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HOURLY RAINFALL AND GOES INFRARED RADIANCES IN AMAZONIA

by

Dean Gregory Butzow

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Geography

Western Michigan University
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HOURLY RAINFALL AND GOES INFRARED RADIANCES IN AMAZONIA

Dean Gregory Butzow, M.A.

Western Michigan University, 1993

Ground-based hourly rain of the Amazon Basin was investigated for the period January 1988 to December 1990. UFPa, Careiro, and CEPLAC rain stations were selected to represent the rain characteristics of coastal Amazonia, central Amazonia near the river, and central Amazonia in the "terra firme" respectively.

Throughout the period, UFPa exhibits a distinct diurnal cycle, with peak rain occurring from the mid-afternoon to early evening hours. The diurnal cycles of the inland stations is less pronounced, presenting significant nocturnal and early morning components.

Results from the pulse analysis of the hourly rainfall time series, lead to an average model of Amazonia's rain events.

Ground-based hourly rain was compared to hourly infrared GOES radiances for the period July 1989 to June 1990 over Careiro. Weak anti-correlation values between rain and radiance indicate no rain producing cold clouds and the possible occurrence of rain from warm clouds.

Dedicated to my Parents
Two Very Special People
To Whom I'll Always be Grateful

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Dean Gregory Butzow

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Western Michigan University, 1993

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CHAPTER I

INTRODUCTION

Rainfall over Amazonia has been studied by scientists for a number of years. However, detailed rain system classification has not yet been done over that region. Also, the precipitation that falls over Amazonia has not been adequately measured which may account for inaccurate results when used in climate and chemical transport models.

In this thesis it is hypothesized that:

1. There is periodicity in the rain events.
2. Rainfall in the upland (terra firme) should be heavier than rainfall along the large rivers, as a consequence of a land/river circulation.
3. Rain events can be represented as a model which describes the essential behavior of the rain in Amazonia.
4. Rain is significantly anticorrelated with radiance in Amazonia.

I will test these hypotheses with the rainfall data recorded for the three year period of 1 January 1988 to 31 December 1990.

CHAPTER II

LITERATURE REVIEW

Lying within latitudes 10° north and 20° south, Amazonia is characterized by its tropical rain forests. Tropical rain forests are biologically diverse, predominantly evergreen, with heavy rainfall, and relatively constant average temperatures (around 80°F) (Miller, 1990). The sun's vertical rays move between latitudes 23° 27' N and 23° 27' S and cross the equator every six months, strongly influencing the distribution of weather patterns in the Amazon region (Salati, 1987). With upwards of 2 meters falling through the course of a year, rain is a primary factor in Amazonia's climate (Cutrim, 1983). Annually, rainfall is heavier in the north than in the south. Seasonally, rainfall oscillates with the movement of the sun. Because of this oscillation, the south has a distinct "dry" season or less wet season, which varies markedly from year to year (Molion, 1987). Seasonality is further confirmed by Ribeiro and Adis (1984) who studied the Manaus region (central Amazonia) and found the existence of a dry season between June and November and a rainy season from December until May.

During the summer in the Southern Hemisphere, the area

of maximum precipitation extends from 0° to 10° S, south of the Amazon River, and from that period onward, the area of maximum precipitation moves progressively toward the Northern Hemisphere (Salati, 1987). Precipitation is usually from heavy showers or thunderstorms produced by convective cumulus clusters. It is found that over the whole of Amazonia about 50% of the total precipitation that falls on the forest is recycled and returns to the atmosphere in the form of water vapor (Molion, 1987; Salati, 1987).

Maximum values of annual precipitation are observed in the coastal region of Brazil. Somewhat lower values of annual precipitation are observed in the central Amazon and larger values again on the westward edge of the Amazon in the mountains of Peru and Columbia (Molion, 1987). On the coast, this may be caused by the position of the Inter-tropical Convergence Zone (ITCZ), an east-west band of heavy convection. The position of the ITCZ is governed by the location of the thermal equator and lags seasonally with the passage of the sun across the actual equator. Hastenrath and Lamb (1977) showed that, over the Atlantic, the ITCZ moves southward progressively from its northernmost position during the Southern Hemisphere winter and reaches its southernmost position by the end of summer (March). Thus, the ITCZ is responsible for most of the rainfall in Amazon coastal areas (Molion, 1987).

Kousky found that the entire coast receives most of its rainfall during the period 2100-0900 hours or 9 P.M. to 9 A.M. The vicinity of the north coast and the area 100 km inland receives maximum rainfall during the period of 0900-1500 hours or 9 A.M. to 3 P.M. The maximum rainfall within 150-300 km of the coast and on the high terrain area falls during the period 1500-2100 hours or 3 P.M. to 9 P.M while the coastal area receives the least amount of rain during this period (Kousky,1980). Kousky (1980) suggests that the occurrence of rain induced by the sea breeze may affect the annual mean distribution of precipitation in the basin. The nighttime maximum along the East Coast is probably due to the convergence between trade winds and the land breeze. The annual totals at approximately 500 km from the coast are considerably smaller because of reduced daily convection. At night, there is some precipitation in this region, although it is less intense than during the day because of reduction in thermal contrast (Salati, 1987).

Kousky also studied the diurnal rainfall of UFPa. He found that during the entire year, the heaviest rain occurs at 1700 hours or 5 P. M. In the wet semester (January-April), the heaviest rain falls between 1600-1700 hours or 4 P.M. to 5 P.M. In the dry semester (June-September) it falls between 6 P.M. to 7 P.M. local time (Kousky, 1979).

Oliveira (1990) argued that the presence of the river system (Negro and Amazonas) in the vicinity of Ducke

reserve (interior Amazonia) may induce a circulation at low levels that is from land to river at the end of the night and the beginning of the day, when the thermal contrast between land and river is likely to be larger. This possibly enhancing nocturnal rainfall. It is important to note that the role of the river breeze circulation over the Amazon Basin region is not very clear, because its horizontal and vertical extent as well as its intensity have not been studied (Oliveira, 1990).

Lloyd (1990) analyzed the duration of rainstorms for the period 3 September 1983 to 21 August 1985. Lloyd defined a storm as any period of rain, not necessarily continuous, preceded and followed by periods of at least three hours in which no rain was recorded. Three hours was appropriate for complete drying of the upper and middle canopy. Because rainfall was measured only at hourly intervals, the time of the beginning and end of any storm could not be defined exactly (Lloyd, 1990).

Lloyd's analysis of Reserva Ducke, a "terra firme" station about 40 km northeast of Manaus, showed that the mean annual rainfall was 2732 mm. Mean annual number of rain days with rainfall over 0.1 mm was 253 days. Lloyd found the mean daily intensity of 10.8 mm per rain day on average, on approximately two out of three days. Reserva Ducke receives 50% of its daily rainfall between 1500 and 2100 hours or 3 P.M. and 9 P.M. and 90% during the latter

part of the day. Reserva Ducke receives one storm per rain day with 50% of the storms being a duration of one hour or less (Lloyd, 1990).

Ribeiro and Adis (1984) studied the rainfall of a terra firme station and stations in the vicinity of CEPLAC. They concluded that rainfall registered between 1910 and 1979 confirm the existence of a dry season between June and November (monthly rainfall: 42-162 mm) and a rainy season from December until May (monthly rainfall: 211-300 mm). Annual precipitation amounted to 2105 mm with about 75% of the rainfall recorded during the rainy season. Rainfall collected over 12 months at eight stations in the vicinity of and at CEPLAC were also compared. Considerable differences are found in rainfall patterns (intensity, frequency, and time of rainfall) around the eight stations.

Cohen (1989) studied organized rain systems over Amazonia and found that stability lines that propagate more than 400 km inland travel with an average speed of 16 meters/second, but can vary with speeds between 5 to 25 m/s. The average lasting time for the stability lines is 16 hours, but they can last up to 43 hours and penetrate up to 2100 km inland.

Conventional wisdom holds that most of the rain in the tropics comes from deep convective clouds ranging in size from isolated cumulonimbi to cloud clusters and well organized squall lines (Houze and Hobbs, 1982). But there

is reason to suspect that at times and in places low- and middle-level stratiform clouds contribute significantly to Amazonia's rainfall (Salati, 1985; Greco et al., 1989). Moreover, cumulus cloud bases below 1 km (Harriss et al., 1988) and freezing levels as high as 5 km (unpublished soundings) suggest a potential for significant amounts of rain from warm cumulus clouds (Cotton, 1982). More direct evidence comes from Cutrim (1983). In the course of a study of hourly Amazonian rainfall she recorded 10 cases (with rates as high as 12 mm/h) with cloud top temperatures above 0°C.

CHAPTER III

DATA BASE

Rainfall

For more than a decade the Federal University of Para has operated a small network of autographic rain gauges near the cities of Manaus and Belem in Brazilian Amazonia. At hourly resolutions for three stations, three years of data have been digitized. The stations are the Federal University of Para (UFPA; 1° 28' 18"S, 48° 27' 09"W), Careiro (3° 5' 36"S, 59° 45' 00"W), and CEPLAC (2° 36' 00"S, 60° 3' 00"W); the years are 1988, 1989, and 1990 (Figure 1). UFPA lies at an altitude of ten meters on the northeast coast of Brazil in the city of Belem. Careiro and CEPLAC are located in the interior of Brazil, approximately 1200 km from UFPA, within the Manaus region. Careiro lies along the Rio Negro River at an altitude of 72 meters while CEPLAC lies in the "terra firme", 85 m above sea level, approximately 50 km from Careiro (Figure 1).

