CO_2 seasonality indicates origins of post-Pinatubo sink

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[1] An enhanced carbon sink of ~2PgC/yr was observed following the Mount Pinatubo eruption. In this study we used a biogeochemical model (CASA) linked to an atmospheric tracer model (MATCH) with interannually varying transport, to predict the atmospheric CO_2 response to various hypotheses for the enhanced sink. By comparing the modeled CO_2 growth rate, and seasonal minimum with observation we found that global Net Primary Production could not have increased following the eruption. The enhanced sink is explained by several land and ocean sink mechanisms acting in concert. *INDEX TERMS:* 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 1610 Global Change: Atmosphere (0315, 0325); 1615 Global Change: Biogeochemical processes (4805). **Citation:** Angert, A., S. Biraud, C. Bonfils, W. Buermann, and I. Fung (2004), CO_2 seasonality indicates origins of post-Pinatubo sink, *Geophys. Res. Lett.*, *31*, L11103, doi:10.1029/2004GL019760.

1. Introduction

[2] Sharp decline in the growth-rate of atmospheric CO_2 was observed in the early 1990's (http://www.cmdl.noaa.gov/ccgg/). In 1992, the year that followed the eruption of Mount Pinatubo (June, 1991), the growth rate was the lowest for the period 1983–2003 indicating an enhanced carbon sink of ~2PgC/yr [*Bousquet et al.*, 2000]. This enhanced sink has been linked to the climatic effects of the eruption. Global temperatures dropped by ~0.4°C in 1992. Superimposed over the global cooling, was additional cooling over most of North-America, and warming and cooling over different regions of Eurasia [*Hansen et al.*, 1996]. These climatic anomalies are believed to result from the injection of ~20 Mt of SO_2 aerosols into the stratosphere by the eruption, which affected the radiation budget and atmospheric circulation [*Hansen et al.*, 1992; *Stenchikov et al.*, 2002].

[3] Climatic anomalies affect the growth of atmospheric CO_2 concentrations mainly through the changes in the terrestrial biosphere sink strength [*Bousquet et al.*, 2000]. The terrestrial biosphere sink varies as a result of changes in the imbalance between net primary production (NPP), which removes CO_2 from the atmosphere, and heterotrophic respiration rate (R_h) which emits CO_2. The difference between these opposing fluxes is known as Net Ecosystem Production (NEP = Rh − NPP). Here we will discuss three hypotheses that aim to explain the decrease in the CO_2 growth rate. The first suggests that the cooling caused a decrease in R_h with a larger magnitude than the decrease in NPP [*Lucht et al.*, 2002; *Schimel et al.*, 1996]. A second hypothesis we suggest here is an extension of the first one. It states that changes in precipitation as well as temperature, caused by the atmospheric circulation changes, had an important effect on NEP after the eruption. A third hypothesis suggests that NPP did not decrease following the eruption, but actually increased as a result of increase in the fraction of diffuse radiation caused by the volcanic aerosols [*Gu et al.*, 2003; *Roderick et al.*, 2001]. Diffuse radiation is proposed to be more efficient in driving photosynthesis because of its improved penetration into plants canopies, and the effect of increase in its fraction was believed to dominate over the decrease in total radiation.

[4] In this study, we tested these three hypotheses by predicting the atmospheric CO_2 response to three modeled scenarios of the enhanced sink. In contrast to previous studies, we compared to observations both modeled changes in the atmospheric CO_2 growth-rate as well as changes in the de-trended CO_2 seasonal minimum, which is a measure of the growing season NEP.

2. Materials and Methods

[5] The carbon fluxes exchanged between the biosphere and the atmosphere are calculated using the CASA biogeochemical model [*Potter et al.*, 1993; *Randerson et al.*, 1996]. CASA estimates NPP from the product of light use efficiency (LUE), photosynthetic active radiation (PAR), and the fraction of this radiation absorbed by plants for photosynthesis (FPAR). FPAR is calculated from satellite derived vegetation index (NDVI). LUE is estimated from a specified maximum value of LUE (LUE_max) multiplied by two scalars that represent water stress and temperature stress. R_h is calculated using nine carbon reservoirs representing litter and soil carbon of varying composition, and is a product of the reservoir size, a minimum turnover-time for each reservoir, and temperature and soil-moisture scalars. Interannual temperature fields were taken from NCEP-NCAR reanalysis [*Kalnay et al.*, 1996], and NDVI interannual fields are from GIMMS version e (C. J. Tucker, submitted manuscript, 2004). Climatological radiation is after *Bishop and Rossow* [1991].

