

# Variations of low cloud properties by aerosols and precipitation viewed from satellites

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**Abstract:** Clouds are dominant in deciding the earth radiation and energy budget. Since cloud reflectivity and transmissivity are controlled by its optical properties, it is important to know the relationships between cloud optical properties and relevant parameters. Focusing on precipitation as a relevant parameter in this work, following analyses were performed. Comparisons between the precipitation amount,  $P$ , and monthly-averaged cloud properties (optical depths of low-level water clouds,  $\tau_{\text{low}}$ , and "total clouds",  $\tau_{\text{tot}}$ , effective particle radius,  $r_e$ , and columnar-integrated droplet number of low-level water clouds,  $N_c$ ) over the Amazon basin elucidated the effect of precipitation on low cloud properties and the relationship between precipitation and "total cloud" cover.  $P$  was constructed from ground-based rain gauge data. Low cloud properties such as  $\tau_{\text{low}}$ ,  $r_e$  and  $N_c$  are retrieved from Advanced Very High Resolution Radiometer (AVHRR) remote sensing. Total cloud optical depth  $\tau_{\text{tot}}$  was taken from International Satellite Cloud Climatology Project (ISCCP) products. The relationship between  $r_e$  and  $P$  was positive, while the relationship between  $N_c$  and  $P$  was negative. Because low clouds in this region generally produce little precipitation, these relationships may reflect the scavenging of aerosols by precipitation and suggest the aerosol indirect effect of the first kind. The relationship between  $\tau_{\text{tot}}$  and  $P$  was positive because the "total clouds" included actual precipitating clouds. The thicker clouds are optically, the more water they usually contain.

**Keywords:** aerosols, clouds, precipitation, satellites

## 1. Introduction

The aerosol indirect effect, namely radiative and hydrological influences on climate through cloud modification, is one of the most uncertain processes in cloud-relevant climate issues. There are two kinds of aerosol indirect effect. Twomey (1977)<sup>[1]</sup> showed that additional aerosols enhance cloud albedo by increasing droplet numbers and decreasing droplet size, thereby increasing the optical depth, if the cloud water content is constant. This is the 'Twomey effect' or the aerosol indirect effect of the first kind. Satellite remote sensing has contributed greatly to the understanding of the aerosol indirect effect of the first kind. Coakley et al. (1987)<sup>[2]</sup> used satellite data to find 'ship tracks' that were characterized by decreased particle size and increased optical depth because of ship effluence. This finding focused interest on the aerosol indirect effect of the first kind. Han et al. (1994)<sup>[3]</sup> included a global analysis of water cloud droplet sizes. That study showed distinct differences in effective particle radius between continental and oceanic clouds.

Albrecht (1989)<sup>[4]</sup> proposed that a decrease of the size of cloud droplets due to increased aerosol concentrations makes precipitation formation less efficient, thus prolonging cloud lifetime. This mechanism is the aerosol indirect effect of the second kind. Pioneering work by Rosenfeld (2000)<sup>[5]</sup> used satellite data and showed a striking example of reduced rainfall because of smaller cloud particles influenced by air pollution.

The current understanding of the aerosol indirect effect is nevertheless unsatisfactory. It is therefore important to gather additional examples of the aerosol indirect effect and to investigate mechanisms and feedbacks. The present paper uses observations and relates cloud properties (optical depth, particle size, and droplet number) to changes in precipitation amount. The study region was the Amazon basin (W70-W50, S0-S15), an area of persistent convection. Convective precipitation is generally intense in this region, and this convection highlights distinct characteristics of clouds and precipitation. Several past works on radiation and remote sensing have discussed aerosols and clouds in this region. Kaufman and Fraser (1997)<sup>[6]</sup> found that smoke particles increased the reflectivity of thin and moderately thick clouds, with typical reflectivities between 0.35 to 0.45, and reduced cloud particle size from 14  $\mu\text{m}$  to 9  $\mu\text{m}$ . Kaufman and Fraser (1997)<sup>[6]</sup> also suggested that the aerosol indirect effect depended on precipitable water.

