
Biosphere-Atmosphere Interaction

Award Number: NAG5-9514

**Principal Investigator:**

Inez Fung  
Space Sciences Laboratory  
University of California, Berkeley  
Berkeley CA 94720-4767  
Phone: (510) 643 9367; (510) 643 8336  
Fax: (510) 643 9377  
Email: inez@atmos.berkeley.edu

**Technical Officer:**

Dr. Diane Wickland  
Code YS  
NASA Headquarters  
Washington DC 20546  
(202) 358 0245  
(202) 358-2771  
dwickland@hq.nasa.gov

**Co-Investigators:**

J.G. Collatz  
NASA Goddard Space Flight Center  
A.S. Denning  
Colorado State University  
D.A. Randall  
Colorado State University  
C.J. Tucker  
Goddard Space Flight Center
The work funded by our previous EOS-IDS project “Biosphere-Atmosphere Interactions” has been central to demonstrate that a terrestrial carbon sink is necessary to balance the contemporary carbon budget. Nevertheless the mechanisms and biogeochemical signatures of the terrestrial carbon sink remain elusive. Our proposed work focuses on the following questions:

What are the biophysical and signatures, in addition to NDVI and other biogeochemical signatures, of the terrestrial carbon sink? Are the biophysical and climate signatures detectable by satellite? If so, how?

For logistic reasons, the Progress Reports from the co-investigators are appended separately at the end of this report. An overall summary of our progress, status, and future work is presented below.

**Model and Data Development:**

We have made tremendous progress in the area of model and data development:

(1) The NDVI time series is now corrected for solar zenith angle effects, intra- and inter-satellite sensor calibration, and volcanic aerosol effects. This now permits robust analysis of NDVI trends. See Tucker Report.

(2) MODIS spectral bands and the Terra orbit have been successfully incorporated into the CSU GCM. The first attempt to simulate the top-of-atmosphere NDVI (with surface boundary condition prescribed from the observed NDVI) is successful overall. In general, the GCM simulation of atmospheric scattering and absorption is consistent with what is expected. The simulated NDVI points to area where surface boundary conditions e.g. soil albedo in the Sahara, need to be re-examined. Full details are found in the appended progress report from Randall.

(3) Following the implementation of carbon-13 into the ocean carbon-GCM (Fung, IDS Progress Report 2000), carbon-13 has now been implemented into SiB2. Full details are found in the appended progress report from Denning.

(4) The biophysics model SiB2 and the biogeochemistry model CASA have been modified to include the differential photosynthesis response between sun and shade leaves. This model improvement will permit our inclusion of the effects of atmospheric aerosols, especially those from volcanic eruptions, on terrestrial carbon exchange. Full details are found in the appended progress report from Collatz.

**Modeling and Analysis:**

(1) We have re-examined interannual variability contained in the atmospheric CO2 data from 1976-1994 using empirical orthogonal function/principal components analysis (EOF/PC), and have found a previously-unrecognized varying phase relationship between CO2 growth rate and the southern oscillation index (SOI). Prior to 1988/1990, El-Nino’s (negative SOI) were associated with anomalously high CO2 growth rates.
Post 1990, the phase was opposite. This has tremendous implications for understanding and predicting the response of CO2 fluxes to different climate regimes. See Fung Report.

(2) The NDVI time series data poleward of 35N for the period 1982-1999 have been analyzed to yield generally increasing trends for the period and early growing season. Noteworthy also is the decrease in NDVI following the El Chichon and Pinatubo volcanic eruptions. These re-affirm the temperature sensitivity of photosynthesis for temperate and boreal ecosystems. See Tucker Report.

(3) Climate variability on terrestrial CO2 fluxes were simulated using SiB2, the NDVI time series, and ECMWF reanalysis weather data for 1983-1993. Not unexpectedly, there is strong correlation between CO2 fluxes poleward of 35N and the arctic oscillation (AO). The calculations quantified the dominance of different climate controls for different ecosystems. For example, summer respiration responds more vigorously than spring GPP to climate perturbations during the positive phase of the AO (stronger westerly winds), so that NEE is positive. See Denning Report.

