GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 9, 10.1029/2001GL013607, 2002

Long-term variations of climate and carbon fluxes over the Amazon basin

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Received 11 June 2001; revised 2 November 2001; accepted 14 November 2001; published 10 May 2002.

[1] The Amazon basin contains some of the most productive ecosystems on the planet, yet we have little understanding of their long-term behavior. By examining historical climate records over the Amazon, we identify several modes of climatic variability—including previously undocumented long-term modes. Furthermore, using a process-based ecosystem model, we show that these variations in climate generate variations in terrestrial carbon fluxes on short (3–4 year), intermediate (8–9 year), and long (24–28 year) time scales. The long-term cycles in terrestrial carbon balance have not been previously suggested. Finally, we find that time-lags between productivity and decomposition enhance the short-term variations in net carbon balance, while slightly dampening the long-term variations. Given the worldwide attention on terrestrial carbon cycling, and the potential for "carbon sinks", we suggest that an improved understanding of long-term climatic and ecosystem processes is crucial. Other regions should be examined for potential long-term carbon cycle variations. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1615 Global Change: Biogeochemical processes (4805); 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics

1. Introduction

[2] The potential for worldwide climatic change has sparked increased interest in the global carbon cycle, and in determining the ultimate fate of anthropogenic CO_2 emissions. In particular, there is great interest in understanding the regional patterns of carbon emissions, as well as possible sources and sinks of carbon in the terrestrial biosphere. Under the Kyoto Protocols, developed under the Framework Convention on Climate Change, the use of terrestrial "carbon sinks" to offset anthropogenic CO_2 emissions has taken a prominent role. Yet our current understanding of the terrestrial biosphere is far from complete, making it difficult to quantify the carbon balance on regional scales, and to predict how it may change over time. In particular, the long-term behavior of terrestrial ecosystems—which may include long-term variations in carbon balance, including switching between a net source and a net sink—is poorly documented.

[3] The regional-scale carbon balance of terrestrial ecosystems can be strongly affected by a variety of drivers, including nutrient inputs, land use practices, atmospheric composition, and climate. Variations in climate, in particular, through differential impacts on productivity and decomposition, can strongly affect the net exchange of CO_2 between the atmosphere and the terrestrial biosphere. For example, interannual variations in climate have been found to induce large changes in net ecosystem carbon exchange in a variety of ecosystems [*Goulden et al.*, 1996; *Martin et al.*, 1998]. On the global scale, variations in climate also appear to be correlated to changes in the carbon budget—*Braswell et al.* [1997] found that, globally, warm years are followed by a reduction in the atmospheric CO_2 growth rate two years later. On longer time scales, *Dai and Fung* [1993] estimated that the climate variability over 1940–1988 could potentially explain up to half of the missing terrestrial carbon sink. While causal relationships between climate and terrestrial carbon balance are important, they are not always general; they depend strongly on the type of ecosystem being considered [*Braswell et al.*, 1997; *Kindermann et al.*, 1996].

[4] Climate-induced variations in the terrestrial carbon balance of the Amazon basin may be particularly important to the global carbon cycle. The Amazon basin (Figure 1) accounts for a large percentage of the global carbon pool, with approximately 10% of the global terrestrial primary productivity, biomass and soil carbon [*Fearnside*, 1997; *Keller et al.*, 1997; *Melillo et al.*, 1996]. Moreover, the tropics present the highest interannual variability of terrestrial biospheric CO_2 fluxes [*Kindermann et al.*, 1996]. It has already been demonstrated that interannual climate variability, associated with the ENSO phenomenon, changes the Amazon basin from a net source of CO_2 to the atmosphere during El Niño years, to a net sink of CO_2 during La Niña years [*Tian et al.*, 1998]. Our current understanding of the carbon budget of the Amazon basin is based solely on short-term studies. Before using these studies for future projections, we should first test their persistence over longer-time scales.

[5] In this study, we used long-term climate records for the Amazon basin, linked to a process-based terrestrial ecosystem model, to examine long-term variations in the basin-wide carbon balance so that shorter-term observations of terrestrial carbon sources and sinks can be put into the proper context.

