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Spatial patterns and recent trends in cloud fraction and cloud-related diffuse radiation in Amazonia

Nathalie Butt,[1] Mark New,[2] Gil Lizcano,[2] and Yadvinder Malhi[1]

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[1] As the climate of tropical forest regions changes, there are likely to be concurrent changes in cloud cover and in the light regime experienced by tropical forest canopies. We utilize data from the International Satellite Cloud Climatology Project to examine spatial patterns and trends in cloud cover over Amazonia during the period 1984–2006. Cloud cover seasonality appears to be increasing in Amazonia, with a significant decline in dry season cloud fraction (0.3% yr^{-1}) and increase in wet season cloud fraction (0.1% yr^{-1}) over the last two decades. A novel cloud-related diffuse radiation (CRDR) climatology for Amazonia was derived from satellite cloud data. There is a clear decreasing gradient from the northwest to the southeast: annual CRDR proportion (CRDRP) varies by about 15% across the region. Analysis of trends over time indicates a 1–2% decline in CRDRP in Amazonia over the last two decades, particularly in the east of the region. This is particularly marked in the dry season in the east where CRDRP declined at a rate of 0.3% yr^{-1}, and the wet season decline was 0.1% yr^{-1}. In the west of the region a 1% increase in CRDRP is indicated. Changes in forest composition and productivity may be linked to changes in CRDRP in that decreases in cloud cover in sunny regions or dry seasons may cause a decline in productivity, whereas declines in cloud cover in cloudy regions, or during cloudy seasons, may cause an increase in productivity.

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1. Introduction

[2] In the Earth's climate system, clouds influence the amount and nature of incoming solar radiation, and thus ecosystem primary production. Increases in Amazon rain forest net primary production (NPP) over recent decades have been variously linked to changes in cloud cover and solar radiation and/or $\mathrm{CO_2}$ fertilization [*Lewis et al.*, 2004]. *Nemani et al.* [2003] explored the three-way interaction between radiation, moisture availability and temperature as related to ecosystem NPP and suggested radiation was the primary constraint on Amazon forest productivity. Using International Satellite Cloud Climatology Project (ISCCP) global monthly data for cloud cover, and Earth Radiation Budget Experiment daily observations of total solar irradiance data, *Nemani et al.* [2003] proposed that the >1% yr^{-1} increase in modeled NPP in this region was driven by cloud cover decrease and total radiation increase.

[3] Although these results were derived from models, *Graham et al.* [2003] also found tropical forest $\mathrm{CO_2}$ uptake and growth were limited by radiation during the wet season using field experiments: there were significant increases in photosynthesis, vegetative growth and reproduction with enhanced irradiation. The picture is further complicated by seasonality and weather events such as El Niño/La Niña: El Niño acts to reduce cloud cover, and thus increase radiation, while La Niña generally has the opposite effect. It remains unclear exactly how system-wide responses in NPP are related to changes in solar radiation; for example, *Clark et al.* [2003] found no relationship between eight years of annual pyranometer irradiance (total radiation) and interannual variations in canopy species tree growth in their tropical forest plots. However, as total and diffuse radiation influence photosynthesis and productivity differently, it may be that changes in diffuse radiation proportion do not act strongly on canopy trees.

[4] Confusion as to the conclusions of different research [*Fearnside*, 2004] is confounded by the fact that definite trends in tree growth in lowland tropical forest have not been conclusively established. There is thus no across-the-board agreement from forest plot data, and it has been indicated that tree growth and NPP are both decelerating [*Clark et al.*, 2003; *Feeley et al.*, 2007], and accelerating [*Laurance et al.*, 2004; *Lewis et al.*, 2004] in tropical forests. This uncertainty is further complicated by issues of scale: some of these studies have been at stand level, some looking at several species only, while others were carried out at biome level. However, the larger scale data set analyses do suggest increasing dynamism: perhaps not apparent in smaller scale analyses such as that by *Clark et*

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[1] Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, UK.

[2] School of Geography and the Environment, University of Oxford, Oxford, UK.

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al. [2003], where the dynamics of recruits were not included, and *Feeley et al.* [2007].

[5] The differential response of vegetation, such as in terms of seedling crown orientation/light interception, to diffuse and direct radiation is well known [*Ackerly and Bazzaz*, 1995], and it has also been shown that vegetation productivity is sensitive to fluctuations in diffuse radiation [*Roderick et al.*, 2001]. Diffuse radiation penetrates deeper into the lower canopy than direct radiation and there is evidence that where diffuse radiation has increased, radiation use efficiency (i.e., uptake of carbon dioxide and thus productivity) has also risen in different systems [*Healey et al.*, 1998; *Rocha et al.*, 2004].

[6] While vegetation models can offer important insights as to how productivity may be changing with changes in climatic and atmospheric variables, they do not generally include diffuse radiation as an input (at best they tend to use a two-stream approximation method to estimate it from the direct radiation input) and thus are unable to predict/analyze the dynamic interaction between diffuse radiation and productivity. Another complicating factor is that a plant's physiological response to radiation inputs to the system varies at different stages in its life cycle (i.e., seeds, seedlings, saplings and adult trees respond differently).

[7] Plant distribution and productivity are thus closely related to variation in incident solar radiation (insolation), but there has been little investigation of cloud cover and diffuse radiation in tropical South America. It has not yet been quantified how diffuse radiation and forest productivity and dynamism here are related, and how diffuse radiation budgets may change with climate.

