

GLOBAL CHANGE NEWSLETTER

GLOBAL
CHANGE

Issue No. 54
June, 2003

www.igbp.kva.se

The International Geosphere–Biosphere Programme (IGBP):

A scientific research programme for the study of global change

IGBP is sponsored by the International Council for Science (ICSU)

Human role in Earth System changes

Each of the science features presented in this edition of the Global Change NewsLetter address the role that humans play in the changes that are currently occurring in the Earth System, whether it be the hydrosphere, the biosphere, or in the modelling of these complex interactions. In our first article, Arjen Hoekstra introduces the novel concept of 'virtual water trade' and discusses how world trade of water-intensive products contributes to changes in regional water systems. The article by James Reynolds et al.

addresses the complexities of desertification, whether or not humans necessarily play a significant role in that process, and how they may or may not

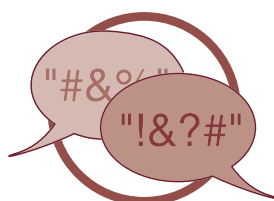
be adversely affected by land degradation. The third science feature, by Costanza et al. presents the GUMBO model, a complex model that incorporates human systems into integrated models of the Earth System.



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Discussion Forum

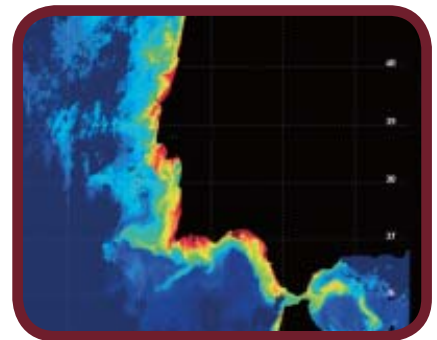
The effect of the Mt. Pinatubo eruption on global net ecosystem productivity—what caused the slowed growth of atmospheric CO₂ concentration?



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National Committees play an integral role in IGBP Science

In this series, we introduce a new subsection under Science Features: National Committee Science.



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Discussion Forum

After the Mt Pinatubo volcanic eruption in 1991, the rate of increase of atmospheric CO₂ was much lower than expected. The cause of this reduced rate of increase in CO₂ is the subject of much debate in the scientific community. Here we present two different viewpoints.

“Using the Lena-Potsdam-Jena (LPJ) dynamic vegetation model, Lucht et al. (2002) concluded that the increase in net ecosystem productivity following the eruption was not due to increase in CO₂ uptake by vegetation but due to a decrease in heterotrophic respiration associated with cooling.”

Decreased heterotrophic respiration reduced growth in atmospheric CO₂ concentration

The interannual variability in the rate of growth of atmospheric CO₂ is governed primarily by terrestrial ecosystem processes [1]. In the two years following the eruption of Mt. Pinatubo in June 1991, the rate of increase of atmospheric CO₂ concentration (~0.72 ppm/year) was about half the average rate (~1.43 ppm/year) from 1968-2001 (e.g. see [2] (Figure 1)). The reduction in the rate of increase of atmospheric CO₂ concentration following the eruption has been attributed to an increase in net ecosystem productivity of the terrestrial biosphere. This note addresses the debate about whether this increase in global net ecosystem productivity was caused by an increase in photosynthetic CO₂ uptake by vegetation (associated with an increase in the fraction of diffuse radiation due to increased volcanic aerosol concentration in the atmosphere) or by a decrease in ecosystem respiration (associated with a decrease in mean global annual temperature). Climate records show that the eruption was followed by a 0.5 °C decrease in mean global annual temperature [3], a 33% increase in diffuse radiation and a 3% reduction in global solar radiation[4].

The interannual variability in CO₂ uptake by the terrestrial biosphere is driven primarily by changes in precipitation and temperature. Incoming solar radiation shows very little interannual variability. However, the large fraction of incoming solar radiation which is diffuse relative to direct may significantly influence the CO₂ uptake by the vegetation. Measurements in forest ecosystems have shown that canopy CO₂

exchange is sensitive to the diffused component of incoming solar radiance [5]. Researchers have also shown that gross CO₂ uptake by plants is higher under diffused radiation (e.g., see [6,7]) because the photosynthetic rate of individual leaves saturates at high irradiance. Since individual leaves in low irradiance have a higher light-use efficiency (LUE, CO₂ uptake per unit radiation) the canopy as a whole is more efficient in low irradiance.