2. Results and Discussion

[6] We used the CRU05 historical climate data set [*New et al.*, 2000]. Since this data set has a gap in the Amazon basin during the

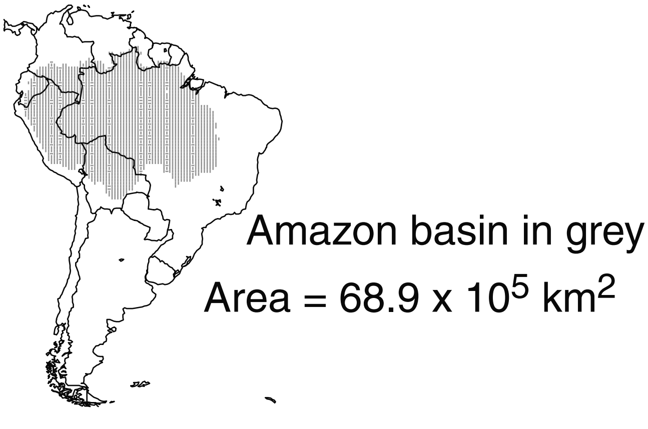

Figure 1. Spatial domain of the Amazon and Tocantins drainage basin.

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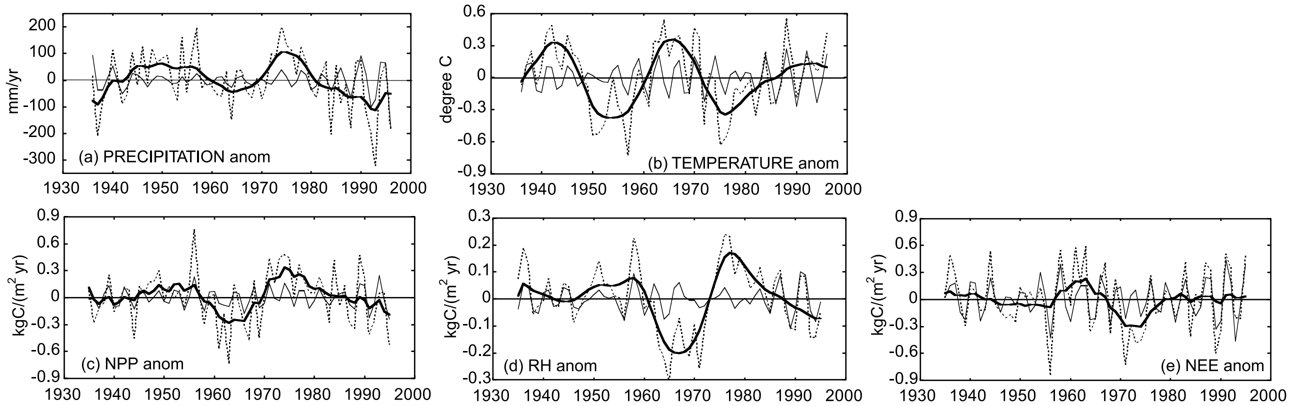

Figure 2. Spectral analysis of CRU precipitation (a), CRU temperature (b), NPP (c), RH (d), and NEE (e) over 1935–1995. The interannual anomalies series is the dashed curve; the thin and the thick full curves are the reconstructions of respectively the long-term and short-term modes of variability using a singular spectrum analysis (SSA) with a window of 10 year. Note that RH has a different scale from NPP and NEE.

earlier part of the 20th century, we focus on the 1935–1995 period with continuous data. The power spectra of the 1935–1995 annual temperature and precipitation anomalies show several preferred time-scales of variability: a "long-term" mode of 24–28 years, an "intermediate-term" mode around 8–9 years, and a few "short-term" modes of 3–6 years.[1]

[7] The long-term modes of climate variability in the Amazon—which have not been documented in detail before—are particularly interesting because they exhibit the highest power spectral density. However, the long-term modes constitute only about two realizations in this short time series. Therefore, to study these variations more carefully, we used Singular Spectrum Analysis (SSA), a data-adaptive filter that is appropriate for short noisy time series [*Dettinger et al.*, 1995; *Schlesinger and Ramankutty*, 1994]. SSA decomposes a time-series into its orthogonal basis functions; the eigen vectors with the largest eigen values represent the greatest variability in the data.

