Modelling the atmospheric CO_2 consumption and river carbon inputs to the oceans by continental erosion

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Continental erosion is a sink for atmospheric carbon. Atmospheric 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 (DIC) to the oceans by rivers (Fig. 1).

Concerning organic carbon, the CO_2 consumption is governed by the photosynthesis reaction, which can be written as following:

$$CO_2 + H_2O \rightarrow CH_2O + O_2 \qquad (1)$$

All carbon in the organic matter in rivers is of atmospheric origin. Only the part of POC mobilized via the erosion of organic rich sedimentary rocks may be distinguished here because of its much older age, but this part is only of minor importance in the global POC budget (Ludwig *et al.*, 1996a).

Also for riverine HCO_3^- ions resulting from the weathering of silicate rocks, all carbon comes from the atmosphere (mainly via soil CO_2), as it can be seen, for example, in the following equation for the hydrolysis of albite:

$$2\ NaAlSi_3O_8 + 2\ CO_2 + 11\ H_2O \rightarrow 2\ HCO_3^- + Al_2Si_2O_5(OH)_4 + 2\ Na^+ + 4\ H_4SiO_4 \qquad (2)$$

For HCO_3^- ions resulting from the weathering of carbonate rocks, however, only half of the carbon originates from atmospheric / soil CO_2, while the other half comes from the carbonate mineral. This can be shown, for example, in the following equation for the calcite dissolution:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2\ HCO_3^- \qquad (3)$$

Objectives. The purpose of this paper is to present a modelling tool allowing a global and regional quantification of the amount atmospheric CO_2 consumption by continental erosion in order to

TABLE 1. Regional budgets for the atmospheric C2 consumption by continental erosion and for river carbon fluxes to the oceans

	Area * (10^3 km^2)	Q (10^9 m^3/yr)	F_{TSS} (Gt/yr)	F_{DOC} (TgC/yr)	F_{POC} (TgC/yr)	$F_{CO_2\text{-}RW}$ (TgC/yr)	F_{CARB} (TgC/yr)
Polar	3892	762	0.03	3.1	1.0	3.4	1.4
Tundra and Taiga	23232	6930	0.65	45.9	15.0	33.0	8.6
Temperate Dry	9635	729	2.40	2.9	12.5	4.3	2.0
Temperate Wet	16918	7753	3.30	35.4	32.7	47.7	24.6
Tropical Dry	21790	3101	4.52	16.0	27.8	14.9	5.4
Tropical Wet	24919	22403	5.09	101.7	68.5	126.3	47.7
Desert	5940	66	0.04	0.3	0.3	0.4	0.2
Total	106326	41744	16.03	205.2	157.9	230.0	90.1
Africa	18288	4120	0.97	20.0	10.7	11.5	4.9
Europe	9564	3079	0.84	16.6	10.5	18.5	7.3
North America	23020	7142	3.14	39.4	27.6	40.5	17.2
South America	17732	11150	2.94	51.8	34.3	52.8	8.0
Asia	32518	15318	7.93	73.0	71.6	104.3	52.7
Australia	4476	773	0.21	3.9	3.0	2.2	0.1
Antarctis	728	162	0.01	0.6	0.2	0.1	0.1
Total	106326	41744	16.03	205.2	157.9	230.0	90.1

* Calculated without endoreic regions and regions that are under permanent ice cover. *Q*, runoff; *FTSS*, sediment fluxes, *FDOC*, DOC fluxes, *FPOC*, POC fluxes; *FCO2-RW*, atmospheric CO_2 consumption by rock weathering; *FCARB*, bicarbonate ions resulting from carbonate minerals.

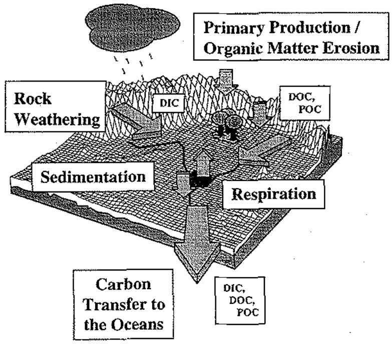

FIG. 1. Schematic Sketch of the atmospheric CO_2 consumption by continental erosion.