Rain was collected at each station by a mechanical rain gauge. This rain gauge accumulates up to 10 mm of rain, then siphons and resets the pen to the zero position on the graph. Rain was recorded on pluviographs which had resolutions of ten minutes and 1 mm of rain. The pluvio-

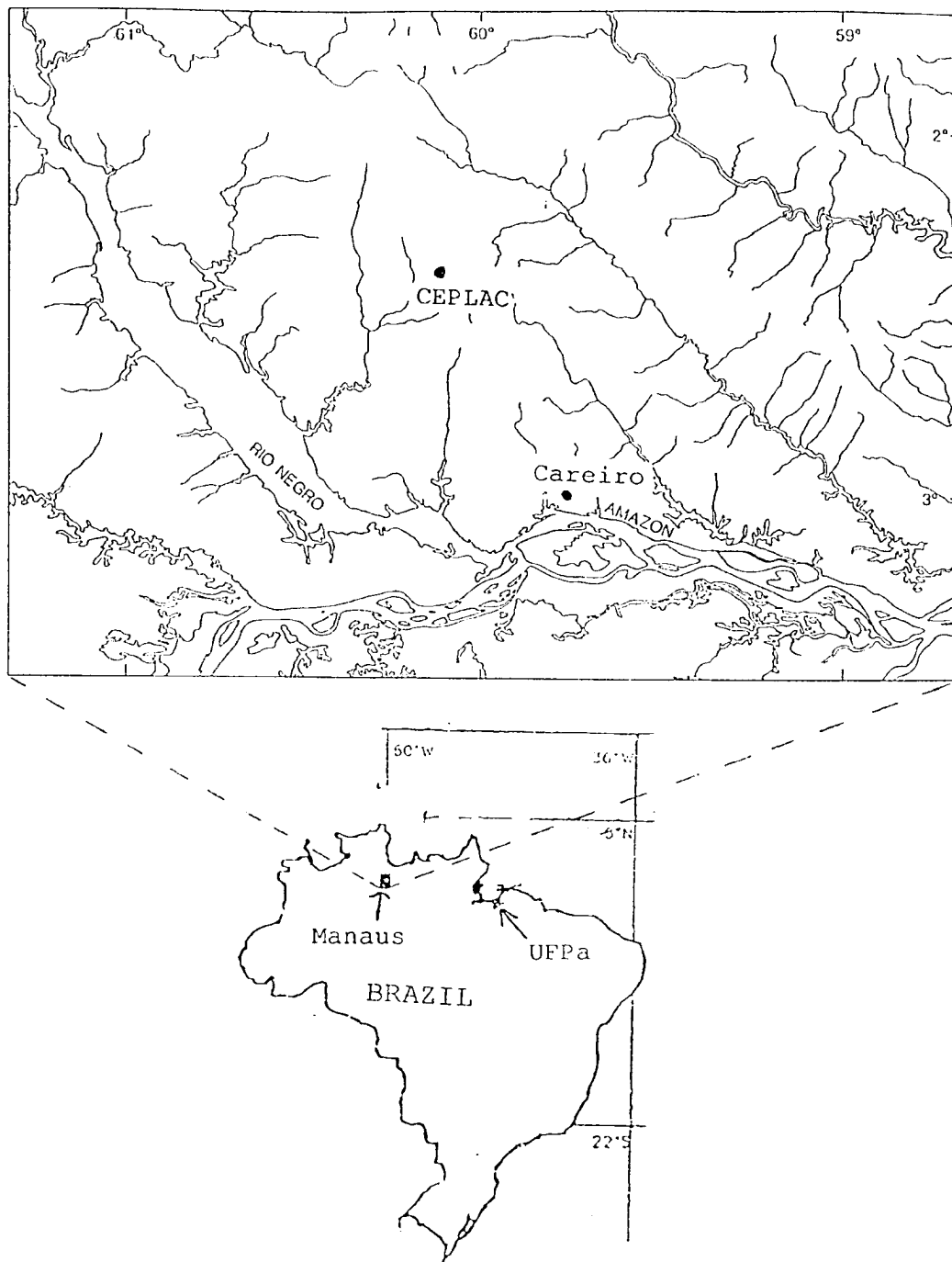


Figure 1. Study Site Locations of UFPA, Careiro, and CEPLAC.

grams were removed every 24 hours at 7:00 am local time by an operator who sent them bimonthly to UFPa. The hourly rainfall was digitized manually, by students supervised by a professor, into a spreadsheet format by the Meteorology Department at UFPa. At this point, gross errors were corrected.

Radiance

Through the course of one year (July 1989 - June 1990), the University of Wisconsin-Madison collected hourly GOES-7, Geostationary Operational Environmental Satellite, infrared radiances from over Careiro (Lat. $3^{\circ} 5' 36''$ S, Long. $59^{\circ} 45' 00''$ W). During this period, the sub-point of GOES-7 was 108° W over the equator at an altitude of 36,000 km. Radiances were archived at a temporal resolution of every one half hour and then averaged to generate a matching hourly time series for comparison with the hourly rain time series. Spatial resolution found each pixel covered an area of 8 km by 8 km. Careiro was the only station that was used to analyze rainfall and radiance data because it was the only station with complete rain and radiance data. The radiance values were analyzed along with the hourly rainfall data for a one year period (July 1989 - June 1990).

CHAPTER IV

RAIN TIME SERIES

In the context of time series, a rain event is defined as the sequence of one or more finite rain rates bounded on either side by one or more rain rates. Programs have been developed to transform the hourly surface rain data from Brazil into a more useable data format for processing and analysis. The RAINXFERM (rain transform) program, developed by the University of Wisconsin-Madison, is used to transfer the spreadsheet format of hourly rain into a continuous string of hourly rain in ASCII format.

The program allows for descriptive information of hourly rain about the site and processes one or more monthly data files. The program determines an absolute time reference to allow for co-location in time for future inter-site comparisons. By definition, 0.00 midnight January 1, 1982 is taken to be the epoch date. The program then converts civil time to Julian date. There is a defacto limit of 120 files (10 years worth of data) that can be accepted in this program. Time series plots of hourly rainfall were made for the three year period (1988-1990), and the one year period (July 1989 - June 1990), which coincided with the radiance data set.

Radiance Time Series

The radiance data were extracted, in boxes of 3 by 3 pixels, with a central infrared pixel located with the rain station location, from GOES band 8 (11 microns) for a period of one year. This task was performed using McIDAS, the Man-computer Interactive Data Access System, which process image data. Using a McIDAS command, the central pixel (pixel 5) of the box was selected. The central pixel was chosen after it was determined that there was a high correlation among the pixels and with the average radiance of the nine pixels box. RADXFRM, which is similar to the RAINXFRM program, was used on the radiance data. The radiance transform program transforms the radiance data from McIDAS format into a string ASCII format.

Diurnal Cycle

The diurnal cycle was investigated utilizing the hourly rainfall data for UFPa, Careiro, and CEPLAC. A program, RAINDIUR, put the hourly rain data, retrieved directly from the spreadsheet format, into a format that listed the rain totals and the number of rain events for each hour of the day. Specifically, the diurnal distribution of hourly rain events for the three year period was analyzed along with the rain totals for each hour of the day for the this period.

Pulsatile Analysis

In order to achieve a conceptual model of the Amazon rain event, the hourly rain time series was broken down into rain and no rain periods. A program, RAINANAL, (also developed by the Space Science and Engineering Center's University of Wisconsin-Madison group), identified an individual rain event (pulse) which is defined as the interval of time between the first non-zero value following a zero value and the last zero value following the last non-zero value. When a missing value was encountered the program assumed the most recent state. So, for example, if the missing value occurred in the middle of the rain event, that time mark was considered to be part of the rain event.

The 11 derived pulse parameters are: (1) T_1 = time of the start of the rain event, i.e., time of first non-zero report; (2) T_2 = time of maximum rain rate; (3) T_3 = time of the end of the rain event, i.e., time of last non-zero report; (4) T_{31} = duration of rain event ($T_{i3} - T_{i1} + 1$); (5) T_{13} = duration since last rain event ($T_{1(i)} - T_{3(i-1)} - 1$); (6) R_{MAX} = maximum rain rate recorded during rain event; (7) R_{SUM} = total rain recorded during rain event; (8) R_{SUM1} = total rain recorded before and including the time of maximum rain; (9) R_{SUM2} = total rain recorded following the time of maximum rain; (10) T_{21} = duration of time between start and maximum rain ($T_{i2} - T_{i1}$); and (11) T_{32} = duration

of time between maximum rain and end rain ($T_{i3}-T_{i2}$).

CHAPTER V

HOURLY RAIN ANALYSIS

Hourly rainfall for each of the three stations, UFPa, Careiro, and CEPLAC, was recorded every hour for the three year period 1 January 1988 - 31 December 1990.

It is found that throughout the course of the three year period, Careiro averaged 289 rain events per year while CEPLAC averaged 374 rain events per year and the coastal station, UFPa, averaged the greatest number of rain events per year with a total of 451. UFPa also recorded the greatest average yearly rain total with 2,475 mm. Careiro and CEPLAC had similar average yearly rain totals for the three year period with Careiro receiving 2,101 mm of rain per year and CEPLAC receiving 2100 mm of rain per year. Careiro received a greater average amount of rain per year than did CEPLAC. This contradicts the concept that stations in the "terra firme" should receive greater rainfall totals than stations situated on the river.

Year rainfall totals for the period 1 July 1989 - 30 June 1990 included UFPa with 2,207 mm, Careiro with 2,283 mm, and CEPLAC with 1,886 mm. The number of rain events, that is the number of periods with a measurable rainfall, were as follows: UFPa recorded 404 rain events, Careiro

295 rain events, and CEPLAC 363 rain events. Careiro received the greatest amount of rain while CEPLAC received the least amount of rain. Once again, this contradicts the climate of the region being that stations in the "terra firme" should receive higher rainfall totals than stations located along the river. However, CEPLAC was missing 132 (3.5%) of its hourly rain data compared to the 21 hours (0.6%) missing at Careiro and the 33 hours (0.9%) missing at UFPA for the one year period. CEPLAC's higher percentage of missing data may account for the lesser rain fall totals than those recorded at UFPA and CEPLAC.

Month by month cross-correlation of hourly rain time series between Careiro and UFPA, approximately 1285 km apart, for July 1989 to June 1990, revealed the highest correlation of hourly rain to be 0.483 at a lag of 40 hours during November 1989. All other months had relatively low correlations. Low correlation values between hourly rain were also found between the two adjacent stations, approximately 50 km apart, of Careiro and CEPLAC.

CHAPTER VI

DIURNAL ANALYSIS

The diurnal signature for Careiro found that the river station experienced late afternoon to early evening maximum in rainfall for the three year period of 1988 to 1990 (Figure 2). Over 36% of the total rain fell during the period of 1500 to 2100 local time with a peak rain total of 445 mm and a peak number of 154 rain events occurring at 1400 local time and 1500 local time, respectively. However, there was also a nocturnal peak in rain, indicating a bimodal diurnal signature. Over 24% of the total rain fell during the nocturnal hours of 0100 to 0600 local time with a nocturnal peak of 305 mm occurring at 0300 local time. Minimum rain activity was found to occur near midnight or 2400 local time.

