Detecting Climate Change Concurrent with Deforestation in the Amazon Basin: Which Way Has It Gone?

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Abstract

To detect climate change in the Amazon Basin, as possibly induced by deforestation, time series of monthly mean outgoing longwave radiation (OLR), an index of tropical convection, and monthly rainfall totals at Belém and Manaus for the past 15 years are analyzed. A systematic bias in the original OLR series was removed prior to the analysis. Linear regression analysis and nonlinear Mann–Kendall rank statistic are employed to detect trends. Over almost all of the basin, the OLR trend values are negative, indicating an increase of convection with time. The largest negative and statistically significant values are found in the western equatorial portion of Amazonia, where rainfall is most abundant. Consistent with this, the rainfall series at Belém and Manaus also feature upward trends. Small positive and statistically insignificant, OLR trend values are confined to the southern fringe of the basin, where deforestation has been most drastic. Thus, there is little indication for a rainfall increase associated with deforestation, but rather a strong signal of enhanced convection in the portion of Amazonia contributing most strongly to the total precipitation over the basin.

1. Introduction

Possible climatic change caused by progressive deforestation in the Amazon Basin (Fig. 1), which holds about half of the world's remaining rain forest, has received much attention. There is a wide range of estimates of deforestation rates. For the period from 1978 to 1988, Myers (1991) and World Resources Institute (1990) give estimates ranging from 50 000 to 80 000 km^2 per year, while Fearnside et al. (1990) and Nobre et al. (1991) report rates of 21 000 and 20 000 km^2 per year, respectively. Over the same period, Skole and Tucker (1993), using Landsat satellite and the Geographic Information System, determined an increase of deforested area from 78 000 to 230 000 km^2, out of a total of about 4 000 000 km^2 forest area in Brazilian Amazonia, corresponding to deforestation rate of 15 000 km^2 per year. Myers (1991) presents evidence indicating that the forest thus affected does not recover. Deforestation is concentrated in the southern and eastern fringes of Brazilian Amazonia and along the major transportation lines in the interior (Fig. 2). The neighboring Amazonian countries such as Colombia and Peru have also experienced a high rate of deforestation (e.g., Myers 1991). This drastic removal of biomass may have implications for the regional climate, biodiversity, the global carbon cycle, and the large-scale atmospheric circulation.

The climatic effects of the conversion of tropical rainforest to grassland have been the subject of various numerical model experiments. The processes involved are complex. When forest is replaced by pasture, the absorption of solar radiation at the surface is reduced because of the higher albedo for grass

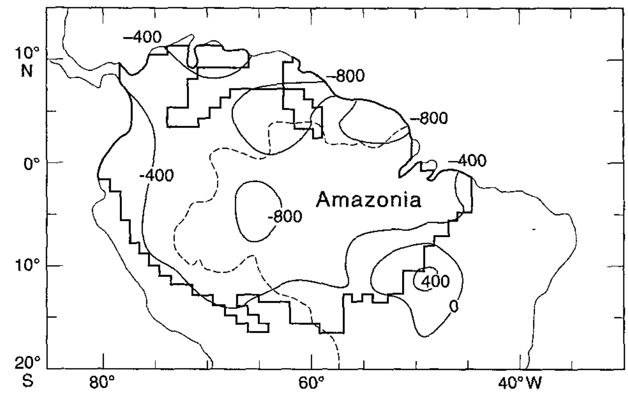

FIG. 1. Map summarizing information on numerical modeling experiments of Shukla et al. (1990) and Nobre et al. (1991): boundary of Amazonia where rain forest is replaced by grassland, depicted by heavy solid lines in 1° latitude–longitude resolution; and rainfall difference (deforested—control), depicted by thin solid lines in millimeters. National boundary of Brazil is entered as thin broken line.