[8] Clearly, as a first step to unraveling system NPP relationships with diffuse radiation it is necessary to quantify diffuse radiation variations in space and time. In this paper we describe the development of a large-scale, high-resolution, cloud-related diffuse radiation proportion (CRDRP) climatology, using satellite cloud data. We first discuss the satellite data and describe the model we will use. We then consider recent trends in cloud fraction, present the CRDRP climatology for Amazonia, and consider CRDRP trends in relation to forest productivity.

2. Data and Methodology

[9] The ISCCP, originally set up in 1982 to gather data about how clouds affect the radiation budget of the Earth [*Schiffer and Rossow*, 1983], provides high-resolution coverage of our region of interest (Amazonia) from the mid-1980s onwards. Although some analyses of these satellite data have previously suggested that apparent trends may be artifactual with regard to low-level cloud measurements [*Evan et al.*, 2007], an evaluation of ISCCP and long-term surface-observed cloud cover data gives a strong indication that cloud cover (specifically high level cloud, but also in general) has decreased globally from the 1970s [*Norris*, 2005]. *Warren et al.* [2007], using meteorological station data, found a large decrease in cloud cover for South America for the period 1971–1996, and that interannual variations in tropical regions were correlated with ENSO. Their analyses showed small decreases for Eurasia and Africa, while there was no significant trend in North America.

[10] Earlier studies have used satellite data to estimate surface radiation [e.g., *Gautier et al.*, 1980; *Dedieu et al.*, 1987; *Stuhlmann et al.*, 1990], but diffuse radiation has previously been approximated by using the negative correlation between diffuse fraction (diffuse/total surface radiation) and atmospheric transmission (total surface/extraterrestrial radiation). Our model, derived using high temporal resolution data, predicts CRDRP directly from either ground or satellite-derived cloud fraction. This measure of diffuse radiation is referred to as 'cloud-related diffuse radiation' as it is not a measure of clear sky diffuse radiation proportion and also does not deal with diffuse radiation induced by atmospheric haze, which may be particularly important in biomass burning seasons [*Rosenfeld*, 2006].

2.1. Satellite Data

[11] The ISCCP DX product is derived from data collected by polar and geostationary satellites, and is a 3 hourly cloud/cloud free value based on a cloud fraction algorithm, analyzed per 30 km × 30 km mapped pixel. This method assumes that each 'cloud' pixel is 100% covered by clouds. Complete 1984–2006 3 hourly ISCCP DX Pixel Level Cloud Cover data are processed for each individual satellite and are then aggregated to a 0.5° grid across Amazonia: the first time DX data have been used in this way.

[12] These per-pixel values are then aggregated to cloud fraction estimates three times a day, as a mean of the three hours upon which the data are centered (for example, values for 09:00 are the mean of the data from 07:30–10:30). Data were available daily at 3 hourly UMT/GMT time steps for each time zone. For each pixel we take the weighted averages of the adjacent 3 h values to derive the local 09:00, 12:00 and 15:00 estimate. This linear interpolation and distance weighting (proportional to the distance to the longitude border of each time zone) is applied across the entire region, and these values are aggregated to daily means. The data were assessed at daily, 5 daily, 10 daily and monthly means to establish the best correlation with observed cloud fraction (using our high-temporal frequency data from a weather station in Brazil, as used in the model described in section 2.5). This is because ten days is a long enough period to smooth out anomalous fluctuations, yet retains sufficient data points to provide a statistically robust correlation. We thus use this ten day averaging period, but where we do use monthly means they are derived from these 10 day data. We also derive annual averages using these 10 day daily means for each pixel.

2.2. Data Set Comparison

[13] To test the robustness of the new DX data processing we cross-compare our 0.5 degree cloud fraction data with the station data of *Hahn and Warren* [2003]. This large data set is compiled from millions of visual observations of cloud cover made at thousands of weather stations worldwide, between 1971 and 1996. The period 1984–1996 is covered by both these observed station data and our ISCCP satellite data. The ISCCP D2 product is also used to compare large-scale trends: these data cover part of the same temporal range as the DX data (1984–2001) but are at lower spatial resolution than the DX data. The D2 cloud fraction is derived from the proportion of cloudy pixels over

