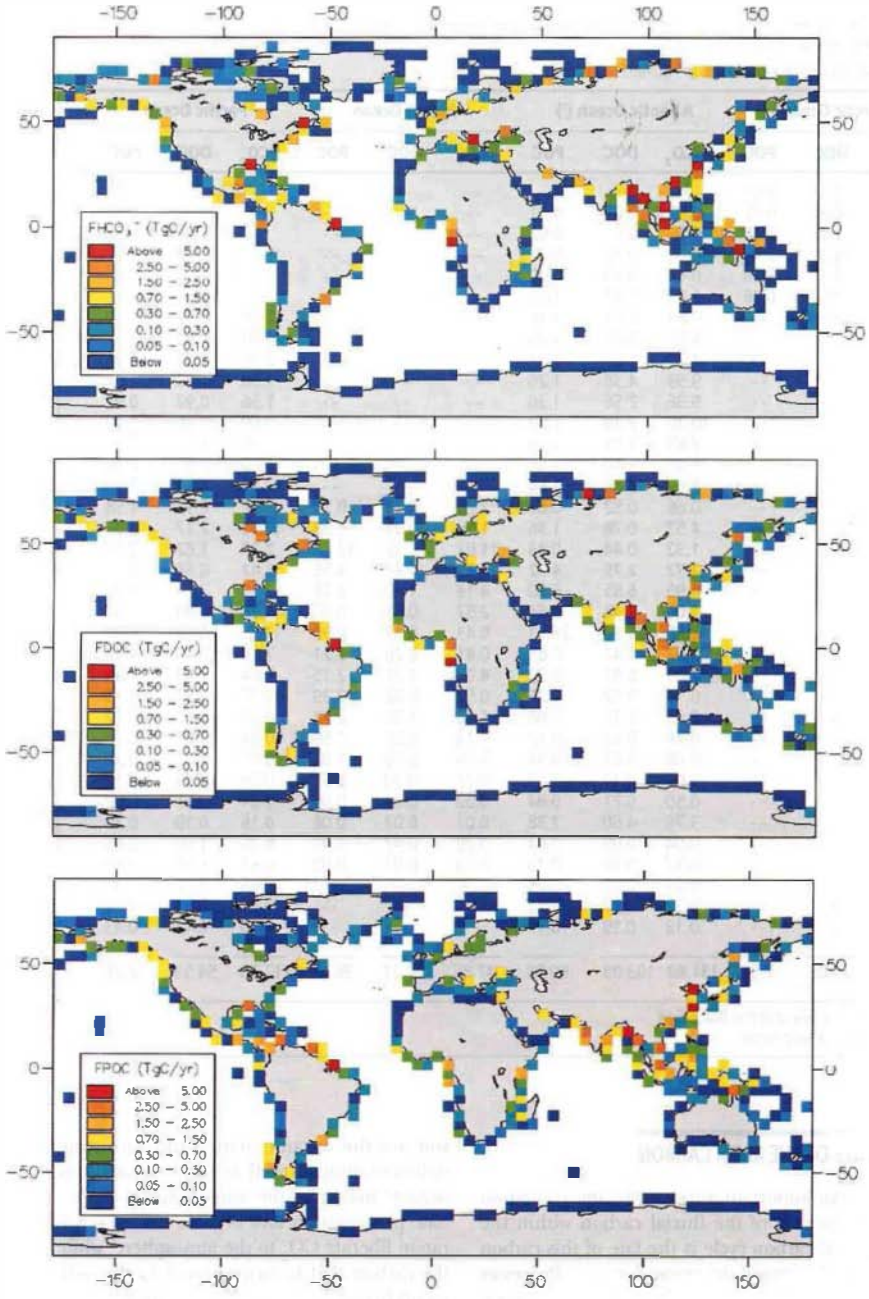
RIVER CARBON INPUTS TO THE OCEANS

The figure shows the spatial distribution of river inputs of alkalinity, dissolved organic carbon, and particulate organic carbon to the world's oceans. In the table, the carbon fluxes are detailed with respect to the different ocean basins for latitudinal bands of 4° each. In order to facilitate
we show and discuss here only the fluxes calculated in the 4° × 5° latitude/longitude resolution. The results calculated in the finer 2° × 2.5° latitude/longitude resolution are not much different.