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In final form 4 January 1994.
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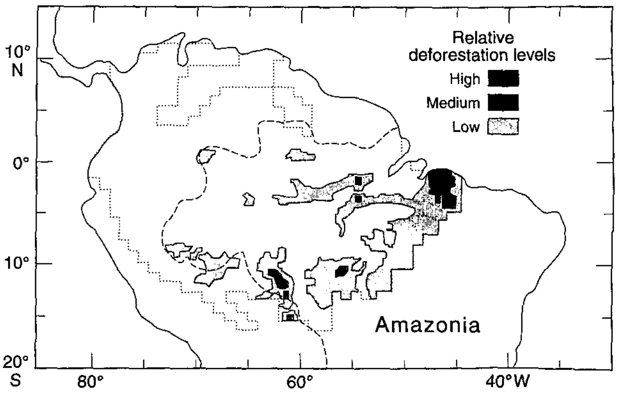

FIG. 2. Map showing the deforested area in Brazilian Amazonia in 1988 (adapted from Skole and Tucker 1993). Boundaries of Amazon forest and Brazil are entered as thin dotted and broken lines, respectively.

as compared to forest. Reduced surface net radiation would leave less energy for evapotranspiration, and smaller roughness length of grass may have consequences for surface temperature and sensible heat transfer, with further implications for the Bowen ratio. Differences between the results from various model experiments are then not surprising. Dickinson and Henderson-Sellers (1988) used a coarse-resolution atmospheric general circulation model (GCM) coupled with a biosphere model to diagnose the effect of converting Amazon rain forest to grassland and inferred reduced precipitation and evaporation and a lengthening of the dry season. More recently, a similar numerical simulation was conducted using a higher-resolution GCM and prescribing basinwide deforestation (Nobre et al. 1991; Shukla et al. 1990). Like the Dickinson and Henderson-Sellers study, these simulations also indicated a basinwide rainfall decrease of about 20%–30% (~600 mm) due to deforestation, and the areas of the largest decrease (>800 mm) are found in the central and northern portion of the basin (Fig. 1). Conceivably, this rainfall decrease would reduce the moisture flux convergence and latent heating in the basin, thereby inducing large changes in local and regional atmospheric circulation.

However, observational evidence of such climatic change in Amazonia so far is lacking. Richey et al. (1989) analyzed long-term (1903–85) river-flow data of Manacapurú near Manaus (Fig. 3) and concluded that the river-flow fluctuation was marked by a 2- to 3-yr periodicity and that there was no statistically significant change on the decadal time scale.

Given the important role of the Amazon Basin in global climate change and in the general circulation of the atmosphere as a major heat source, it is appropriate to determine whether there are any real observable changes over time in the regional climate that would validate these model results. Such information is of interest for inferences on the future evolution of the global circulation, and it may also be helpful in the development of long-term sustainable land use policies. It is desirable to ascertain the direction and statistical significance of any change and to examine whether the change occurs coherently in the entire basin or is rather concentrated in certain areas with most pronounced deforestation (Fig. 2).

2. Observations

Two independent datasets are used in this study: the monthly rainfall totals at Belém and Manaus in Brazil (Chu 1991) and daily averaged outgoing longwave radiation (OLR) data from NOAA's scanning radiometer mounted on polar-orbiting satellites. The OLR data are available at 2.5° latitude–longitude resolution for almost 15 years from June 1974 to September 1990 (a gap in 1978). The missing data in 1978 are filled by the long-term means. Longer series exist for rainfall records, but for the sake of comparison, a common period (June 1974 to September 1990) for rainfall at Belém and an almost common period (June 1974 to December 1988) for rainfall at Manaus are adopted.

Regarding OLR measured from the NOAA polar-orbiter satellites, the infrared sensors detect longwave radiation emitted from the earth in the 10.5–12.5-μm wavelength band (the water vapor window). In this

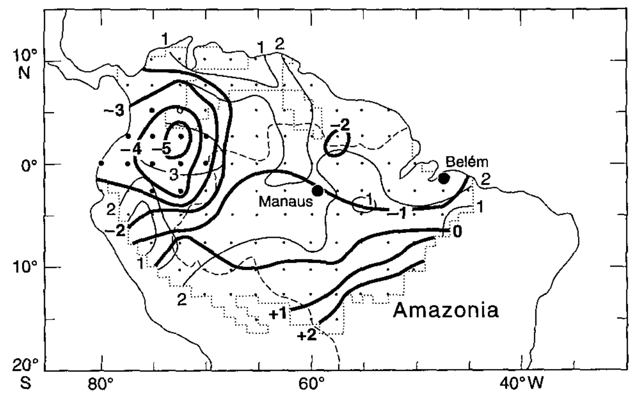

FIG. 3. Map of observed OLR trends and rainfall. Heavy solid lines denote linear OLR trend in 10^{-1} W m^{-2} per year, with spatial resolution of 2.5°, period June 1974 to September 1990, with heavy dots indicating significance at 5% level (open circle also indicates significance but this grid point lies outside the forest domain defined in Fig. 1). Thin solid lines denote annual mean rainfall in meters. Also entered is small dot grid denoting the 2.5° latitude–longitude resolution, for which OLR series were evaluated. Boundaries of Amazon forest and Brazil are entered as thin dotted and broken lines, respectively. Manaus and Belém are indicated by large dots.