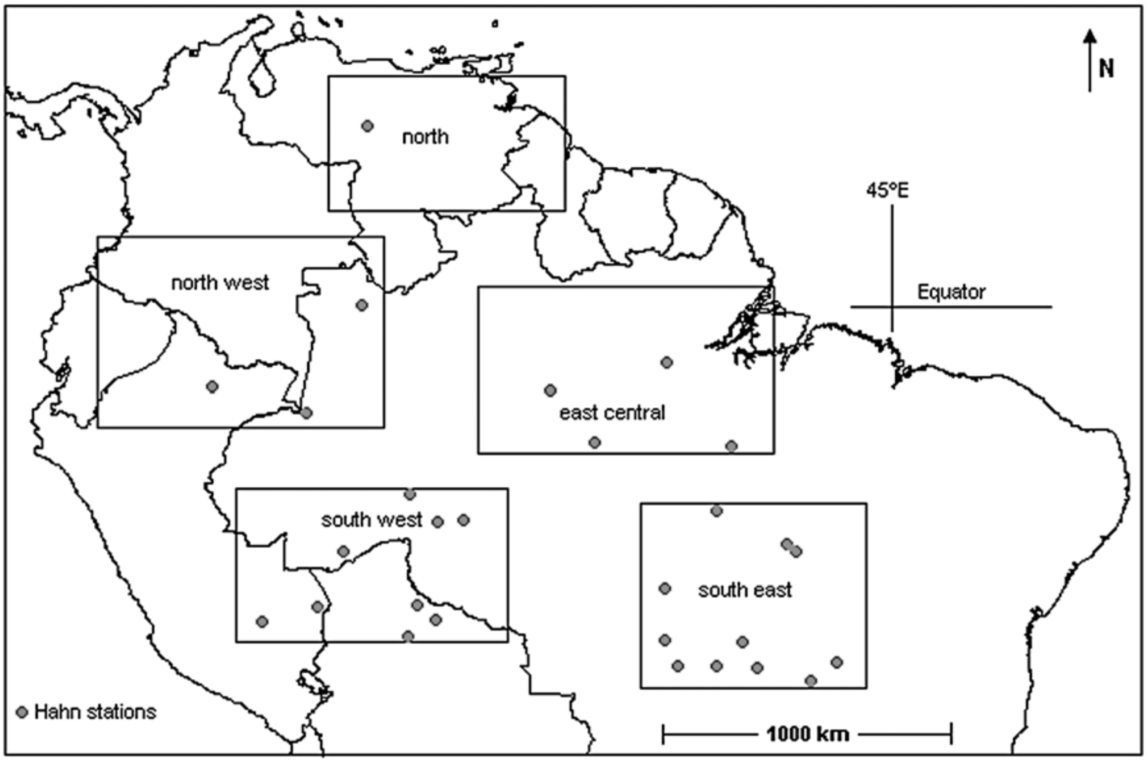

Figure 1. Location of the five subregions. Grey discs represent the Hahn stations.

an approximately 280 km equal-area grid and is calculated by dividing the number of cloudy satellite pixels by the total number of pixels [*Rossow et al.*, 1996].

2.3. Satellite Coverage Variations

[14] During the course of the 23 years of the DX data, several different satellites were utilized to generate the data set. We use data from GOES (geostationary operational environmental satellite) 6, 7, 8 and 12; these cover the years 1984–2006. As there was a distinct step change in the cloud fraction data at the GOES 7–GOES 8 changeover, we adjusted the GOES 6 and GOES 7 data using a calibration factor (see auxiliary material Figure S1).[1] This removed the step without altering any long-term trends.

2.4. Seasonal Variations and Trend Analysis

[15] Using Climate Research Unit (CRU) long-term precipitation data [*New et al.*, 1999] we establish the dry quarter and wet quarter (driest and wettest three months, respectively), using mean monthly totals, for each 0.5 degree pixel. For each pixel we then calculate the corresponding dry and wet quarter cloud fraction using monthly means (derived from the 10 day data), in order to explore possible seasonal variation in cloud fraction.

[16] We select five subregions, east-central, north, northwest, southeast and southwest (Figure 1), and investigate the long-term annual and monthly trends in each region. We then compare each with the overall, basin-wide trends.

[17] We also include CRU and Climate Prediction Center Merged Analysis of Precipitation (CMAP) rainfall data (http://climexp.knmi.nl, accessed January 2009) for comparison with CRDRP of spatial patterns and trends over time. We apply Sen's slope estimator (as described by *Alexander et al.* [2006]) to our data to establish the statistical significance of cloud fraction, CRDRP, and rainfall trends over time.

2.5. Cloud-Related Diffuse Radiation Model

[18] The relationship between cloud-related diffuse radiation proportion and cloud fraction has previously been quantified using observations at two sites in the Amazon basin, and we developed an empirical model to predict cloud-related diffuse radiation from cloud fraction (N. Butt et al., Diffuse radiation and cloud fraction in two contrasting Amazonian forest sites, submitted to *Agricultural and Forest Meteorology,* 2009). Although diffuse radiation is very highly correlated with cloud fraction, the quantity of diffuse radiation is relevant for ecophysiological interpretation and thus we apply the model to acquire long-term and large-scale estimates of CRDRP. The model is a predictive empirical model of the form:

$$\mathrm{CRDRP} = R_d/R_s = \mathrm{a} + \mathrm{b}\,cl, \qquad (1)$$

where R_d = diffuse radiation at surface, R_s = total radiation at surface, cl = cloud fraction; a = 0.15 (±0.07), b = 0.71 (±0.10).

3. Results

3.1. Data Set Comparison

[19] Across the whole region, the DX and D2 cloud fraction and CMAP and CRU rainfall annual cycles closely

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[1] Auxiliary materials are available with the full article. doi:10.1029/2009JD012217.