[8] We performed SSA on the 1935–1995 Amazon climate record, and reconstructed the time-series for the largest eigen vectors (Figures 2a–2b). For both temperature and precipitation, most of the variance is explained by the long-term (24 year for temperature and 28 year for precipitation) mode (56% and 35% of the total variance, respectively; Table 1). It is the only systematically statistically significant mode of climate variability (Table 1).[2] The second main climate signal corresponds to the short-term fluctuations (3–6 year mode), which explain 21% and 29% of the total variance in temperature and precipitation respectively (Table 1). The intermediate-term (8 year) mode of variability is only detected in the precipitation time series with SSA, and explains 18% of the variance (not shown). We focused our analysis on the two main modes (short and long-term), as we were more confident about their existence in the climatic records.

[9] Previous studies have associated the short-term mode of climate variability with the ENSO phenomenon. Typically, an El Niño period is dry and warm in the Amazon basin, while a La Niña period is wet and cool [*Kousky et al.*, 1984; *Marengo*, 1992; *Zeng*, 1999]. The long-term mode of climate variability in the Amazon, on the other hand, has never been examined in any detail before. Independent reconstruction of Amazon basin temperature [*Victoria et al.*, 1998], Amazon River discharge at Manacapurú [*Richey et al.*, 1989], and Amazon River discharge at Obidos [*Marengo and Hastenrath*, 1993] suggest the same patterns.[3] Furthermore, other authors [*Hastenrath*, 1991] have identified a similar long-term mode of precipitation variability in Northeast Brazil (also with a time-scale of ~28 years), which is related to large-scale circulation patterns in the tropical Atlantic sector. *Vuille et al.* [2000] showed that a tropical Atlantic circulation teleconnection extends to the Central Andes; it is therefore likely that the climate variation over the Amazon is related to the same large-scale circulation.

[10] In order to estimate the impact of these climatic variations on the terrestrial carbon balance, we used the IBIS terrestrial ecosystem model [*Foley et al.*, 1996; *Kucharik et al.*, 2000]. In this study, we ran IBIS through a "spin-up" initialization procedure,[4] and then simulated the 1935–1995 period using the CRU05 climate data; no other environmental drivers (increasing atmospheric CO_2 concentrations, land use, or increasing nutrient inputs) were considered in this simulation. We focused our analysis on the simulated impact of climate variations on the annual carbon fluxes, including net primary production (NPP), and microbial (heterotrophic) respiration (RH). The net ecosystem exchange (NEE) of carbon is simply the difference between RH and NPP; thus positive (negative) NEE corresponds to a source (sink) of CO_2 to the atmosphere.

[11] In the simulation, both NPP and RH show the same major modes of variability as the climate: a long-term mode (~26 years for RH and ~28 years for NPP), an intermediate-term mode (of 8 years) and a series of short-term modes (of 3–4 years) (Figures 2c–2d). NPP variability is strong in both the short and long-term modes, while RH variability is strongest in the long-term mode (Table 1). Overall, the variations in RH are significantly damped compared to variations in NPP (the standard deviation of NPP and RH are respectively 0.293 Pg-C/yr, and 0.121 Pg-C/yr); the long residence time of carbon in vegetation and soil results in a

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[1] 1935–1995 annual cloudiness anomalies also present the same two shorter modes of variability and a significantly different long-term mode around 35 years. This paper focuses on the 24–28 year mode of variability, thus we discarded cloudiness from the rest of our discussion.

[2] We repeated this analysis separating the dry from the wet regions (defined by a mean annual precipitation threshold of two meters), and noticed that the long-term modes were still dominant for temperature and precipitation in both regions.

[3] Victoria et al. temperature record shows a warming trend from 1975 to 1995, which is absent from CRU05 record. This is mainly due to their subset of station. CRU05 temperature time series using Victoria et al. mask also shows this positive trend.

[4] The spin-up initialization procedure consists in a 300-year simulation using a surrogate variable climate to let the carbon pools reach equilibrium. The 300-yr surrogate climate record was created using the CRU climate data over 1936–1995, by first detrending it, and then concatenating it 5 times.

delayed-oscillator effect, and a more "red" power spectrum [*Hasselmann*, 1976].

[12] NEE also exhibits preferred modes of variability around 3–4 years, 8 years, and 24 years (Figure 2e). Interestingly, unlike NPP and RH, NEE variations are strongest in the short-term mode of 3–4 years. Compared to NPP, the strength of long-term NEE variability is significantly diminished, while the strength of short-term NEE variability is enhanced (Table 1). This "high-pass filter" type of behavior in NEE has not been documented before. To examine this further, we need to understand the major climatic drivers of NPP and RH in the Amazon basin and their interactions.

