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A global model for present-day atmospheric/soil CO_2 consumption by chemical erosion of continental rocks (GEM-CO_2)

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ABSTRACT

The flux of atmospheric/soil CO_2 consumed by chemical weathering of the continents (F_{CO_2}) can be estimated from river fluxes of bicarbonates. Using published data for 232 small monolithologic watersheds, empirical relationships between F_{CO_2} and runoff (Q) have been determined for the major rock types outcropping on the continents. For validation, the models fitted to these relationships are applied to the Garonne, Congo and Amazon river basins to calculate the average CO_2 consumption on these large river basins; the model results are close to previous estimates based on field measurements. The model (GEM-CO_2: Global Erosion Model for CO_2 fluxes) is then applied at the global scale and allows the determination of latitudinal variations of the consumption of atmospheric/soil CO_2 by chemical erosion. The main results show that the consumption of CO_2 is mainly localized in the Northern hemisphere, because of large continental area with a high proportion of carbonate rocks, and in equatorial regions which are very humid. Finally, the mean annual CO_2 consumption for the whole continents amount to 0.26 Gt C y^{-1}, and 72% of this flux is removed in the Northern hemisphere.

1. Introduction

The present-day average flux of atmospheric/soil CO_2 consumed by global chemical erosion, and exported to the oceans as bicarbonate ions, is estimated to be 0.28 to $0.30 \cdot 10^{15}$ g y^{-1} of carbon (0.28 to 0.30 Gt C y^{-1}) (Berner et al., 1983; Meybeck, 1987; Probst, 1992). On the other hand, the flux of particulate and dissolved organic carbon transported by rivers to the oceans is estimated to 0.3 Gt C y^{-1} (Degens et al., 1991) to 0.4 Gt C y^{-1} (Schlesinger and Melack, 1981; Meybeck, 1982). On the whole, about 0.7 Gt C y^{-1} are transferred by continental erosion from the soil-biosphere reservoir to the oceans. This carbon flux is quite low but not negligible compared to the other main carbon fluxes in the global carbon cycle such as the fossil fuel combustion of about 5.2 Gt C y^{-1} (Rotty, 1983) and the net sea-air flux of 1.7 and 2.8 Gt C y^{-1} (Sarmiento and Sundquist, 1992).

Many authors have pointed out the strong influence of continental weathering in the geologic carbon cycle (Garrels and Mackenzie, 1971; Walker et al., 1981; Berner et al., 1983; Tardy, 1986; Berner, 1991). Moreover, recently, Sarmiento and Sundquist (1992) have noted the importance of river carbon input to the oceans as a component of the estimate of global air–sea CO_2 fluxes.

The consumption of atmospheric/soil CO_2 by continental weathering is mainly influenced by drainage and air temperature (Garrels and Mackenzie, 1971; Holland, 1978; Berner et al., 1983; Tardy, 1986; Meybeck, 1987; Amiotte Suchet and Probst, 1992; Probst, 1992; Probst et al., 1992) and by the proportion of carbonate rocks outcropping on the continents (Probst et al., 1994).

The HCO_3^- ions measured in surface waters mainly come from the carbonate mineral dissolution and from atmospheric/soil CO_2 used in the

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chemical weathering of silicate and carbonate minerals. During the weathering of silicate rocks, the totality of the HCO_3^- ions released in solution comes from atmospheric/soil CO_2 as it can be noted for example in the albite hydrolysis:

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2HCO_3^- + 2Na^+ + 4H_4SiO_4. \quad (1)$$

Considering the weathering of carbonate rocks, only half of the HCO_3^- ions released in solution come from the atmospheric/soil CO_2 as it can be seen for example in the calcite dissolution:

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

Thus, on a monolithologic drainage basin, the flux of CO_2 consumed by rock weathering can be estimated from the flux of bicarbonate ions transported by stream waters at the outlet of the basin.

A simple model recently developed by Amiotte Suchet and Probst (1993a) permits one to calculate the flux of atmospheric/soil CO_2 consumed by rock weathering. This model is based on a set of empirical relationships between the flux of atmospheric CO_2 consumed by rock weathering and the drainage for the major rock types outcropping on the continents. This model has been applied and validated on three different large river basins: the Garonne (France) in temperate climate (Amiotte Suchet and Probst, 1993a), and the Congo and the Amazon in tropical equatorial climate (Amiotte Suchet and Probst, 1993b). Some attempts to calculate the mean global CO_2 consumption by rock weathering, using continental rock outcrops and mean continental drainage, have already been done (Garrels and Mackenzie, 1971; Holland, 1978; Berner et al., 1983; Kempe, 1984; Meybeck, 1987). However, all these studies, which only gave a mean global estimate, did not propose to analyse spatial variability of CO_2 consumption. Indeed, the Temperate Stream Model proposed by Meybeck (1987), which is the most complete of all previous models, did not take into account the spatial distributions of lithology and drainage on the continents. In this paper, a simulation is performed for the whole continental area, using maps of continental drainage and lithology, which allows one to determine latitudinal distribution of the consumption of atmospheric/soil CO_2 by chemical erosion.