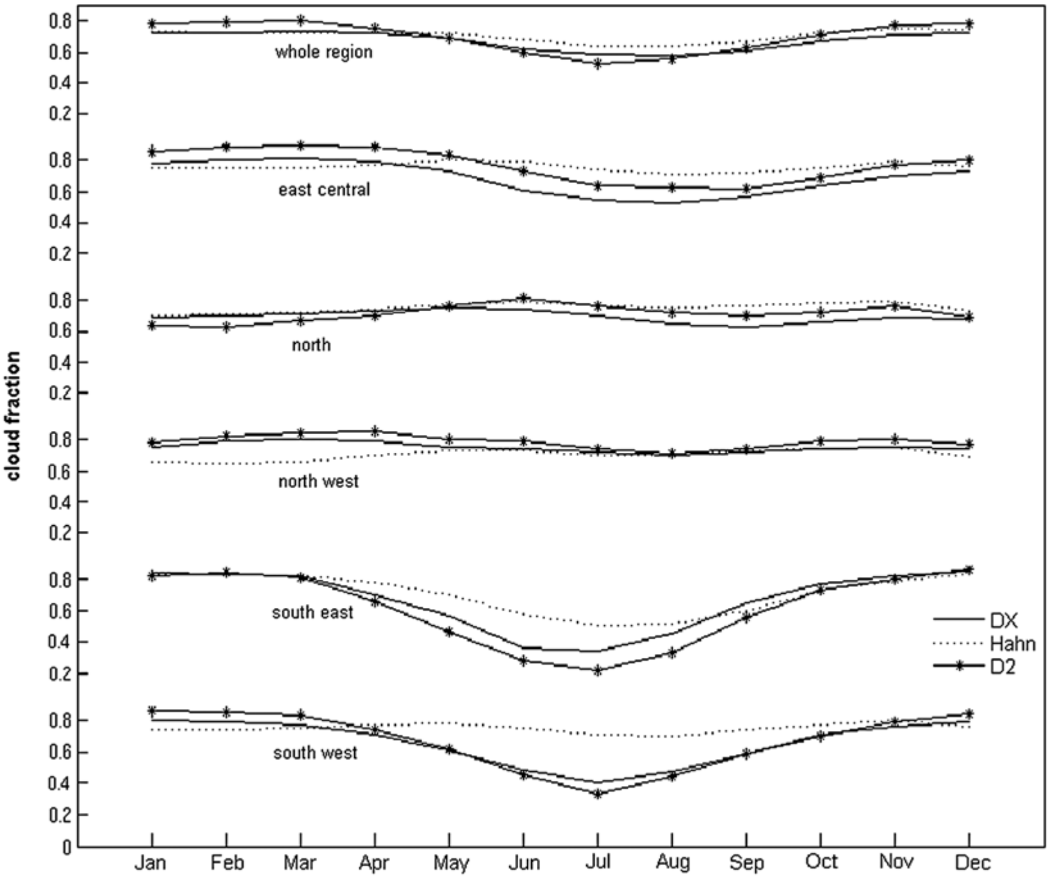

Figure 2. Annual cycle comparison of long-term cloud fraction means for the three data sets (DX, D2, and Hahn) for the region as a whole and the 5 subregions.

followed the same pattern, with a reduction across June–September; D2 had the strongest seasonal variation (Figure 2). For the subregions, the DX and D2 cloud fraction seasonal trends were similar, whereas the Hahn station cloud data did not show as strong a seasonality in any of the five subregions. Interestingly, in the north region, none of the three cloud fraction cycles fluctuated as strongly as the rainfall, which peaks in June/July/August. As this area is less seasonal than southern (drier) regions, and has year-round cloud and rainfall, the mid wet season rainfall spike may not be related to an increase in cloud cover.

[20] The Hahn station data are spatially sparse. There are four stations in the east-central region, nine in the southwest, three in the northwest, eleven in the southeast and one in the north region (Figure 1). It is therefore possible that there are regional biases operating which are responsible for at least some of the disparity between the seasonal cycles of the station and satellite data. Comparisons of individual stations with nearest pixel DX data indicated that in general the station cloud fraction values fluctuated more and were on average slightly higher than the satellite cloud fraction data; generally ISCCP values have been estimated to be approximately 0.1 lower than observed values [*Rossow and Schiffer*, 1999]. Where availability for the two data sets coincided, most of the comparisons gave a reasonable match.

[21] Long-term trends in both the satellite and station cloud fraction data are negative. For the region as a whole, and for all the subregions individually, the D2 data showed a significant ($P < 0.01$) reduction in cloud cover; the DX data showed a marked decrease for the region as a whole and for the eastern regions ($P > 0.10$); and the Hahn station data showed a significant overall regional decline in cloud cover ($P < 0.05$) (see auxiliary material Table S1 for details). Regionally, the mean seasonal cycles of the three data sets did not differ significantly.

[22] Basin wide, the D2 cloud fraction data vary least across the year but show the strongest negative trend over time. Hereafter we use the DX data product for the modeling and analyses as, in addition to the strong correspondence with the annual rainfall cycle, these data have the longest temporal range, a larger and more consistent spatial coverage than the station data, and a higher spatial resolution than the D2 data. We were also able to work with individual satellite data sets using the DX product, whereas the D2 product provided only one aggregated data set.

3.2. Monthly and Seasonal Analyses of Cloud Fraction Patterns

[23] Analyzing the long-term trends in cloud fraction on a monthly basis, the period May to August showed a strong decrease in cloud fraction (0.35% year^{-1}, 8% overall average for May–August) averaged over the whole region (Figure 3; Table 1 gives P values for the trends). There was also a significant increasing trend across the whole region for February. This implies an overall increase in cloud fraction seasonality. By subregion, east-central Amazonia had a strong decrease in cloud fraction in the late dry season