window, variations in OLR are caused mainly by clouds within the field of view. In the case of deep convective clouds, the sensors measure radiation from the top of clouds. In the case of clear sky, the satellite radiometer monitors longwave radiation emitted mainly from the earth surface. In the Tropics, the satellite-derived OLR mainly reflects cloud-top temperatures, with *low* OLR values corresponding to cold and high clouds, which generally denote *enhanced* convection. Thus, an inverse relationship generally holds between OLR and convection.

OLR data have been used extensively to study tropical convection (e.g., Lau and Chan 1983; Graham and Barnett 1987) and even to estimate tropical rainfall (e.g., Motell and Weare 1987; Yoo and Carton 1988). Recently, Waliser et al. (1993) compared OLR data to the frequency of the deep convective cloud type of the shorter series of the International Satellite Cloud Climatology Project stage C2 dataset (Rossow and Schiffer 1991). In the C2 dataset, the deep convective cloud type is defined when the cloud-top pressure is less than 440 mb and when the optical thickness has a value greater than 23. In this comparison, Waliser et al. (1993) found good agreements in regions where deep convection prevails. Accordingly, OLR is regarded as a reasonable indicator of convective activity in the Amazon Basin.

Gadgil et al. (1992) reported a systematic bias in OLR, with values in the 1980s consistently lower than those in the 1970s. The sources of bias of OLR in the 1980s include the differences in equatorial crossing time and uncertainties in sensor calibration among satellites, as described in Gadgil et al. (1992) and Chelliah and Arkin (1992). We used a formula suggested by Gadgil et al. (1992) to correct for this bias. Only the bias-removed OLR series are presented in this study.

3. Methods

To remove the annual cycle of convection, which in the Amazon Basin is substantial (Horel et al. 1989), the individual monthly rainfall and corrected OLR series are subtracted from the corresponding long-term monthly mean. Two statistical methods are used separately to quantify the direction and magnitude of the "trend." The first relies on conventional least-square techniques to estimate the slope, β, of a simple linear regression line. The second method is the Mann–Kendall rank statistic, τ, as in Kousky and Chu (1978). The use of τ involves ranking and counting of each individual member relative to others in a raw (unranked) series. A negative estimate of τ implies a decrease of a variable with time. In principle, the latter method is nonlinear and based on ranks, so that results are more robust to the start and end points of data than the regression analysis.

4. Results

Figure 3 maps the linear trend of the OLR series along with the pattern of annual rainfall. Over almost all of the basin, the OLR trend values are negative, indicating an increase of convection with time. The largest negative and statistically significant values are found in the western equatorial portion of Amazonia, where rainfall is abundant (e.g., Legates and Willmott 1990). Small positive and statistically insignificant, OLR trend values are confined to the southern fringe of the basin, where deforestation has been most drastic.

As a complement to Fig. 3, Fig. 4 displays the OLR trend based on the Mann–Kendall rank statistic. It supports the above assessment, in likewise showing prevailing negative trends, with largest and statistically significant values over the western equatorial portion of Amazonia, and small positive OLR trend values confined to the southern portion of the basin.

Figure 5 shows the time series plot of the area-averaged OLR in western equatorial Amazonia where the trend is most pronounced (Fig. 3). From 1974 to 1990, the linear regression analysis indicates a decrease in the area-averaged OLR by about 7 W m^{-2}, and in the center of this region the decrease is as large as 9 W m^{-2}. Comparatively large OLR values, indicative of reduced convective activity, are associated with the 1976–77, 1982–83, and 1986–87 El Niño events.