2. Flux of atmospheric/soil CO_2 consumed by rock weathering (F_{CO_2}) as a function of the drainage (Q)

The relationships between F_{CO_2} and Q were calculated using the data published by Meybeck (1986) concerning runoff and concentrations of the major dissolved elements for 232 French monolithologic drainage basins (Amiotte Suchet and Probst, 1993a). The lithologies of these small watersheds are representative of the major rock types which outcrop on continents.

For each watershed we have calculated the bicarbonate river flux using the runoff and the HCO_3^- concentration. The atmospheric/soil CO_2 consumed by rock weathering was considered to be equivalent to the whole HCO_3^- flux for streams draining silicate rocks (eq. (1)) and to half of the HCO_3^- flux for streams draining carbonate rocks (eq. (2)). An empirical relationship between F_{CO_2} and Q was then determined for each rock type (Amiotte Suchet and Probst, 1993a). F_{CO_2} increases when the runoff increases and, as it can be seen in Fig. 1, for a given runoff, F_{CO_2} varies according to the rock type. Hence, F_{CO_2} is 17 time higher on carbonate rocks than on plutonic and metamorphic rocks, which consume the lowest amount of atmospheric/soil CO_2. The F_{CO_2} consumed by the other rock types range between these two extremes. Thus, going from the smallest F_{CO_2} to the highest, the rock types could be classified as follow: plutonic and metamorphic rocks, sands and sandstones, acid volcanic rocks, evaporitic rocks, basalts, shales and carbonates rocks. Note that F_{CO_2} is twice as high for the weathering of basalts as for the weathering of acid volcanic rocks, which are structurally very similar. In this study, it is assumed that all these rocks, except carbonate and evaporitic rocks, do not contain any carbonate minerals. This assumption is not correct of course, especially for shales or sandstones. But, at a global scale, it is difficult to estimate the proportion of carbonate minerals in such rocks, because this proportion is highly variable. Thus, the relationship between F_{CO_2} and the drainage intensity for shale may be subject to caution.

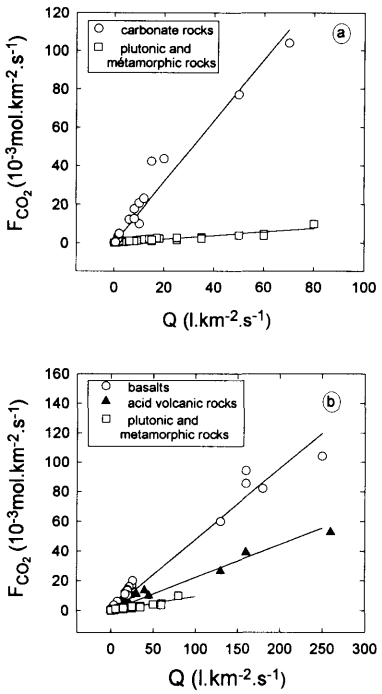

Fig. 1. Relationships between the flux of atmospheric CO_2 conumed by rock weathering (F_{CO_2}) and the stream runoff (Q) for watersheds on (a) carbonate rocks and plutonic and metamorphic rocks and (b) for watersheds on basalts, acid volcanic rocks and plutonic and metamorphic rocks (Amiotte Suchet and Probst, 1993a).

3. Validation of this empirical modelling on large river basins

For validation, these relationships have been tested on three different large river basins: the Garonne in temperate climate and the Congo and the Amazon in tropical-equatorial climate (Amiotte Suchet and Probst, 1993b). Each drainage basin area is divided in small grid cells which are each treated as a monolithologic drainage basin and for which the drainage intensity and the lithology are determined from maps. For each cell, F_{CO_2} is calculated using the empirical relationships between F_{CO_2} and Q determined by Amiotte Suchet and Probst (1993a) as described above.

