Time Trends in Rainfall Records in Amazonia

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Abstract

This paper reports the results of statistical analyses for the detection of time trend in 48 rainfall records from sites in the Amazon Basin with more than 15 yr of record. Using a nonparametric test for trend in monthly rainfall, three results emerge: (a) irrespective of the statistical significance of time trends, positive and negative trends occur with approximately equal frequencies over the Brazilian Amazon hydrographic basin; (b) the number of statistically significant time trends, whether positive or negative, is very much greater than can be ascribed to chance variation; (c) significantly negative time trends are more common than significantly positive time trends in monthly rainfall. Over the period of approximately 30 yr covered by the records, during which deforestation has been rapid, negative trends seem to have occurred more frequently in two regions of western and central Amazonia, and positive trends more frequently in eastern Amazonia. There is some qualitative agreement between the disposition of contours defining regions of negative trend (reduced rainfall) in the rainfall records, and the contours defining regions of reduced rainfall following 50% deforestation, as predicted by the U.K. Hadley Centre for Climate Prediction and Research. However, the rainfall records show positive trends (increased rainfall, confirming the conclusion of Chu et al.) in some parts of the region where the Hadley Centre predicts reduced rainfall, following deforestation of 50% or more.

1. Introduction

The possibility that Amazon deforestation may adversely affect regional climate and water balance arouses widespread concern. Much has been written on the subject, and estimates of the rate at which deforestation is occurring vary widely. Chu et al. (1994) cite estimates given by Myers (1991) and the World Resources Institute (1990) of 50 000–80 000 km^2 yr^{-1} for the period 1978–88, while estimates by Fearnside et al. (1990), Nobre et al. (1991), and Skole and Tucker (1993) are substantially lower, in the range of 15 000–21 000 km^2 yr^{-1}. Even the lower figures represent very substantial areas in absolute, if not in relative, terms. Deforestation to the southern and eastern edges of the Brazilian Amazon has been very considerable, although other researchers (Gentry and Lopez-Parodi 1980) draw attention to the extent of deforestation in Amazonian Bolivia, Peru, Ecuador, and Colombia.

Because of the difficulty and expense of making careful measurements in remote and climatically hostile areas of Amazonia, much of what has been written about the climatological and hydrological consequences of deforestation has reported predictions from mathematical models (Shukla and Mintz 1982; Dickinson and Henderson-Sellers 1988; Lean and Warrilow 1989; Shukla et al. 1990; Polcher and Laval 1993). These models have sometimes lacked the information necessary to validate satisfactorily all their assumptions, although the recent Anglo-Brazilian Climate Observation Study (ABRACOS) has provided valuable information about the soil–vegetation–atmosphere interaction for both forest and pasture under Amazonian climatic conditions. Typically, the mathematical models have compared full forest cover with a hypothetical surface, where the forest has been totally replaced by degraded pasture, and have involved other assumptions that might be called into question. However, recent model runs using data from the ABRACOS study (Lean et al. 1995) have considered the more realistic case of partial deforestation amounting in total to 50% of the entire basin.

Where total deforestation has been assumed, several of the modeling studies reported in the literature have predicted reductions in precipitation in some areas of Amazonia. Shukla et al. (1990) present diagrams showing reductions in annual rainfall in the range 200–800 mm, with reductions in evapotranspiration in the range 200–400 mm. More recent studies that use data collected by the ABRACOS Project (Institute of Hydrology 1994), again assuming total deforestation, predict an increase in temperature, averaged over the entire Amazon Basin, of 2°C, a reduction of 17% in evaporation, and a 6% reduction in rainfall, with the greatest reduction in rainfall (20%) occurring near the mouth of the Amazon. The 6% reduction quoted in the Institute of Hydrology report is smaller in absolute terms than the reductions predicted by Shukla et al. (1990), although the 20% reduction predicted for the mouth of the Amazon—of

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TABLE 1. Details of 48 rain gauge sites with long-term (>15 yr) records in Amazonia.

