

Oxidation and Reduction Rates for Organic Carbon in the Amazon
Mainstream Tributary and Floodplain, Inferred from
Distributions of Dissolved Gases¹

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Abstract. Concentrations of CO_2 , O_2 , CH_4 , and N_2O in the Amazon River system reflect an oxidation-reduction sequence in combination with physical mixing between the floodplain and the mainstem. Concentrations of CO_2 ranged from 150 μM in the Amazon mainstem to 200-300 μM in aerobic waters of the floodplain, and up to 1000 μM in oxygen-depleted environments. Apparent oxygen utilization (AOU) ranged from 80 μM to 250 μM . Methane was highly supersaturated, with concentrations ranging from 0.06 μM in the mainstem to 100 μM on the floodplain. Concentrations of N_2O were slightly supersaturated in the mainstem, but were undersaturated on the floodplain. Fluxes calculated from these concentrations indicated decomposition of 1600 $\text{g C m}^{-2}\text{y}^{-1}$ of organic carbon in Amazon floodplain waters. Analysis of relationships between CH_4 , O_2 and CO_2 concentrations indicated that approximately 50% of carbon mineralization on the floodplain is anaerobic, with 20% lost to the atmosphere as CH_4 . The predominance of anaerobic metabolism leads to consumption of N_2O on the floodplain. Elevated concentrations of CH_4 in the mainstem probably reflect input from the floodplain, while high levels of CO_2 in the mainstem are derived from a combination of *varzea* drainage and *in situ* respiration.

Metabolic processes in rivers change dramatically with increasing river size (Van-
note et al., 1980). Much is known of small streams, yet the sequence of metabolic
processes operating in very large rivers is essentially unknown. Many large river sys-
tems are located in the tropics, have extensive floodplains, and are regions of high pri-
mary and secondary production (Welcomme, 1979). Large rivers may be very important
to global biogeochemistry. For example, recent studies suggest that tropical river basins
may be strong sources of such gases as methane to the troposphere (Mayer et al., 1982;
Keller et al., 1983), indicating the potential for global influence by the highly productive,
strongly reducing aquatic environments associated with these rivers.

The productivity of large tropical systems and the apportionment of production
between flowing waters and floodplain are not well known. There is little evidence
detailing linkages between mainstem, floodplain and off-channel processes in these rivers
(cf. Welcomme, 1979). Analysis of patterns of organic matter production in such
environments is complicated by the large scale and the temporal and spatial hetero-
geneity of major habitats. Hence it is difficult to extrapolate from traditional, site-
intensive studies to determine mesoscale patterns of metabolic processes in large sys-
tems.

Distributions of biologically reactive dissolved gases provide useful indices for rates
of production and consumption of organic matter (Odum, 1957). We attempt here to use
such distributions to integrate the effects of metabolic transformation over large areas
and over time in the Amazon River system. We examine the oxidation and reduction of
organic carbon in mainstem, tributary, and floodplain waters by analyzing the spatial and

temporal distributions of dissolved carbon dioxide (CO_2), oxygen (O_2), methane (CH_4), and nitrous oxide (N_2O). The distribution of CO_2 provides a measure of total rates for mineralization of carbon, and the distributions of CH_4 , N_2O , O_2 and CO_2 help elucidate the relative importance of aerobic oxidation, anaerobic oxidation, and methanogenesis.

The data discussed here were acquired as part of the CAMREX (Carbon in the Amazon River Experiment) project. We are indebted to the skilled crew of the LM *Amanai*, especially M.R. de Souza, A.M. Silva, and P.I. de Almeida. We thank B. Forsberg, L. Martinelli, W. Clark and F. Gimmelfarb for assistance in sample collection and analysis.

The Amazon River System

The Amazon River system consists of a 6700 km main channel and floodplain fed by tributaries that drain 6 million km^2 of Andean and lowland basins. The structure of a representative region is represented in Figure 1. The extensive floodplain, or *varzea* represents 100,000 km^2 of lowlands connected to the main channel via a network of channels, or *paranas*. It is periodically inundated by the annual 10-m rise and fall of the river. During high water much of the floodplain is under water and the lakes (isolated oxbows and depressions) are typically 6-8 m deep. Some lakes stratify on a time scale of weeks (Melack and Fisher 1983; Tundisi et al., 1984). As the river falls, land is re-exposed and the lakes become isolated from the main channel, with depths decreasing to 1-2 m.

Primary production occurs almost exclusively in and along the extensive floodplain, and not in the main channel (Junk, 1970; Sioli, 1975; Wissmar et al., 1981). In central

Amazon lakes, plankton production is initiated as river water enters the floodplain at rising water, dropping its sediment load (Schmidt 1970, 1973; Junk 1970, 1973; Fisher and Parsley 1979). Rooted macrophyte growth in these lakes and along the river banks starts at low water; by high water, much of this material has been uprooted, and either decays *in situ* or is carried away (Junk, 1973, 1976, 1985). In the Amazon River mainstream, dissolved CO₂ is supersaturated by a factor of about 10 and *in situ* O₂ consumption is on the order of several $\mu\text{M O}_2\text{hr}^{-1}$ (Richey et al., 1980; Wissmar et al., 1981; Devol et al., in press). As the summation of these processes, Sioli (1975) and Junk (1985) hypothesized that the *varzea* would be a net exporter of organic matter to the mainstream during falling water.