An increase in net ecosystem productivity following the Pinatubo eruption could have been due to an increase in CO₂ uptake by the terrestrial biosphere, a reduction in respiration from vegetation and soils, or both. An increase in CO₂ uptake by the terrestrial biosphere is likely because of an increase of 33% in diffuse radiation. Equally likely is the reduction in ecosystem respiration due to a decrease in mean global annual temperature of 0.5 °C.

Based on a LUE ecosystem model, Roderick et al. [6] estimate that the Mt. Pinatubo eruption may well have resulted in the removal of an extra 2.5 Pg of carbon from the atmosphere (~1.2 ppm) due to the stimulation of the terrestrial vegetation with more diffuse radiation. Baldocchi et al. [7] also suggest that a possible increase in photosynthesis due to increased diffuse radiation may have reduced the growth rate of atmospheric CO₂.

However, recent results from a modelling study [8] and northern hemisphere (NH) normalized difference

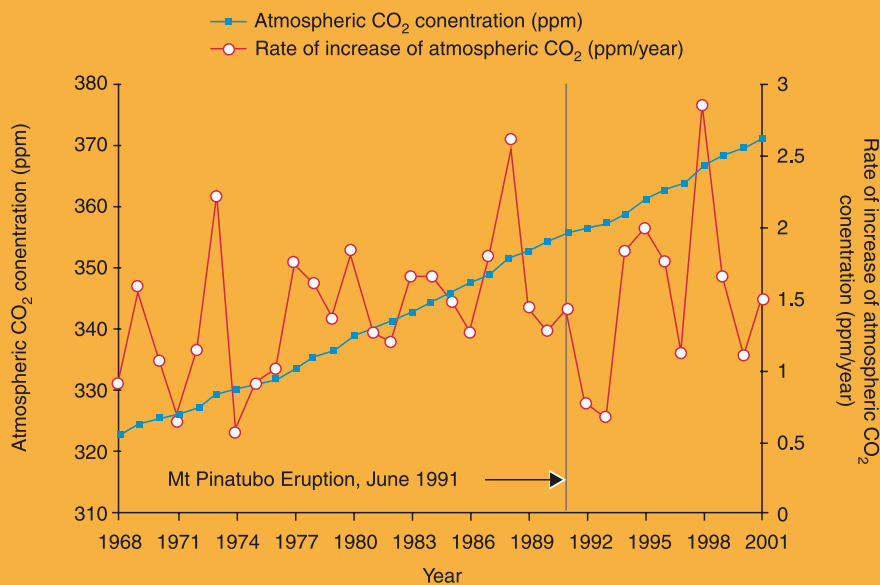


Figure 1. Atmospheric CO₂ concentration (ppm) from Mauna Loa (Keeling et al., 1995) and its rate of increase (ppm/year) for the 1968-2001 duration. The average rate of increase of atmospheric CO₂ concentration from 1968-2001 is ~1.43 ppm/year. The rate of CO₂ increase in the atmosphere dropped to ~0.72 ppm/year for two years following the Mt. Pinatubo eruption.

vegetation index (NDVI) data reported by Slayback et al. [9] suggest that CO₂ uptake by vegetation did not increase following the eruption. Using the Lena-Potsdam-Jena (LPJ) dynamic vegetation model, Lucht et al. [8] concluded that the increase in net ecosystem productivity following the eruption was not due to increase in CO₂ uptake by vegetation but due to a decrease in heterotrophic respiration associated with cooling. Lucht et al. [8] did not simulate an increase in vegetation carbon in years following the eruption, rather they simulated a decrease in NH boreal zone modelled leaf area index. The decrease in NH leaf area index simulated by Lucht et al. [8] is consistent with the clear drop in NDVI data reported by Slayback et al. [9]. The drop in observed NH NDVI data following the eruption indicates that the increase in diffuse radiation following the eruption did not help the vegetation to increase its carbon uptake. On the contrary, the carbon uptake by vegetation following the eruption most likely reduced due to cooler temperatures. Even if the diffused radiation did help the vegetation to photosynthesize more, it appears that the photosynthesis was even more constrained by cooler temperatures. Slayback et al. [9] show that the drop in NDVI is greater at higher latitudes. The boreal zone in Canada and Siberia experienced the largest drop in NDVI such that the calculated NDVI trend for these regions over the 1982-1999 duration is almost zero, despite the general NH greening trend [10].