For the Garonne drainage basin (52,000 km^2 at La Réole gauging station) the model was performed using hydroclimatic and geologic maps (BRGM, 1980, 1983). Results show high variations in the consumption of atmospheric/soil CO_2 among grid cells (from $13 \cdot 10^3$ moles km^{-2} y^{-1} to $2400 \cdot 10^3$ moles km^{-2} y^{-1}). The mean flux of CO_2 consumption (F_{CO_2}) for the whole basin is equivalent to $224 \cdot 10^3$ mole km^{-2} y^{-1} for a drainage of 345 mm y^{-1}. This result can be compared (Table 1) to fluxes calculated on the basis of bicarbonate river fluxes measurements: $441 \cdot 10^3$ moles km^{-2} y^{-1} for a humid period with a drainage of 415 mm y^{-1} (Etchanchu, 1988) and $113 \cdot 10^3$ moles km^{-2} y^{-1} for a dry period with a drainage of 155 mm y^{-1} (Semhi et al., 1993). If we assume a linear relationship between the CO_2 and the drainage intensity, the drainage value used in the model calculation should give a CO_2 flux of about $350 \cdot 10^3$ moles km^{-2} y^{-1}. Thus, the model underestimate the CO_2 flux of about 36%. This difference can be explained by the large outcrops of shales on the Garonne basin (30% of the basin area), which contains a highly variable proportion of carbonate minerals (Revel, 1982). Unfortunately, it was not possible to estimate such proportions and it has not been taken into account in the modelling. Nevertheless, according to the model, 57% of the total bicarbonate river flux comes from atmospheric/soil CO_2. This contribution is close to the estimate (55%) given by Etchanchu (1988).

For the Congo drainage basin ($3.7 \cdot 10^6$ km^2), the model calculation is performed using the drainage map of Africa (UNESCO, 1977) and the simplified geological map of Nkounkou and Probst (1987). Model estimates of the atmospheric/soil CO_2 consumed by rock weathering (F_{CO_2}) in the Congo drainage basin vary between $14 \cdot 10^3$ and $400 \cdot 10^3$ moles km^{-2} y^{-1}; the mean F_{CO_2} is $65 \cdot 10^3$ moles km^{-2} y^{-1}. This mean is comparable to the estimates ($53 \cdot 10^3$ moles km^{-2} y^{-1}) of Probst et al. (1994) calculated using a global geochemical method based on ionic ratio of the dissolved major elements transported by the Congo at Bazzaville (see Table 1). As for the Garonne basin, if we assume a linear relationship between the CO_2 and the drainage intensity, the drainage value used in the model calculation should give a CO_2 flux of about $55 \cdot 10^3$ moles km^{-2} y^{-1}. Thus, the model result seems 15% overestimated probably because large areas of the Congo basin are covered by deep lateritic formations which are depleted in alterable minerals

Table 1. *Comparison of simulated results obtained for the different basins with estimation made by different authors (1-Stallard, 1980; 2-Probst et al., 1994; 3-Etchanchu, 1988; 4-Semhi et al., 1993) using field measurements. D-drainage intensity (mm y^{-1}), D%–% of total drainage, S%–% of total basin area, F_{CO_2}-flux of atmospheric CO_2 consumed by rock weathering (10^3 moles km^2 y^{-1}), F%–CO_2% of HCO_3^- river flux*

River basin	D	Carbonate outcrop		Atmospheric CO_2 consumed		Ref.
		S%	D%	F_{CO_2}	F%	
Amazon	1125	9.2	7.0	271	67.8	this model
	1345			285	70.5	(1)
	1080			310	67.4	(2)
Congo	370	10.6	2.5	65	79.8	this model
	355			53	74.7	(2)
Garonne	345	37.8	31.2	224	57	this model
	415			441	55	(3)
	155			113	55	(4)

and which were not considered in our model. Consequently, the contribution of F_{CO_2} to the total bicarbonate river flux (79.8%) is slightly higher than the contribution (74.7%) estimated by Probst et al. (1994).