The diurnal cycle for the three year period of CEPLAC, the station located in the "terra firme" near Manaus, approximately 50 kilometers from Careiro, found a maximum rain total and a maximum number of rain events also occurring in the late afternoon to early evening hours for the three year period (Figure 3). A peak rain total of 654 mm and a peak number of 213 rain events occurred at 1500 local time. About 41% of the total rain fell between the after-

Rain Totals and Number of Rain Events

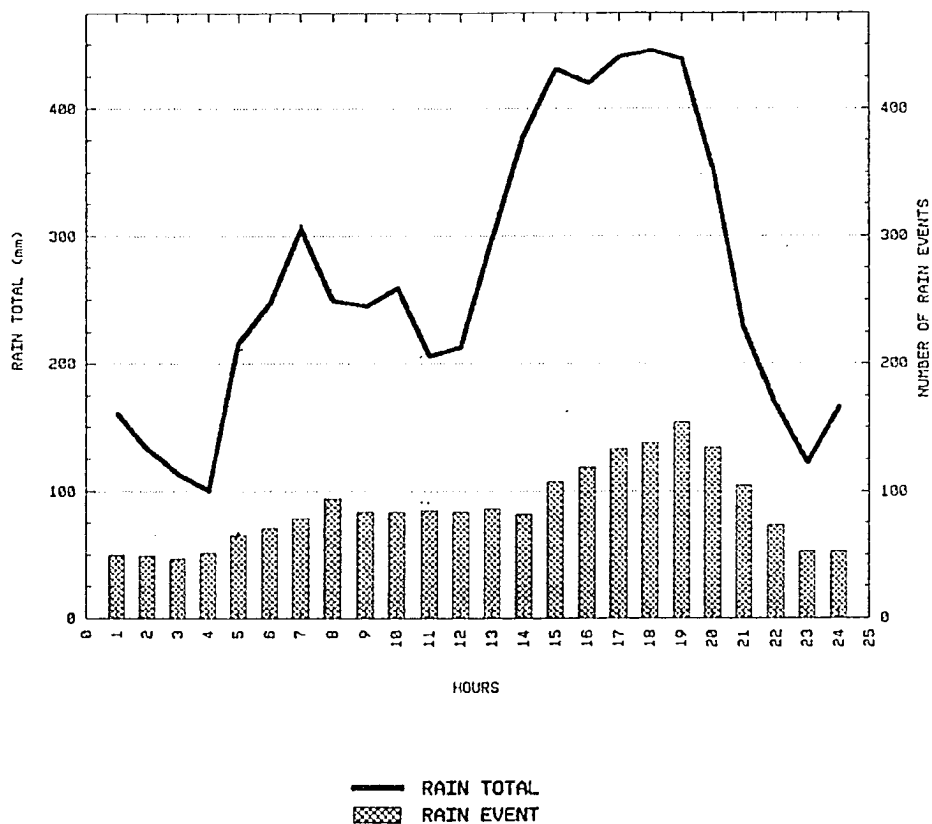


Figure 2. Diurnal Cycle of Careiro for the Period
1 January 1988 to 31 December 1990.

Rain Totals and Number of Rain Events

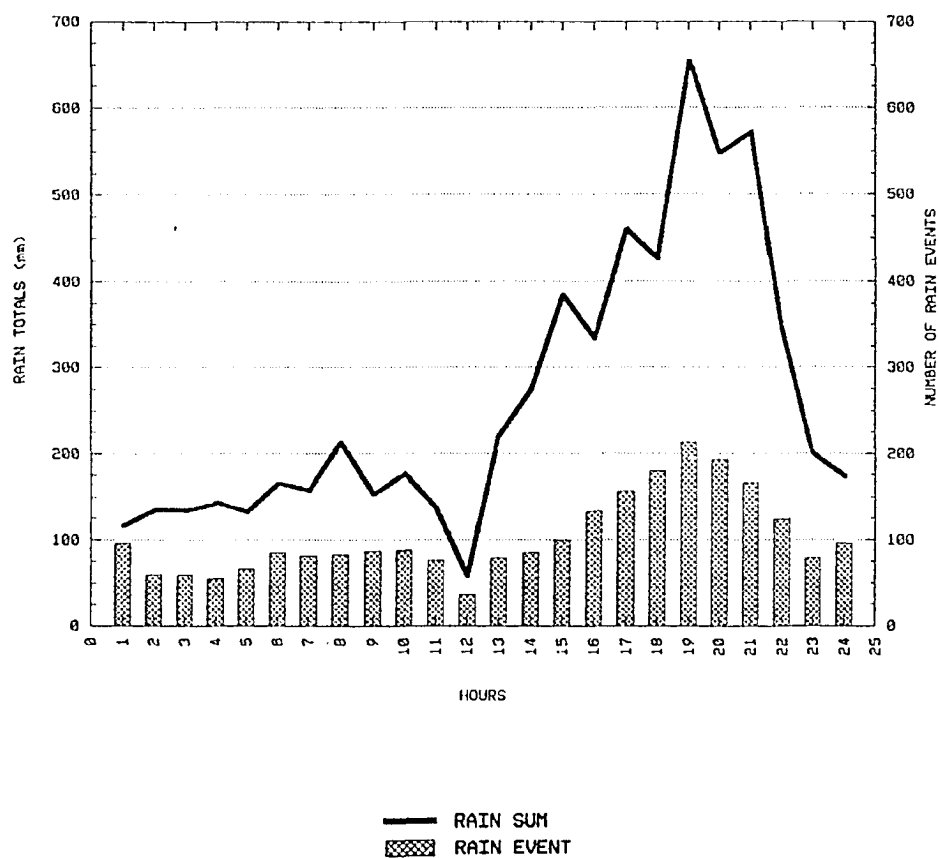


Figure 3. Diurnal Cycle of CEPLAC for the Period
1 January 1988 to 31 December 1990.

noon hours of 1500 and 2100 local time.

A nocturnal secondary peak was also found in CEPLAC, although it was not as pronounced as the nocturnal peak found at the neighboring station Careiro. Approximately 16% of the total rain fell during the night hours of 0100 and 0600 local time. Figure 4 shows a nocturnal peak of over 200 mm at 0400 local time. A distinct minimum rain total of about 50 mm and a minimum number of rain events was found at 0800 local time.

Diurnal analysis for UFPa for the three year period, January 1988 to December 1990, revealed a distinct diurnal signature as shown on Figure 4 . Maximum rain totals and the maximum number of rain events were found to occur in the late afternoon to early evening hours with a peak rain total of 1035 mm and a peak number of 277 rain events occurring at 2000 UTC or 1700 local time. Minimum rain totals and a minimum number of rain events were found to occur during the night to early morning hours with a minimum in rain activity occurring at 0900 local time for the three year period, completely different from the results found at Careiro.

Rain Totals and Number of Rain Events

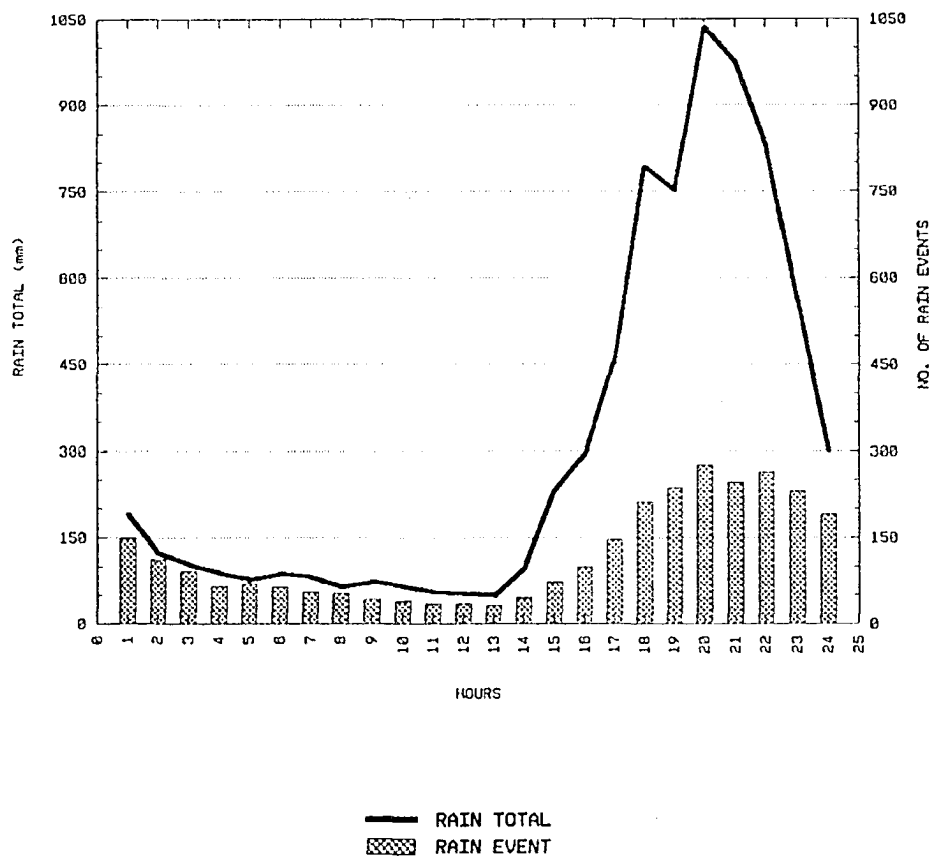


Figure 4. Diurnal Cycle of UFPa for the Period
1 January 1988 to 31 December 1990.

CHAPTER VII

PULSATILE ANALYSIS

Each rain event was analyzed for the three year period of January 1988 to December 1990. Rain events were analyzed so that a model of rainfall over the three stations could be developed.

Analysis of the average rain accumulation per event, as shown on Table 1, found that for the three year period, Careiro had a greater average rain accumulation per event, 7.3 mm, compared to an accumulation of 5.5 mm at UFPa and 5.6 mm at the neighbor station of CEPLAC. Careiro also had a greater median, 2.1 mm, than UFPa, 1.7 mm, and also CEPLAC, 1.5 mm. The maximum rain total for all events also was found at Careiro with 150.5 mm. This is a considerable difference when comparing with UFPa which had a maximum rain of 69.6 mm and CEPLAC with a maximum rain event total of 127.6 mm.