There are caveats associated with both NDVI measurements and the LPJ modeling study. The change in observed NDVI characteristics in 1992 may be due to the incorrect aerosol correction or it may reflect actual changes in vegetation growth due to

global cooling [9]. The LPJ model does not take into account the diffuse and direct fractions of incoming radiation to model photosynthetic CO₂ uptake, rather it models CO₂ uptake as a function of total incoming radiation [11].

If confidence can be placed in NDVI data, then the overall decrease in NH NDVI following the Pinatubo eruption (despite an increase in diffuse radiation) suggests that temperature plays a primary role in affecting net CO₂ uptake rates by the terrestrial biosphere. Additionally, while the Mt. Pinatubo eruption was helpful in slowing the rate of growth of atmospheric CO₂ for two years, the NDVI data appear to show that the eruption had an adverse effect on NH foliage biomass and therefore possibly photosynthetic CO₂ uptake.

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“Here we concur that changes in the Earth’s carbon cycle due to a pulse of aerosols are not simple processes that can be explained by changes in a single variable. We proffer the explanation that regional differences in several climate forcings have conspired to produce a complex answer to this question. We also critique the evidence upon which Dr. Arora bases his conclusion.”

Mutliple ecosystem interactions lead to overall reduced growth in atmospheric CO₂ concentration

The terrestrial biosphere is a complex system, which by definition consists of intertwining parts that are subject to multiple feedbacks. The emergence of new properties, as one transcends scales, is one particular feature of complex systems. The ability to perform an experiment on a large and complex system like the terrestrial biosphere is difficult and rare, but in 1991 a unique pulse experiment was performed on the Earth’s climate system and biosphere-- Mt Pinatubo erupted, injecting huge quantities of dust and sulphate aerosols into the atmosphere. The dust and aerosols from this volcanic eruption veiled the Earth’s surface for several years and has provided us the opportunity to examine how the terrestrial carbon cycle is responding to coincident changes in the Earth’s surface radiation budget.

One of the notable feature of this ‘pulse-experiment’ was a 0.5 °C global cooling [1]. The second notable feature was a short-term reduction in the secular trend of growing atmospheric CO₂, as measured at the Mauna Loa monitoring station [2]. Because simultaneous reductions in the anthropogenic sources and increases in oceanic sinks were not recorded, it has been deduced that the net terrestrial biosphere sink increased [3]. One school of thought has concluded that the 0.5 °C global cooling reduced global respiration and leaf area index (e.g. [4]). Another group of investigators [5-7] have proposed that the veil of dust following the Mt Pinatubo eruption may have led to an increase in photosynthesis in some regions of the world. These researchers based this proposition on theoretical and experimental evidence that canopy photosynthesis is more efficient under diffuse light than under clear skies.

Dr. Arora addresses this issue in the Discussion Forum of this newsletter and concludes that the reduction in temperature explains the temporal change in atmospheric CO₂ post Pinatubo; his arguments are derived mostly on the work of Slaybeck et al. [8] and Lucht et al. [4] and their observed and modelled changes in NDVI.

Here we concur that changes in the Earth’s carbon cycle due to a pulse of aerosols are not simple processes that can be explained by changes in a single variable. We proffer the explanation that regional differences in several climate forcings have conspired to produce a complex answer to this question. We also critique the evidence upon which Dr. Arora bases his conclusion.

In order to understand how the terrestrial carbon cycle responds to environmental perturbations, one needs to decompose the net carbon flux into its constituent components and examine the forcing upon each component. By definition, net ecosystem exchange is the difference between gross photosynthesis (GPP) and ecosystem respiration (Reco). GPP is most sensitive to changes in sunlight, temperature, leaf area index and soil moisture. Reco is most sensitive to changes in temperature, soil moisture, size of the soil and plant carbon pools and disturbance. To understand how the terrestrial carbon cycle responded to the Mt. Pinatubo eruption we must assess how the volcanic eruption changed environmental forcings of the carbon cycle (light, temperature, soil moisture) in time and space. We must also assess if the relative sensitivity of GPP and Reco changed.