For the Amazon drainage basin ($4.6 \cdot 10^6$ km^2 at Obidos) the drainage intensity and the lithology have been determined using, respectively, the drainage map of South America (UNESCO, 1977) and the simplified geologic map given by Stallard and Edmond (1983). As it can be seen on the map resulting from the modelling (Fig. 2), the flux of atmospheric CO_2 consumed by rock weathering (F_{CO_2}) for grid cells of the Amazon basin ranges between $14 \cdot 10^3$ and $3600 \cdot 10^3$ moles km^{-2} y^{-1}. Average F_{CO_2} for the whole basin is $271 \cdot 10^3$moles

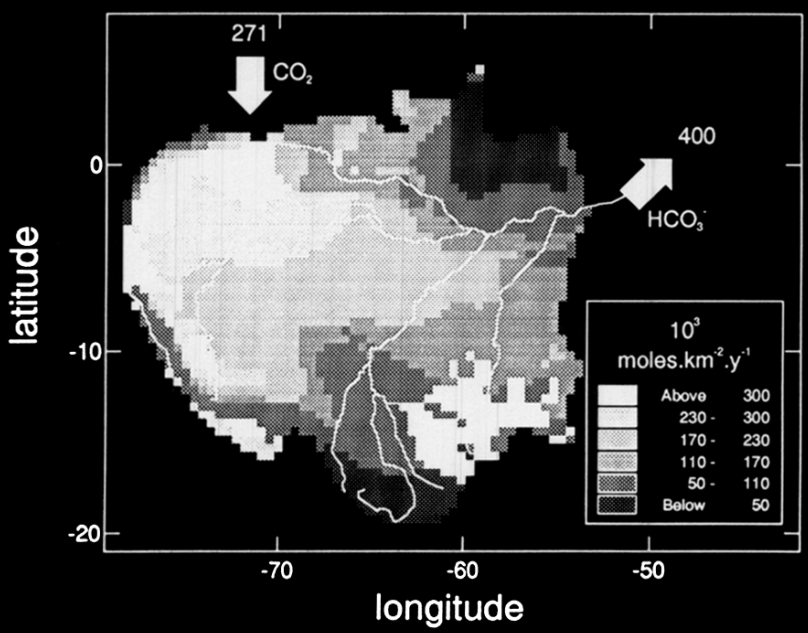

Fig. 2. Map of the mean annual specific CO_2 fluxes (F_{CO_2}) consumed by rock weathering and total bicarbonate river flux on the Amazon basin. All fluxes expressed in 10^3 moles km^{-2} y^{-1}.

$km^{-2}\,y^{-1}$, which is lower than the values estimated by Probst et al. (1994) ($310 \cdot 10^3$ moles $km^{-2}\,y^{-1}$) and Stallard (1980) ($285 \cdot 10^3$ moles $km^{-2}\,y^{-1}$) using a global geochemical method based on HCO_3^- river flux measurements (Table 1). The difference (about 5 to 12%) between the model simulation and the results based on HCO_3^- measurements can be explained by some simplifications of the geologic map we have used. For example, the paleozoic sediments of the Amazon basin are largely silicate rocks like shales or sandstones but they also contain carbonate rocks (Stallard and Edmond, 1983) which could not be taken into account in our study. However, the contribution of the atmospheric CO_2 to the bicarbonate river flux calculated in this study (67.8%) is very closed to that given by Probst et al. (1994) (67.4%) and Stallard (1980) (70.5%).

These simulations on three large river basins show that the empirical modelling of CO_2 consumption by weathering recently proposed by Amiotte Suchet and Probst (1993a) can be applied successfully to large river basins in tropical-equatorial climates as well as in temperate climates. The simulated results are of the same order of magnitude as estimates obtained using field measurements (Table 1). Nevertheless, some differences appear which can be partly attributed to the drainage intensity of the study period. During a dry period, the atmospheric CO_2 flux consumed by rock weathering is lower than during a more humid period. However, some sources of uncertainties in our model have to be pointed out. The first one is the inevitable simplifications of the lithological maps of the basins and the mineralogical and lithological heterogeneity of rocks such as shales. Also, the presence of deep lateritic profiles on the Congo basin has probably induced an overestimation of the model results, while large outcrops of heterogeneous shales on the Garonne basin has led to an underestimation of the model results.

Another source of uncertainty is that the model does not take into account some other factors such as temperature, vegetation, elevation, slopes, which are believed to influence chemical erosion and CO_2 consumption (Garrels and Mackenzie, 1971; Holland, 1978; Berner et al., 1983; Tardy, 1986; Meybeck, 1986, 1987). Nevertheless, at a global scale, all these variables have a weak influence compared to the drainage intensity and to the lithology, as shown by Probst (1992) and Amiotte Suchet (1994). Moreover, on small watersheds, fluctuations of CO_2 consumption are well explained by the drainage variations and the lithological diversity (Fig. 1).

A quantitative appraisal of the error induced by all these sources of uncertainty may be difficult, but if the error seems quite important on the Garonne basin (about 36%), it is smaller on the Congo and Amazon basins (5 to 15%).