DNAEE code	Lat. (°)	Long. (°W)	Period of record	Number of complete months	Mean annual rainfall (mm)	τ
00470001	-4.38	70.03	1961–90	260	2863	-0.182*
00367000	-3.08	67.93	1972–92	235	2876	-0.107*
00368001	-3.45	68.80	1972–92	234	2786	-0.100*
00166000	-1.80	66.55	1973–92	201	2787	0.038
00266000	-2.53	66.03	1967–90	239	2522	0.005
00466000	-4.88	66.90	1961–88	187	2632	-0.040
00463001	-4.08	63.13	1961–90	252	1992	0.200*
00867001	-8.73	67.38	1972–92	229	2036	-0.186*
00968001	-9.03	68.57	1972–92	227	1838	-0.107*
00061000	-0.45	61.80	1972–92	234	2224	0.025
00062000	-0.98	62.92	1960–90	261	2500	-0.104*
00067000	-0.13	67.08	1961–90	263	2902	0.047
00360000	-3.13	60.02	1961–90	277	2258	0.068
08068000	0.07	68.23	1961–92	292	3504	-0.050
08069000	0.62	69.20	1961–92	295	3241	-0.284*
00560000	-5.12	60.38	1972–92	214	2457	-0.137*
00561000	-5.82	61.30	1967–90	194	2505	0.009
00863000	-8.77	63.92	1961–92	277	2186	-0.011
01065002	-10.80	65.38	1972–92	213	2102	-0.154*
01260001	-12.73	60.13	1967–87	225	2020	0.106*
01559006	-15.00	59.97	1965–91	230	1276	0.073
00155000	-1.77	55.87	1968–91	227	2521	-0.069
00256000	-2.63	56.73	1961–92	300	2251	0.045
00358000	-3.13	58.47	1961–92	203	2409	0.154*

the order of 400 mm—lies within their predicted range. However, when deforestation was assumed to be 50% of the entire basin, the model of Lean et al. (1995) predicted (a) a reduction in mean areal precipitation of 0.19 mm day^{-1}, equivalent to 3% of annual rainfall (say, 60 mm for an annual rainfall of 2000 mm), (b) a decrease in evaporation of 0.31 mm day^{-1} (7%), and (c) an increase in mean surface temperature of 1.5°C.

Given the consistency, in sign if not in magnitude, of the changes in rainfall predicted by various models, it is natural to ask, as did Chu et al. (1994), whether other evidence exists to support it. Independent confirmation of model predictions is also desirable from other points of view: since modelers compare methodologies with one another, a measure of agreement between model predictions is to be expected. Using monthly mean outgoing longwave radiation (OLR) records and monthly rainfall totals at Manaus (June 1974–December 1988) and Belém (June 1974–September 1990), Chu et al. (1994) found negative trends for OLR over most of the Amazon Basin, indicating an increase of convection with time, and, consistent with this finding, they found positive trends in the monthly rainfall sequences at both Manaus and Belém, after standardizing data to remove the annual cycle.

Other authors have attempted to seek evidence of climatic change in runoff records, with inconclusive results. Richey et al. (1989) analyzed annual runoff measured at Manacapurú, near Manaus, for the period 1903–85, but found no statistically significant change at the decadal timescale, although there was evidence of a periodicity with a period of 2–3 yr. Gentry and Lopez-Parodi (1980) reported that the height of the annual flood at Iquitos increased significantly over the 17-yr period 1962–78. Their conclu-

Table 1. *Continued.*

DNAEE code	Lat. (°)	Long. (°W)	Period of record	Number of complete months	Mean annual rainfall (mm)	τ
00254000	−2.43	54.70	1968–91	247	2440	−0.064
00352001	−3.20	52.20	1928–89	637	1881	0.114*
00048000	−0.73	48.52	1961–91	317	3549	0.004
00052000	−0.60	52.55	1968–91	246	2331	−0.074
00148005	−1.02	48.93	1950–82	373	2372	0.117*
08051002	0.17	51.05	1967–89	241	2505	0.048
00549002	−5.35	49.15	1952–91	211	1952	0.190*
00466001	−4.83	66.75	1975–92	185	2637	−0.176*
00772000	−7.63	72.67	1961–90	184	2107	0.043
00773000	−7.45	73.67	1976–92	179	2612	0.014
00564000	−5.67	64.33	1972–89	182	2478	0.036
00764001	−7.25	64.78	1972–90	182	2386	0.029
00967000	−9.97	67.80	1969–91	192	1942	0.070
00360001	−3.32	60.58	1972–92	201	2257	−0.011
08261000	2.82	61.27	1975–92	208	1931	−0.000
08360000	3.45	60.43	1975–92	189	1427	0.108*
00658000	−6.75	58.93	1975–92	187	2458	−0.219*
00760000	−7.25	60.40	1974–92	207	2560	0.005
00556000	−5.15	56.83	1972–92	181	2004	−0.217*
01157000	−11.65	57.23	1973–89	182	2131	−0.068
01454000	−14.38	54.22	1973–91	191	1886	0.025
00053000	−0.42	53.70	1972–89	196	2314	−0.037
00152001	−1.73	52.23	1963–91	184	2399	0.074
00154000	−1.75	54.42	1972–91	205	1723	−0.034