[13] Warm and dry years, by increasing autotrophic respiration and water stress, decrease NPP [*Kindermann et al.*, 1996], while wet and cool years favor growth by reducing water stress [*Asner et al.*, 2000; *Malhi et al.*, 1999]. Over the 1935–1995 period, temperature and precipitation are anti-correlated (correlation coefficient, r^2, of −0.46), at both short and long time-scales (Figures 3–4). As a result, interannual changes in NPP in this region are correlated with precipitation and anti-correlated with temperature (r^2 of 0.68 and −0.7 respectively). RH can also respond to changes in climate (especially through changes in soil temperature and soil moisture), but in our model simulations, we find that the climatic effect on RH is overwhelmed by the influences of annual litter fall amounts in preceding years. We find a significant time lag between perturbations in NPP and the resulting changes in RH (RH perturbations lag NPP perturbations by 26 months). This ~2-year time lag is a cumulative result of the residence times of carbon in vegetation and soil [*Schlesinger*, 1991], and is found to be a reasonable estimate in field studies of the Amazon as well [*Trumbore*, 2000; *Trumbore et al.*, 1995].

[14] We find that this ~2-year lag between NPP and RH results in the high-pass filter behavior of NEE (see Figure 4). The short-term mode of carbon variability has a 3–4 year time scale. With a ~2-year lag between NPP and RH, the two terms become effectively anti-correlated at the short time scale. Thus, NEE becomes enhanced in amplitude due to the constructive interference between NPP and RH. This result is corroborated by a previous modeling study by *Tian et al.* [1998], as shown in Figure 3. At the long time scales, however, NPP and RH are still effectively correlated (a 2-year lag on a roughly 26–28 year cycle), and NEE is slightly damped by destructive interference.

[15] These results are also supported by the global scale study of *Braswell et al.* [1997] who observed an anti-correlation between temperature and satellite-derived vegetation "greenness" and a positive correlation between temperature and CO_2 growth rate, and the opposite tendency at a 2-year time lag. They suggested that this phenomenon could be potentially explained by competition for nutrients between plants and microbes. In the Amazon basin however, such behavior can be simulated by simply accounting for the ENSO climate variability (3–4 year mode).

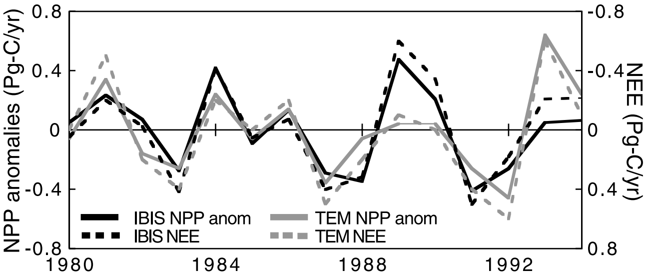

Figure 3. Comparison of IBIS and TEM simulations of the NEE and NPP fluxes over the Amazon basin over 1980–1994. Both models simulate highly correlated NEE and NPP and an amplitude of NEE interannual variability larger than that of NPP.

Table 1. Percentage of Variance Explained by the Main Modes Identified Using Singular Spectrum Analyses (SSA)

	Short-term mode	Intermediate mode	Long-term mode	Remaining Variance
Precipitation	21%	18%	35%[a,b]	26%
Temperature	21%[a]	–	56%[a,b]	23%
Cloudiness	15%	30%[b]	–	55%
NPP	33%[a]	10%	34%[a,b]	23%
RH	20%[a]	10%	62%[b]	8%
NEEE	44%[a,b]	15%	20%	21%

[a] Significant mode at a 90% level using the Multi-Taper Method under a red noise hypothesis.

[b] Significant mode using SSA implying that its associated eigen values are above the noise floor [*Ghil and Vautard*, 1991] (in the case of the long term mode of precipitation, only one of the two associated eigen values is above the noise floor).

3. Conclusions

[16] This paper raises three major points.

[17] First, our study shows that there are several modes of climate variability in the Amazon basin—ranging from fairly short (3–4 years) to very long (24–28 years) periods.

[18] Second, using process-based ecosystem model simulations, we find that that the Amazon basin can have long-term, climate-induced variations in the terrestrial carbon balance. Only considering variations in climate (and no other environmental changes, such as increasing CO_2 and land use), we find that the Amazon is almost neutral from the late 1930s to the late 1950s (−0.42 Gt-C over 1935–1957), a net carbon source during the 1960s (+1.98 Gt-C over 1958–1967), a net sink during the 1970s (−2.54 Gt-C over 1968–1978), and back to nearly neutral during the 1980s and 1990s (+0.61 Gt-C over 1979–1995).