(4) SiB2 simulations of C-13 discrimination by C-3 plants shows that, globally, the degree of discrimination is linearly proportional to the net annual assimilation. This is counter to the generally constant discrimination used in inversions of the carbon cycle. Analysis of the results suggests that different regions have different discrimination/assimilation relationships, and that shifts in the C3/C4 ratio of net assimilation are the primary control on interannual variations in terrestrial discrimination on the global scale. See Denning Report.

In summary, each co-investigator has focused on a different aspect of the interannual variations in climate, ecosystem functioning, and CO2 exchange. The model development and analysis set the stage for our comprehensive analysis of carbon sinks, their response to climate variability, and their atmospheric signatures.
Varying relationship between CO\textsubscript{2} growth rate and ENSO

We have carried out an empirical orthogonal function/principal components analysis of the CO\textsubscript{2} data from a global observational network, the “Globalview CO\textsubscript{2} data”. The “Globalview” data is a compilation of measurements from ~80 sites worldwide, with the stations located mainly at remote marine sites. The EOF/PC analysis identifies in the data coherent spatial patterns of variability (EOF\textsubscript{k}(stn)) associated with the dominant patterns in temporal variability (PC\textsubscript{k}(t)), with the EOF/PC’s ordered by their contribution to the variance in the data.

\[ g(stn,t) = \frac{\partial}{\partial t} \text{CO}_2(stn,t) = \sum_k PC_k(t) \times EOF_k(stn) \]

In our analysis, two statistically-significant modes of interannual variability emerge. The leading mode suggests interannual modulations in CO\textsubscript{2} sources/sinks, while the next-to-leading mode may represent a dipolar land-ocean response. The PCs are compared to several climate indices using simple linear regression. The gravest PC reflects ENSO-like variability, although the phase relationship appears to change around 1990. It is shown, however, that this PC exhibits a statistically-significant, stationary phase relative to an index of the Pacific Decadal Oscillation (PDO) throughout the sampling period. The next-to-leading PC also bears some relationship to PDO indicators. These relationships intimate that, while ENSO may play a role in interannual CO\textsubscript{2} variability, the ENSO-growth rate relationship is not stationary, and other modes of interannual variability may influence year-to-year changes in CO\textsubscript{2}.

Figure 1a. Spatial distribution of EOF\textsubscript{1} and EOF\textsubscript{2} of the growth rate in atmospheric CO\textsubscript{2}. The growth rates were computed using 89 stations of the NOAA Globalview CO\textsubscript{2} data set (top panels) as well as with the 17 stations with long observational records (bottom panels).
Climate signatures of terrestrial carbon sinks

A major goal of our work is to seek possible physical climate signatures of terrestrial carbon sink. There are many mechanisms that together contribute to a terrestrial carbon sink. We can generalize these mechanisms to those that increase aboveground biomass via enhanced photosynthesis (e.g. CO2 and/or N fertilization, recovery from past natural or anthropogenic disturbances, encroachment of invasive species) and those that increase belowground biomass by increasing the residence time of carbon soils (as a result of direct management or indirect response to climate and other perturbations). The processes that increase aboveground biomass will have an atmospheric signature because of the coupling of the carbon-water-energy cycles.

To pave the groundwork for analyzing the possible physical climate signature of the carbon sink, we have begun an exploration of the relationship between gross primary productivity (GPP) and a variety of physical climate parameters to figure out the cleanest physical climate signal(s) of carbon sink. We are using output from the 100+years of the control run of the NCAR Community Climate System Model (CCSM) as the basis for our exploration. The CCSM is a coupled atmosphere-land-ocean-ice global climate model, where the GPP parameterization (Bonan et al.) follows the stomatal conductance formulation of Sellers et al. (1996). A preliminary result is that variations in GPP are correlated with variations in diurnal temperature range. This finding was hypothesized previously by our team (Collatz et al., Geophys. Res. Lett. 2000) and confirmed in analysis of the daily maximum temperature in the US (Durre et al., J Climate, 2000). Our 100 year simulation is long enough, so that we can thus establish the statistical significance (i.e. noise level) of the relationship globally, and form the foundation for detecting change.