The average maximum rain per event is defined as the greatest average rain total to fall during a one hour period for a particular event. Table 1 shows the Careiro had the greatest average maximum rain for the three year period with a maximum total of 4.7 mm per event. CEPLAC recorded the least maximum rain per event for the period

Table 1

Pulsatile Analysis for the Period
1 January 1988 to December 1990

	UFPa			Careiro			CEPLAC		
	Av	Med	SD	Av	Med	SD	Av	Med	SD
Accumulation (mm)	5.5	1.7	9.2	7.3	2.1	13.9	5.6	1.5	10.5
Maximum (mm)	4.1	1.4	6.7	4.7	1.6	7.5	3.9	1.1	6.5
Accn to (& Incl) Peak	4.7	1.5	7.7	5.5	1.8	9.2	4.6	1.7	7.5
Accn From Peak to end	0.8	0.0	2.5	1.8	0.0	6.1	1.2	0.0	3.7
Duration (Hour)	2.1	2.0	1.7	2.4	2.0	2.0	2.2	2.0	3.4
Interlude (Hour)	17.3	12	23.4	27.6	15	47.8	21.1	12	30.4
Duration: Begin to Peak (Incl. Peak)	1.4	1.0	0.85	1.4	1.0	0.78	1.4	1.0	0.84
Duration: Peak to end (Incl. Peak)	1.7	1.0	1.3	2.0	1.0	1.7	1.9	1.0	1.5

Av = average Med = median SD = standard deviation

with a maximum rain of 3.9 mm per event. The coastal station, UFPa, recorded a three year average maximum rain value of 4.1 mm (Table 1).

Careiro received the greatest maximum rain for one hour of a particular event with a maximum rain 61.8 mm. Careiro's neighbor, CEPLAC, received the least maximum rain for the three year period with 51.10 mm while UFPa recorded a maximum rain of 60.0 mm for the three year period (Table 1).

The sum of the maximum rain for the three year period accounted for 65.5% of the total rain at Careiro and 69.2% of the total rain at CEPLAC. Just over 75% of the total rain fell as maximum rain for the coastal station of UFPa.

The rain sum from the beginning of the event to and including the peak rain of the event found Careiro with the greatest average of 5.4 mm for the three year period (Table 1). CEPLAC, once again, had the least average rain total from the beginning of the event to the peak of the event with 4.5 mm recorded for the three year period. UFPa recorded a rain sum from beginning to peak of 4.7 mm for the three year period.

Careiro had the greatest maximum sum from the beginning of the event to the peak for the three year period with a maximum sum of 88.6 mm. For the three year period, CEPLAC recorded 85.0 mm and UFPa recorded the least value with 60.0 mm.

For the three year period, the average yearly rain sum from the beginning of the event to, and including the peak rain sum of the event, accounted for 75% of the total rain that fell at Careiro, 80% of the total rain that fell at CEPLAC, and a little over 85% of the total rain that fell at UFPA.

The tail-end of the event accounted for a small portion of the rain total, implying that the more intense rain falls at the beginning of the storm, before the peak rain. For the three year period, the average yearly sum for the tail-end of the storm accounted for 25% of the total rain at Careiro, 20% at CEPLAC, and only 15% at UFPA with average event totals of 1.8 mm for Careiro, 1.2 mm for CEPLAC, and 0.8 mm for UFPA (Table 1) .

The duration of the rain event is a description of how many hours the event lasted. Table 1 shows that for the three year period centrally located Careiro had an average storm duration of 2.4 hours which was longer than its neighbor CEPLAC which had an average storm duration of 2.2 hours. The coastal station, UFPA, had the smallest storm duration with an average time of 2.1 hours.

The maximum storm duration was found at CEPLAC with a maximum duration of 19 hours for the three year period. Careiro had a maximum storm duration of 15 hours while UFPA had a maximum duration of 14 hours.

Analysis of the average number of hours that it

rained per year finds that Careiro had the least number of hours of rain with an average of 692 hours per year. UFPa had the greatest number of hours of rain with an average of 954 hours per year while CEPLAC had an average of 825 hours of rain.

Figure 5 shows the frequency distribution for Careiro for the attribute of duration for the one year period (1989-1990). Careiro was found to have less than 70% of the total rain events lasting between one and two hours, with no rain lasting over 14 hours. Figure 5 shows that for UFPa, approximately 75% of the rain events lasted between one and two hours with none lasting over 14 hours. This being a sample of what occurred during the three year period.

The interlude defined as the time between rain events with at least one hour between events. Table 1 shows that Careiro had the longest interlude between rain events with an average time of 27.58 hours, or just over one day, for the three year period. Both UFPa and CEPLAC had a smaller number of hours between rain events with UFPa having an average interlude of 17.28 hours and CEPLAC an average interlude of 21.07 hours.

Careiro also had the greatest maximum time between rain events with 24 days or 578 hours of no rain for the three year period. UFPa had the smallest maximum time between rain events with 9 days or 218 hours of no rain for

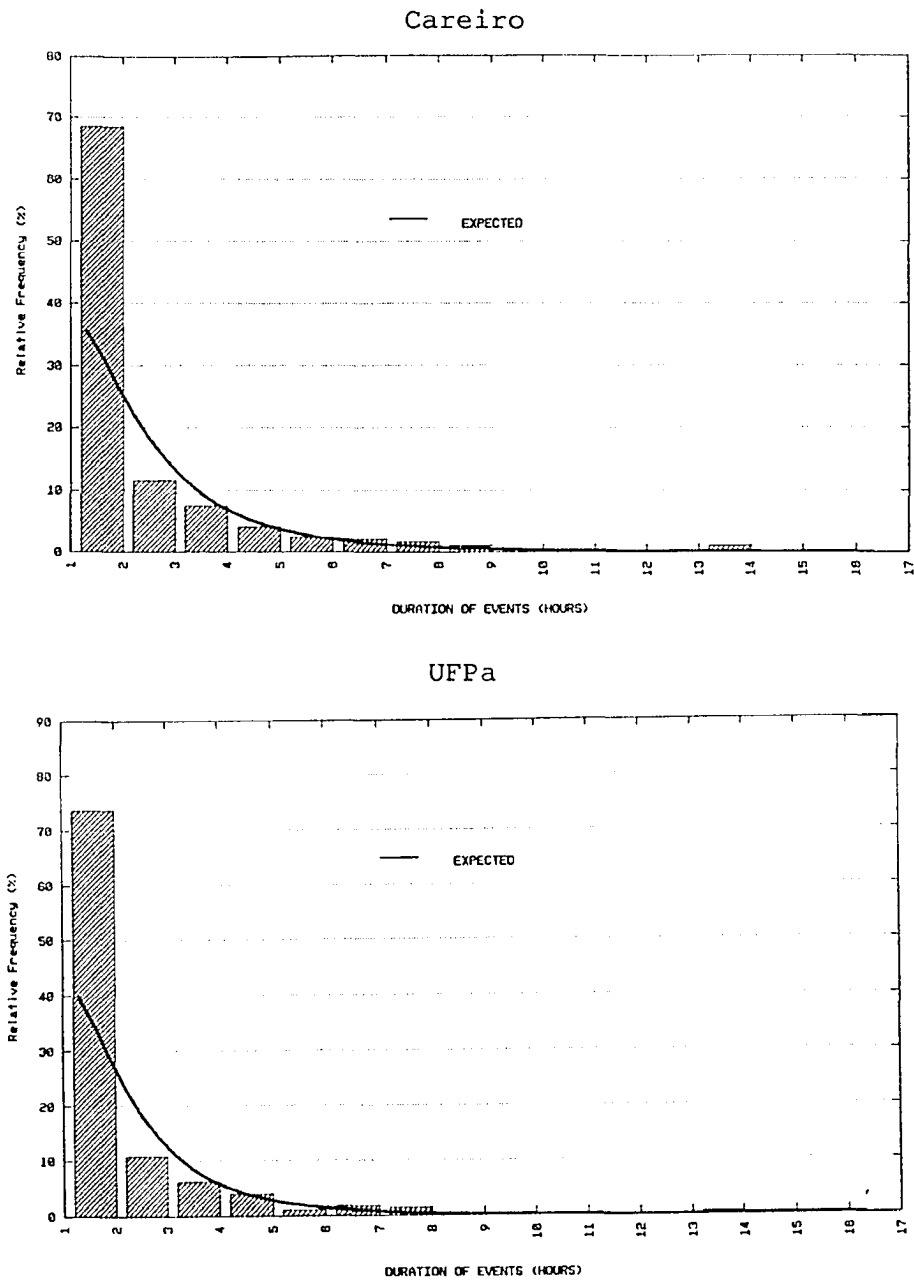


Figure 5. Frequency Distribution for Duration of Rain Events for Careiro and UFPa During the Period 1 July 1989 to 30 June 1990.

the three year period. CEPLAC had a maximum interlude of 12 days or 283 hours for the three year period.

Figure 6 shows the frequency distribution for the attribute of the interlude between the rain event for Careiro. This figure shows that over 75% of the total rain events that occurred for the one year period (1989-1990), over 75% of the events fell within 28 hours or over one day of each other. UFPa, Figure 6, shows that over 75% of the rain events that occurred at this coastal station fell within 24 hours or one day of each other.

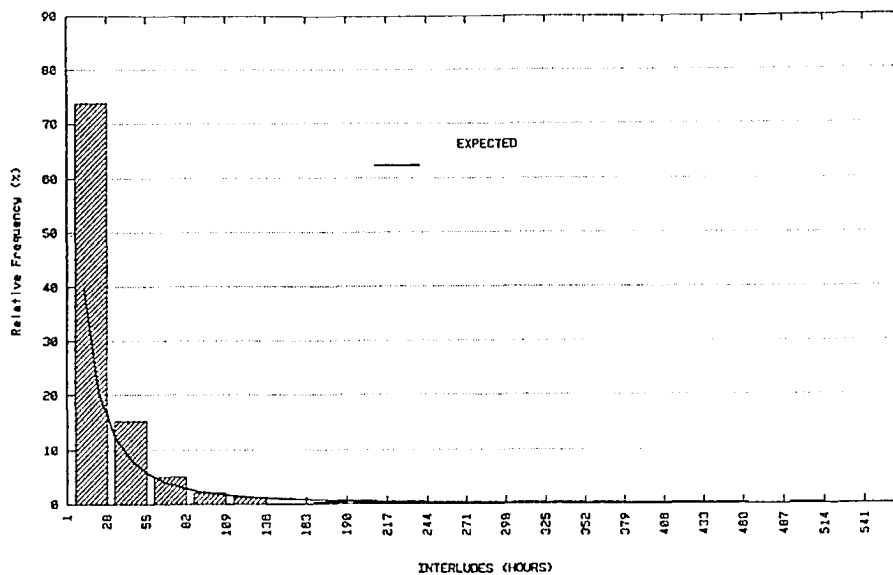
The time from the beginning of the rain event to the peak of the event found Careiro with the greatest average time of 1.4 hours for the three year period (Table 1). UFPa had an average time of 1.4 hours for the three year period. CEPLAC had an average time of 1.3 hours between the beginning of the rain event to the peak of the rain event for the three year period.

