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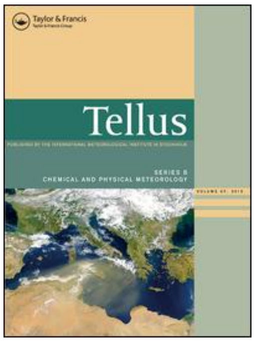

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KEYNOTE PERSPECTIVE

Can a strong atmospheric CO_2 rectifier e ect be reconciled with a “reasonable” carbon budget?

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ABSTRACT

Atmospheric CO_2 accumulates near the Earth’s surface because of relatively deeper vertical mixing when photosynthesis is active than when it is not. Some models simulate an excess of more than 2.5 ppmv CO_2 in the remote Northern Hemisphere due to this “rectification” of an annually balanced terrestrial carbon cycle. The covariance between CO_2 flux and vertical mixing, and the resulting vertical structure of CO_2 are generally consistent with field data at local scales, but it is di cult to reconcile such a strong rectifier signal with current ideas about the global carbon budget. A rectifier e ect of 2.5 ppmv at northern flask sampling stations implies an unreasonably strong northern sink of atmospheric CO_2, and a corresponding source in the tropics or Southern Hemisphere.

Current understanding of the global carbon budget is derived largely from global-scale constraints: the rate of change of the concentration and isotopic composition of atmospheric CO_2, the north–south gradient in annual mean concentration, the amplitude of the seasonal cycle and its variation with latitude. Observational data indicate that the carbon budget varies significantly from year to year, with the global carbon sink ranging from about 1 GtC/yr to perhaps as much as 5 GtC/yr (Conway et al., 1994; Keeling et al., 1995; Francey et al., 1995). In addition, understanding of carbon exchange mechanisms is derived from site-level studies (e.g., eddy correlation flux towers, oceanographic measurements of sea-surface p_{CO_2}, and ^{14}C profiles of soil organic matter).

In nature, the carbon budget is true to all of these observational constraints simultaneously. We would like this to be true for carbon budgets we infer from data, however, in practice this is almost never the case. Inversion studies have typically focused only on the behavior of the time-averaged data at remote marine surface locations. Site-based flux data are only used for validation. Bottom-up studies which attempt to diagnose fluxes from ancillary data such as spectral vegetation indices and ecological principles (Potter et al., 1993; Melillo et al., 1993) typically ignore the atmospheric constraint, except as needed for validation.

One of the strongest lines of evidence for a terrestrial sink in the northern hemisphere is the magnitude of the Arctic-to-Antarctic gradient in annual mean CO_2 concentration measured by the global flask air sampling networks (Tans et al.,

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1990; Enting et al., 1995; Fan et al., 1998). Interpretation of this spatial structure is complicated by the fact that the flask network samples the surface only, and is intentionally focused at remote marine boundary layer sites. Denning et al. (1995, 1996a,b) have shown that this gradient may be significantly influenced by covariance between terrestrial ecosystem metabolism and vertical atmospheric transport (the atmospheric "rectifier" e ect).

The idea behind the atmospheric rectifier is simple: photosynthesis and thermally driven buoyant convection in the atmosphere are both driven by solar radiation, and therefore "beat" on the same diurnal, synoptic, and seasonal frequencies. Photosynthesis exceeds ecosystem respiration during times and at places of deeper buoyant mixing, whereas respiration exceeds photosynthesis when mixing is shallow and ine cient. This covariance leads to a time-mean vertical partition of CO_2 in the atmosphere over active vegetation, with higher concentrations near the surface (reflecting respiration) and lower concentrations aloft (reflecting photosynthesis).

The global redistribution of CO_2 due to the rectifier e ect has been investigated by Denning et al. (1995, 1996a,b) using the Colorado State University (CSU) General Circulation Model (GCM). Simulated atmospheric CO_2 transport included resolved advection and parameterized vertical transport due to dry and penetrative moist convection. A unique feature of the CSU GCM is the use of a vertical discretization scheme in which the top of the turbulent planetary boundary layer (PBL) is identified as a coordinate surface. The PBL depth is prognosed at each time step from a turbulence kinetic energy budget and entrainment calculation, directly coupling the surface energy budget to the mass of air which exchanges tracer with the surface. Surface fluxes of energy, moisture, momentum, and CO_2 are calculated at each time step using the Simple Biosphere Model (SiB2, Sellers et al., 1996), which relates canopy conductance and fluxes to the rate of photosynthetic carbon assimilation. Thus CO_2 exchange is mechanistically coupled to the surface energy budget, the depth of the PBL, and the subgrid-scale vertical transport of CO_2 in the atmosphere. Covariance between annually balanced terrestrial CO_2 flux and transport in the model produces a north–south gradient of about 2.5 ppm at the locations of remote marine boundary layer flask stations. The rectifier e ect simulated by the CSU GCM was among the strongest in a recent intercomparison exercise involving 12 tracer transport models (TransCom, Law et al., 1996).