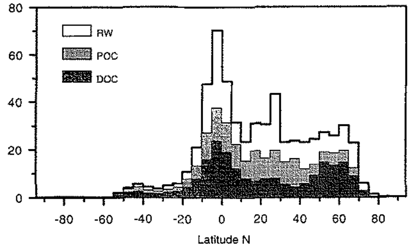

FIG. 2. Holospheric distribution of the atmospheric CO_2 consumption by continental erosion. DOC, dissolved organic carbon; POC, particulate organic carbon, RW, rock weathering. All values in TgC/yr.

evaluate its importance within the global carbon cycle. For all carbon forms, the major controlling factors were determined, and empirical regression models have been established making it possible to extrapolate the fluxes to regional and global scales. Because the river carbon fluxes are strongly coupled to the fluxes of water and of sediments, such an investigation is not possible without a similar examination of the major controls of these two key parameters at the global scale.

Methods. Our approach is mainly based on a set of 60 major world rivers. The hydroclimatic, biological, geomorphological, and lithological characteristics of the drainage basins are extracted from a large number of environmental data sets using the digitized basin contours. These characteristics are then used for statistical analyses together with literature data for these rivers on the observed fluxes of DOC, POC, DIC, water, and sediments.

Results. Dissolved inorganic carbon fluxes can be related to a combination of drainage intensity together with the rock type drained by the surface waters. For a given drainage intensity, greatest weathering rates occur on carbonate rocks, followed by shales, basalts, evaporites, acid volcanic rocks, and sands and sandstones. Plutonic and metamorphic rocks show the lowest weathering rates (Amiotte-Suchet and Probst, 1993; 1995). For dissolved organic carbon, a multiple regression model including drainage intensity, basin slope, and the amount of carbon stored in the soils is the best model to predict fluxes on a global scale. They become greater with increasing drainage intensities, flatter morphologies, and larger carbon reservoirs in the soils (Ludwig *et al.*, 1996b). For the fluxes of particulate organic carbon, sediment fluxes are the dominant controlling parameter. It can be shown that POC fluxes generally increase with increasing sediment fluxes, but the percentage of organic carbon in the total suspended solids clearly decreases with increasing sediment concentrations. This relationship was mathematically fitted, allowing to calculate POC fluxes to the oceans as a function of sediment yields (sediment fluxes divided by basin area) and of drainage intensity (Ludwig *et al.*, 1996a).

Sediment yields can be best correlated by forming the products of hydroclimatic, geomorphological, and lithological factors, that is drainage intensity, basin slope, an index characterizing rock hardness, and an index characterizing rainfall variability over the year. The best correlated parameter combination varies to some extent when the rivers are grouped according to their average climatic situation, but it is always a combination of the above mentioned parameters that yields the greatest correlation coefficients (Ludwig and Probst, 1998).

When the determined regression models are applied to the total continental area on the basis of the corresponding data sets for the controlling factors yields a total amount of 0.70 GtC that is discharged to the oceans every year by continental erosion. About 46% can be attributed to DIC, 31% to DOC, and 23% to POC (Ludwig *et al.*, 1998). The corresponding fluxes of water and of sediments are 41750 km^3/yr and 16 Gt/yr, respectively. These values compare well with previous literature estimates. Consequently, for all of these river fluxes, global maps showing the distribution of the specific fluxes on the continents have been created, and detailed budgets can be given, for example, with respect to the different continents, major climate types (table), or latitudional bands (Fig. 2). Moreover, when coupling our modelling with a generalized global river routing scheme, not only the atmospheric CO_2 consumption on the continents but also the local inputs of the river carbon into the oceans can be determined in a grid point resolution (Ludwig *et al.*, 1996b).