[19] Finally, we find an interesting "resonance" phenomenon, wherein the intrinsic time lag between primary production and microbial respiration processes modulate the variability in net ecosystem carbon exchange. This process amplifies short-term modes of variability (3–4 year modes, which are related to ENSO), but dampens the long-term modes (24–28 years) of variability.

[20] In sum, these results point to the need for extreme caution in interpreting short-term measurements of carbon fluxes.[5] If such long-term fluctuations in terrestrial carbon balance do indeed exist then we will require much longer-term observational records than we presently have to fully understand and extrapolate the current short-term eddy flux or inversion-based estimates of the source and sinks of carbon across an entire region.

[21] The specific results of this study are dependent on the quality of long-term climate records, and the reliability of the terrestrial ecosystem model simulations. Nevertheless, we know that long-term climate variability is not unique to the Amazon, and it is not surprising that such modes exist there as well. Moreover, the "resonance" phenomenon that we suggest—constructive interference between NPP and RH at short time scales and destructive interference at long time scales—is something that should be explored in other ecosystems. This study raises serious questions regarding our ability to use short-term observations and modeling

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[5] Currently, there are several direct observations of NEE at sites scattered across the Amazon using eddy flux tower measurements or aircraft measurements (as part of the LBA Experimental plan or from previous work).

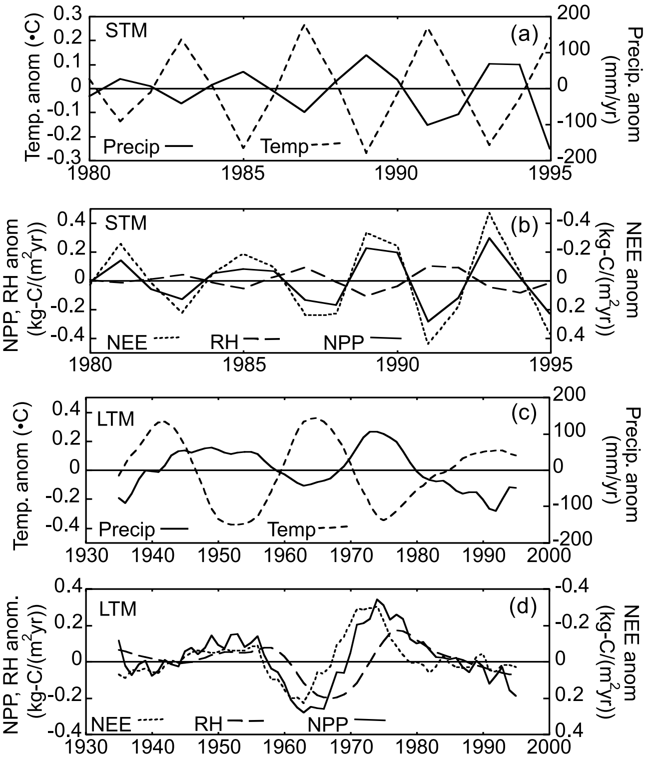

Figure 4. Illustration of the interaction between different time scales of variability in climate and carbon fluxes. Short-term mode of variability (STM), focusing on just the last 15 years (1980–1995) for clarity: (a) temperature and precipitation, and (b) carbon fluxes. Long-term mode of variability (LTM): (c) temperature and precipitation, and (d) carbon fluxes. Note that the axis for NEE is plotted in reverse.

exercises to study the global carbon cycle. We must ask ourselves if our observations and our models are good enough to be able to understand the long-term behavior of the global carbon cycle? The implications of this question go far beyond science; they also touch upon the prospects of "managing" the global carbon cycle and the international discussions of greenhouse gas emissions and climate change.

[22] **Acknowledgments.** We are grateful to Chris Potter for his helpful review of the manuscript, and Stefan Hastenrath for useful insights regarding tropical climate variability. We would like to thank Martin Heimann, Carol Barford, and Mike Coe for reading a first draft of this paper and providing very useful suggestions, and Jeff Cardille for his help with the figures. This project was supported by a Presidential Early Career Award, the NASA-IDS program, and by the NASA-LBA-Ecology program.

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