Publications:


Tucker et al. at GSFC have made progress on two important fronts:

(1) a better-behaved NDVI data set which hasn't had the life beaten out of it by excessive parental discipline; is largely free of solar zenith angle effects (thanks to Jorge Pinzon, a former student of Susan Ustin, UC Davis); is free of within, between, and among satellite NDVI trends; and has been corrected (full radiative transfer-based stratospheric aerosol correction for both El Chichon and Mt. Pinatubo volcanic periods); and

(2) The aerosol optical thickness data for the El Chichon and Mt. Pinatubo volcanic periods have also been used to calculate total downwelling PAR at the bottom of the stratosphere and its direct and diffuse fractions. Until now we have refrained from publishing any papers on global NDVI trends, or related NPP studies, because we had a residual solar zenith angle component tropically and sub-tropically. Our previous 1981-2000 data set contains a very small residual solar zenith angle components north or south of 30 degrees latitude, so this wasn't a problem for the various papers published so far (i.e., CU, BU, GSFC).

A summary of a paper in press at the Int. J. Biometeorology (a special edition on phenology) follows:
Higher Northern Latitude NDVI and Growing Season Trends from 1982 to 1999
Compton J. Tucker, Daniel A. Slayback, Jorge E. Pinzon, Sietse O. Los, Ranga B. Myneni, & Malinda G. Taylor

Abstract: Normalized difference vegetation index data from the polar-orbiting National Oceanic and Atmospheric Administration meteorological satellites from 1982 to 1999 show significant variations in photosynthetic activity and growing season length at latitudes > 35 N. Two distinct periods of increasing plant growth were apparent: 1982 to 1991 and 1992 to 1999, separated by a reduction from 1991 to 1992 associated with global cooling resulting from the volcanic eruption of Mt. Pinatubo in June 1991. Average May to September normalized difference vegetation index from 45 to 75 N increased +9% from 1982 to 1991, decreased -5% from 1991 to 1992, and increased +8% from 1992 to 1999. Variations in normalized difference vegetation index were associated with variations in the start of the growing season of -5.6, +3.9, and -1.7 days, respectively, for the three time periods. Our results support surface temperature increases within the same time period at higher northern latitudes where temperature limits plant growth.
Impacts of diffuse light on Canopy Photosynthesis and NPP

The fraction of solar radiation reaching the surface that is diffuse depends on a number of conditions including sun angle, cloudiness, atmospheric humidity and aerosol loading. There are several reasons that motivate our investigations of the impacts of diffuse light on primary productivity:

- Shade leaves may contribute significantly to canopy photosynthesis (and transpiration). As incident diffuse light increases the intensity of light on the shaded portion of the canopy may also increase. Measurements of the response of NEE to PAR, especially in high latitude forests, show higher light use efficiencies on cloudy versus sunny days (Baldocchi et al, Goulden et al, Fan et al, Hollinger et al)
- In the Sellers et al canopy integration approach all leaves in the canopy light saturate at the same level of incident PAR at the top of the canopy. One characteristic of this model is a somewhat unrealistic "square wave" response over the course of the day. Will a sun/shade parameterization remedy this?
- Analysis of multi-layered canopy models show that rather simple approaches that specify the canopy as two leaves, one sun and one shade, produce results that compare well with more complex models.
- It has been proposed that factors such as cloudiness and aerosol loading could have significant impacts on interannual variability and trends in the terrestrial carbon sink through alterations in the partitioning of solar radiation into diffuse and direct components. Roderick et al 2001 have suggested that the extra diffuse radiation caused by Mt. Pinatubo aerosols could have increased productivity by an extra 1-2.5 GtC/yr accounting at least in part for the low atmospheric CO2 growth rate after the eruption.

