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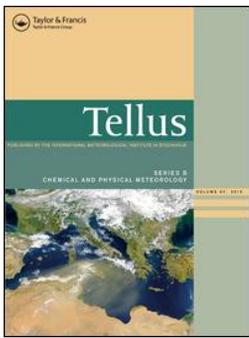
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KEYNOTE PERSPECTIVE

## Can a strong atmospheric CO<sub>2</sub> rectifier effect be reconciled with a “reasonable” carbon budget?

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### ABSTRACT

Atmospheric CO<sub>2</sub> 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<sub>2</sub> in the remote Northern Hemisphere due to this “rectification” of an annually balanced terrestrial carbon cycle. The covariance between CO<sub>2</sub> flux and vertical mixing, and the resulting vertical structure of CO<sub>2</sub> are generally consistent with field data at local scales, but it is difficult to reconcile such a strong rectifier signal with current ideas about the global carbon budget. A rectifier effect of 2.5 ppmv at northern flask sampling stations implies an unreasonably strong northern sink of atmospheric CO<sub>2</sub>, 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<sub>2</sub>, 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  $p_{\text{CO}_2}$ , and <sup>14</sup>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<sub>2</sub> 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" effect).

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 inefficient. This covariance leads to a time-mean vertical partition of  $\text{CO}_2$  in the atmosphere over active vegetation, with higher concentrations near the surface (reflecting respiration) and lower concentrations aloft (reflecting photosynthesis).

The global redistribution of  $\text{CO}_2$  due to the rectifier effect has been investigated by Denning et al. (1995, 1996a,b) using the Colorado State University (CSU) General Circulation Model (GCM). Simulated atmospheric  $\text{CO}_2$  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  $\text{CO}_2$  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  $\text{CO}_2$  exchange is mechanistically coupled to the surface energy budget, the depth of the PBL, and the subgrid-scale vertical transport of  $\text{CO}_2$  in the atmosphere. Covariance between annually balanced terrestrial  $\text{CO}_2$  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 effect simulated by the CSU GCM was among the strongest in a recent inter-comparison exercise involving 12 tracer transport models (TransCom, Law et al., 1996).

The rectifier effect simulated by the CSU GCM is consistent with atmospheric observations, at least at local to regional scales. The annual mean  $\text{CO}_2$  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  $\text{CO}_2$  concentration measured by continuous analyzers, and the CSU GCM is able to reproduce the concurrent diurnal cycles of both  $\text{CO}_2$  concentration and PBL depth quite well (Denning et al., 1996c).  $\text{CO}_2$  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  $\text{CO}_2$  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 effect simulated in the CSU GCM is difficult to reconcile with other ideas about the carbon cycle, however. To test the compatibility of the  $\text{CO}_2$  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  $\text{CO}_2$  was prescribed according to the processes described in Table 1. Air-sea exchange of  $\text{CO}_2$  was prescribed according to a recent compilation and interpolation of about 250 000 measurements of air-sea  $p_{\text{CO}_2}$  difference (Takahashi et al., 1997), which includes seasonal variations. We prescribed the air-sea flux using the gas exchange coefficients of Wanninkhof (1992). Annual mean concentrations were extracted for each of 77 flask stations in the GlobalView network from the final year of the



(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 effect of a carbon sink due to the combined effects of CO<sub>2</sub> 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 effect of a sink with a globally integrated flux of 1 GtC/yr. The effect 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 effects of elevated CO<sub>2</sub> 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 atmo-

spheric 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<sub>2</sub> 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 effect 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<sub>2</sub> and N fertilization, nor captured by careful analysis of sea-surface  $p_{\text{CO}_2}$  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 effect is present and quite strong. If further research proves that this effect 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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