[6] In this study, we replaced the original CASA soil moisture module (driven by precipitation, radiation and air temperature) by the interannually varying NCEP-DOE reanalysis soil-moisture product for the depths of 0–10 cm, and 10–200 cm. This product is significantly improved relative to the previous product of the NCEP-NCAR reanalysis [*Kanamitsu et al.*, 2002]. We used the moisture scalar for photosynthesis of *Pan and Mahrt* [1987] (with the 10–200 cm layer) and the moisture scalar for respiration of *Kirschbaum* [1999] (with the 0–10 cm layer). The temperature scalars were the same as in the original CASA parameterization.

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[7] Three sink scenarios were explored: Scenario 1 and 2 use climatological radiation, fixed LUE_max, and interannually varying NDVI, temperature and soil moisture. In scenario 2 we assumed that water stress effect on NPP is fully captured by NDVI, and hence ignored the NPP water stress scalar. Ignoring this scalar can be justified, since plant roots may have access to water deeper than the top 200 cm used in the soil moisture stress calculation, and hence NPP (and NDVI) would be less sensitive to soil-moisture in the upper soil column than R_h. As a result, NEP (=R_h − NPP) in scenario 2 becomes more negative, i.e., a greater carbon sink, under drought conditions, compared to scenario 1. Scenario 3 is identical to 1, but includes the volcanic aerosols enhancement of NPP after *Roderick et al.* [2001]. That study estimated that the increase in diffuse radiation, caused by the volcanic aerosols, increased LUE by $\sim$10%, while total radiation decreased in $\sim$3%, leaving a net positive effect of 7%. We adjusted LUE and PAR according to this values for each latitude band the volcanic aerosols cloud reached, using the zonal temporal distribution of the volcanic aerosols from *Sato et al.* [1993].

[8] The CASA NEP R_h fluxes from the three scenarios, and fossil fuel fluxes from *Andres et al.* [1996] and *Marland et al.* [2003], all for the years 1989–1995, were used as inputs for the Model of Atmospheric Transport and Chemistry (MATCH) [*Rasch et al.*, 1997]. Parameterization for advection, convective transport, and boundary layer mixing used in MATCH are identical to those in the Community Atmospheric Model (CAM) and the Community Climate System Model (CCSM) [*Boville and Gent*, 1998]. MATCH, at T63 (1.8° × 1.8°) resolution and 28 vertical levels, was forced by NCEP-NCAR reanalysis interannual winds for the 1989–1995 period [*Kalnay et al.*, 1996].

[9] MATCH outputs are compared to the observed growth-rate of atmospheric CO_2 and the seasonal minimum. These parameters were calculated after *Thoning et al.* [1989] by using zonal bands from *GLOBALVIEW* [2003] reference marine boundary layer matrix [*Masarie and Tans*, 1995] and continuous measurements from the NOAA/CMDL observatories [*Conway et al.*, 1994] at Mauna Loa, and at the South Pole.

3. Results and Discussion

3.1. Did NPP Increased Following Pinatubo?

[10] The observations show an elevation in CO_2 seasonal minimum and a decrease in the CO_2 growth-rate following the Pinatubo eruption (Figures 1a, 1b). Scenario 3 was the only simulation that fully reproduced the north hemisphere extra-tropical enhanced sink in 1992 ($\sim$−1Pg/yr [*Bousquet et al.*, 2000]). However, the modeled enhancement of NPP at middle and high latitudes by the volcanic aerosols also caused a sharp lowering of the modeled seasonal CO_2 minimum, in contradiction to the observations (Figures 1b, 1d). As a result, we reject the third hypothesis (diffuse radiation enhanced NPP), as well as any other hypothesis (e.g., *Vukicevic et al.* [2001]) that suggests an increase in NPP at middle or high latitudes after the Pinatubo eruption. In addition, the modeled enhanced NPP in tropical regions, caused a decline in the south hemisphere CO_2 growth-rate that is much larger than the observed one (Figure 1c). This mismatch further indicates that NPP did not substantially increased in tropical regions either. We conclude that the effect of increased diffuse radiation on NPP after the eruption was probably only enough to compensate for the reduction in total radiation.