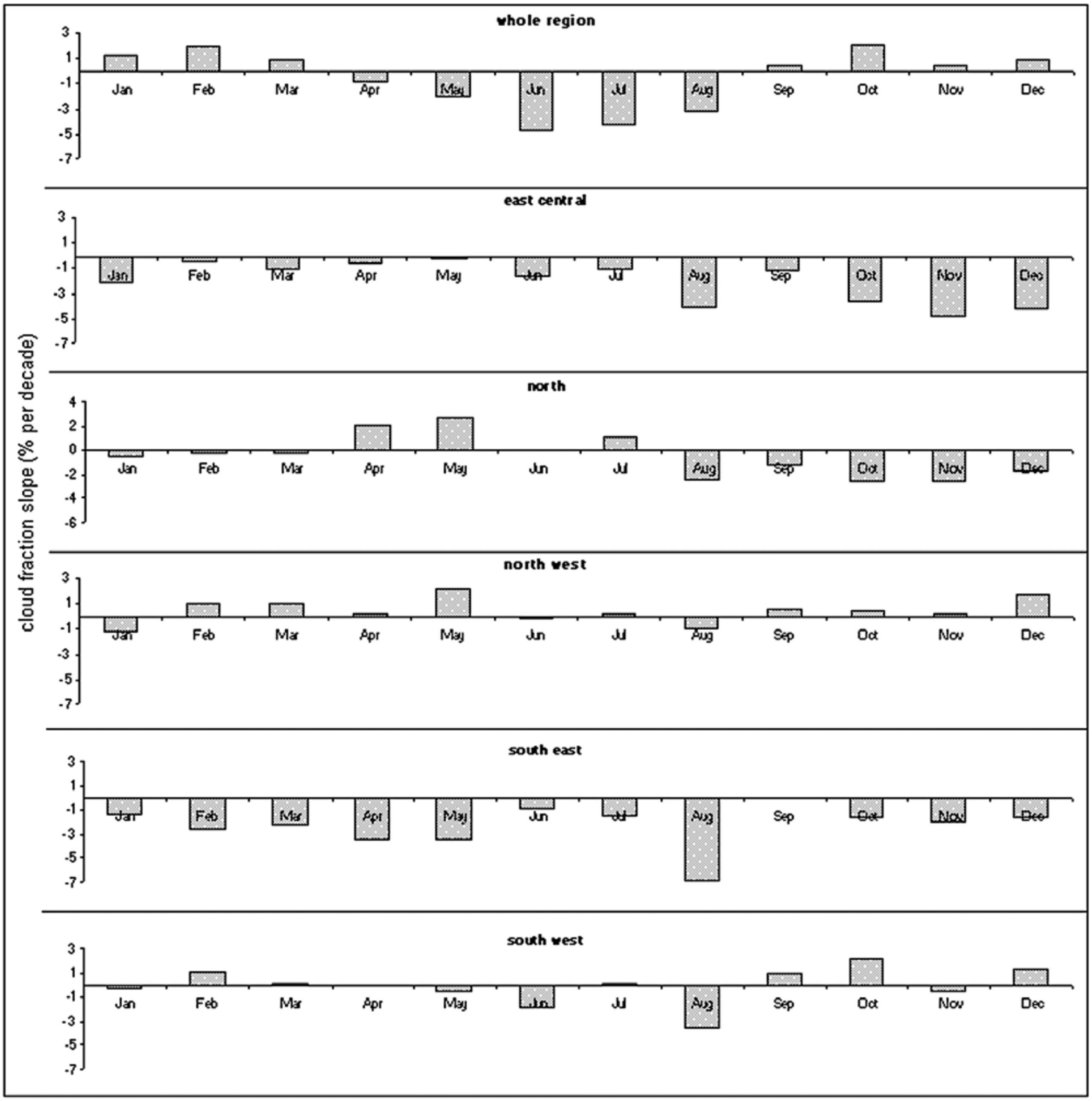

Figure 3. Monthly trends in cloud fraction (% cloud fraction per decade), by region, for the period 1984–2006.

(October and November), and the north region had a strong decrease in the local late wet season (August and October). In the northwest, the wettest and least seasonal region, there was a positive trend in cloud cover for all months apart from January, June and August. In the southwest there was no strong trend, though some indication that cloud fraction generally declined in the dry season (middle months of the year) and increased at other times. The largest year-on-year decline was for August cloud cover in the southeast; this coincides with the driest, and peak burning, season in the most rapidly deforesting region of Amazonia. This is also the region most likely to experience rainfall decline as a consequence of global climate change [*Malhi et al.*, 2008].

Table 1. P Values for Slope Trends in Cloud Fraction Over Time by Month and Region

	Whole Region	East Central	North	Northwest	Southeast	Southwest
January	0.17	0.19	0.87	0.32	0.43	0.79
February	0.03	0.74	0.96	0.29	0.43	0.19
March	0.40	0.40	0.87	0.25	0.14	0.91
April	0.44	0.57	0.31	0.83	0.18	1.00
May	0.01	0.75	0.14	0.01	0.20	0.75
June	0.00	0.46	1.00	0.87	0.63	0.43
July	0.01	0.67	0.60	0.75	0.60	1.00
August	0.01	0.13	0.09	0.34	0.29	0.20
September	0.92	0.63	0.43	0.56	1.00	0.71
October	0.20	0.06	0.05	0.75	0.40	0.04
November	0.79	0.04	0.15	0.85	0.20	0.79
December	0.25	0.11	0.34	0.32	0.14	0.13