We are addressing these issues on two fronts. First, we are testing various parameterizations within SiB2 model to account for sun and shade leaf responses in canopies. This new version of SiB2 is used to study the sensitivity of canopy photosynthesis to diffuse light under different conditions. Second, using CASA modified to account for diffuse light responses we are examining the potential sensitivity of NPP to observed variations in stratospheric aerosols during the '80s and '90s.

SiB2 simulations that include sun/shade parameterization provide insights that can be usefully applied to CASA type global NPP models. Figure 1 below illustrates the behavior of canopy photosynthesis as diffuse radiation varies. As diffuse fraction increases the total amount of absorbed PAR decreases while light use efficiency, $\varepsilon$, increases. This results in a maximum daily canopy photosynthesis at intermediate levels of diffuse fraction. The maximum is fairly broad and canopy photosynthesis is not very sensitive until APAR becomes low at high diffuse fractions.
Preliminary analysis of global surface solar radiation data suggests that productive vegetation is largely operating at diffuse fractions near the maximum and further increases in diffuse fraction caused by such things as increased cloudiness would tend to reduce productivity as a result of associated reductions in APAR. A possible exception is the influence of stratospheric volcanic aerosols. For instance, the eruption of Mt. Pinatubo in the early '90's apparently increased diffuse radiation by around 20% while decreasing total incident radiation by only ~3%. Vermote and Tucker have derived a global aerosol product for the '80s and '90s from AVHRR that quantifies the impacts of El Chichon and Mt. Pinatubo eruptions on diffuse and total PAR. Using modified versions of SiB2 and CASA we plan to compare the potential impacts of these eruption events with other forcing variability such as temperature, precipitation and NDVI. Preliminary analysis using SiB2 suggests that sensitivity to increased diffuse fraction (with no change in total radiation) depends in part on the diffuse fraction and LAI. For instance, photosynthesis in canopies with low LAI and/or operating at high diffuse fractions to begin with, is not stimulated much by increased diffuse light.
Progress report on

Simulation of MODIS Radiances with a GCM

David Randall

Colorado State University

April 2002
1. Objectives and methods

NASA’s MODIS instrument, flying on the Terra platform, is providing radiance data with high spectral resolution. Our primary goal is to compare these data with simulated radiances generated by a general circulation model (GCM), in order to constrain the land-surface parameterization used in the GCM. The simulated radiances will be made available for use by the EOS IDS teams led by Inez Fung, Chris Field, and Jim Randerson.

The approach is to compute the radiances using a new radiative transfer code developed by Graeme Stephens and colleagues (Stephens et al., 2001; Gabriel et al., 2001). The radiances are computed instantaneously using the simulated positions of the sun and the Terra platform. In order to do this we had to simulate Terra’s orbit.

For simplicity, we ignore any simulated clouds, so all radiances are computed for clear-sky conditions. This approach is satisfactory because the observed radiances will be used only for clear-sky conditions anyway.

The simulated results depend most strongly on the optical properties of the Earth’s surface. For land points, these are determined by combining the optical properties of the soil, the optical properties of the vegetation, and the vegetation cover and the prescribed seasonally varying state of the vegetation (“greenness”). The greenness and vegetation cover are, in turn, influenced by the observed normalized difference vegetation index (NDVI), which is prescribed based on satellite data. We can compute a simulated NDVI that depends on the observed NDVI as shown in Fig. 1. It should be clear from Fig. 1 that there is no guarantee whatsoever that the simulated NDVI will agree well with the prescribed observed NDVI. The degree of agreement contains information about the simulated optical properties of the land surface, the radiative transfer code, and the optical properties of the atmosphere.

2. Results to date

We now have the capability to compute radiances from the GCM results. The results shown below were obtained by outputting the relevant data from the GCM, and computing the radiances offline. In the future we will add the capability to compute the radiances inside the GCM as it runs; this is discussed in the next section.