Comparing the different basins, the weathering CO_2 flux of the Amazon is 4 times larger than that of the Congo, mainly because of the different drainage intensities. The simulations also show that the abundance of carbonate areas is a major factor controlling the weathering CO_2 flux and its contribution to the total bicarbonate river flux. For example, the weathering CO_2 flux is 3.4 times higher for the Garonne basin than for the Congo, mainly because the carbonate rock outcrops are 3.5 times more abundant in the Garonne basin. Consequently, the contribution of weathering CO_2 flux to the total bicarbonate river flux appear to be a negative function of the drainage contribution of carbonate areas as a proportion of the total drainage basin.

4. Global model distribution of CO_2 consumption

The validation of the modelling for three large drainage basins in different bioclimatic zones allows us to apply the same modelling to the global scale (GEM-CO_2: Global Erosion Model for CO_2 fluxes). The first results of this simulation are presented here*. The grid resolution is $1° \times 1°$. For each grid cell, a mean lithology has been determined using simplified lithological maps and soils maps published by the FAO-UNESCO (1971, 1975, 1976, 1978, 1979, 1981) for each continent. The drainage intensity has been calculated after the data of Willmott (1985) on the mean monthly precipitations and evapotranspiration on the continents. These climatological data have been

* Resulting numeric data corresponding to CO_2 consumption and to HCO_3^- river transport will be available at the Carbon Dioxide Information Analysis Center (CDIAC, Oak Ridge National Laboratory, USA) on ftp server (ftb cdiac.esd.ornl.gov).

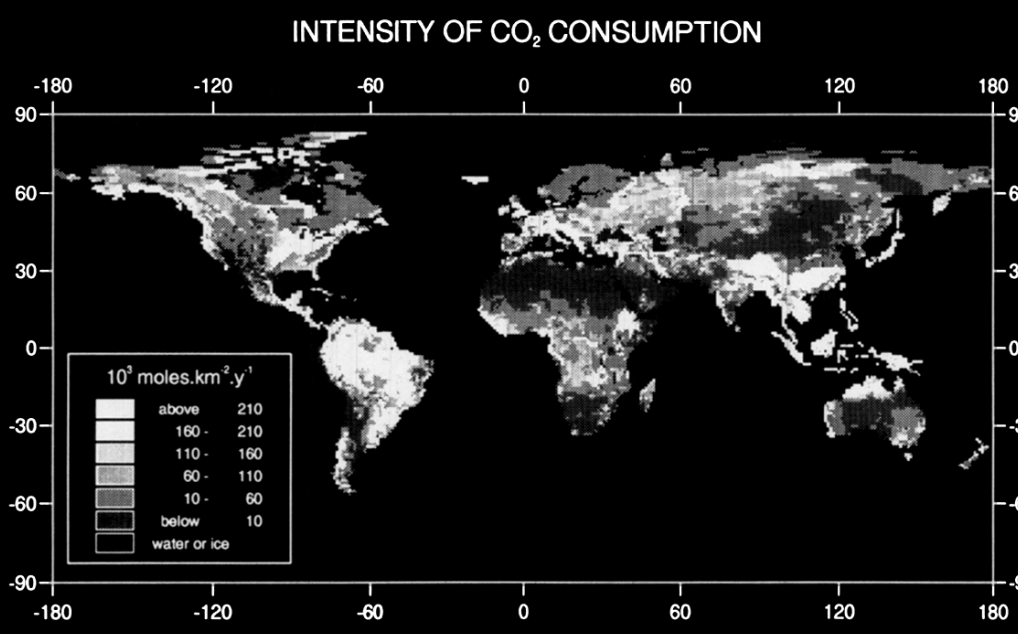

Fig. 3. Global model distribution of the mean annual CO_2 consumption by chemical weathering of continental rocks*.

supplied by the NCAR (National Center for Atmospheric Research, Boulder, Colorado).