Two cloud types were considered over the Amazon basin: low-level clouds composed of water and clouds of any level or constituent (low, middle, and high; water and ice). The present study examined 1) how cloud properties relate to changes in precipitation amount, and 2) how the responses are influenced by cloud type (low-level cloud and total cloud). These analyses will deepen the understanding of the aerosol indirect effect.

Section 2 describes the datasets used in this work. Results are shown in Section 3. Section 4 contains a summary and conclusion.

## 2. Data

Data that describe low cloud properties, type-segregated cloud amounts, total cloud optical depth, and precipitation amount were used in this work.

### 1) Low-level water cloud properties

Water cloud properties were derived from Advanced Very High Resolution Radiometer (AVHRR) data from NOAA satellites using an algorithm proposed by Kawamoto et al. (2001)<sup>[7]</sup>. The optical depth at visible wavelength  $\tau_{\text{low}}$ , effective particle radius  $r_e$  and cloud top temperature  $T_c$  were derived from data in three different channels, visible (0.64 micron), near-infrared (3.73 micron) and infrared (11 micron). A lookup table for which satellite radiances were calculated under various conditions of cloud properties, angular orientations and water vapor was prepared. The inversion was performed to derive low cloud properties comparing lookup table values and satellite radiances. The lookup table was built using the output from a radiative transfer model that solves the radiative transfer equations with a combined discrete-ordinate-matrix-operator method and a LOWTRAN-7 gas absorption model. National Center for Environmental Protection/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data were used as ancillary input meteorological data (humidity, pressure, and temperature profiles) in the actual data analysis. Sensor signals for the visible channel were calibrated with calibration constants from Rao and Chen (1996)<sup>[8]</sup>. The on-board internal blackbody was used for calibration in the near-infrared and infrared channels. The columnar cloud particle number density  $N_c$  was estimated from  $\tau$  and  $r_e$  using the method in Nakajima et al. (2001)<sup>[9]</sup>. Two parameters out of three ( $r_e$ ,  $N_c$  and  $\tau_{\text{low}}$ ) are independent for low clouds, so issues on  $r_e$  and  $N_c$  are mainly discussed. Monthly averaged (January, April, July and October) datasets for each property in 1993 were produced at 0.5-degree spatial resolution. In selecting cloudy pixels, the following thresholds are adopted to avoid ice clouds and potential overlapping cloud cases. 1) Brightness temperatures are more than 260K, 2) brightness temperature differences are less than 1K and 3) reflectivity is more than the ground reflectivity + 3 % (Kawamoto et al. 2001)<sup>[7]</sup>.

### 2) Cloud amounts and total cloud optical depth

International Satellite Cloud Climatology Project (ISCCP) statistics were used to describe cloud amount data for three cloud types (low, middle and high cloud-tops) and total cloud (both water and ice) optical depth  $\tau_{\text{tot}}$ . These parameters are determined at visible, near-infrared and infrared wavelengths assuming a water droplet effective radius of 10  $\mu\text{m}$  and an ice crystal effective radius of 30  $\mu\text{m}$ . Cloud top pressure thresholds used in the ISCCP classification are 680 – 1000 hPa for low cloud-tops, 440 – 680 hPa for middle cloud-tops and 50-440 hPa for high cloud-tops. The ISCCP also provides cloud property datasets at different spatial (either 30 km or 280 km) and temporal (3-hourly to monthly) resolutions. Resolutions used in this study are 30km (adjusted to smaller resolution) for spatial and monthly for temporal. These datasets combine sun-synchronous (e.g., NOAA) and geosynchronous (e.g., GOES, METEOSAT, GMS) satellites. Atmospheric profiles and surface parameters such as snow/ice detection, reflectivity, and temperature are archived in the datasets in addition to cloud properties. The datasets include data for over 18 years, starting in July 1983. Data acquisition details can be found at <http://isccp.giss.nasa.gov/>.