Sampling Collection and Analysis

A series of cruises was conducted along a 2000 km reach, from Vargem Grande to Obidos, Brazil, approximately every 4 months at different stages of the hydrograph (Richey et al., 1986). A complete suite of hydrological and chemical measurements were made at eleven mainstream and seven tributary stations. Extensive sampling of the floodplain took place in the vicinity of these stations. Cruises were numbered 1 (April-May 1982, mid-late rising water), 2 (August-September 1982, falling water), 3 (November-December 1982, early rising water), 4 (March-April 1983, mid-rising water following brief falling period) 5 (June-July 1983, post-high water), 6 (October-November 1983, very early rising water), 7 (February-March 1984, mid-rising water), 8 (July-August 1984, post-high water), and 9 (July-August 1985, high water).

Sampling locations were distributed to represent various habitat types: mainstem, tributaries, *paranas*, surface of standing waters, and bottom of standing waters. At each station along the mainstem samples for dissolved CO_2 and O_2 were taken at 5 sites and for CH_4 and N_2O at 2 sites, spaced equally across the river, using a Niskin bottle. Samples from the *varzea* waters were taken at the surface and at the bottom (with lesser frequency) at locations accessible by small outboard, primarily during daylight. Upriver, these included the small, sheltered oxbow-type lakes of the region, as well as flooded fields and forests, *paranas* and areas covered by dense growths of macrophytes. Downriver, the *varzea* was sampled mostly in the characteristic large open lakes.

The Niskin bottle was subsampled for measurement of O_2 , N_2O , and CH_4 by filling 60-ml glass-stoppered BOD bottles to overflowing. Thirty ml Erlenmeyer flasks were used to collect samples for analysis of dissolved inorganic carbon. Determinations of pH were made immediately after collection, using a closed container and a Corning Model 130 pH meter with Orion Ross electrode. Alkalinity was determined by micro-Gran titration (Edmond, 1970). Free dissolved carbon dioxide (CO_2) was calculated from pH and alkalinity (Skirrow 1975). Stallard (1980) showed that these calculated parameters agreed with those measured by infrared CO_2 analysis, for a variety of Amazon waters, and we found comparable results using gas chromatography. Oxygen concentrations were determined using a YSI Model 58 or Radiometer oxygen meter and electrode standardized as described by Devol (1978), except that nitrogen-purged water was used as the zero solution.

For Cruises 1-8, samples for CH₄ and N₂O were preserved with HgCl₂, returned to the laboratory at Harvard University for measurement using flame ionization (FDS) and electron capture gas chromatography, respectively. On Cruise 9, CH₄ was measured immediately on board the research vessel using FID gas chromatography.

Conceptual framework for analysis of dissolved gas distributions

The rate of change of the concentration, C , of a gas in a water parcel is determined by exchange with the atmosphere (F), biological reactions (B) within the parcel, net physical transport (advection and diffusion) from adjacent parcels or sediments (T), and ionic equilibrium reactions (I),

$$dC/dt = F/H + B + T + I, \quad (1)$$

where H is depth of the water column and t is time. The flux of gases between atmosphere and water can be calculated using an empirical boundary layer model for gas exchange (Liss and Slater, 1974), calibrated using measurements by Devol et al. (in press) for the Amazon:

$$F = D(C - C_{eq})/z \quad (2)$$

where F is the diffusive flux of gas through the air-water interface, D is the molecular diffusion coefficient, z is the empirical thickness of a hypothetical stagnant boundary layer, C_{eq} is the concentration at equilibrium with the atmosphere and C is the observed concentration in the water.

The terms in Eq. 1 cannot be evaluated solely from observed distributions. We can, however, obtain useful information about these terms for CO₂ and O₂ by considering the ratio of their respective concentrations. For reference, consider an isolated water parcel

at steady state ($dC/dt=0$) with transport terms $T=0$ for both O_2 and CO_2 . At ambient conditions (pH 6-7, alkalinity of 500-1000 μEq), with dissolved CO_2 of 100-150 μM or higher, the CO_2 produced through respiration remains primarily as dissolved CO_2 , thus term I may be neglected ($I \approx 0$) for both gases. The principal terms in Eq. 1 would then be biological production/consumption and exchange with the atmosphere. If oxidation were strictly aerobic, then approximately one mole of CO_2 would be evolved per mole of O_2 consumed. Likewise, for every mole of CO_2 fixed via photosynthesis, O_2 is increased by one mole. Hence $B_{CO_2}/B_{O_2} = -1$ and

$$D_{CO_2} ([CO_2] - [CO_2]_{eq})/z = -D_{O_2} ([O_2] - [O_2]_{eq})/z \quad (5)$$

The ratio of excess CO_2 to O_2 depletion, defined as R_q , would be given in this case by

$$R_q = -([CO_2] - [CO_2]_{eq})/([O_2] - [O_2]_{eq}) = \frac{D_{O_2}}{D_{CO_2}} = 1.2, \quad (6)$$

where $D_{O_2} = 2.1 \times 10^{-5}$ and $D_{CO_2} = 2.6 \times 10^{-5}$ (Broecker and Peng, 1974). Systematic deviations of R_q from 1.2 provides an indication of anaerobic metabolism. Essentially, R_q is a "riverine respiratory quotient", normalized for differences in diffusion coefficients.