The global map of CO_2 consumption (F_{CO_2}) resulting from the simulation (Fig. 3) shows high variations in F_{CO_2} (up to $7000 \cdot 10^3$ moles $km^{-2}\,y^{-1}$ in South Eastern Asia for example). High CO_2 consumption is observed in very humid regions such as the South East Asia and the Amazon basin, but also in temperate region such as the Eastern USA and Western Europe. Whereas, CO_2 consumption is less active in Africa, even in tropical-equatorial latitudes, because of large outcrops of plutonic and metamorphic rocks and of sands and sandstones. The mean annual consumption of atmospheric/soil CO_2 on the whole continental area resulting from the modelling is 0.26 Gt C y^{-1}, which is agreement with previous estimates varying between 0.25 and 0.30 Gt C y^{-1} (Berner et al., 1983; Meybeck, 1987; Probst, 1992). Fig. 4 shows the latitudinal distribution of the mean annual CO_2 consumption (Fig. 4a), of the drainage intensity and of the carbonate rocks area (Fig. 4b) and of the mean annual net sources of atmospheric CO_2 (Fig. 4c, after Tans et al., 1989). It can be noted 3 maxima in the specific flux of CO_2 consumption (Fig. 4a): (i) between 40° and 60° South, which corresponds to a quite high drainage intensity of the tip of South America (Fig. 4b), (ii) between 0° and 10° South, which corresponds to the very humid climate of tropical equatorial regions (Fig. 4b) and (iii) between 30° and 40° North, where large carbonate rock areas outcrop (Fig. 4b). Considering the latitudinal distribution of the total uptake of CO_2 by chemical erosion (Fig. 4a), the peak corresponding to the tip of South America has disappeared because of it small area of occurence, while the peak of the Northern hemisphere is enhanced because of the relatively large continental area in these latitudes. The latitudinal distribution of CO_2 consumption can be compared to the mean annual atmospheric CO_2 budget calculated by Tans et al. (1989) for the different latitudes (Fig. 4c). High levels of CO_2 consumption in the northern hemisphere coincides with a net sink of atmospheric CO_2, while the contrary is observed for equatorial regions. The CO_2 consumption occurs mainly in the Northern hemisphere, with about $16 \cdot 10^{12}$ moles y^{-1} of CO_2 (0.19 Gt C y^{-1}), which corresponds to 72% of the global CO_2 consumption by continental weathering.

* See footnote, previous page.

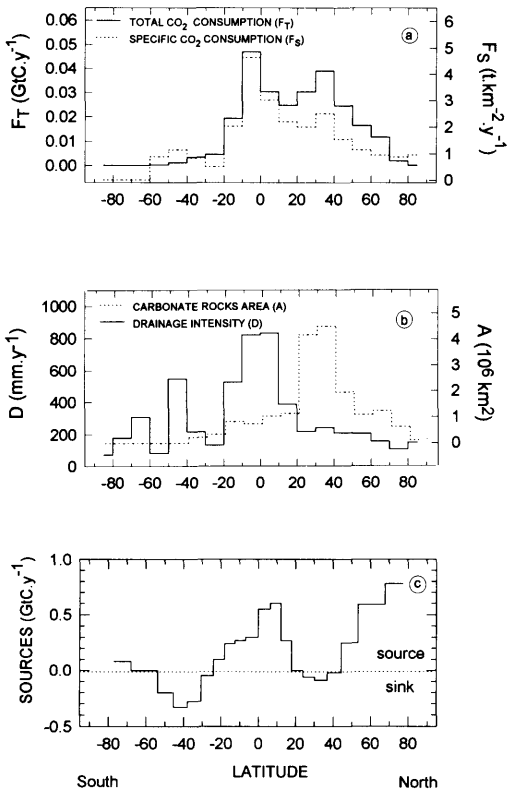

Fig. 4. Latitudinal distributions of (a) the specific flux (F_S) and the total flux (F_T) of CO_2 annually consumed by rock weathering, (b) the continental drainage intensity and the carbonate rock areas on continents, (c) the mean annual CO_2 budget in the atmosphere (sources and sinks taking into account of the fossil fuel emissions) calculated by Tans et al. (1989) for the period 1981–1985.

5. Conclusion

The main factors controlling the consumption of atmospheric/soil CO_2 by chemical weathering of continental rocks are the drainage and the lithology. The model developped by Amiotte Suchet and Probst (1993a) has been tested on three large river basins for validation. Model results are in agreement with previous estimates based on field measurements. The modelling is then performed at the global scale (GEM-CO_2) and results show that the consumption of CO_2 is mainly localized in the Northern hemisphere, because of large continental area with a high proportion of carbonate rocks, and in equatorial regions which are very humid.

In the future, input budgets of HCO_3^- for the different oceans and output budgets of carbon for several continental zones could be determined using this modelling. The model will also be used to estimate global seasonal fluctuations of CO_2 consumption and to simulate the effects of the chemical erosion on the carbon cycle in response to climate change. Such an application is presently performed for the last glacial-interglacial periods.

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