### 3) Precipitation amount

Precipitation datasets used in this study were as in Xie and Arkin (1996)<sup>[10]</sup>. Their merging algorithm takes the ground-based gauge observations, satellite estimates derived from infrared, outgoing longwave radiation and microwave sensors, precipitation distributions from the National Centers for Environmental Prediction (NCEP)-National Center for Atmospheric Research (NCAR) reanalysis. Using this algorithm, a globally monthly precipitation datasets, called the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) has been created. Concerning details about the treatment, the reader should be referred to Xie and Arkin (1996)<sup>[10]</sup>. Although they constructed datasets for precipitation amount on a global scale, we subtract data over only the Amazonian basin for this study in 0.5-degree and monthly resolutions.

## 3. Results

Figure 1 shows the annual cycle of monthly-mean precipitation amounts ( $P$ ) in 1993 with standard deviation. The standard deviation is calculated for the target region of the monthly-mean of each month. This figure captures the seasonal variation in precipitation. January and February are the rainy period; July and August are the dry period. Precipitation amounts in the rainy season exceed 100 (mm/month). Figure 2 shows the annual cycle of the amounts of the three cloud types (high, middle, and low cloud-tops) in 1993, taken from ISCCP statistics. High cloud-tops are remarkable in the rainy season and decrease considerably in the dry season. The annual cycle of middle cloud-tops resembles that of high cloud-tops but is less variable. Amounts of low cloud-top are comparatively small throughout the year, but there are relatively large amounts of low cloud-tops during the dry season. Such a temporal distribution of low cloud-tops could have resulted from the use of satellite data and the absence during the dry season of high and middle cloud-tops that obscure the view of low clouds.

Figures 3 and 4 trace the annual cycles of  $P$  with  $r_e$  and  $\tau_{low}$ , respectively. Note that analyses for low cloud properties (the different numbers of dots) are for only 4 months (January, April, July, October). Kawamoto and Nakajima (2003)<sup>[11]</sup> suggested that  $r_e$  is related to precipitation, and the figure clearly shows that  $r_e$  is larger in the rainy season and smaller in the dry season. Conversely,  $\tau_{low}$  is smaller in the rainy season and is larger in the dry season. Figure 5 shows the annual cycle of  $\tau_{tot}$  and  $P$ . The two values show similar trends. Low clouds can be seen from satellites only when above clouds are absent. Using thresholds for selecting water clouds, ice clouds such as thin cirrus and deep convective clouds would be avoided.

The relationship between cloud properties and precipitation was studied using the following procedure. Values of  $P$  were divided into bins, and cloud properties in the same geographical grid (0.5-degree) were collected for each precipitation amount bin for the four months in 1993. Average and standard deviation of cloud parameters for each precipitation amount bin were calculated. Nakajima et al. (2001)<sup>[9]</sup> used a similar method to compare parameters.

Figures 6 and 7 show plots of  $P$  versus average  $r_e$  and  $N_c$ , respectively. As  $P$  increases,  $N_c$  decrease and  $r_e$  increases. These behaviors can be explained as follows. It is widely accepted that low clouds may produce drizzle, but not heavy rain. Judging from the values of  $r_e$  (Figure 6), the low clouds here are mainly non-precipitating clouds. Figures 6 and 7 would show the unilateral effects of precipitation on low cloud properties. Rainy regimes (e.g. more than about 80 mm/month) reflect clean conditions, as cloud condensation nuclei (CCN) are scavenged from the atmosphere, so  $N_c$  is lower. Cloud droplets can grow larger in a clean atmosphere with fewer CCN. Additionally, rainfall provides sufficient humidity for particle growth. A decrease in  $N_c$  is linked to a decrease trend in  $\tau_{low}$  (not shown). Such clouds are similar to oceanic clouds. Note that the rate at which these cloud parameters vary with precipitation amount becomes less steep during heavy rain (exceeding 100 mm/month). There may be some saturation to the response. The dry region (less than 25 mm/month) might be polluted. In dry areas, CCN removal is suppressed, so  $N_c$  is higher and the many cloud droplets may stay small. Frequent biomass burning events during the dry season introduce many aerosols into the atmosphere, adding potential CCNs. Low cloud properties are greatly influenced by precipitation and accompanying CCN removal. Such a relationship between cloud properties and CCN numbers is consistent with conclusions by Twomey (1977)<sup>[1]</sup>. Aerosol optical depth (AOD) over the Amazon retrieved from the Multiangle Imaging SpectroRadiometer (MISR) can be used to verify the above speculations. MISR uses nine different angles and four wavelengths (Diner et al. 2001)<sup>[12]</sup> to derive aerosol properties with high accuracy over both ocean and land. The time period is not exactly the same, but AOD means for DJF and JJA are about 0.16 and 0.28, respectively. Those seasonal AOD contrasts are consistent with the processes discussed above.