[11] Three additional arguments support our conclusion. First, tree ring studies show no evidence for increased NPP after past eruptions [*Krakauer and Randerson*, 2003]. Second, eddy-flux tower measurements at Harvard Forest showed that 1992 had the lowest annual photosynthetic rate for the period 1992–2000 [*Barford et al.*, 2001; *Law et al.*, 2002]. This low photosynthetic rate contradicts a recent study based on the same data set [*Gu et al.*, 2003], which modeled a photosynthesis enhancement in response to the Mount Pinatubo eruption. This contradiction may arise since the later study analyzed only cloudless conditions and assumed that ecosystem respiration depended on temperature only. Third, using monthly global radiation data at the top of the atmosphere and at the surface at 2.5° resolution [*Rossow and Zhang*, 1995], we calculated that the 1992 anomaly (weighted by NPP and relative to 1989–1990) in the product of LUE and total radiation was only 0.11% rather than 7%, indicating negligible effect on NPP. The LUE anomaly was calculated according to *Roderick et al.* [2001] equation 7 from the diffuse radiation anomaly, which was calculated after *Roderick et al.* [2001] equation 6.

[12] The finding of a small direct effect of aerosol loading on NPP has implication beyond that for volcanic aerosols. A trend of decrease in global surface radiation, resulting from increase in anthropogenic aerosols loading, has been observed in the past 50 years [*Stanhill and Cohen*, 2001]. In contrast, a trend of decrease in cloudiness in the tropics was modeled to cause an increase in NPP [*Nemani et al.*, 2003]. Our results suggest that in both cases NPP may not change significantly, since the effect of changes in total radiation will be approximately balanced by opposite changes in diffuse radiation. However, more research is needed do confirm this suggestion.

3.2. Alternate Explanation for the Post-Pinatubo Sink

[13] Scenario 1 failed to reproduce any post-Pinatubo enhanced sink (that is true also for higher temperature sensitivity – not shown), and thus the hypothesis associated with it (temperature effects alone) is rejected. In contrast to both Scenarios 1 and 3, the changes in the seasonal cycle minimum simulated by Scenario 2 for the 1985–1995 period are well correlated with observations (r = 0.6, Figures 1b, 1d), demonstrating the importance of the contrasting effects of soil moisture on NPP and R_h (cf. [*Lucht et al.*, 2002]). However, the growth rate anomalies are not well simulated by this scenario (r = 0.1, Figures 1a, 1b), and the predicted post-Pinatubo enhanced sink is smaller by $\sim$0.5 Pg/yr for each hemisphere than is required by the observations. Thus, the second hypothesis (temperature and moisture effects) also falls short of explaining the enhanced sink. Nevertheless, Scenario 2 may still simulate correctly terrestrial NEP, while the additional variance in CO_2 growth rate is likely contributed by variance in biomass burning and ocean-atmosphere flux, not taken into account in our model. Since both of these sources have different seasonality than middle and high latitudes NEP, negative anomalies in their fluxes during 1992–1993 would close the gap between the