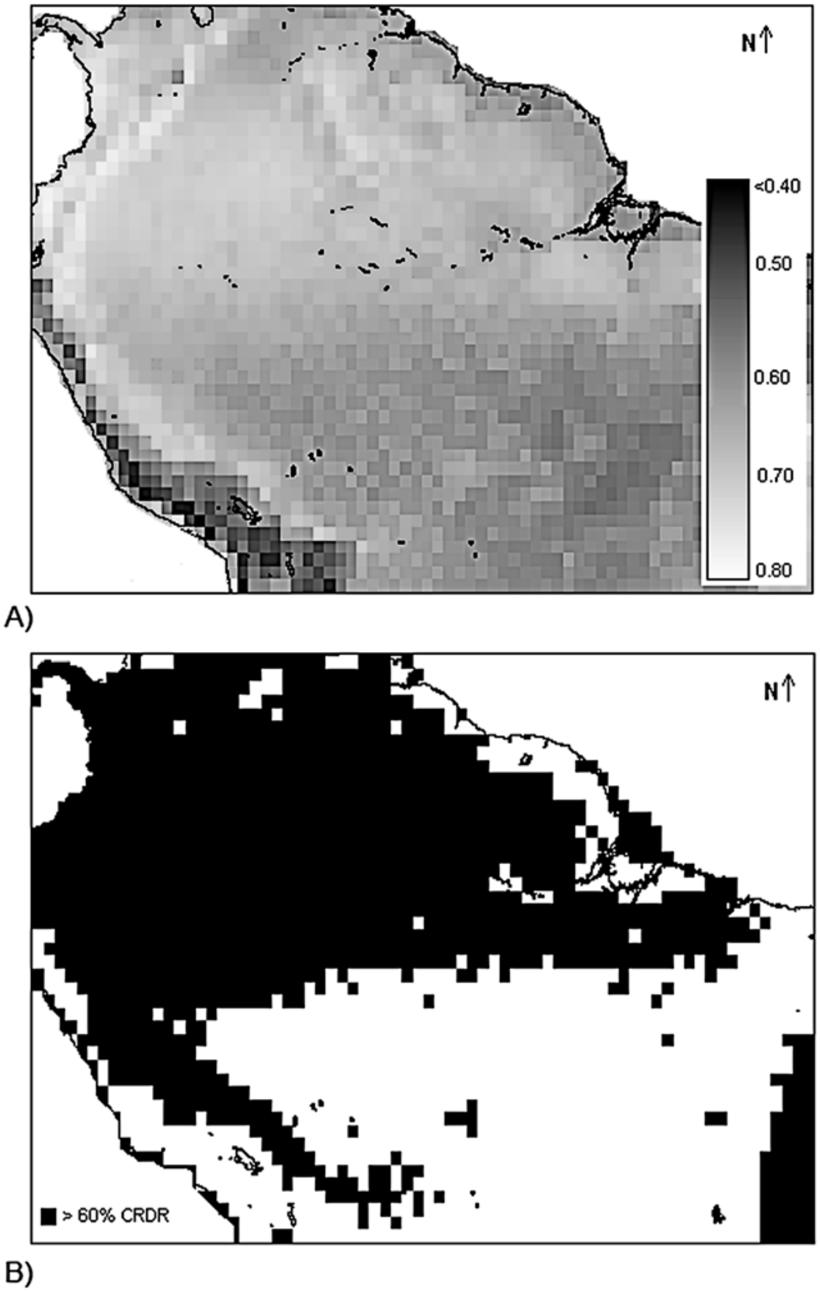

Figure 4. (a) Long-term CRDRP means, calculated from 10 day averages as modeled from the International Satellite Cloud Climatology Project DX cloud fraction. The numbers are CRDRP values. (b) Areas where CRDRP is >~60%.

[24] We also analyzed possible seasonal variations in cloud fraction. The driest quarter across the whole region showed a highly significant decreasing trend in cloud fraction over time ($P < 0.01$) and the wettest quarter a moderately significant increase ($P < 0.10$). Amazon-wide, the dry season showed a year-on-year decline of about 0.3% year^{-1} in cloud fraction, while the wet season cloud fraction increased by about 0.1% year^{-1}.

3.3. CRDRP Climatology

[25] The spatial distribution of modeled CRDRP derived from long-term means shows a broad gradient from the south of the region (with the lowest CRDRP) to the north (Figure 4a). The northwest had the highest; a 71% long-term mean, and the southeast the lowest CRDRP; a 58% long-term mean. As we would expect, this tallies with the precipitation and cloud gradient from the drier south to the wetter north. The mean CRDRP for the whole region was 68% and the range was from just under 50% in the southeast to 74% in the northwest. Also as we would anticipate, the highest proportion of CRDRP was found over the montane cloud forests on the eastern flank of the Andes mountain range. The areas where mean CRDRP is greater than 60% are indicated (Figure 4b). This is a physiologically