Globally, we calculate the overall river carbon input to be about 710 TgC/yr, with 205 TgC being discharged as DOC, 185 TgC as POC, and 320 TgC as HCO_3^-. Of the latter figure, 230 TgC stem from the atmosphere, while the remainder 90 TgC originate from carbonate mineral dissolution. 43% of the total river carbon enter the oceans in the Atlantic Ocean, 34% in the Pacific Ocean, 15% in the Indian Ocean, and 8% in the Arctic Ocean. Note that about 28% of the total carbon input is discharged by the 10 largest world river basins only.

The spatial distribution of river carbon inputs to the oceans is similar for the 3 carbon species because for all of them the fluxes are strongly coupled to the spatial distribution of the freshwater input to the oceans. Differences are found, however, at local scales. Mainly the ratio of inorganic (HCO_3^-) to organic (DOC + POC) carbon can vary (R_{IO}). The variability of organic carbon fluxes is more closely coupled to the variability of drainage intensity than it is the case for the fluxes of inorganic carbon. HCO_3^- fluxes are also strongly dependent on the nature of the outcropping continental rocks. Consequently, R_{IO} follows more or less the distribution of lithology. Especially large carbonate outcrops in river basins lead to great R_{IO} values in the ocean grid elements nearest to the river mouths. Because of the carbonate rich watersheds of certain rivers discharging to these zones, R_{IO} values of 1.5 to more than 2 can be found, for example, in the Atlantic Ocean in the latitude bands of 48-52° N (e.g. the St. Lawrence River) and of 40-44° N (some European rivers such as the Rhône), or in the Pacific Ocean in the 28-32° N (e.g. the Changjiang) and in the 20-24° N (e.g. the Hungho) latitude bands. On the continents, large carbonate outcrops are mainly
phere, such as in the south-east of Asia, in western Europe, or in the eastern United States. For this reason, R_{IO} is greater in the parts of the oceans north of the equator than south of it. Greatest average values are found in the North Pacific (R_{IO} = 0.94) and in the northern Indian Ocean (R_{IO} = 0.90). In the South Atlantic and in the southern Indian Ocean the ratio of inorganic to organic river carbon inputs are lowest (R_{IO} = 0.65 and 0.60, respectively).

With respect to the two organic carbon forms, DOC and POC, one can note that dissolved carbon inputs are dominant in the Atlantic Ocean. The DOC to POC ratio, R_{DP}, is on average 1.4 in the North Atlantic, and 1.8 in the South Atlantic. Particulate carbon inputs are more abundant in the Pacific and in the Indian Ocean. In the northern Indian Ocean relative POC fluxes are greatest (R_{DP} = 0.6 on average) because of the great sediment fluxes that are characteristic for the rivers draining the South and Southeast of the Himalayan region (e.g. the Ganges/Brahmaputra, Indus, and Irrawaddy rivers). On the other hand, by far the greatest average R_{DP} is found for the Arctic Ocean. Mechanical erosion rates on the continents
small in the northernmost boreal climate zones. At the same time, the soils are often rich in organic carbon. For these reasons, more than three qu
carbon input occurs here in the dissolved form.



River carbon fluxes to the world's oceans calculated for 4° × 5° latitude/longitude gnd elements: $FHCO_3$, alkalinity; FDOC, dissolved organic carbon, and FPOC, particulate organic carbon.

Apports de carbone par les fleuves aux océans calculés pour des mailles de 4° × 5° latitude/longitude : $FHCO_3$, alcalinité ; FDOC, carbone organique dissous et particulaire.

Table River Fluxes of carbon to the world's oceans (10^{12} gC/yr).
Apports de carbone par les fleuves aux océans (10^{12} gC/an).