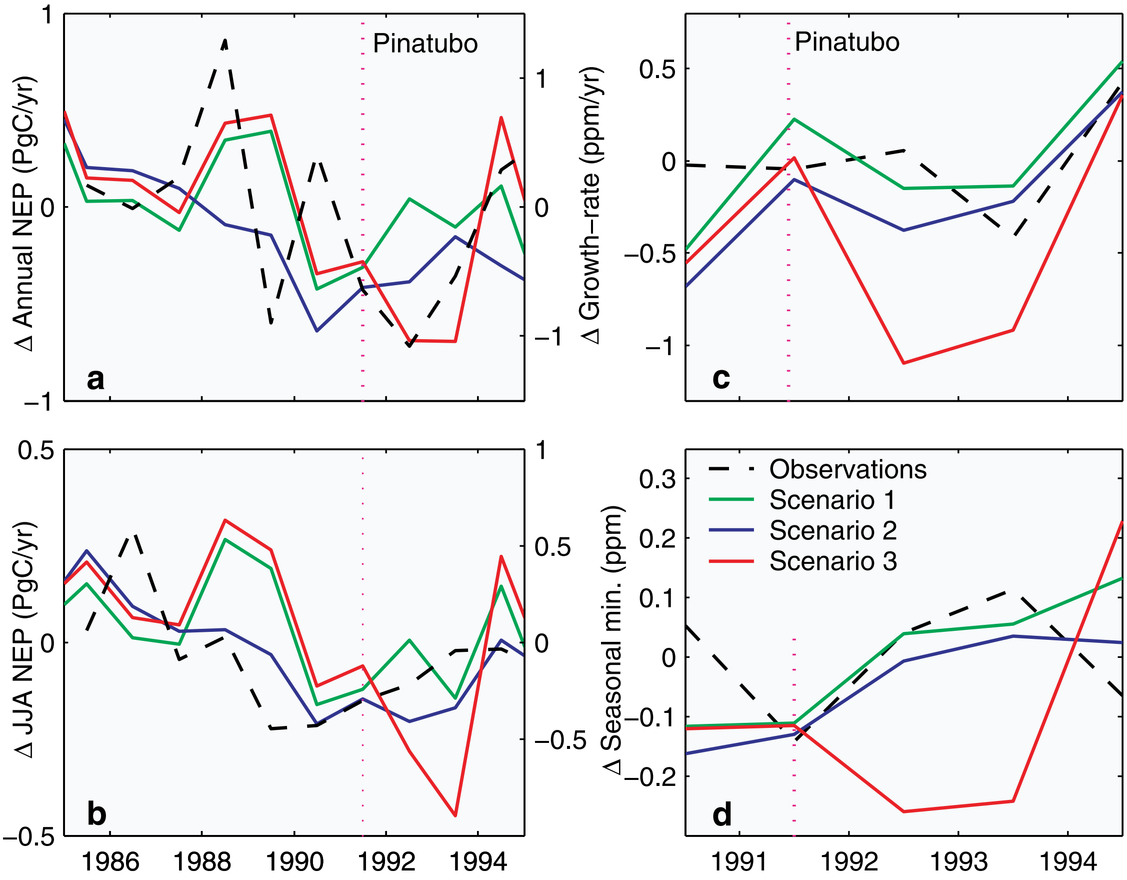

Figure 1. a. Modeled annual NEP (left scale) and observed mean CO_2 growth-rate (right scale) anomalies (20°N–90°N). b. Modeled June-July-August (JJA) de-trended NEP (left scale), and mean seasonal minimum (right scale) anomalies (20°N–90°N). c. Observed and modeled CO_2 growth-rate anomalies at the South Pole. d. Observed and modeled anomalies of the CO_2 seasonal minimum at Mauna-Loa.

simulated and observed growth rates without affecting the correctly simulated seasonal minimum.

[14] Indeed, a negative anomaly (~0.5 Pg/yr) in the flux from the equatorial Pacific, induced by the 1991–1994 El Niño event, was reported for these years, based on direct measurements [*Feely et al.*, 1999], ocean model [*Le Quere et al.*, 2000], and atmospheric ^{13}C based inversion studies [*Battle et al.*, 2000; *Rayner et al.*, 1999].

[15] Negative anomalies in the atmospheric growth-rate of CO, CH_4 and H_2 [*Langenfelds et al.*, 2002] in 1992–1993, and the longitudinal distribution of the enhanced sink [*Bousquet et al.*, 2000] may indicate a reduction in biomass burning during 1992–1993 (unusual for El Niño years) in Central America and northern South America, where large biomass burning flux anomalies have been reported lately (~0.5 Pg/yr) [*van der Werf et al.*, 2004]. Although the 1992 trace gases anomalies were also influenced by changes in atmospheric chemistry caused by Pinatubo cooling and SO_2 aerosols [*Bekki and Law*, 1997; *Dlugokencky et al.*, 1996; *Savarino et al.*, 2003], the centering of the CO anomaly around 20°N supports our suggestion of reduced biomass burning in that region.

[16] The decline in the CO_2 growth-rate in the early 1990s started before the Pinatubo eruption, and no similar decline was observed following the 1982 El Chichon eruption. Both observations corroborate our suggestion of important contribution from the ocean and reduced biomass burning to the growth-rate decline.

4. Conclusions

[17] By comparing observed and modeled changes in the atmospheric CO_2 growth-rate and its seasonal minimum, we conclude that NPP did not increase following the Mount Pinatubo eruption. The enhanced sink in 1992–1993 is explained as a unique combination of an enhanced ocean sink, a retarded hetrothrophic respiration driven by cooling and drying of the upper layers of the soil, and reduced biomass burning, acting in concert.

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