The concentration of O_2 is generally below equilibrium with the atmosphere and the concentration of CO_2 is generally above atmospheric equilibrium. For comparison with Eq. 6 we define the departure of O_2 from atmospheric equilibrium as the apparent oxygen utilization (AOU),

$$AOU = [O_2]_{eq} - [O_2] \quad (7a)$$

and similarly define CO_2^* as

$$CO_2^* = [CO_2] - [CO_2]_{eq} \quad (7b)$$

Anoxia corresponds approximately to $\text{AOU} \approx 250\mu\text{M}$.

Results from all sites were converted to the defined quantities in (7a) and (7b), and aggregated for mainstem, tributary, *parana* (surface), lake surface, and lake bottom waters, respectively. "Lake" in this application refers to still as opposed to flowing waters. Data are presented as means \pm one standard deviation, unless otherwise noted.

Results

The aquatic environments of the Amazon were characterized by positive values for CO_2^* and AOU (i.e. an excess of respiration over photosynthesis), and by a general association between high levels of AOU and high CO_2^* (Figure 2). Mainstem values for CO_2^* exceeded levels expected for atmospheric equilibrium ($\sim 10\mu\text{M}$) by a factor of 10-20, with mean CO_2^* of $131 \pm 70 \mu\text{M}$. Mainstem O_2 averaged about 35% undersaturated relative to the atmosphere, with mean AOU of $84 \pm 22 \mu\text{M}$ (Fig. 2a). The mean CO_2^* in tributaries was $180 \pm 116 \mu\text{M}$, while AOU averaged $94 \pm 51 \mu\text{M}$.

Gas concentrations on the *varzea* fell, generally, into two categories: (1) aerobic waters where CO_2^* was less than about $250 \mu\text{M}$ and AOU less than $200 \mu\text{M}$, and (2) microaerobic or anaerobic waters where CO_2^* exceeded $250 \mu\text{M}$ and AOU exceeded $200 \mu\text{M}$ (Fig. 2b). The primary linkages between the mainstem and the *varzea*, the *paranas*, had higher mean CO_2^* ($165 \pm 102 \mu\text{M}$) than did the mainstem, where AOU values were similar. However, when AOU was greater than $200 \mu\text{M}$, the mean CO_2^* was much larger, $410 \pm 90 \mu\text{M}$.

Lake surface waters are influenced by input from *paranas* and by local drainages

(Forsberg et al., in review) and by plankton photosynthesis and respiration. As might be expected, lake surface waters had a broader range of gas concentrations than did the mainstem or the *paranas*, with mean values for CO_2^* of $190 \pm 95 \mu\text{M}$ in the low AOU environments and $496 \pm 200 \mu\text{M}$ where AOU was high. There was a second group of surface waters, generally black water (see Sioli 1985) lakes of low alkalinity, where a very wide range of values was observed for CO_2^* , $214 \pm 141 \mu\text{M}$. Lake bottom waters were generally much more depleted in oxygen and highly enriched in CO_2 than the mainstem, *paranas* or lake surface waters. When AOU was less than $200 \mu\text{M}$, CO_2^* averaged $244 \pm 90 \mu\text{M}$, while the average for waters with AOU greater than $200 \mu\text{M}$ was $500 \pm 146 \mu\text{M}$.

Methane concentrations were supersaturated with respect to atmospheric equilibrium in all surface waters (Fig. 3). Even the turbulent mainstem was supersaturated by a factor of 30, with a mean value of $0.053 \pm .091 \text{ nM}$ (Fig. 3a). Methane concentrations increased exponentially with increasing CO_2^* in the *varzea*, (Fig. 3b). Variance about the mean was considerable due to high values in anaerobic environments. When AOU was less than $200 \mu\text{M}$, the overall mean CH_4 in the *paranas*, lake surface, and bottom waters was $0.38 \pm .69 \mu\text{M}$. In high AOU environments, mean CH_4 in the *paranas*, surface, and bottom waters was $17.9 \pm 30.7 \mu\text{M}$, $58.8 \pm 76.8 \mu\text{M}$, and $55.0 \pm 67.6 \mu\text{M}$, respectively. The resultant overall mean of lake surface samples was $11.9 \mu\text{M}$. The maximum CH_4 concentrations observed were close to $100 \mu\text{M}$, where the fugacity of CH_4 is about 1 atm, i.e. bubbles can form.

Nitrous oxide exhibited a distribution pattern very different from the other dissolved gases (Fig. 4). Mainstem N_2O averaged 13.4 ± 2.5 nM, or about 1.5 times saturation (Fig. 4a). Tributary values were slightly lower, averaging 10.8 ± 3.3 nM. Nitrous oxide levels on the *varzea* decreased with increasing CO_2^* and AOU, in contrast with results for CH_4 (Fig. 4b). The overall *varzea* mean was 8.9 ± 3.7 nM in waters with AOU less than $200 \mu\text{M}$, and 4.4 ± 2 nM for waters with AOU greater than $200 \mu\text{M}$. There was essentially no dissolved N_2O in anoxic waters.