With regards to the issue of global cooling and reduced respiration we present the data on the global temperature anomaly after the Mt. Pinatubo eruption (Figure 1). Upon inspection, one sees that major cooling was concentrated in the middle of North America and Siberia, little or no cooling occurred over the tropics and warming over west Europe. Since there are regional differences in cooling and warming, so there will be regions with decreased respiration (e.g. the boreal forest region) and regions with increased respiration. While global respiration might have been reduced, since global mean temperature decreased after the Mt. Pinatubo eruption, the question is: could this factor alone explain the observed large drop in the growth rate of

atmospheric CO₂? Gu et al. [7] listed several lines of evidence that suggested a no to this question:

“First, long-term records of CO₂ and temperature generally show that there is a time lag between fluctuations in CO₂ and those in temperature [2]. However, the response of atmospheric CO₂ after the eruption appears to be rapid. Second, the magnitude of the global surface cooling (up to 0.5°C in mid-1992) is within the range of annual temperature swings since the 1950s [1]. Previous cooling of this magnitude did not cause a drop in the atmospheric CO₂ growth rate as large as the one observed after the eruption. Third, modelling of the effects of the eruption on atmospheric CO₂ using a coupled general circulation climate-carbon cycle model showed that the cooling stops short of fully accounting for the observed atmospheric CO₂ anomaly [3].”

In using cooling to explain the post-Pinatubo variations of atmospheric CO₂, one must also note that cooling can potentially reduce annual GPP by shortening the length of the growing season and by decreasing leaf area index. Given these considerations, we believe other mechanisms, in conjunction with the cooling scenario, are needed to account for the atmospheric carbon budget. To support this view further, we cite new evidence from a recently published global inversion modelling study of interannual variability of CO₂ exchange, by Rodenbeck et al. [9]. They state:

“...according to our estimates the distribution of anomalous carbon uptake regions across the globe is markedly uneven. The regions that are mainly responsible for enhanced carbon uptake are the Amazon basin and the East of North America. For the rest of the world, flux anomalies are small. Comparison of these flux anomalies with the climate anomalies indicates that increased carbon uptake tends to coincide with increased precipitation, although the comparison is not entirely conclusive.”

The regional enhancement of photosynthesis in eastern North America, deduced by the data inversion work of Rodenbeck et al. [9], is consistent with our results deduced from direct carbon flux measurements [7].

With regards to Arora’s dismissal of the diffuse radiation effects, we raise several caveats. First, his arguments were based on the interpretation of NDVI data using the Lund-Potsdam-Jena (LPJ) biogeochemical model. The LPJ model has many strengths but it does not consider diffuse light effects on photosynthesis. Secondly, temperature response functions of carbon exchange of ecosystems are not static. Respiration rates of most ecosystems will acclimate and shift with long-term changes in temperature [10]; at present most biogeochemical models do not account for this effect. Thirdly, changes in NDVI are used to infer changes in leaf area index and GPP. NDVI based models only infer GPP, they do not measure it directly like we did with the eddy covariance technique [7]. Finally, there still remains the question of imperfect aerosol corrections to NDVI after the Pinatubo eruption [8].

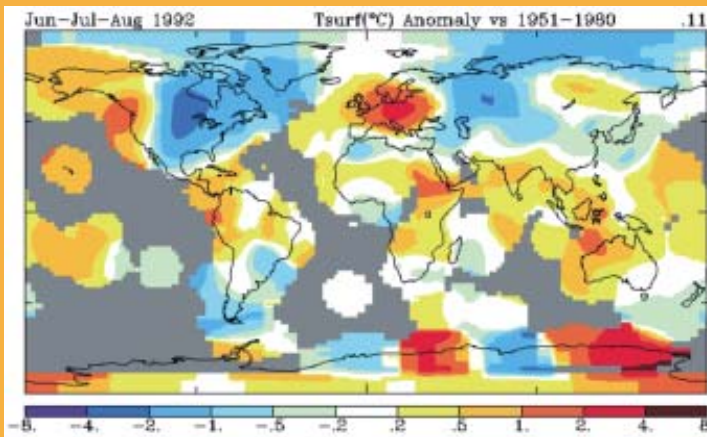


Figure 1. Global temperature anomaly after the Mt Pinatubo eruption. Data are generated from NASA GISS. <http://www.giss.nasa.gov/data/update/gistemp/maps/>; data source Peterson, T.C., and R.S. Vose 1997. An overview of the Global Historical Climatology Network temperature database. Bull. Amer. Meteorol. Soc. 78: 2837-2849.

In closing we note that a growing number of FLUXNET field sites are installing diffuse radiation sensors at their field sites. We now anticipate the next volcanic eruption and are ready to observe directly how carbon fluxes at points across the globe may respond to such an event.

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