Latitude Band	Arctic Ocean			Atlantic Ocean (1)			Indian Ocean			Pacific Ocean		
	HCO_3^-	DOC	POC	HCO_3^-	DOC	POC	HCO_3^-	DOC	POC	HCO_3^-	DOC	POC
84-88 N	0.10	0.01	0.01	--	--	--	--	--	--	--	--	--
80-84 N	0.12	0.05	0.05	0.07	0.01	0.01	--	--	--	--	--	--
76-80 N	5.34	1.45	0.48	0.06	0.01	0.02	--	--	--	--	--	--
72-76 N	12.72	14.25	3.44	0.63	0.10	0.07	--	--	--	--	--	--
68-72 N	8.05	7.77	3.16	0.04	0.10	0.09	--	--	--	--	--	--
64-68 N	1.31	1.53	0.46	1.08	1.37	1.06	--	--	--	--	--	--
60-64 N	--	--	--	0.84	3.64	1.46	--	--	--	2.81	1.96	1.99
56-60 N	--	--	--	5.02	8.98	3.25	--	--	--	4.20	3.69	4.11
52-56 N	--	--	--	4.27	5.07	0.82	--	--	--	2.75	5.05	3.31
48-52 N	--	--	--	9.99	4.38	1.26	--	--	--	1.98	1.46	1.51
44-48 N	--	--	--	5.36	2.56	1.36	--	--	--	1.56	0.92	0.97
40-44 N	--	--	--	10.30	2.34	2.53	--	--	--	2.00	0.96	1.40
36-40 N	--	--	--	3.63	1.09	1.19	--	--	--	1.09	1.27	7.51
32-36 N	--	--	--	1.49	1.40	1.15	--	--	--	1.29	1.51	2.38
28-32 N	--	--	--	8.67	5.46	4.64	--	--	--	27.94	4.12	7.90
24-28 N	--	--	--	0.66	0.52	0.67	2.25	0.13	0.75	3.52	0.92	1.58
20-24 N	--	--	--	4.57	0.78	1.36	1.56	0.31	1.33	11.35	2.17	3.07
16-20 N	--	--	--	1.32	0.44	0.43	11.01	7.72	12.34	2.77	1.62	2.27
12-16 N	--	--	--	2.72	2.75	4.32	16.38	4.87	8.55	2.42	0.68	3.31
08-12 N	--	--	--	4.95	6.85	6.50	4.13	1.30	2.28	7.58	3.76	4.41
04-08 N	--	--	--	1.00	2.48	1.66	2.57	0.61	0.81	3.96	2.60	2.97
00-04 N	--	--	--	48.36	36.20	26.91	0.43	0.82	0.96	11.35	6.10	6.90
00-04 S	--	--	--	2.92	1.47	0.85	0.41	0.20	2.21	7.19	5.43	4.36
04-08 S	--	--	--	7.09	6.81	2.32	4.93	1.83	2.15	2.64	1.14	1.83
08-12 S	--	--	--	0.75	0.52	0.29	0.53	0.32	0.39	10.77	2.84	4.19
12-16 S	--	--	--	0.05	0.13	0.08	1.43	1.96	2.22	0.20	0.08	0.12
16-20 S	--	--	--	0.76	0.42	0.25	1.14	0.65	0.50	0.04	0.20	0.23
20-24 S	--	--	--	0.08	0.27	0.34	0.60	0.76	1.01	0.07	0.22	0.26
24-28 S	--	--	--	0.05	0.17	0.13	0.22	0.20	0.33	0.09	0.13	0.14
28-32 S	--	--	--	0.50	0.71	0.84	0.02	0.04	0.06	0.01	0.01	0.02
32-36 S	--	--	--	3.76	4.60	2.38	0.01	0.02	0.06	0.16	0.19	0.30
36-40 S	--	--	--	0.04	0.09	0.04	0.20	0.47	0.40	0.79	1.09	1.03
40-44 S	--	--	--	0.12	0.16	0.18	0.03	0.07	0.03	0.87	1.52	1.64
44-48 S	--	--	--	0.01	0.01	0.04	--	--	--	0.68	2.12	1.91
48-52 S	--	--	--	0.32	0.97	1.22	--	--	--	0.07	0.35	0.21
52-56 S	--	--	--	0.13	0.19	0.19	--	--	--	0.16	0.42	0.43
TOTAL	27.55	25.05	7.58	131.63	103.03	69.88	47.86	22.27	36.40	112.30	54.53	72.28

(1) Including the Mediterranean Sea and the Black Sea
(1) Incluses la Méditerranée et la Mer Noire.