To investigate potential sources of the excess CH_4 in the main channel, cross-channel transects were taken on cruise 9 at 5 locations equally spaced across the main channel. Significant cross-channel gradients were observed at all stations, (Fig. 5). Concentrations of CH_4 at most stations were greatest off one bank (usually the left, or north bank), fell at mid-channel, then either remained low or increased toward the opposite bank.

Discussion

The nominal value for R_q in aerobic conditions ($=1.2$) is compared to the observations in Table 1. All measured values for R_q were larger than 1.2. The highest values, $R_q = 1.8$ to 2.1, were found in *varzea* waters where $\text{AOU} > 200 \mu\text{M}$. Slightly lower values, $R_q = 1.7$ to 1.9, were observed in tributaries and in aerobic surface and bottom waters ($\text{AOU} < 200 \mu\text{M}$), and the lowest values, about 1.4, were found in mainstem and well oxygenated *parana* waters. The standard error of the mean for R_q in each type of environment was less than 10% of mean value.

Observed R_q values indicate that there is substantial surplus CO_2^* relative to AOU in all waters. It follows that CO_2 has been produced without O_2 consumption, i.e. anaerobically. The surplus CO_2^* increases sequentially from the mainstem to *paranas* and from *paranas* to anoxic *varzea* waters. *Paranas* have R_q values reflecting source waters, with low R_q when mainstem waters are flowing onto the *varzea* and higher R_q values when water is flowing off the *varzea* into the mainstem. Tributaries are intermediate.

Devol et al. (in press, 1986) estimated a boundary-layer thickness $z \approx 50 \mu\text{m}$, for air-water exchange on the mainstem, and $z = 300 \mu\text{m}$ for the *varzea*, using floating chambers. These experiments may be expected to underestimate water-air exchange in the still waters of the *varzea* (Brutsaert and Jirka, 1984; Wannikopf et al., 1985; Devol et al., in press, 1986), and we therefore adopted an estimate of $z \approx 150 \mu\text{m}$ for the *varzea*. Note that, in the discussion which follows, we are most interested in examining ratios between fluxes of CO_2 , O_2 , CH_4 and N_2O , and therefore the particular value chosen for z is relatively unimportant.

Estimates of air-water gas exchange flux F are shown in Table 2. The estimate for the mainstem evasive flux of CO_2 was $2100 \text{ gC m}^{-2}\text{y}^{-1}$, approximately equal to the riverine transport of dissolved inorganic carbon (Stallard and Edmond 1983; Devol et al., in press, 1986). The mean *varzea* flux was somewhat lower, $1300 \text{ gC m}^{-2}\text{y}^{-1}$.

The diffusive flux of CH_4 calculated for the mainstem, $1 \text{ gC m}^{-2}\text{y}^{-1}$ is considerably less than the $65 \text{ gC m}^{-2}\text{y}^{-1}$ for the *varzea*. The flux calculated from dissolved CH_4 concentrations accounts only for the diffusive component of the total flux. Ebullition

(bubbling) is observed in the *varzea* on many occasions, and could be the main mechanism of transport from the sediments to the overlying waters and subsequently to the atmosphere. Devol et al. (in review) and Crill et al. (in review) made direct measurements of both ebullition and evasion, showing that ebullition accounts for 70 to 90% of the CH_4 flux. Hence, we estimate the total CH_4 flux from the *varzea* to be on the order of $300 \text{ gC m}^{-2}\text{y}^{-1}$. This value is comparable to fluxes observed in freshwater swamps in Louisiana ($160 \text{ gC m}^{-2}\text{y}^{-1}$, DeLaune et al., 1983), and is significantly greater than fluxes in most temperate swamps (4 to $40 \text{ gC}^{-2}\text{y}^{-1}$ Harriss et al. 1981, 1982). The mean emission rate from the entire central Amazon basin has been estimated to be about $5 \text{ gC m}^{-2}\text{y}^{-1}$ (Wofsy, 1985). However, the soils of terra firme forests consume CH_4 from the atmosphere (Keller et al., 1983, 1986). The large floodplain area and high emission rates for CH_4 indicate that Amazon floodplain could provide a major part of the observed regional emissions of CH_4 .

A conceptual model can now be presented to describe the sequences of biological and physical processes which produce the observed dissolved gas concentrations. Total decomposition of organic carbon is represented by the sum of CO_2 and CH_4 fluxes; thus, from Table 2, biogenic emissions are estimated to be

$$F_{\text{CO}_2} + F_{\text{CH}_4} = 1300 + 300 \text{ gC m}^{-2}\text{y}^{-1} = 1600 \text{ gC m}^{-2}\text{y}^{-1}.$$

This value is comparable to estimates of total primary production entrained in the *varzea* waters, as derived from site-specific primary production experiments ($1000 - 2000 \text{ gC m}^{-2}\text{y}^{-1}$; Devol et al., 1983; Bayley in press). The aerobic part of organic carbon decomposition may be calculated from the flux of O_2 into the water ($2200 \text{ gO}_2 \text{ m}^{-2}\text{y}^{-1}$),

corresponding to about $825 \text{ gC m}^{-2}\text{y}^{-1}$. A similar value can be calculated from Melack and Fisher's (1983) analysis of eighty diel cycles of dissolved oxygen in Lago Calado. This estimate is probably an upper limit, because O_2 may be consumed in reactions with other reduced elements, such as sulfide and iron.