sion is open to some doubt because there is appreciable year-to-year serial correlation in the annual flood record, and the period in question may have been part of a low-frequency fluctuation. In any case, looking for evidence of deforestation in runoff records is complicated by the fact that any effects of deforestation on rainfall are confounded with other effects of deforestation on surface and subsurface hydrological processes.

Although Chu et al. (1994) included an analysis of monthly rainfall records from two Amazon sites (Manaus and Belém) in their study, there are rainfall records from many other Amazon sites that could have been included in their analysis. Moreover, Belém and Manaus have both developed extensively during the last three decades, and it is conceivable that local rainfall patterns at both sites may have been modified by urban development. In this paper, we report some results from an analysis of records from all rainfall records at sites within the Brazilian Amazon, made available to us by the kindness of the Brazilian Departamento Nacional de Águas e Energia Elétrica (DNAEE). In particular, we have extended the analysis of Chu et al. (1994) to all sites within the region with more than 15 yr of record, of which there are 48.

2. Observations and methodology

Of more than 500 stations for which DNAEE provided records, many are of short duration, but 48 of them provided records deemed adequate for the investigation of possible time trends in rainfall, which might be associated with periods of deforestation. Details of these stations and their periods of record are shown in Table 1; Fig. 1 gives a map showing the

FIG. 1. Map showing positions of the 48 rain gauge sites with more than 15 yr of record. Open circles show sites without statistically significant trend, closed circles show sites with statistically significant trend; positive or negative numbers show the magnitudes of Mann–Kendall τ statistic. The shaded area corresponds to the contoured area of Fig. 2.

position of the sites and the position of the region within the South American subcontinent. The shaded box defines the region used to derive a contour plot shown in Fig. 2, to be discussed later in the paper.

To look for trends, we followed basically the procedure used by Chu et al. (1994); namely, annual cycles were removed by subtracting, from the rainfall measured in each complete month of record, the long-term mean for that month, calculated from the entire record. All incomplete months were omitted. In addition, all calculations were repeated by dividing these differences by the appropriate monthly standard deviations. The resulting series of differences, and of standardized deviates, were then examined for trend, both by calculating the Mann–Kendall statistic τ and the linear regressions of monthly rainfall (with annual cycle removed, as described above) on time. The Mann–Kendall statistics, which make no assumptions about probability distributions for the original data, were tested for significance using a standard normal distribution. The linear regression coefficients were formally tested as t statistics, although the statistical requirements for t tests to be valid (normality of error distribution; homogeneity of error variances) were open to question. Table 1 shows the Mann–Kendall statistics for the 48 sites using the standardized deviates. Individual results obtained by using the unstandardized differences (those used by Chu et al. 1994) and by linear regression are not given in the table, since all methods gave conclusions that were identical apart from small differences of detail. It should also be noted that the procedure used to standardize the rainfall records should remove much of any decadal-scale fluctuation, if it exists, although a residue of such a fluctuation would remain where–as must inevitably be the case–the period of record is not an integral number of such fluctuations.

3. Discussion

Of the 48 τ values shown in Table 1, 23 are negative (a negative value indicates a negative trend in standardized monthly rainfall) and 25 are positive, numbers that are not inconsistent with the hypothesis of equally likely positive and negative τ values taken over the region as a whole. The 48 gauges are not randomly distributed over the hydrographic region, so we cannot necessarily deduce from this result that the net trend over the region can be taken to be zero. However, when we come to consider those values of the Mann–Kendall statistic, which are significantly different from zero at the 5% level, we find that no less than 19 of the 48 are significant, with 7 positive and 12 negative τ values. In addition to showing the sites of the 48 gauges, Fig. 1 also shows the spatial positions of the 19 significant τ values. In a series of 48 independent statistical tests, all of which use a Type I error of 0.05, we should expect 48/20, or slightly more than two such tests, to give significance purely by chance. Therefore, there is significant evidence of time trends in monthly rainfall at some sites within the hydrographic region, and we explored the possibility of spatial trends by plotting and drawing contours of equal τ values. Figure 2 shows these contours, calculated using all 48. Two other contour plots, one obtained using τ values calculated from data with the annual cycle removed but without standardizing by dividing by monthly standard deviations and the other obtained using linear regression coefficients, were virtually identical to Fig. 2 and are not presented here.