The maximum time between the beginning of the event and the time of the peak rain was 11 hours for both UFPa and CEPLAC. Careiro experienced a smaller maximum time than its neighbor stations with a time of nine hours.

The average yearly sum of hours from beginning time to peak time is the least in Careiro with 400 hours while UFPa and CEPLAC have an average yearly time of 617.3 hours and 503.0 hours respectively.

The tail-end of the rain event experienced a longer

Careiro



UFPa

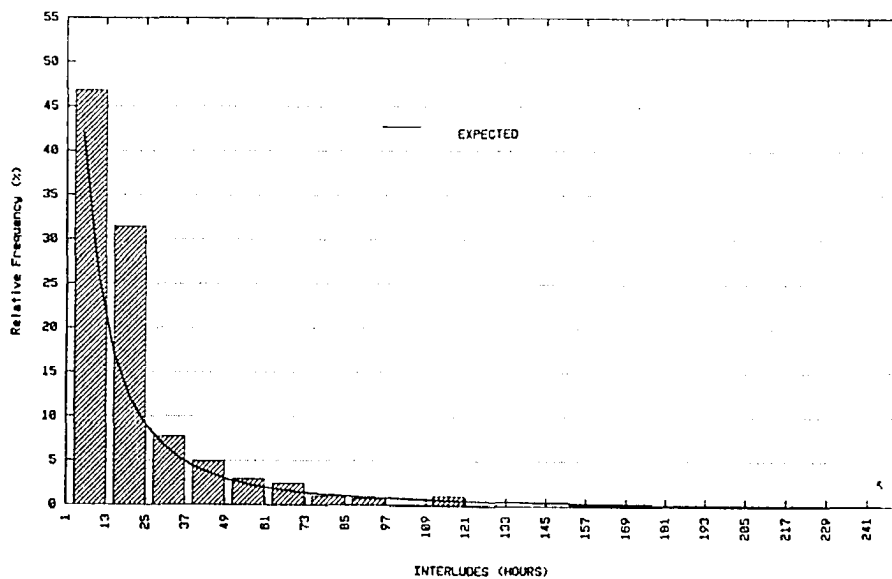


Figure 6. Frequency Distribution for Interlude Between Rain Events for Careiro and UFPa During the Period 1 July 1989 to 30 June 1990.

time for all three stations than did the time from the beginning time of the event to the peak time of the event. Careiro had the longest tail-end of the storm with an average recording of 2.0 hours for the three year period (Table 1). UFPa and CEPLAC had relatively similar time frames for the tail end of the storms with UFPa having an average time of 1.7 hours and CEPLAC an average time of 1.9 hours per year.

The maximum time for the tail end of the rain event for the three year period was found at CEPLAC with a maximum time of 16 hours. UFPa had a maximum time of 12 hours while Careiro had a maximum time of 14 hours.

Table 2 displays more specific results for the rain event model. From the average duration and the average accumulation of rain for the early period of the event, the peak of the event, and the later part of the event, the rain rate (mm/hr) was calculated. The table shows that Careiro experiences the most intense rainfall with an early rainrate of 2.0 mm/hr, a peak rainrate of 4.7 mm/hr, and a late rainrate of 1.8 mm/hr. UFPa had an early rainrate of 1.5 mm/hr, a peak rainrate of 4.1 mm/hr, and a late rainrate of 1.1 mm/hr. Finally, CEPLAC had an early rainrate of 1.8 mm/hr, a peak rainrate of 3.9 mm/hr, and a late rainrate of 1.3 mm/hr. This information is displayed graphically in Figure 7. The average rainrate for each station is shown along the vertical line. The horizontal

Table 2
Model Rain Event
Rain Rates

	UFPa			Careiro			CEPLAC		
	Dur (h)	Acc mm	Rate mm/hr	Dur (hr)	Acc mm	Rate mm/hr	Dur (h)	Acc mm	Rate mm/hr
Early	0.4	0.6	1.5	0.4	0.8	2.0	0.4	0.7	1.8
Peak	1.0	4.1	4.1	1.0	4.7	4.7	1.0	3.9	3.9
Late	0.7	0.8	1.1	1.0	1.8	1.8	0.9	1.2	1.3
Σ	2.1	5.5	-	2.4	7.3	-	2.3	5.8	-

Dur=Duration Acc=Accumulation Σ =summation

Assumptions:

1. Peak rain is recorded over a 1-h period
2. Sum of rain falls from Early, Peak, and Late periods must equal accumulation

Consequences:

1. Duration (Early) = D(Beginning through Peak) - 1
Duration (Late) = D(Peak through End) - 1
2. Accumulation (Early) = Acc'n(Beg'g through Peak) - Acc'n(Peak)
3. Rate (Early) = Acc'n (Early) / Duration (Early);
Rate (Late) = Acc'n (Late) / Duration (Late)

axis displays the amount of time in hours for the average duration of the station's rain event and also the average interlude of time between rain events. The figure displays the remarkable feature of the event model analysis, the similarity in rain fall from station to station. The noticeable exception is the interlude of time between rain events, with Careiro having the greatest interlude.

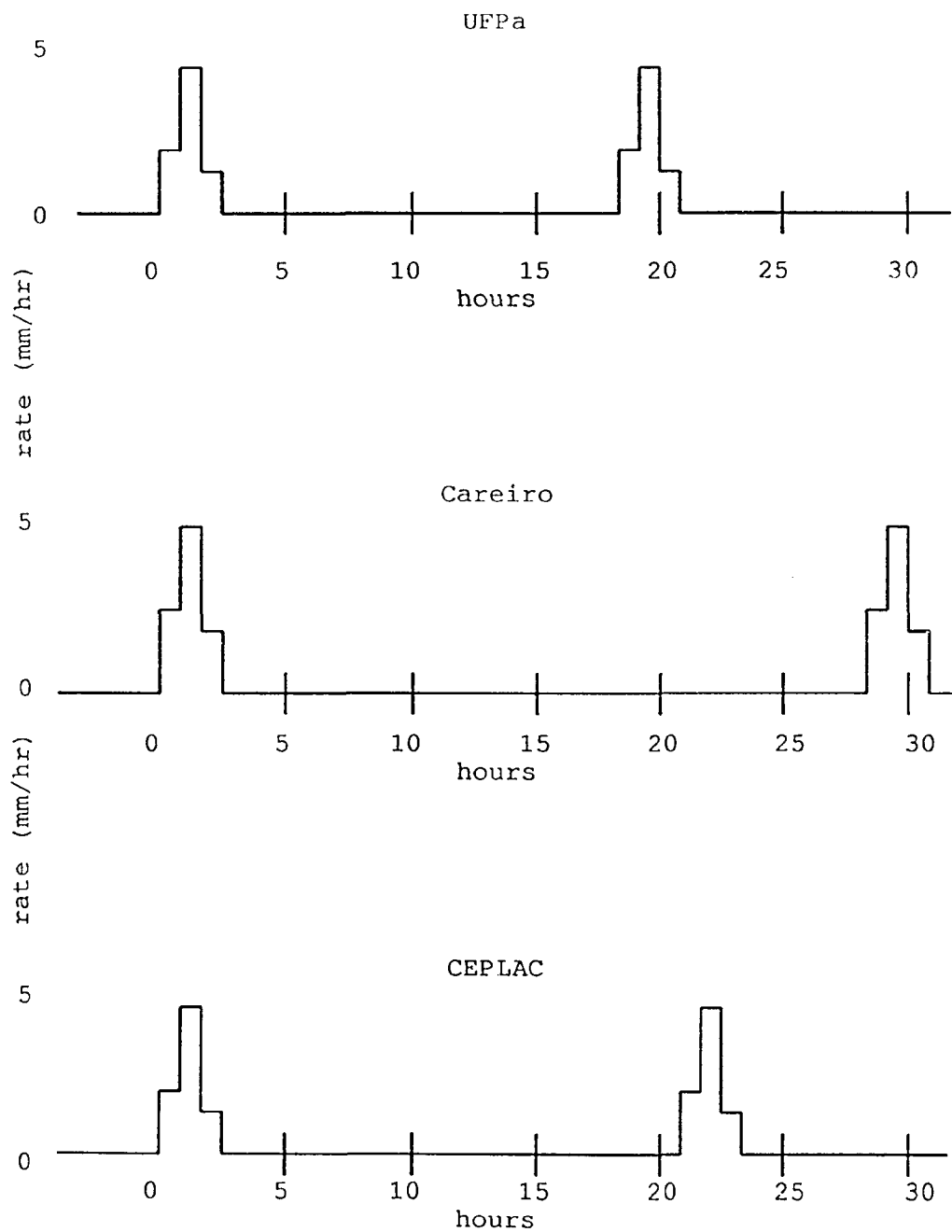


Figure 7. Model of Rain Events for UFPA, Careiro, and CEPLAC for January 1988 to December 1990.

CHAPTER VIII

RADIANCE AND RAINFALL

Cloud-top radiance is compared to rainfall at Careiro for the period 15 July 1989 to 30 June 1990. A correlation coefficient of -0.3 was found for the year period. A negative correlation value is expected because colder cloud top temperatures (low radiance values) should produce greater rain fall totals. Analyzing the month of September (dry season) (Figure 8) and the month of February (wet season) (Figure 9), a correlation of -0.237 at lag 0 hours was found for September and a correlation of -0.210 at lag 0 hours was found for February. Figures 8 and 9 show that there are incidents in which warm clouds (higher radiance values) produced significant rain totals and also incidents in which cold clouds (low radiances) produced little to no rain.