Aerobic oxidation of organic matter accounts for less than 65% of the total CO_2 emitted ($825/1300$), and less than 55% of the total mineralization rate for organic carbon ($825/1600$). The remainder of the CO_2 is presumably produced anaerobically. Approximately one mole of CO_2 is produced for every mole of CH_4 (e.g., during acetate fermentation); hence, most of the anaerobic CO_2 could be derived directly from methanogenesis.

We estimate that nearly 20% of the organic carbon mineralized is released to the atmosphere as CH_4 ($300/1600$). Conversion of organic C to CH_4 accounts for 5-10% of net production in typical freshwater lakes and marshes (Rudd and Hamilton, 1978; Fallon, 1980; Delaune et al., 1983), and conversion is less efficient in marine environments (Martens and Goldhaber, 1978; King and Wiebe 1980). Methanogenesis becomes the dominant pathway of anaerobic metabolism once nitrate, sulfate and N_2O are removed. Nitrate and sulfate concentrations in *varzea* waters are low, generally less than $5 \mu\text{M}$ (Forsberg et al., in review; J. Richey, unpubl. data), and a significant fraction of the nitrate is probably assimilated for primary production. The influx of N_2O from the atmosphere is very small compared to carbon mineralization rates. Thus, rates of denitrification and sulfate reduction are limited by available oxidized species. The large fraction of organic matter converted to CH_4 may reflect the low ambient levels of O_2 .

electron acceptors in the Amazon.

Inputs from the *varzea* impact the levels of CH_4 in main channel, as shown by the cross-channel gradients of dissolved CH_4 (Fig. 5). *In situ* sources are probably limited in the mainstem, as the sediments are mobile, sandy and, presumably, oxygenated to a significant depth, precluding significant methanogenesis. Tributaries are only slightly elevated in CH_4 . J. Richey (unpubl. data) has calculated inputs of *varzea* water to the main channel to be on the order of 1 to 10% of the mainstem discharge, depending on the season. Input of waters at these rates with CH_4 levels typical of the *varzea* ($>10 \mu\text{M}$), appears adequate to supply the CH_4 levels of $0.1\text{--}1.0 \mu\text{M}$ as observed in the mainstem.

Conclusions

The results presented here indicate that simultaneous measurements of dissolved biogenic gases provide a powerful technique for analyzing mesoscale patterns in the oxidation of organic matter in a large river system. Analysis of results for the Amazon River indicate that:

(1) Dissolved concentrations of CO_2 , O_2 , CH_4 and N_2O in the Amazon are regulated by oxidation-reduction reactions. The redox sequence is controlled by supply of organic matter and by the amount of oxygen available through invasion from atmosphere.

(2) Net decomposition rates for organic carbon in Amazon *varzea* waters are approximately $1600 \text{ gC m}^{-2}\text{y}^{-1}$, with about $1300 \text{ gC m}^{-2}\text{y}^{-1}$ as CO_2 and $300 \text{ gC m}^{-2}\text{y}^{-1}$ as CH_4 . Approximately 40% of the CO_2 is produced by anaerobic processes. Estimates

of the anaerobic CO₂ production rate (475 gC m⁻²y⁻¹), derived from the invasion rate for O₂ and from the evasion rate of CO₂, are in harmony with estimates for CH₄ emission rates if we assume a production ratio of about 1 for CO₂/CH₄ during methanogenesis.

(3) High levels of CO₂ in the mainstem are derived from a combination of *varzea* drainage waters and *in situ* respiration. High levels of CH₄ in the mainstem are probably derived from the *varzea*.

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Table 1. Calculation of the ratio $R_q = \text{CO}_2^*/\text{AOU}$ (Eq 4).

s.e. = standard error of the mean.

| | R_q | s.e. |
|---|-------|------|
| Mainstem | 1.4 | .04 |
| Tributaries | 1.9 | .12 |
| <i>Varzea</i> with $\text{AOU} < 200 \mu\text{M}$ | | |
| <i>Paranas</i> | 1.4 | .10 |
| Surface | 1.8 | .06 |
| Bottom | 1.7 | .12 |
| <i>Varzea</i> with $\text{AOU} > 200 \mu\text{M}$ | | |
| <i>Paranas</i> | 1.8 | .12 |
| Surface | 2.1 | .22 |
| Bottom | 2.1 | .10 |

Table 2. Diffusive flux of gases between the atmosphere and water from Eq. 2. As a first approximation it is probably realistic to consider an effective *varzea* boundary layer of 150 microns (see text). Diffusion coefficients of 2.1×10^{-5} , 2.6×10^{-5} , 2.3×10^{-5} and $2.7 \times 10^{-5} \text{ cm}^2/\text{s}$ for CO_2 , O_2 , CH_4 and N_2O respectively (Broecker and Peng, 1974) were used, and mean mainstem and *varzea* surface water (*paranas* and lakes) concentrations C^* (ambient - equilibrium) were used.