As a test of the method, we have computed the simulated NDVI following the logic outlined in Fig. 1. The simulated NDVI calculations were based on radiances for 645 nm (the middle of MODIS channel 1) and 868 nm (a little offset from the middle of MODIS channel 2). At these two wavelengths the atmosphere has very little gaseous absorption of radiation, so that Rayleigh scattering dominates the atmospheric effects. The results, shown in Fig. 2, were produced by Laura Fowler and Norman Wood, with assistance from Donald Dazlich, all of of Colorado State University. Prof. Graeme Stephens is the supervisor of Norman Wood, and has been very cooperative in this effort.
The top panel of Fig. 2 shows the observed NDVI for January. This is used to set up the boundary conditions for the GCM, including the surface albedos. The center panel shows the corresponding distribution of the NDVI as computed for one particular January day, using the simulated radiances produced by the GCM, as seen by the simulated Terra platform. The grey regions are either in dark or else not sampled during the simulated day used here. The simulated and observed patterns of the NDVI are generally similar, as expected. Nevertheless, there are some notable discrepancies. Over the Sahara, for example, the observed NDVI is on the order of 0.1, while the simulated values are around 0.2. We are currently investigating the sources of these discrepancies, keeping in mind the logic shown in Fig. 1. The excessive simulated NDVI for the Sahara is quite possibly due to errors in the optical properties of the soil. The “flaming pink” (small positive) values seen at some ocean points in the simulated NDVI are of course spurious and should be ignored.

The lower panel shows the corresponding simulated results computed for a hypothetical planet with no atmosphere. Comparison with the middle panel indicates the effects of the simulated Rayleigh scattering and absorption in the relevant bands of the radiative transfer code.
Figure 2: The top panel shows the observed NDVI for January. This is used to set up the boundary conditions for the GCM, including the surface albedos. The center panel shows the corresponding distribution of the NDVI as computed for one particular January day, using the simulated radiances produced by the GCM, as seen by the simulated Terra platform. The grey regions are either in dark (especially near the North Pole) or not sampled by Terra on the simulated day in question. The lower panel shows the corresponding simulated results computed for a hypothetical planet with no atmosphere.
3. What remains to be done, and a time-table

Additional work is needed before our radiance diagnostic can be considered complete. Table 1 summarizes what is left to do.

**Table 1: Tasks still to be completed, comments on each task as needed, and a timetable for the completion of each task.**

<table>
<thead>
<tr>
<th>Task</th>
<th>Comments</th>
<th>Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add the radiance calculation to the GCM so that it can be done</td>
<td>1. Terra orbit calculation should be refined.</td>
<td>June 2002</td>
</tr>
<tr>
<td>“on the fly”</td>
<td>2. Need to input channel-matched optical properties of the Earth’s surface (see next task)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Need to output diagnostics</td>
<td></td>
</tr>
<tr>
<td>Create a set of prescribed optical properties for the Earth’s surface that is matched to the MODIS channels</td>
<td>1. Input from Greg Asner is needed here.</td>
<td>July 2002</td>
</tr>
<tr>
<td></td>
<td>2. We will have to add these optical properties to the GCM, as input files.</td>
<td></td>
</tr>
<tr>
<td>Add the remaining MODIS channels to the radiance calculation</td>
<td>Need to devise tests to evaluate the results of this step</td>
<td>August 2002</td>
</tr>
</tbody>
</table>

Once these tasks have been completed, we need to make model results available for use by our colleagues. As a first step, we can perform a simulation driven by the observed sea-surface temperatures since the Terra launch. The observed NDVI can also be used if this can be made available by Jim Tucker’s group.

We need to make a plan for how additional simulation results can be made available to the team. This topic should be discussed by the various parties involved.