Correlation Coefficient = -0.237 at lag 0 Hours

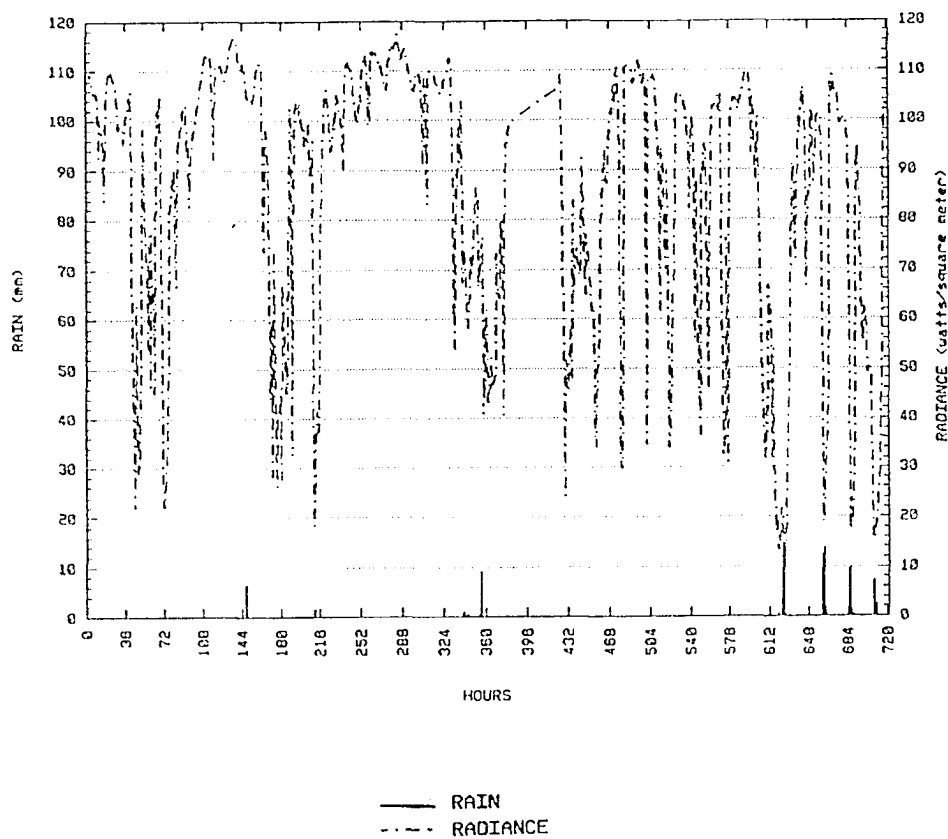


Figure 8. Radiance Versus Rainfall for Careiro During the Month of September 1989.

Correlation Coefficient = -0.218 at lag 0 Hours

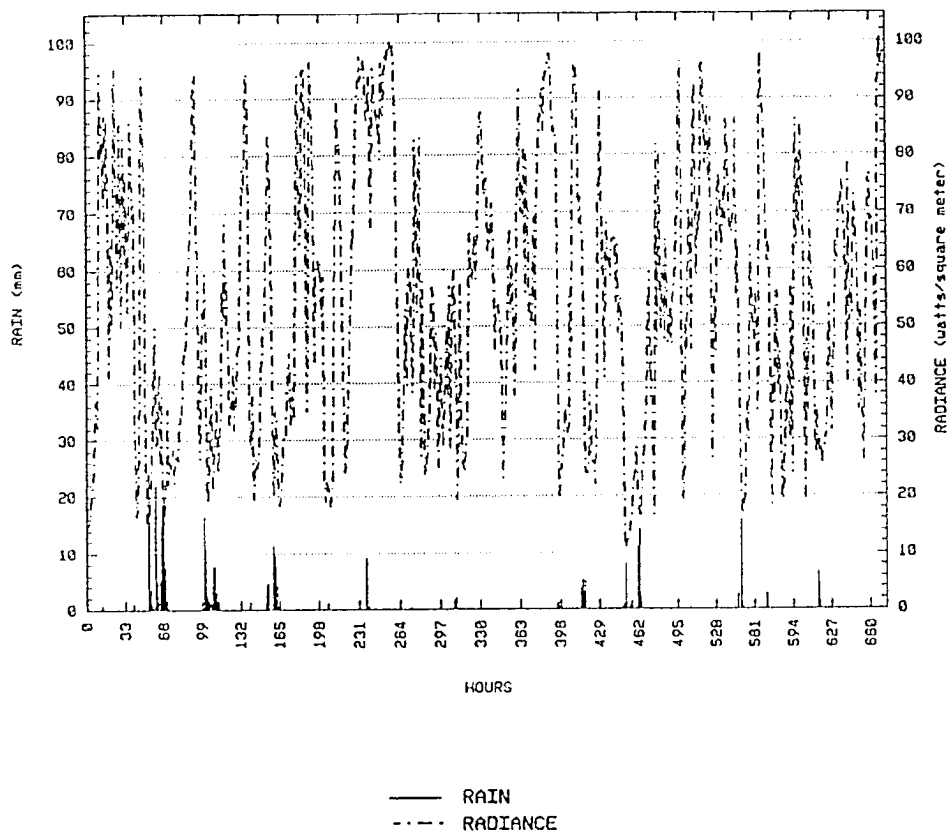


Figure 9. Radiance Versus Rainfall for Careiro During the Month of February 1990.

CHAPTER IX

DISCUSSION OF RESULTS

Hourly rain analysis revealed that UFPa received the greatest amount of rain. It is expected that UFPa would receive the greatest rain total due to its coastal location and the induced sea breeze. CEPLAC should have received more rain than Careiro due to CEPLAC's location in the "terra firme" and the land-to-river circulation which may enhance rain in the "terra firme". Missing data may have contributed to CEPLAC's lesser rain total. The mean annual rainfall recorded for the Manaus region for July 1989 to June 1990 was found to be 2085 mm (average of mean average annual rainfall at Careiro and mean average annual rainfall at CEPLAC). This total is considerably less than the 2732 mm that Lloyd (1990) found for the period 3 September 1983 to 21 August 1985. However, these results were about 20 mm short of 2105 mm recorded by Ribeiro and Adis (1984) for the period of study 1910 to 1979. Missing observations at UFPa, Careiro, and CEPLAC may account for the discrepancy. Respectively, 245 hours (0.9%), 780 hours (3.0%), and 690 hours (2.6%) of the rain data were recorded as missing for the three year period.

The low correlation value between UFPa and Careiro

indicated that the instability lines which originate along the coast and move westward do not play a vital role in the rainfall in interior Amazonia.

The low correlation values found between Careiro and CEPLAC are not that surprising. Ribeiro and Adis (1984) collected rainfall over 12 months at eight stations in the vicinity of Manaus. Considerable differences were found in rainfall patterns (intensity, frequency, and time of rainfall) around the eight stations (Ribeiro, 1984). These results imply lack of coherence (on the 50 km scale) in the rain systems. These low correlations for a range of lags implies little or no propagation along the axis connecting Careiro and CEPLAC and also suggests small, local convective rain systems as the dominate form of rain production in this area.

Both Careiro and CEPLAC presented diurnal bimodal signatures with a peak rain found in the late afternoon to early evening hours and secondary peak found during the nighttime hours. Careiro, which lies along the Negro River, had a strong secondary peak in nighttime rain. This secondary peak may be due to the nightly circulation from land to river. Lloyd (1990) also found that Reserva Ducke (Manaus area) receives 50% of its daily rainfall between 1500 and 2100 hours or 3 P.M. and 9 P.M. and 90% during the latter part of the day. Overall, it can be concluded that all three stations received a peak rain in the late

afternoon to early evening hours indicating the strength of convective activity during the latter part of the day.

The diurnal signature for the three year period at UFPa was in agreement to the diurnal signature that Kousky found at Belem. It was found that maximum rains fell during the late afternoon to early evening hours for the coastal station of Belem, while minimum rain values were recorded during the night to early evening hours. However, the diurnal signature for UFPa is not in entire agreement with Kousky's overall results. While Kousky found that the entire coast receives most of its rainfall during the nighttime hours, the three year period found maximum rain to fall in the late afternoon to early evening hours. Kousky (1980) suggested that the occurrence of rain induced by the sea breeze may affect the annual mean distribution of precipitation in the basin. The nighttime maximum along the East Coast is probably due to the convergence between trade winds and the land breeze. The annual totals at approximately 500 km from the coast are considerably smaller because of reduced daily convection. At night, there is some precipitation in this region, although it is less intense than during the day because of reduction in thermal contrast (Salati, 1987).

A problem that developed with the rainfall and radiance values over Careiro is that the radiance values covered an area of 8 km by 8 km while the hourly rain is

recorded at a specific point or rain gauge. Thus, it may be found that there are low radiance values (cold cloud-top temperatures) producing a measurable rain within the 8 km by 8 km area and not at the specific point where the rain gauge was recording.

Another problem with the radiance-rain analysis is that stations were missing either ground-based data or radiance data so there was not a complete set of rain versus radiance data to analyze. Careiro, for example, was missing 1454 hours (17%) of its radiance data for the one year period. Thus, it was difficult to predict which cloud top temperatures were related to the rain that had fallen in the area. One possible way to overcome this problem in future studies is to use radiance or ground-based data for stations that are near those stations missing radiance or ground-based data.

Because of the above problems, monthly lag correlations between rain and radiance were not as high as what was to be expected. It is assumed that cold clouds (strong vertical development) would produce the most rain. However, the figures illustrate that possibly low- and middle-level clouds contribute to Amazonia's rainfall. This study reinforces the view that warm clouds do produce rain over Amazonia. We cannot claim this fact because (a) the satellite observes only one per half hour and (b) even if it sampled every one half minute, the satellite

observation is indirect.

CHAPTER X

CONCLUSIONS

The analysis of hourly rain over Amazonia for the period 1 January 1988 to 31 December 1990, convey to the following conclusions:

1. The low correlation between the hourly rain records of neighboring stations Careiro and CEPLAC suggests little or no propagation along the axis connecting the stations and a predominance of local convection in Central Amazonia.

2. Low correlation coefficient value obtained from the lag correlation between coastal station UFPA and inland station Careiro indicate that the instability lines described in the literature which originate along the coast and travel westward across Amazonia do not have a strong effect in the rainfall in over Central Amazonia.

3. The rainfall accumulation was greater at the coastal station than it was at the inland stations.

4. The rainfall accumulation was greater at the station along the river than it was at the station in the "terra firme".

5. The diurnal analysis shows that the station on the coast of Amazonia reveals a strong diurnal signature of

rain with a late afternoon maximum, while the stations in Central Amazonia shows a less structured cycle with nocturnal secondary maximum.