| Site | C^* (μM) | $F(\text{g m}^{-2} \text{ y}^{-1})$ |
|----------------------|-------------------------|-------------------------------------|
| Mainstem | | |
| CO_2 | 131 | 2080 |
| AOU | 84 | 4400 |
| CH_4 | .050 | .9 |
| N_2O | .004 | .1 |
| <i>Varzea</i> | | |
| CO_2 | 250 | 1320 |
| AOU | 130 | 2240 |
| CH_4 | 12 | 66 |
| N_2O | .0004 | -.004 |

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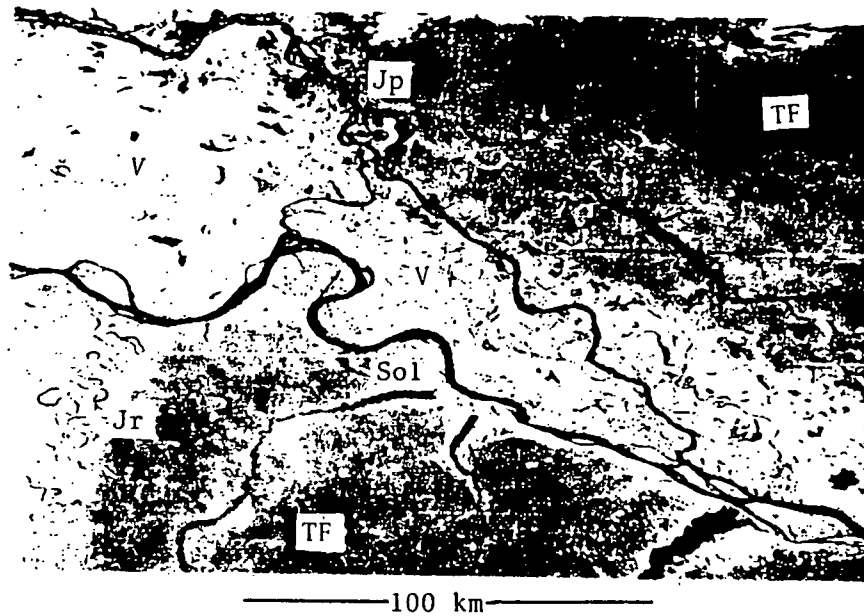