Figure 2 shows that, in general, contours of the more negative τ values tend to lie toward the west of the region, although there is evidence of an "island" of negative values near the center of the grid area. In broad terms, therefore, the rainfall records that are presently available show that negative time trends in monthly rainfall appear to be more prevalent in western and central Amazonia. The smaller number of positive time trends tend to be scattered in eastern Amazonia, at a few sites (such as Manaus) in the region of the main water course, and with one isolated positive trend to the south of the region, where the number of gauges with usable records is small. The U.K. Hadley Centre for Climate Prediction and Research (1995) has kindly provided us (Lean et al. 1995) with maps showing their most recent predictions of rainfall distribution (a) following 100% deforestation (Fig. 3) and (b) 50% deforestation (Fig. 4). Both Figs. 3 and 4, giving contours of millimeters of rainfall per day, show contour features that are qualitatively similar to those shown in our Fig. 2, although the Hadley predictions show more extensive areas of reduced rainfall, with areas of increased rainfall of 0–0.5 mm d^{-1} only in the southern part of the region. We emphasize, however, that Figs. 3 and 4 may be consistent with our Fig. 2. The latter shows trends in rainfall data over the last 30 yr or so, while the former show what is expected to happen in the future following a degree of deforestation much more extensive than in the past, subject to the various assumptions implicit in the Hadley model.