The rectifier e ect simulated by the CSU GCM is consistent with atmospheric observations, at least at local to regional scales. The annual mean CO_2 concentration exhibits a gradient in the annual mean between 11 m and 400 m on a tall television tower in northern Wisconsin (about 8 ppm) that is twice as strong as the gradient between Alert (83°N) and the South Pole (about 4 ppm) (Masarie and Tans, 1995; GlobalView, 1997). At this site, boundary-layer mixing depth measured by a radar wind profiler is inversely correlated with CO_2 concentration measured by continuous analyzers, and the CSU GCM is able to reproduce the concurrent diurnal cycles of both CO_2 concentration and PBL depth quite well (Denning et al., 1996c). CO_2 concentration is elevated by more than 20 ppm in central Amazonia relative to concurrent measurements on the Atlantic coast of Brazil (S. Wofsy, personal communication), reflecting the pooling of respiration air over the forest as predicted by the model. The seasonal and diurnal cycles of the vertical profile of CO_2 concentration measured at tall towers in Wisconsin, North Carolina, and Hungary all show the patterns predicted by the CSU GCM: elevated concentrations near the ground, lower concentrations aloft, and a huge diurnal cycle that obscures low-level seasonality (Bakwin et al., 1995; Haszpra and Nagy, 1997).

The strong rectifier e ect simulated in the CSU GCM is di cult to reconcile with other ideas about the carbon cycle, however. To test the compatibility of the CO_2 rectifier with some widely used hypotheses about the carbon budget, a 5-year integration of the global model was performed in which surface exchange of CO_2 was prescribed according to the processes described in Table 1. Air–sea exchange of CO_2 was prescribed according to a recent compilation and interpolation of about 250 000 measurements of air–sea p_{CO_2} di erence (Takahashi et al., 1997), which includes seasonal variations. We prescribed the air–sea flux using the gas exchange coe cients of Wanninkhof (1992). Annual mean concentrations were extracted for each of 77 flask stations in the GlobalView network from the final year of the

Table 1. *Tracer calculations and boundary conditions used, and implied carbon budget*

Process	Data source	Annual emissions
fossil fuel emission	Marland et al. (1989)	6.0 GtC/yr
air–sea gas exchange	Takahashi et al. (1997)	−1.2
balanced terrestrial biosphere	SiB2 (Denning et al., 1996a)	0.0
net terrestrial sink	SLAVE (Friedlingstein et al., 1995)	S
deforestation flux	Houghton et al. (1987)	3.1–(6.0–1.2–S)

Assumes atmospheric increase of 3.1 GtC/yr.

simulation, and compared to the flask data (shown in Fig. 1a). Tropical deforestation has almost no influence on the annual mean CO_2 concentration measured at the flask stations (Denning, 1994), so this tracer was used to balance the global budget.

The seasonal and diurnal rectification of terrestrial CO_2 exchange simulated by SiB2 produced a meridional gradient of about 3 ppm at remote marine boundary layer sites in the annual mean, with much higher concentrations over continental sites (Fig. 1b). Note that the observed concentrations are also much higher at these sites. This may be the signal of the natural rectifier. When the influence of fossil fuel, deforestation, air–sea exchange, and the simulated rectifier are subtracted from the observations, the result is the influence of the net terrestrial carbon sink on the annual mean concentration at the flask network