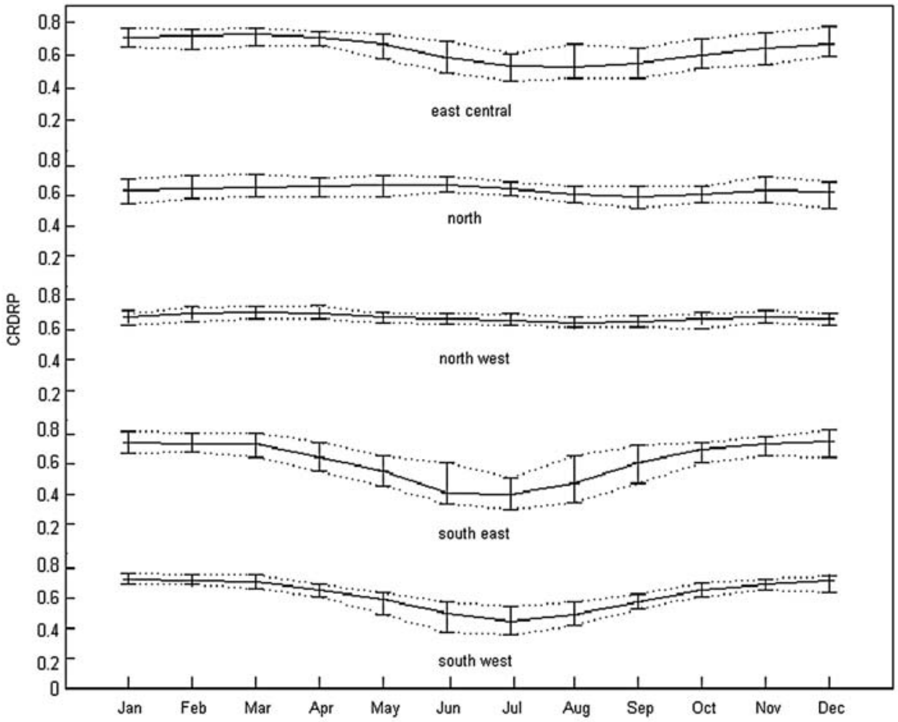

Figure 5. Long-term modeled CRDRP minima, maxima, and means for the 5 subregions.

significant threshold in terms of forest productivity in relation to light regimes.

[26] Long-term minima, maxima and means clearly show the differences between the regional annual cycles (Figure 5). The largest fluctuation in CRDRP was in the southern regions, an approximately 35% difference between the wet and dry seasons (November–March and June–September, respectively). The north and northwest regions showed the smallest change, a < 5% fluctuation, as would be expected in this largely aseasonal area. The CRDRP seasonal cycle in the east-central region was less pronounced than in the south but stronger than in the north; the fluctuation between the wet and dry seasons here (January–April and June–September, respectively) was approximately 20%. In the drier southwest the interannual variability in rainfall and CRDRP are well aligned. In the northern regions however, while rainfall shows interannual variability, CRDRP fluctuates less over time; suggesting that in aseasonal areas CRDRP (and cloud amount) is decoupled from rainfall.

[27] In terms of trends over time, the CRDRP inevitably mirrored trends in cloud fraction (the slope trends are for cloud fraction, although the values are slightly smaller; see Figure 3). There was a small decrease in CRDRP over the whole region, with the southeast, north and east-central regions all showing downward trends (see auxiliary material Figure S2). Annual rainfall increased by 2% across the region as a whole ($P < 0.10$), and 5% in the northwest ($P < 0.05$), between 1984 and 2006. The interannual fluctuations in the rainfall are largely governed by ENSO cycles. In terms of quantitative changes in CRDRP, the region as a whole and the north showed an annual 0.05% annual decrease, and east-central and southeast regions a 0.1% annual decrease. The northwest and southwest regions showed very small annual increases: 0.04% yr^{-1} and 0.03% yr^{-1}, respectively. See Table 2 for P values for trends in CRDRP (and cloud fraction) and rainfall, for seasonal and annual analyses, and annual rates of change for strong trends (CRDRP and cloud fraction z statistic and P values are the same).

4. Discussion

[28] The DX data were selected to use for cloud fraction input to the CRDR model after comparison with one other satellite data set and one station data set. The advantage of using satellite data is that they can provide reliable data sets at large spatial scales where it would not be possible to have a station network of sufficient density to provide the same accuracy of coverage at reasonably high resolution.

[29] Although the ISCCP program and its products were not specifically designed for long-term trend analysis, analyzing the data by cross-comparing at different spatial scales means that we can draw cautious conclusions about the changes in cloud fraction and CRDRP in Amazonia. Inspection of the dates and locations of satellite and satellite instrument changes indicated no significant inhomogeneities, but one small one: we accounted for the step change at the GOES 7–GOES 8 changeover with a calibrated adjustment (see auxiliary material Table S1). The comparison of the satellite data with ground-observed station data suggests that although the large-scale trends are in accord, the highly localized nature of the station data means it is difficult to make inferences at intermediate scales using these data.

[30] For the first time for Amazonia, we have here produced a CRDRP climatology, and identified a clear broad north–south gradient across the region for this newly quantified physical parameter, more specifically oriented southeast-northwest. This ranges from a low of 50% in the

Table 2. The 1984–2006 Trends in Rainfall, CRDRP, for Annual and Seasonal Means, for the Whole Region and the Five Subregions[a]

	Rainfall			CRDRP		
	Annual Means	Wet Season	Dry Season	Annual Means	Wet Season	Dry Season
Whole region	inc (0.08)			dec (0.17)		
East central	inc (0.10)	inc (0.02)	dec (0.43)	dec (0.43) 0.1%	dec (0.63)	dec (0.11) 0.3%
North	inc (1.00)	inc (0.14)	inc (0.06)	dec (0.28)	inc (1.00)	dec (0.87)
Northwest	inc (0.01)	inc (0.01)	inc (0.29)	inc (0.27)	dec (0.14)	inc (0.56)
Southeast	inc (0.29)	inc (0.34)	dec (0.13)	dec (0.27) 0.1%	dec (0.10) 0.1%	dec (0.19) 0.3%
Southwest	inc (0.79)	inc (0.08)	inc (0.71)	inc (0.60)	dec (0.10)	dec (0.63) 0.1%

[a] Trends in rainfall are year^{-1}; CRDRP comprises cloud fraction from the International Satellite Cloud Climatology Project DX Product; inc is increase; and dec is decrease. P values (in brackets) calculated from Sen z statistic. Annual percentage rates of change are included for strong CRDRP trends.

southeast to a high of 75% in the northwest, with a greater than 15% annual difference between the northwest and the southeast in mean CRDRP.