FATE OF THE RIVER CARBON

An important question for the evaluation of the role of the fluvial carbon within the global carbon cycle is the fate of this carbon once it entered the oceanic system. Processes that withdraw carbon from the ocean reservoir are the organic matter and carbonate sedimentation, as well as the respiration of organic matter in the water column. Carbonate precipitation and organic matter respiration liberate CO_2 to the atmosphere, while the carbon that is incorporated in the sediments becomes part of the lithosphere.

Supposing a steady state, *i.e.* assuming that the river input fluxes are balanced by the withdrawal of carbon in the oceans, Smith and Hollibaugh (1993) concluded from a review of literature data that approximately one third of the total organic river input is lost to the lithosphere, while two thirds return to the atmosphere by respiration. They estimated the absolute amount of riverine organic carbon input to be 408 TgC/yr, which is very close to the value of 390 TgC/yr we find. According to their findings, about equal amounts of the fluvial organic carbon becomes involved in the coastal organic matter cycling (mainly in the estuaries) and in the offshore ocean organic matter cycling, but the ratio of burial to respiration in the coastal zone may be about 6 to 4, while this is only 1 to 9 in the open oceans. No distinction is made between the fate of POC and DOC because much of the POC in the water column and in the upper sediment layers may be converted to DOC. When applied to our results, this means that about 265 TgC/yr of the fluvial organic carbon input returns to the atmosphere after being oxidized in the oceans. 30% of this carbon is respired in the coastal waters, *i.e.* mainly in the grid elements to which the river carbon is discharged (**fig.**). The remaining 70% is subjected to slow oxidation in the open ocean waters.

For inorganic carbon, an assumed steady state implies that carbonate sedimentation in the oceans balances the river HCO_3^- fluxes. As an effect of carbonate precipitation, half of the HCO_3^- river carbon is fixed in the sediments, while the other half is released to the atmosphere. With our values, this makes 160 TgC/yr for each flux. Regionally, carbonate sedimentation in the oceans is limited to the regions where the sea floor lies above the calcite compensation depth (CCD).

DISCUSSION AND CONCLUSIONS

We calculate that about 620 TgC of atmospheric carbon is consumed by continental erosion every year and predict the input of this carbon to the oceans along the coastlines of the continents. Assuming a steady state between the river input and the oceanic output fluxes, the carbon return from the oceans to the atmosphere can be estimated to be 425 TgC/yr. The remainder of 195 TgC should enter the atmosphere over the continents through volcanism (about 70 TgC/yr: Berner *et al.*, 1983; Williams *et al.*, 1992) and the oxidation of fossil organic matter in sedimentary rocks (about 125 TgC/yr; Kramer, 1994; Sarmiento and Sundquist, 1992).

However, a great uncertainty in the budget discussed here is the variability of the metabolism in the coastal zones. Although Smith and Hollibaugh (1993) concluded that the coastal ocean is globally net heterotrophic, *i.e.* respiration exceeds primary production, they reported also that this is not the case for all sites for which data are available. They present indications that the heterotrophic character of an estuary increases with greater primary production rates, whereas estuaries with low productivity tend to be net autotrophic, *i.e.* carbon production exceeds carbon consumption. Looking at the very uneven distribution of the river carbon inputs (**fig.**), it becomes evident that a strong variability of the coastal metabolism could naturally have a great influence on the fate of the organic carbon once it is discharged to the oceans. Moreover, there are no means to verify whether the oceans are actually in a steady state with respect to the river carbon inputs. Kempe (1995) argued that large areas of the world's coastal zones may have lost their natural heterotrophic status and become autotrophic because of anthropogenic eutrophication, thereby causing either an increase in marine organic carbon burial or an increase in the oceanic DOC and dissolved inorganic carbon pools. A typology of coastal zones with regard to the organic matter cycling could help to improve the budget calculations in this respect. The development of a coastal typology is one of the framework activities of the LOICZ (Land-Ocean Interactions in the Coastal Zone) core project of the International Geosphere Biosphere Program (IGBP, 1995).