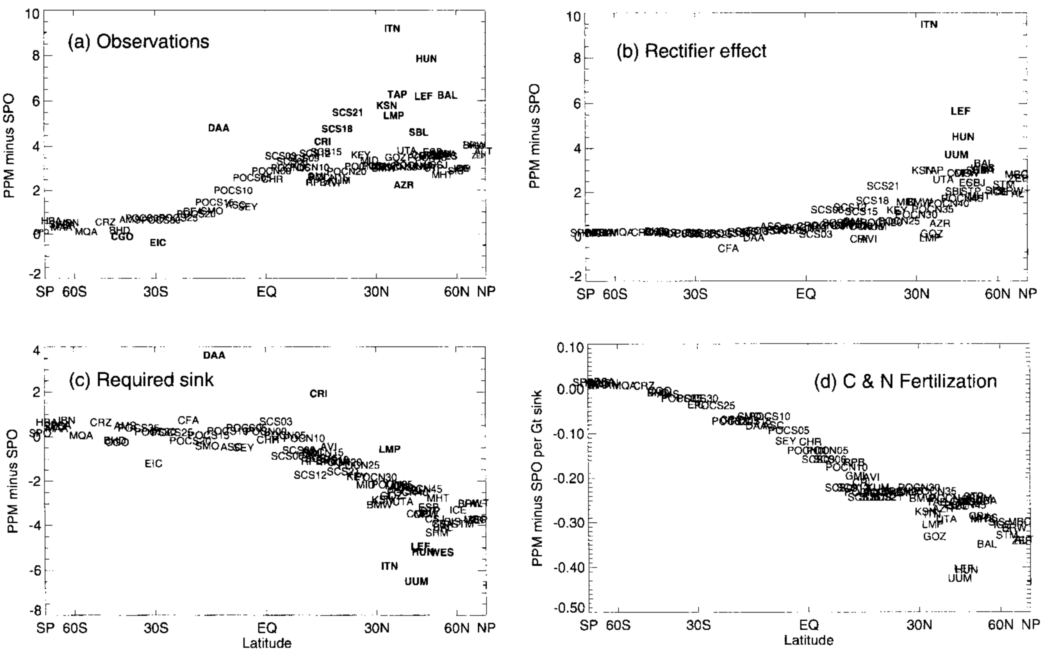

Fig. 1. Meridional profiles of annual mean CO_2 mole fraction at the locations of global view flask stations. The abscissae are scaled according to the sine of latitude, and the scales on the ordinate vary from panel to panel. The letter codes correspond to the station codes used for the stations in the globl view data. Panel (a) shows observational data. Panels (b) through (d) show results for the final year of a 5 year tracer simulation in the CSU GCM. (b) is the result of a balanced biosphere using SiB2; (c) is the di erence between the observations and the sum of fossil fuels + air–sea exchange + SiB2, indicating the required e ect of a sink which balances the carbon budget and matches the annual profile of the data; (d) shows the e ect of a 1 GtC/yr sink due to CO_2 fertilization and nitrogen deposition as simulated by SLAVE.

(Fig. 1c). This "fingerprint" indicates that the sink must be very strong at middle to high northern latitudes, and it must have a disproportionate influence at continental sites such as ITN, LEF, HUN, WES, and UUM.

Fig. 1d shows the e ect of a carbon sink due to the combined e ects of CO_2 fertilization and nitrogen deposition, which has a tropical maximum in the regions of very high NPP, and also a secondary maximum in midlatitudes associated with high rates of N-deposition and slow carbon turnover in wood and in soils. The plot shows the e ect of a sink with a globally integrated flux of 1 GtC/yr. The e ect on the annual mean concentration at each station can be scaled linearly, so that a 2 GtC/yr sink would produce exactly twice the concentration gradient, and so forth. Scaling the sink in this way also requires scaling the tropical deforestation flux to be consistent with the overall atmospheric increase of 3.1 GtC/yr (Table 1). This sink is not nearly strong enough in the middle latitudes to overcome the combined e ects of elevated CO_2 due to fossil fuel emissions and atmospheric rectification there.

Even adding a large sink of unknown mechanism in the temperate and/or boreal forests is incompatible with the budgets simulated here, because it requires a large tropical source to balance the global budget. Such a large source produces elevated concentrations at tropical sites which are again incompatible with the flask data, and is inconsistent with recent estimates of disturbance rates and tropical uptake (Skole and Tucker, 1993; Philips et al., 1998). The best fit of the results of the simulations presented here to the atmospheric observations is produced by arbitrarily multiplying the annual mean rectifier response by 0.5. This suggests that either (a) the simulated covariance between terrestrial CO_2 exchange and vertical transport by parameterized subgrid-scale motions in the CSU GCM is too strong; (b) there is some counteracting process in the atmosphere at larger scales that eliminates some or all of the e ect by the time airmasses are advected to the remote marine flask stations; or (c) there really is a large (order several GtC/yr) carbon sink in the northern middle to high latitudes that is not explained by current ideas of CO_2 and N fertilization, nor captured by careful analysis of sea-surface p_{CO_2} measurements.

In the future, it would be wise to study the rectifier mechanism in nature, and in models across a numbers of spatial scales. It seems clear that at the local level, the rectifier e ect is present and quite strong. If further research proves that this e ect scales to the zonal mean as simulated in the CSU GCM, it will force a significant reappraisal of current ideas of carbon sinks and their mechanisms.

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