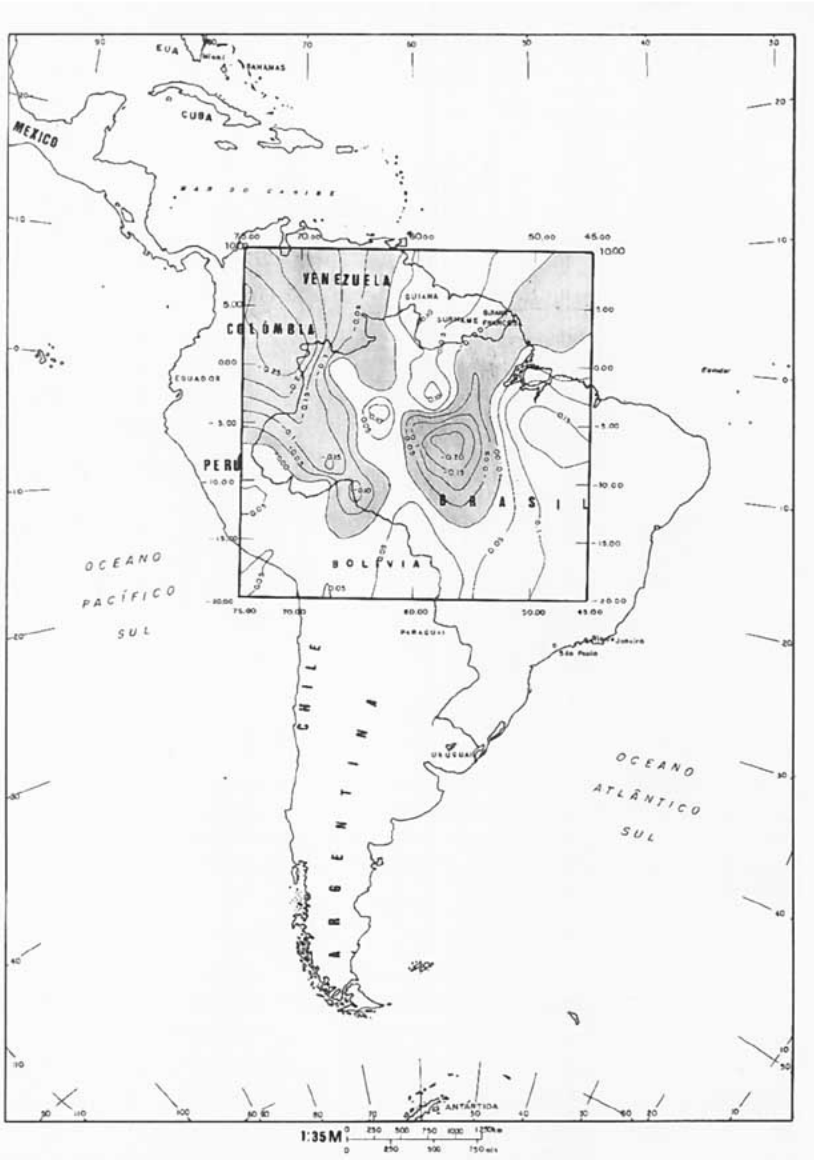

FIG. 2. Contours of equal values of the Mann–Kendall τ statistic; contours calculated using all 48 τ values, irrespective of statistical significance.

We may speculate about the small cluster of three positive τ values shown near the mouth of the Amazon in Fig. 1. Dirmeyer and Shukla (1994) report on the use of an atmospheric general circulation model, with land surface properties represented by the simplified Simple Biosphere model, to investigate the effects on local climate due to deforestation of the Amazon Basin. They conclude that precipitation averaged over deforested areas is not necessarily reduced, and while their model predicted a general reduction in precipitation over the entire Amazon Basin, it predicted an increase in rainfall over adjacent waters of the Atlantic,

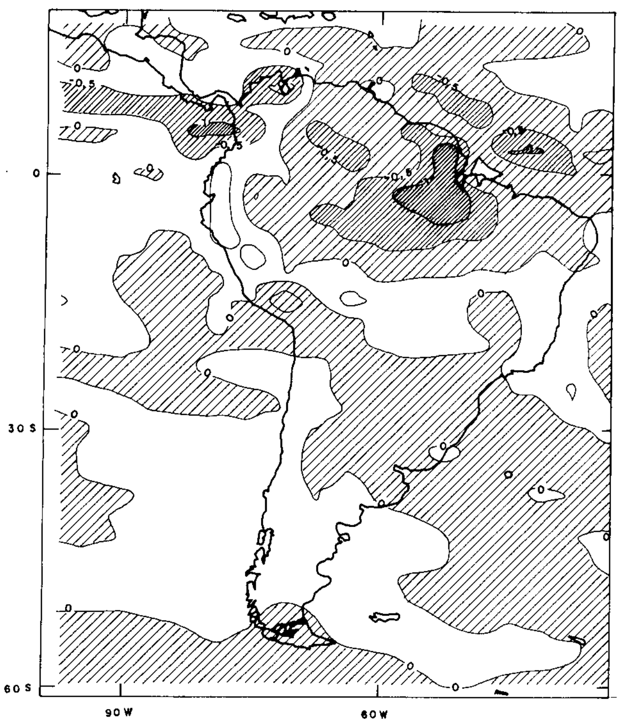

FIG. 3. Map showing changes in rainfall (mm day^{-1}) predicted by the U.K. Hadley Centre for Climate Prediction and Research using a global circulation model and assuming 100% deforestation within the Amazon Basin (reproduced by permission of the NERC Institute of Hydrology).

Pacific, and Caribbean. It is not inconceivable that the three positive τ values near the mouth of the Amazon in Fig. 1 are associated with the phenomenon described by Dirmeyer and Shukla. It would also be of interest to explore the relation between precipitation in Amazonia and Atlantic sea surface temperatures, which are said to show relations on a decadaltimescale. Unfortunately these data are not available to us.

It could also be argued that (a) any analysis for trends in Amazon rainfall should be restricted to a period of record common to all the gauges used, and (b) the rate of deforestation before, say, 1970 was much lower than in the subsequent period so that data post-1970 should be analyzed. Our view is that these arguments have no basis, so long as nonparametric tests for trend (such as the Mann–Kendall τ) are used. If deforestation is a cause of reduced rainfall and if accelerated deforestation causes rainfall to decline more rapidly, then it would indeed be inappropriate to use the same statistical description of the trend (such as a linear regression) irrespective of deforestation rate. The advantage of the Mann–Kendall τ statistic is that it makes no such assumptions.