We do not plan to carry out any additional radiance diagnostic work, after the current project is completed, later in 2002. We have been carrying out this “service job” in order to enable the research of our EOS colleagues, but we do not plan or propose to continue in a service role. Any additional efforts in support of the Biosphere-Atmosphere Interactions Project will be centered around our own research objectives, notably dealing with improved simulations of the boundary layer and tracer transports.
References


The effect of climate on inter-annual variability of terrestrial CO₂ fluxes

We evaluated how climate influences inter-annual variability in simulated fluxes of CO₂ using the Simple Biosphere Model, Version 2 (SiB2) for 1983 to 1993 on a global, 1x1 degree latitude/longitude grid. We used the FASIR 3.04b NDVI dataset and ECMWF Reanalysis weather data. Overall global variability compares well in magnitude with interannual variations in CO₂ growth rate, but the timing of the variations is not well captured by the model. Diagnostics were developed to quantify the influence of temperature, soil moisture, relative humidity, incident light, LAI/FPAR and soil carbon (through the R’ 1-year carbon residence time). These were analyzed in terms of their contribution to the variance of the 132-month anomaly timeseries of simulated GPP, Resp, and NEE.

Globally, soil moisture accounts for 26% of NEE variability; followed by temperature (24%), soil carbon (20%), and Leaf Area Index (19%). Drought stress dominates the regions of highly variable NEE in South America (Figure 1e). The stress may result in part from probably inaccurate specification of interannual precipitation anomalies in the ECMWF reanalysis. LAI dominates variability in low-LAI environments such as deserts and tundra, but low productivity of these regions limits their global influence. LAI has little influence in tropical forests, presumably due to the smoothing effects of cloud interpolation on the NDVI data. PAR has the greatest influence in tropical forests because persistent cloud cover reduces the light available for plant growth. Humidity and canopy temperature have their greatest influence in northern high latitudes, but their global influence is small.

The annual total NEE above 30 degrees latitude shows a strong influence of the Arctic Oscillation (AO). NEE, GPP, and respiration correlate with an AO index based on the first principle mode of sea level pressure anomalies. The NDVI and ECMWF data show similar spatial patterns and correlations. However, 11 years is not long enough to firmly relate NEE variability and the AO due to strong cancellation between GPP and respiration anomalies.

The displacement of warm or cold air with the AO explains why soil temperature control of respiration so strongly influences NEE variability at high latitudes. The AO is characterized by anomalously weak or strong zonal wind centered on 45 degrees. Positive AO polarity has stronger westerly wind and advects warm, oceanic air masses to continental interiors, creating positive temperature anomalies. Negative AO polarity has weaker westerly wind that cannot advect warm air over the continents, producing cold temperature anomalies. While both increase or decrease with temperature, respiration responds more vigorously than GPP. For positive AO polarity, summer respiration exceeds spring GPP, so the annual NEE is positive.
Figure 1: The Influence of each climate factor on NEE inter-annual variability is based on relative magnitudes of standard deviation for each influence variable. Temperature and precipitation are separated into influences on respiration and GPP. A value of 0 implies no influence, a value of 1 implies total control.
Interannual Variability of Stable Carbon Isotope Fractionation in SiB2

Annual rates of assimilation and assimilation-weighted discrimination, referred to hereafter simply as discrimination, are calculated both globally and for each 1°X1° grid cell (Fig. 1). The linear correlation coefficient for relationships between various parameters including annual net assimilation, discrimination, precipitation and photosynthetically active radiation (PAR), is determined for each grid cell in order to look for systematic variations and to suggest cause and effect relationships. For 11 data points and a significance level of 0.05, an r-value of greater than 0.602 or less than –0.602 is considered statistically significant.

**Figure 3.** Correlation between net assimilation and carbon isotope discrimination by grid cell for 1983 through 1993. Only grid cells with a statistically significant correlation are shown. Discrimination against 13C is described here as positive.

A cross plot of assimilation versus discrimination shows that there is positive correlation between these two factors (R² = 0.64; Fig. 4). In other words, on a global scale an increase in annual assimilation is accompanied by an increase in discrimination. However, the positive correlation globally is hard to reconcile with the spatial distribution of r coefficients, which shows that there is a negative correlation in tropical forests and a positive correlation in less productive desert and water-limited regions. One would assume that the relationship between assimilation and discrimination observed in highly productive areas would dominate the global signal. However, the other factor that must be taken into account is the potential for changes in the relative contributions of C3 (discrimination ~ 18‰) versus C4 (discrimination ~ 18‰) plants to total photosynthetic rates.
Figure 4. Relationship between global net assimilation and carbon isotope discrimination. Discrimination is described here as positive.