6. Pulsatile analysis for the three stations begins to build a model for rain over Amazonia.

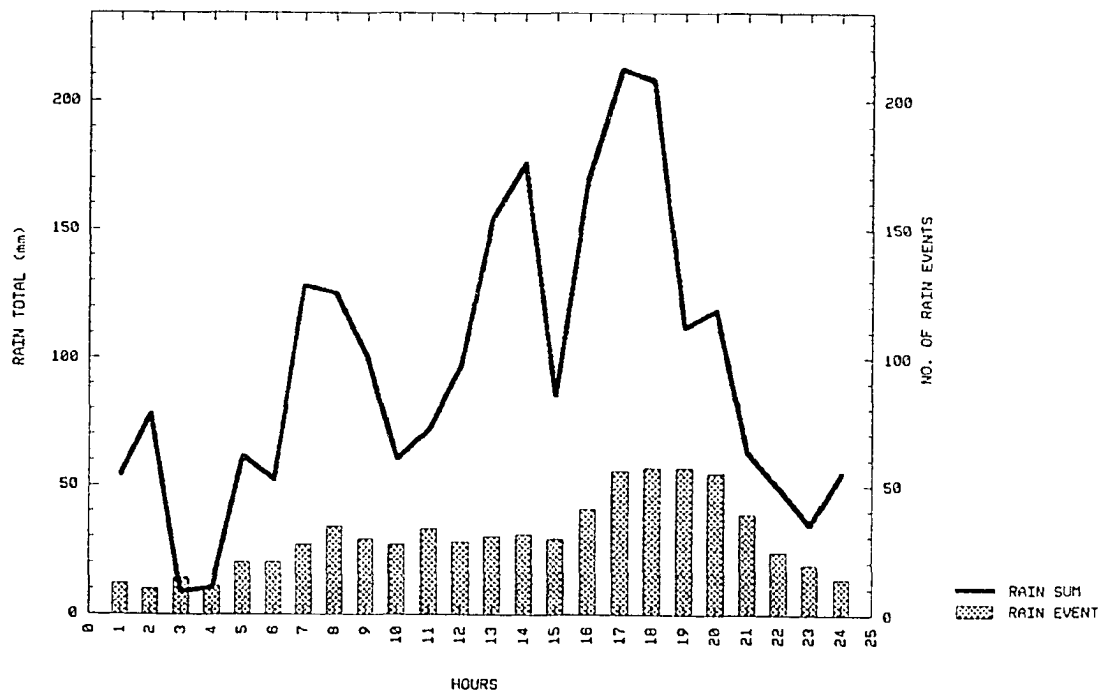
7. Rain and radiance over Careiro are weakly anti-correlated, suggesting a large amount of no rain producing cold clouds and possibly the occurrence of rain from warm clouds.

These results will help to better understand the behavior of the Amazon rain. Prediction models of climate change in Amazonia might benefit from the model rain produced here. This study is by no means conclusive. Further efforts should be taken to improve rain measurements in Amazonia. These should include a denser rain gauge network, automatic data collection, meteorological radars, and improved satellite sensors to measure rain in the tropics.

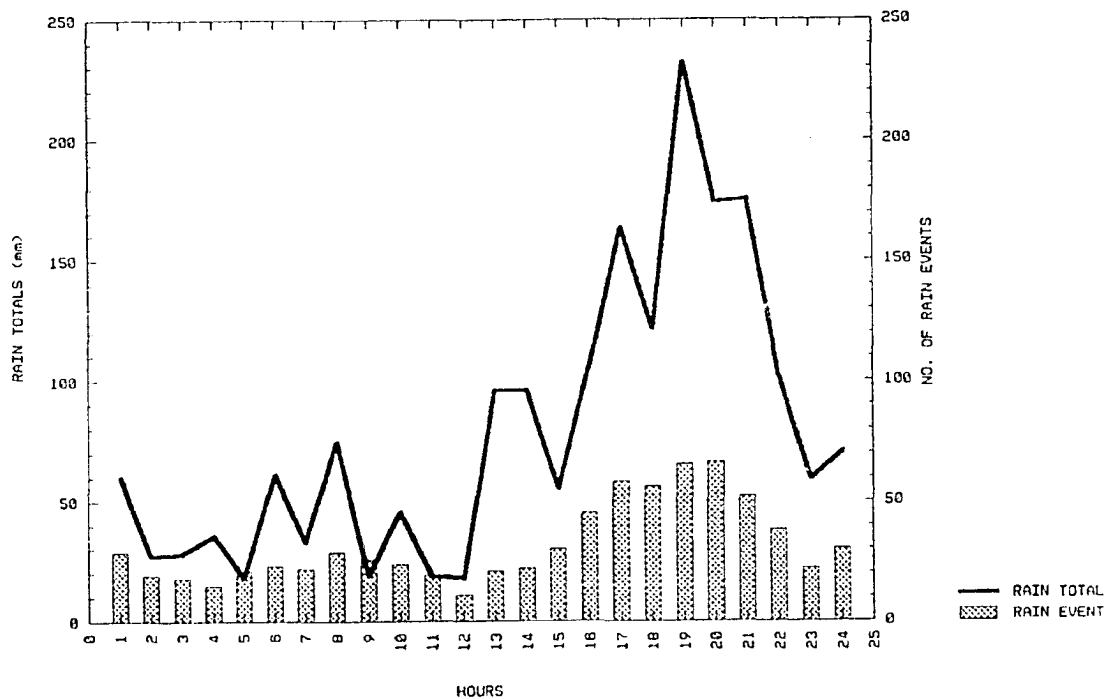
Appendix A

Diurnal Cycles for UFPa, Careiro, and CEPLAC for the Period
July 1989 to June 1990

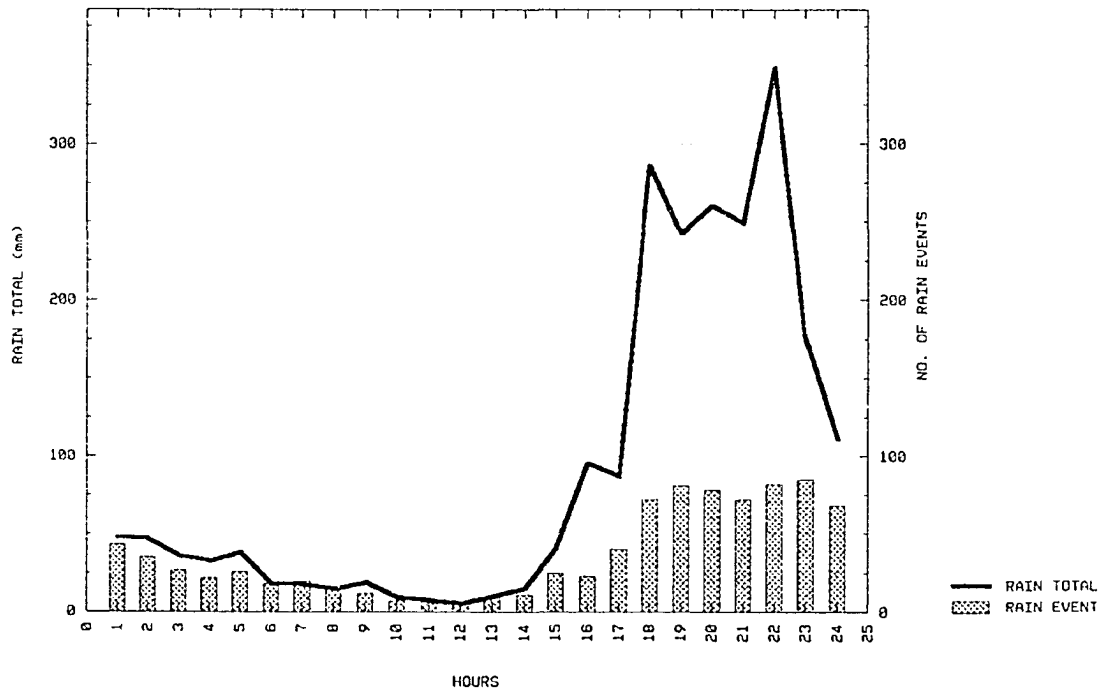
DIURNAL ANALYSIS
NUMBER OF RAIN EVENTS AND RAIN TOTALS
CAREIRO
JULY 1989-JUNE 1990



DIURNAL ANALYSIS
NUMBER OF RAIN EVENTS AND RAIN TOTALS
CEPLAC
JULY 1989-JUNE 1990



DIURNAL ANALYSIS
NUMBER OF RAIN EVENTS AND RAIN TOTALS
UFPA
JULY 1989-JUNE 1990



Appendix B

Pulsatile Analysis Tables for UFPa, Careiro, and CEPLAC for
1 January 1988 to 31 December 1990 and
1 July 1989 to 30 June 1990

Average Rain Accumulation per Event
in millimeters

January 1988-December 1990				July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	5.49	7.27	5.62	5.46	7.74	5.20
Median	1.75	2.10	1.50	1.90	1.80	1.60
Mode	0.10	0.10	0.10	0.10	0.10	0.10
Maximum	69.60	150.50	127.60	66.00	150.50	127.60
SD	9.19	13.88	10.46	9.12	16.87	10.39
Variance	84.53	192.79	109.33	83.17	284.53	108.03
Skewnes	3.09	4.83	4.23	3.02	5.20	6.17
Kurtosis	11.78	34.79	27.27	11.47	35.51	57.38
Sum/ yr	2475.33	2101.23	2100.13	2206.80	2283.80	1886.40

Average Maximum Rain per Event
in Millimeters

January 1988-December 1990				July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	4.10	4.69	3.89	3.99	4.67	3.67
Median	1.40	1.60	1.10	1.40	1.30	1.20
Mode	0.10	0.10	0.10	0.10	0.10	0.10
Maximum	60.00	61.80	51.10	46.50	59.50	49.50
SD	6.72	7.49	6.47	6.52	7.81	5.93
Variance	45.21	56.17	41.82	42.52	61.05	35.11
Skewnes	3.19	3.24	3.14	3.07	3.56	3.28
Kurtosis	13.27	14.68	12.63	11.43	17.67	14.93
Sum/ yr	1845.57	1356.07	1453.13	1611.20	1376.60	1331.70

Rain Sum From Peak of Event to end of Event
in Millimeters

	January 1988-December 1990			July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	0.83	1.82	1.16	0.90	2.06	0.99
Median	0.00	0.00	0.00	0.00	0.00	0.00
Mode	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	28.90	88.50	47.50	17.20	88.50	42.60
SD	2.55	6.09	3.72	2.40	7.86	3.53
Variance	6.50	37.06	13.82	5.78	61.85	12.45
Skewnes	5.72	7.48	6.45	3.94	7.42	7.61
Kurtosis	42.39	76.16	55.17	17.29	66.02	71.58
Sum/ yr	372.60	524.80	433.67	361.70	608.20	361.10