The rainfall of Belém and Manaus (Fig. 3) shows

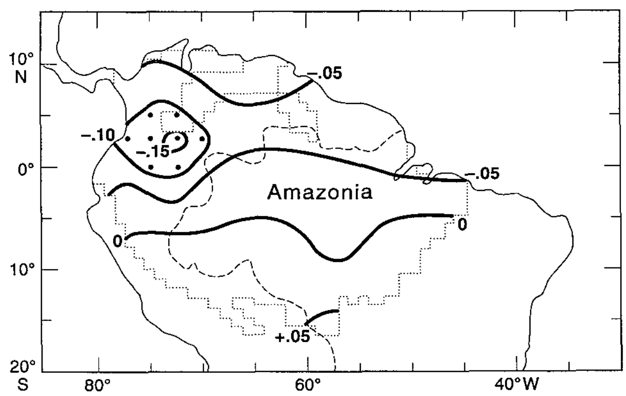

FIG. 4. Map of the spatial distribution of the estimated Mann–Kendall rank statistic τ of OLR, with spatial resolution as in Fig. 3. Heavy dots indicate significance at the 5% level. The period is from June 1974 to September 1990. Boundaries of Amazon forest and Brazil are entered as thin dotted and broken lines, respectively.

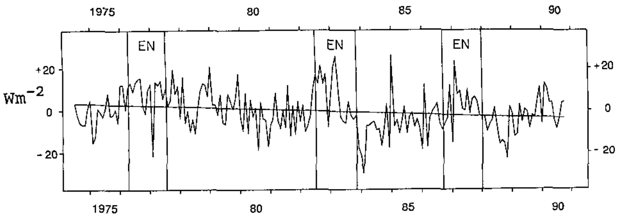

FIG. 5. Time series of the area-averaged monthly OLR series in western Amazonia over solid grid points indicated in Fig. 3. Straight line denotes the linear regression line of which the trend is significant at the 5% level. EN indicates El Niño years.

linear trends of about +2.0 and +0.9 mm per year, respectively; the estimate is larger at Belém than at Manaus, a feature basically consistent with the satellite-derived variable (Fig. 3). The Mann–Kendall rank statistics for Belém and Manaus are +0.07 and +0.04, respectively. Thus, both results indicate an upward trend, although the 5% significance level is not reached.

5. Summary and discussion

Results from two statistical analyses as presented in Figs. 3–5 are mutually supportive in suggesting a slight increase in tropical convection (or rainfall) over much of Amazonia concurrent with deforestation. These results are in apparent contrast to some GCM simulations. One reason for this difference may be due to the fact that deforestation has not yet occurred on a basinwide scale. As the deforested area increases, the effects could be expected to gradually increase. Another reason for the difference between model simulations and observations may be due to limitations of the models: namely, that the GCM failed to accurately simulate the extent and duration of convective cloud cover in the Tropics (Shuttleworth et al. 1990). Using an improved cloud–radiation interaction scheme in the GCM and seasonally varying climatological sea surface temperatures, however, a slight increase in annual rainfall over the entire Amazonia has been simulated as a result of tropical forest removal (Dirmeyer and Shukla 1991). This result agrees better with observations presented in this study.

In the southern fringe of Brazilian Amazonia where deforestation is drastic, there is a weak sign of an upward trend in OLR (e.g., Fig. 3). However, in this region OLR in austral winter may reflect nonconvective cloudiness (Garcia 1985). Accordingly, even the weak positive OLR trend in southern Amazonia may not necessarily imply a decrease of convection.

More important, a coherent slight increase in convection is noted over most of the Amazon Basin, with changes being statistically significant in western Amazonia along the eastern slope of the Andes (i.e., southern Colombia, Ecuador, and northeastern Peru). Two questions immediately arise: What are the causes for the general upward trend in convection? Why is the change so pronounced in western Amazonia? Work is in progress to explore these issues through analyses of large-scale circulation and remote sensing observations in the Amazon Basin and adjacent oceans.

Acknowledgments. This study was supported by the Water Resources Research Center, University of Hawaii—Manoa (PSC and ZPY) and National Science Foundation Grant ATM-9101097 (SH). Rick Katz and Mickey Glantz commented on an earlier draft of this paper. We thank Toby Carlson, Vernon Jones, and an anonymous reviewer for constructive criticism on this paper. P.-S. Chu also benefited from discussions with Tom Schroeder. This is SOEST contribution No. 3519.

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