[31] We explored the seasonal and annual variability of cloud fraction and CRDRP and found a general decrease in cloud fraction in the dry season; annually this was 0.3%, which amounted to a 6% decline over two decades for the whole region. All regions except for the northwest showed a dry season decline, while all regions, with the exception of east-central and southeast regions, showed a wet season increase in cloud fraction. In less seasonal areas, fluctuations in cloud fraction may be independent of variations in rainfall. There has been a region-wide decrease in CRDRP over the 23 year data period, especially in the east-central and southeast regions, while in the northwest and southwest there has been an increase. The decrease in CRDRP is <0.1% year^{-1}, approximating to a 1% total decrease in CRDRP over the last two decades. Plant-climate interactions have long been established; it would be logical to infer that the CRDRP gradient is also reflected in the distribution of plants differently adapted to high and low diffuse radiation conditions.

[32] The strong decrease in cloud fraction over time in the east of the region, and the significant decline in dry season cloud fraction, especially in the drier south of the region, are quite large and may be ecologically significant for forest dynamism in these regions. As there are also wet season increases in cloud fraction, we conclude that cloud fraction seasonality is increasing, along with rainfall seasonality, as also found by *Laurance et al.* [2009]. This increase in seasonality (wetter wet seasons and drier dry seasons) is also consistent with predictions from most climate models [*Malhi et al.*, 2009].

[33] How changes in cloud fraction affect forest photosynthesis and productivity depends on the degree of limitation of overall light supply. Under very cloudy conditions productivity is likely to be limited by total solar radiation, and hence a decrease in cloudiness would cause an increase in productivity. Under lower cloud amount conditions, however, productivity is not generally limited by total radiation, and a decrease in cloud amount may cause a decrease in productivity because the total amount of diffuse radiation declines, resulting in less light penetrating the deeper canopy and thereby a decline in photosynthesis. Moreover, increased sunshine in the water-limited season may increase water stress and additionally reduce productivity. Hence decreasing cloud cover in cloudy areas may tend to increase productivity, while decreasing cloud in sunny areas, or during sunny/dry periods of the year, may decrease productivity. The threshold between these two regimes appears to be approximately where R_d/R_s = 50% for a temperate forest [*Hollinger et al.*, 1994], and around 60% for two sites in Brazilian Amazonia [*Oliveira et al.*, 2007]. If we apply this 60% threshold to our CRDRP mean values for the region (see Figure 4b), we can identify areas where a decline in diffuse radiation could lead to decreasing productivity (south and southeastern Amazonia) and conversely where decreasing diffuse radiation proportions could result in increasing productivity (north and northwestern Amazonia).

[34] Although the CRDRP (and cloud fraction) appears to be decreasing, across the whole region and especially in eastern areas there appears to be an increase in rainfall; significant in the northwest region annually, and in the northwest and in east-central regions in the wet season (CRU/CMAP). This apparent decoupling between rainfall and CRDRP may be related to changes in cloud type, as cloud dimensions are controlled by thermodynamic forcing, or the physical properties of aerosols which can affect cloud both directly and indirectly, and act to decrease and increase cloud while also affecting the residence time of rain within the cloud [*Koren et al.*, 2008; *Kaufman and Koren*, 2006]. There is uncertainty as to whether aerosol levels are increasing or decreasing in the Amazon long-term, with increases in biomass burning further confounding the issue [*Kerr*, 2007], but it is likely that, at least during the study period, they have risen (as deforested area has increased). While this work does not assess the direct effects of aerosols on diffuse proportion, we have previously related a limitation in the predictive power of the model to dry season anthropogenic activity (Butt et al., submitted manuscript, 2009). Clear sky diffuse radiation increases are likely to be caused by a build-up of atmospheric aerosols and dust: there are well-documented spikes in the aerosol loading in South America during August and September [*Holben et al.*, 2001]. Hence, near biomass burning regions, the increase in clear sky diffuse radiation may offset or be greater than the decrease in cloud-related diffuse radiation, leading to an overall increase in diffuse radiation and productivity.

[35] The indicated significant dry season decrease in cloud fraction and CRDRP over the last two decades, combined with the increase in temperature [*Malhi et al.*, 2008], may have contributed to changes in forest dynamism, which could account for some of the changes in forest productivity and composition suggested in other work [e.g., *Phillips et al.*, 2004; *Wright et al.*, 2004; *Laurance et al.*, 2004; *Chave et al.*, 2008]. Factors such as rainfall, total radiation and atmospheric CO_2 amount are also suggested to

be triggers [*Lewis et al.*, 2004; *Phillips et al.*, 2004; *Malhi and Wright*, 2004]. Although the changes in CRDRP (and cloud fraction) are moderate, plants are very sensitive to changes in moisture availability and the combination of increasing temperature and increasing CRDRP seasonality in some areas may be enough to cause changes in productivity in forests currently at the edge of their 'ecophysiological comfort zone'.

[36] **Acknowledgment.** N. Butt's Ph.D. was funded by NERC grant NER/S/J/2004/13097, awarded to O. Phillips, Y. Malhi, and M. New.

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N. Butt and Y. Malhi, Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Rd., Oxford OX1 3QY, UK. (nathalie.butt@eci.ox.ac.uk)

G. Lizcano and M. New, School of Geography and the Environment, University of Oxford, South Parks Rd., Oxford OX1 3TB, UK.