Fig. 1

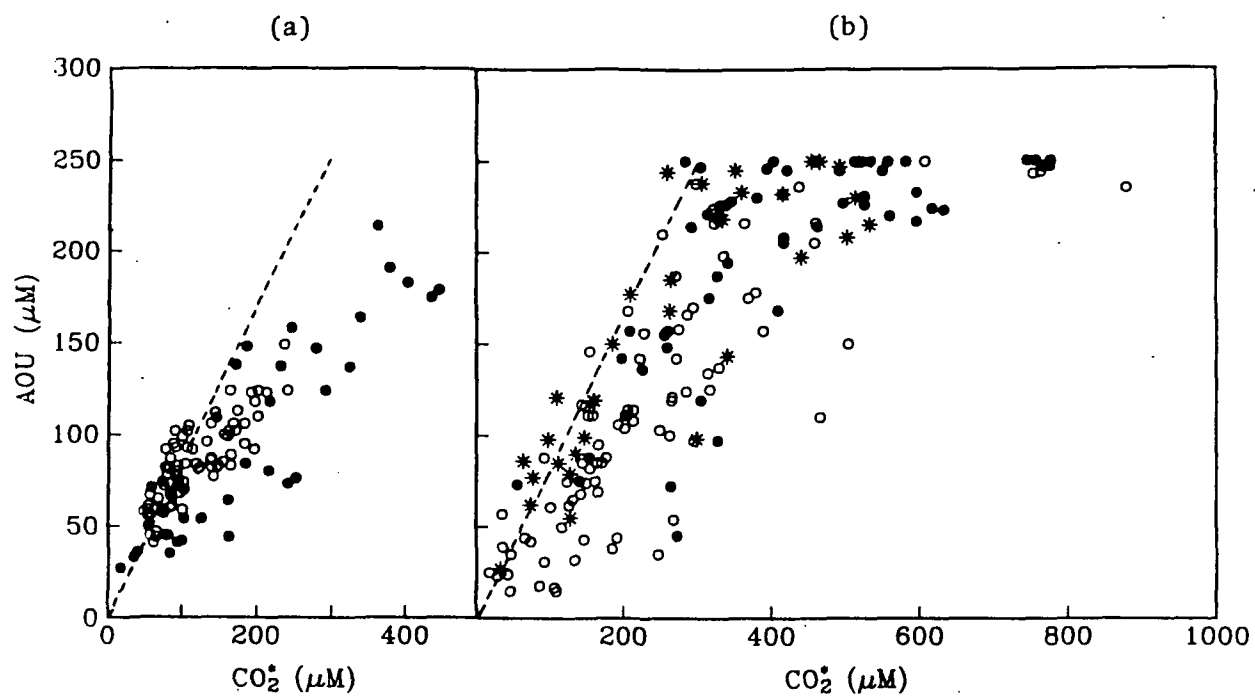


Fig. 2

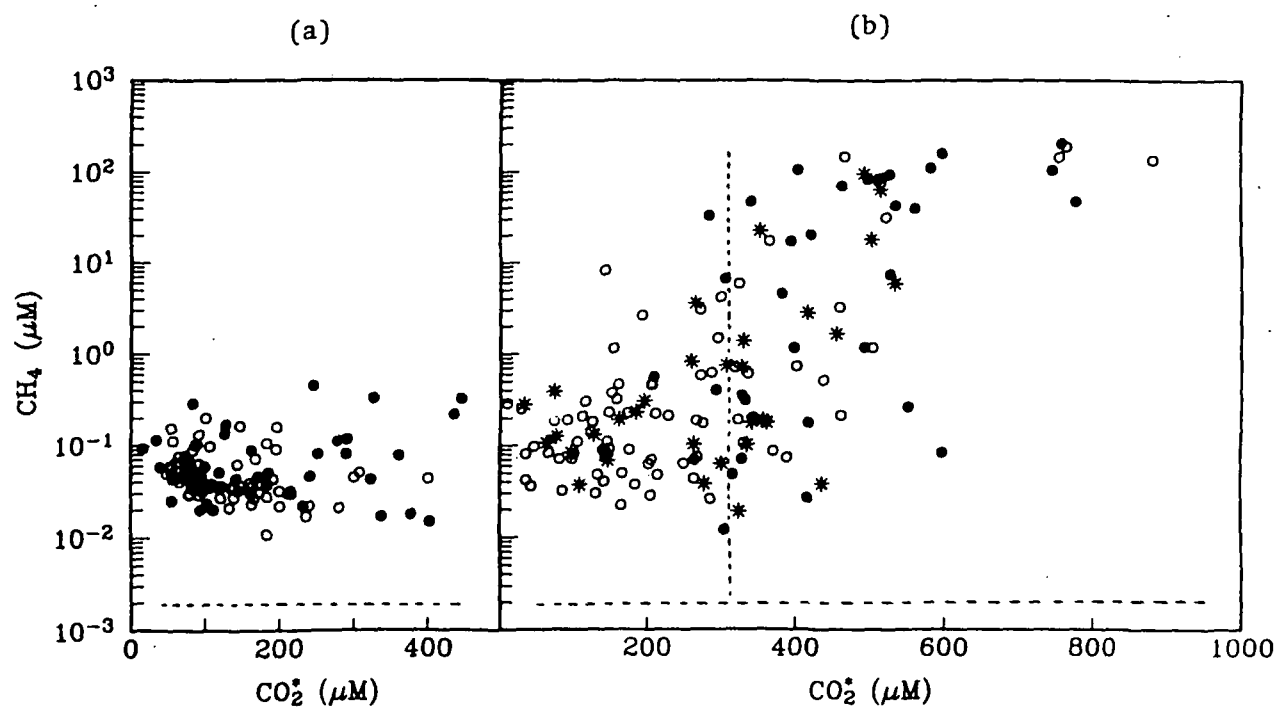


Fig. 3

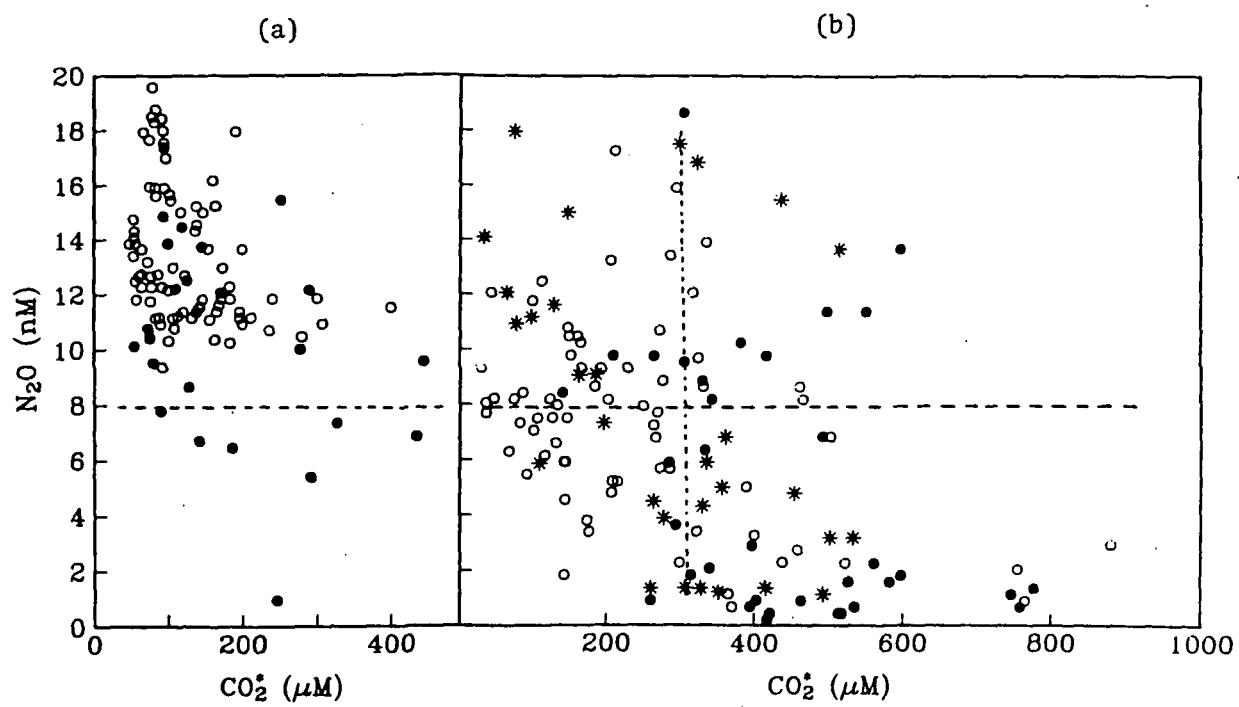


Fig. 4

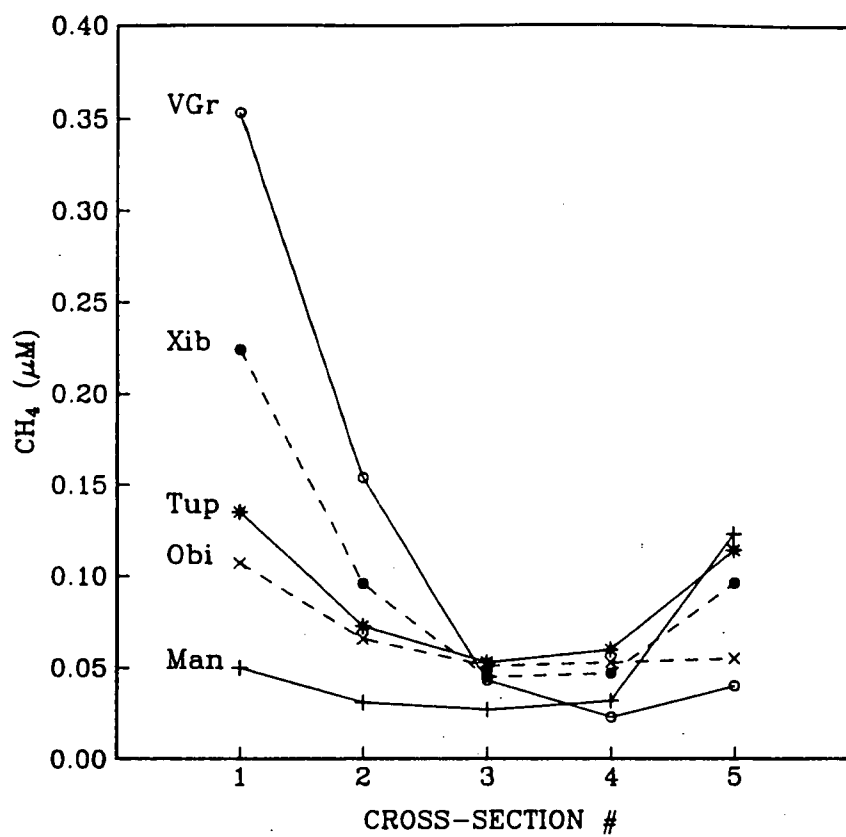


Fig. 5

Figure Captions

Fig 1. Landsat multi-spectral scanner image (bands 5,6, and 7) of the Rio Japura (Jp) and Rio Jurua (Jr) confluence with the Rio Solimoes (Amazon) mainstem (Sol). Light areas represent varzea habitat (V), and dark areas represent terra firme (non-flooded) habitat (TF). Image tapes were provided by the Instituto de Pesquisas Espaciais, and were processed by the Laboratory of Remote Sensing, University of Washington.

Fig. 2. CO_2^* - AOU property-property plots. Dotted line corresponds to the theoretical ratio $R_q = 1.2$. (a) mainstem (o) and tributaries (●); (b) parana (*), surface (o), and bottom waters (●).

Fig. 3. CO_2^* - CH_4 property-property plots. The horizontal dashed line is the atmospheric equilibrium, C_{eq} . The region to the left of the vertical stippled line represents $\text{AOU} < 200 \mu\text{M}$; the region to the right represents $\text{AOU} > 200 \mu\text{M}$. (a) mainstem (o) and tributary (●); (b) parana (*), surface (o), and bottom waters (●).

Fig. 4. CO_2^* - N_2O property-property plots. The horizontal dashed line is the atmospheric equilibrium, C_{eq} . The region to the left of the vertical stippled line represents $\text{AOU} < 200 \mu\text{M}$; the region to the right represents $\text{AOU} > 200 \mu\text{M}$. (a) mainstem (o) and tributary (●); (b) parana (*), surface (o), and bottom waters (●).

Fig. 5. Cross-channel profiles of CH_4 (# = equidistant cross-sections) on the Amazon mainstem at Vargem Grande (VGr), Xibeco (Xib), Tupe (Tup), Manacapuru (Man), and Obidos (Obi).