C4 plants account for approximately 20% of total terrestrial net assimilation. Regions dominated by C4 plants tend to be warm and dry, and subject to seasonal and interannual variations in water availability, which in turn can lead to fluctuations in rates of net assimilation on the same timescales. In this simulation, there are substantial spatial shifts in rates of photosynthesis from one year to the next. For example, in South America from 1986 to 1988, photosynthetic rates increased in the C3-dominated western ‘Amazon’ basin and decreased in the C4-dominated southern ‘Amazon’ basin and the Nordeste Region of Brazil. This shift was largely caused by changes in annual precipitation rates, some of which are admittedly highly suspect, however, it resulted in a change in the relative contribution of C4 plants to global photosynthetic rates, and a corresponding decrease in global discrimination of approximately 0.3‰ over a two period. Therefore, the simulation indicates that shifts in the C3/C4 ratio of net assimilation are the primary control on interannual variations in carbon isotope discrimination of the terrestrial biosphere at the global scale.
Figure 5 Interannual variations in carbon isotope discrimination of the terrestrial biosphere and the fraction of net assimilation by C4 plants for 1983 through 1993. Note that discrimination against $^{13}$C is described here as negative.

Results of the simulation also suggest that variation in net assimilation rates on an interannual time scale is largely controlled by either precipitation or PAR (not shown). These two factors dominate in different areas. In general, availability of light dominates in the tropical forests; whereas availability of water dominates in dry, water-limited regions. We interpret the positive correlation between PAR and net assimilation seen in the central regions of the tropical forests, along with the fact that ECMWF precipitation in these areas is consistently high, as an indication that variation in photosynthetic rates from one year to the next are largely controlled by availability of light. There is essentially never any water stress in these areas and changes in photosynthesis are driven by variations in cloudiness. In contrast, we interpret the positive correlation between precipitation and net assimilation observed in desert areas, along with high variability in ECMWF precipitation in the same areas, as an indication that changes in annual net assimilation in these grid cells are controlled by availability of water. Since carbon isotope discrimination in C3 plants is controlled by the CO$_2$ concentration gradients within the leaf, it is a largely function of net assimilation rates and stomatal resistance. The relationship between discrimination and net assimilation (Fig. 1), in combination with the relationships between, precipitation, PAR and assimilation described above, lead us to conclude that interannual variations in discrimination in C3 plants are controlled by changes in stomatal resistance in water limited regions, and by changes in photosynthetic rates in light-limited areas of the tropical forests.
Finally, are there any variations in either discrimination or photosynthetic rates that can be tied to ENSO activity or the eruption of Mount Pinatubo, and can we trust the results. In answer to the first, there are no variations in discrimination or photosynthesis that can be directly related to ENSO or Mount Pinatubo (Fig. 5). There may be regional differences that could be attributable to El Niño, however, that leads us to the second question: can we trust the results. There are serious questions about the accuracy of precipitation rates in ECMWF reanalysis, particularly in the Amazon region. In general, ECMWF does a good job at simulating seasonal variations and annual rates of precipitation near Manuas and Ji-Paraña, however, in other areas of South America it does less well. More to the point, however, in a comparison of numerous multiyear analyses of rain within the Amazon basin, some based on rain gauge data and others from assimilated weather analyses, the conclusion was that while all of the analyses did well with annual means, and gauge based data sets did best with the spatial distribution of precipitation, none of the data sets were particularly successful at simulating interannual variations in the spatial distribution of rain. Unfortunately ECMWF was not included in this comparison, however, similar model-based assimilated data sets generally had difficulty simulating precipitation in areas with elevated topography. This includes much of the area near the edge of the Amazon basin where ECMWF predicts the greatest variability in precipitation, though this area is poorly characterized even in gauge data. Nonetheless, the dry periods in the western part of study area are suspect and, consequently, though the simulation may accurately capture the interrelationships of the ecosystem, we should look at the absolute values with a much more critical eye.