Rainfall records always contain some element of unreliability associated with changes in local environment and reliability of observers, and it is not impossible that uncertainties from such sources are greater in the Amazon region where field observers need to be particularly strongly motivated to work in conditions of climate, discomfort, and health that are not encountered by observers in temperate regions. Nevertheless, it would be unwise to ignore the evidence of the Amazon rainfall records, and it is remarkable that modeling has been pursued so vigorously without attention to the evidence that they provide. It must also be emphasized that time trends in Amazonian rainfall are not necessarily a direct consequence of deforestation but may be the consequence of factors associated with it.

4. Conclusions

The Mann–Kendall statistic provides a test for positive or negative trend—not necessarily linear—in the standardized monthly rainfall totals, but does not readily give a value for the magnitude of a trend found to be statistically significant. But if we are prepared to accept the slopes of linear regressions as an index of trend (thereby ignoring statistical characteristics of the data that include nonnormality of error distributions and inhomogeneity of variance), the unweighted arithmetic mean of the 12 regression slopes at sites with significant negative τ values gave a reduction, per decade, of 37 mm of rainfall, while the unweighted mean of the 7 regression slopes at sites with significant positive τ values gave an increase per decade of 18 mm. The Mann–Kendall statistic does not provide evidence of other kinds of nonstationarity in rainfall records, such as where variability of rainfall in a particular month of the year increases or decreases with time; nevertheless it provides a robust test for trend, free from assumptions about the mathematical form of the trend or the probability distribution of errors.

Subject to these provisos, analysis of the 48 Amazon rainfall records using the Mann–Kendall statistic leads to two conclusions. The first is that positive and negative τ values (corresponding to positive or negative trends in monthly rainfall, whether or not these are statistically significant) occur with approximately equal frequencies: the number of positive and negative τ values do not differ by more than would be expected by chance, given the hypothesis of zero trend at all 48 sites. The second conclusion is that the number of statistically significant τ values is greater than would be expected by chance, given that the hypothesis of overall trend is absent. Using a Poisson approximation with $\mu = 48/20$ to calculate the binomial probability of observing 19 or more significant τ values, out of 48, when the tests have Type I error of 0.05 = 1/20, it is found that the probability of observing 19 or more

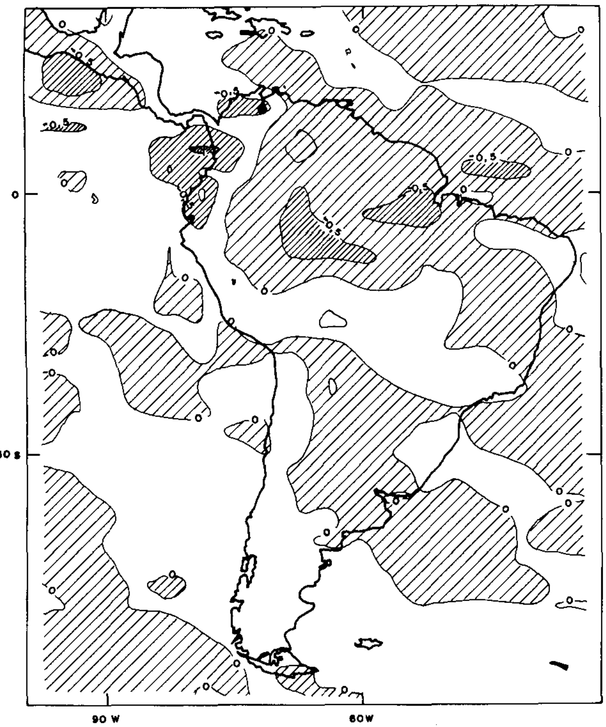

FIG. 4. As for Fig. 3 but assuming 50% deforestation.

significant trends is 1.418×10^{-11}, a very small quantity. Hence, we are led to the conclusion that, while positive and negative trends occur in roughly equal numbers over the region as a whole, the number of positive and negative trends that are statistically significant is much greater than could be expected by chance. Furthermore, the number of significant negative trends is significantly greater ($P < 0.025$) than the number of significant positive trends.

Finally, there is some qualitative agreement between the disposition of contours defining regions of negative trend (reduced rainfall) in the rainfall records and the contours defining regions of reduced rainfall following 50% deforestation, as predicted by the Hadley Centre for Climate Prediction and Research. However, the rainfall records show positive trends (increased rainfall, confirming the conclusion of Chu et al. 1994) in some parts of the region where the Hadley Centre predicts reduced rainfall following deforestation of 50% or more.

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