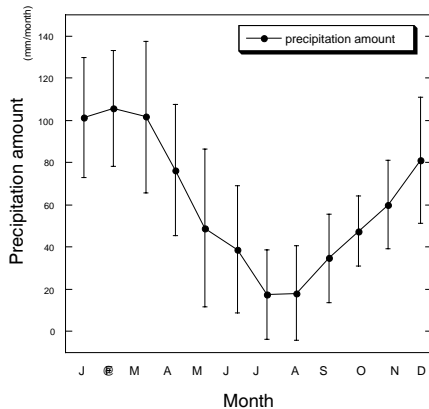


Fig.1 The annual cycle of  $P$

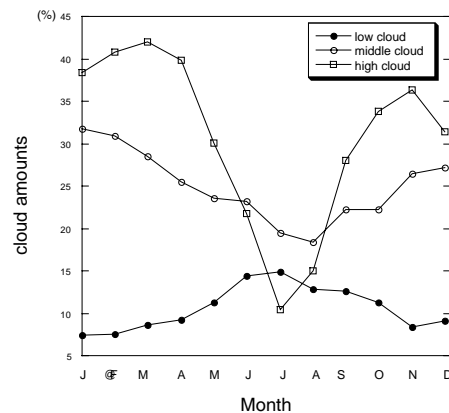


Fig.2 The annual cycle of cloud amounts of three types

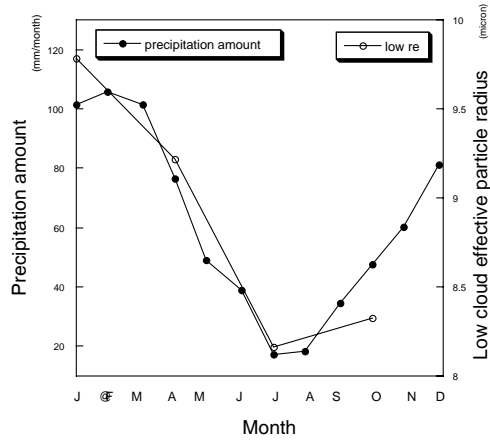


Fig.3 The annual cycle of  $P$  and  $r_e$

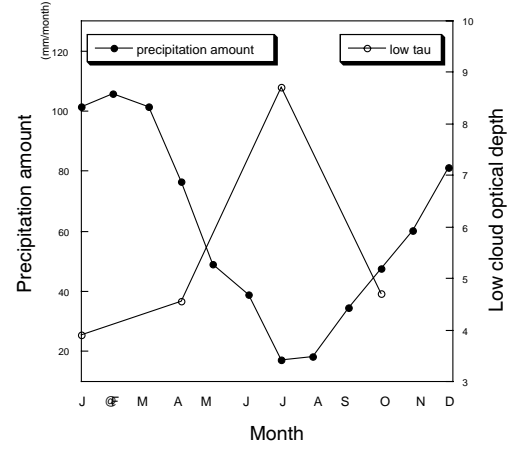


Fig.4 The annual cycle of  $P$  and  $\tau_{low}$

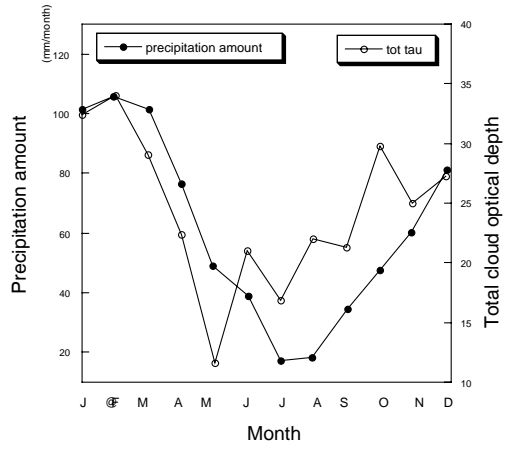


Fig.5 The annual cycle of  $P$  and  $\tau_{tot}$

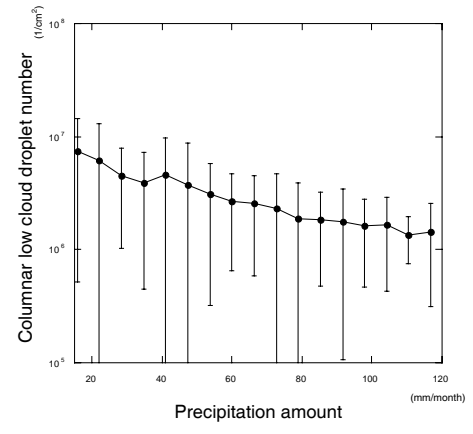


Fig.6 Statistical relationships between  $P$  with  $r_e$

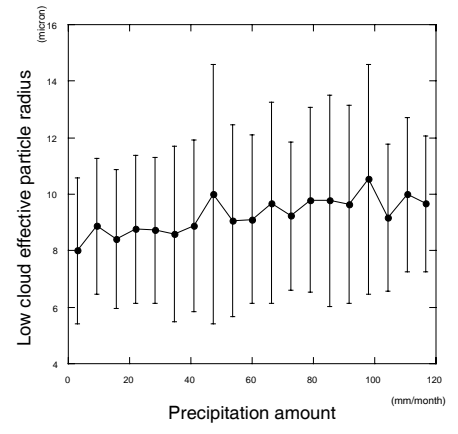


Fig.7 Statistical relationships between  $P$  with  $N_c$

## 4. Concluding remarks

Relationships between cloud properties and precipitation over the Amazon basin were examined to get further understanding of the aerosol indirect effects. Comparisons on a 0.5-degree grid show that as  $P$  increases,  $N_c$  decrease and  $r_e$  increases. Low water clouds produce little rain. The statistical relationships suggest a scavenging effect of precipitation on low cloud properties. Low concentrations of CCN in the rain-rich regime and high concentrations of CCN in the rain-poor regime agree with Twomey (1977)<sup>[1]</sup>. A less steep rate of variation in cloud properties in regions of heavy rain regime suggests saturation with changes of precipitation amount. Another reason for lower aerosol amount in the rainy season is less forest fires. Less forest fires are partly due to the rainy season, and this can be also thought by the effect of rain in a wider sense. The quantitative estimate of both factors (precipitation scavenging and less forest fires) needs further research.

Several subjects warrant future study. Monthly-averaged cloud properties were studied to yield statistical relationships. Such relationships may, however, depend on dynamic meteorological fields such as daily low pressures. It could be worthwhile to consider the effects of cloud development stage (formation, development, and decay) on these relationships with finer temporal resolutions. Classification of cloud development stages from satellite data is a formidable task, so active sensors such as ground-based cloud radars may have to be used. Incorporating with numerical models will also provide valuable knowledge. The satellite algorithm used infers parameters near cloud top ( $r_e$ ) or columnar-integrated ( $\tau$  and  $N_c$ ); profiling information would be very handy to have. Finally, future studies of frontal precipitation systems over China associated with the Asian monsoon can be used to show similarities and differences from the convective areas studied in this work.

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