Rain Sum From Beginning of Event to (and Including) Peak of Event
in Millimeters

	January 1988-December 1990			July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	4.67	5.45	4.46	4.57	5.68	4.20
Median	1.50	1.80	1.30	1.70	1.40	1.40
Mode	0.10	0.10	0.10	0.10	0.10	0.10
Maximum	60.00	88.60	85.00	51.80	84.50	85.00
SD	7.71	9.21	7.80	7.55	10.41	7.65
Variance	59.58	84.82	60.85	57.06	108.39	58.50
Skewnes	3.07	3.82	3.71	3.00	3.82	5.04
Kurtosis	11.53	21.42	19.80	11.43	17.67	14.93
Sum/ yr	2102.73	1576.43	1666.47	1845.10	1675.60	1525.30

INTERLUDE
Hours Between Rain Events

	January 1988-December 1990			July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	17.28	27.58	21.07	19.44	27.04	21.64
Median	12.00	15.00	12.00	14.00	14.00	14.00
Mode	1.00	1.00	1.00	1.00	1.00	1.00
Maximum	218.00	578.00	283.00	218.00	488.00	241.00
SD	23.40	47.76	30.42	26.80	51.08	28.88
Variance	547.41	2280.84	925.08	718.30	2609.45	833.93
Skewnes	3.61	5.36	3.60	3.72	5.29	3.30
Kurtosis	19.14	41.07	17.90	19.30	34.95	16.06
Sum T13/yr	7785.00	7970.00	7875.00	7853.00	7976.00	7857.00

Duration
Hours of Rain Event

	January 1988-December 1990			July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	2.12	2.40	2.21	2.19	2.43	2.10
Median	2.00	2.00	2.00	2.00	2.00	1.00
Mode	1.00	1.00	1.00	1.00	1.00	1.00
Maximum	14.00	15.00	19.00	14.00	14.00	12.00
SD	1.73	2.03	1.84	1.83	2.20	1.65
Variance	2.98	4.14	3.37	3.35	4.82	2.71
Skewnes	2.71	2.37	2.75	2.72	2.48	2.26
Kurtosis	10.48	7.70	12.41	10.31	7.86	6.41
Sum T31/yr	954.00	692.00	825.00	884.00	717.00	761.00

Time From Beginning of Event to Peak of Event
in Hours

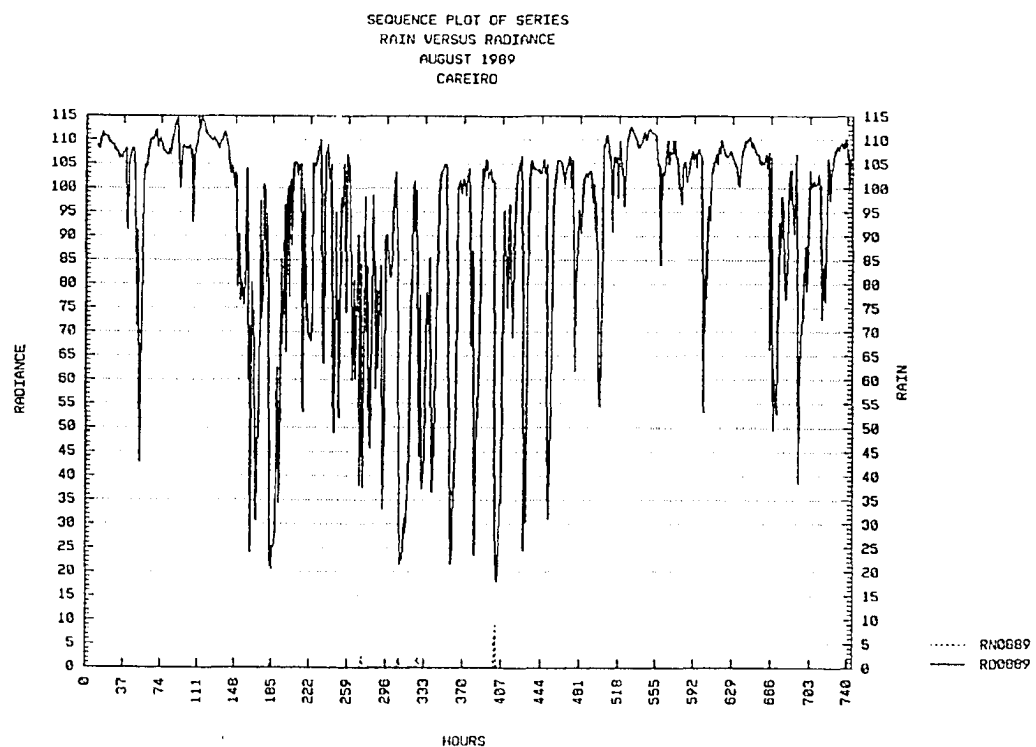
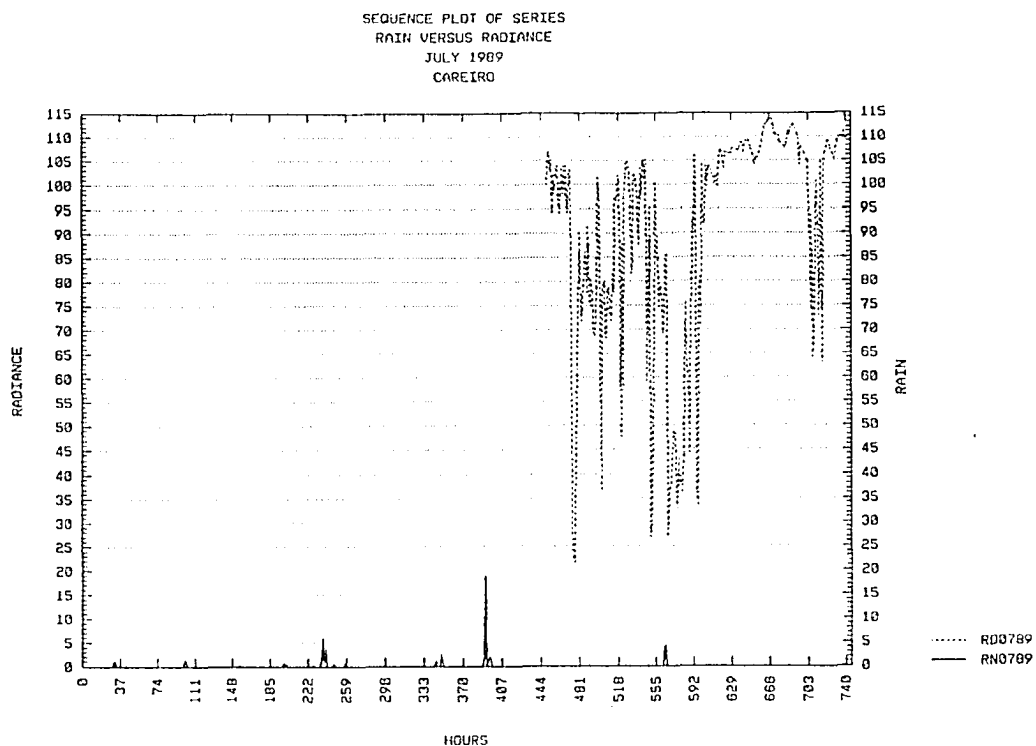
January 1988-December 1990				July 1989-June 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	1.37	1.38	1.35	1.38	1.38	1.32
Median	1.00	1.00	1.00	1.00	1.00	1.00
Mode	1.00	1.00	1.00	1.00	1.00	1.00
Maximum	11.00	9.00	11.00	11.00	9.00	8.00
SD	0.85	0.78	0.84	0.88	0.84	0.80
Variance	0.73	0.61	0.71	0.77	0.70	0.63
Skewnes	4.02	3.14	4.24	4.70	4.09	3.79
Kurtosis	26.20	15.79	27.36	37.54	26.49	19.79
Sum/ yr	617.33	400.00	503.00	556.00	406.00	480.00

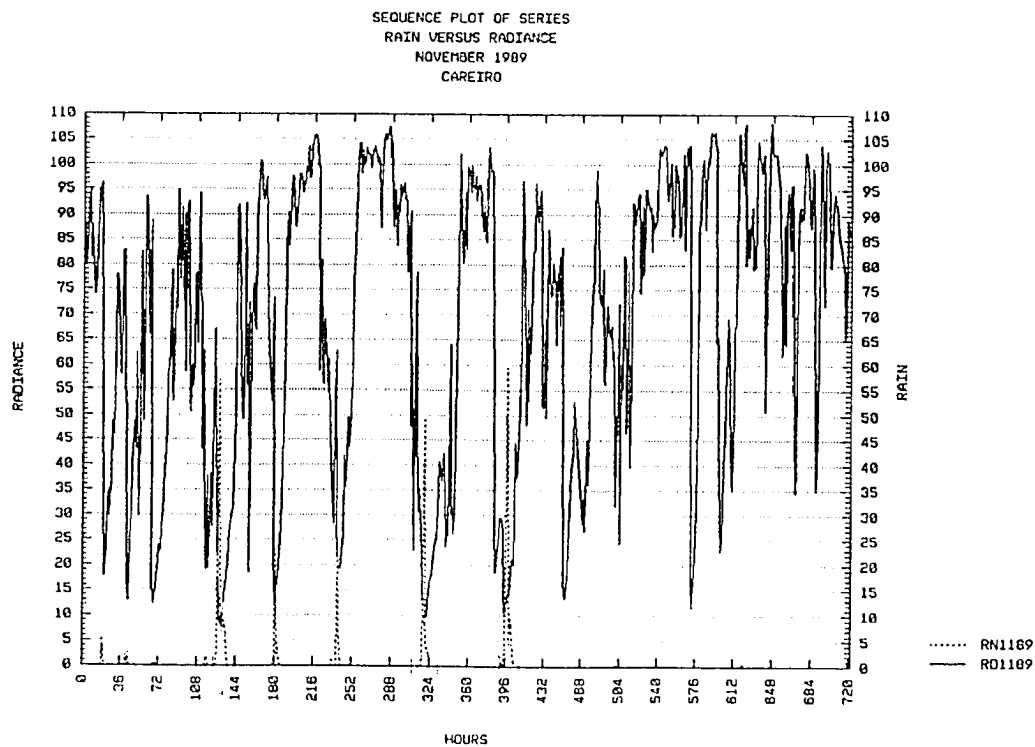
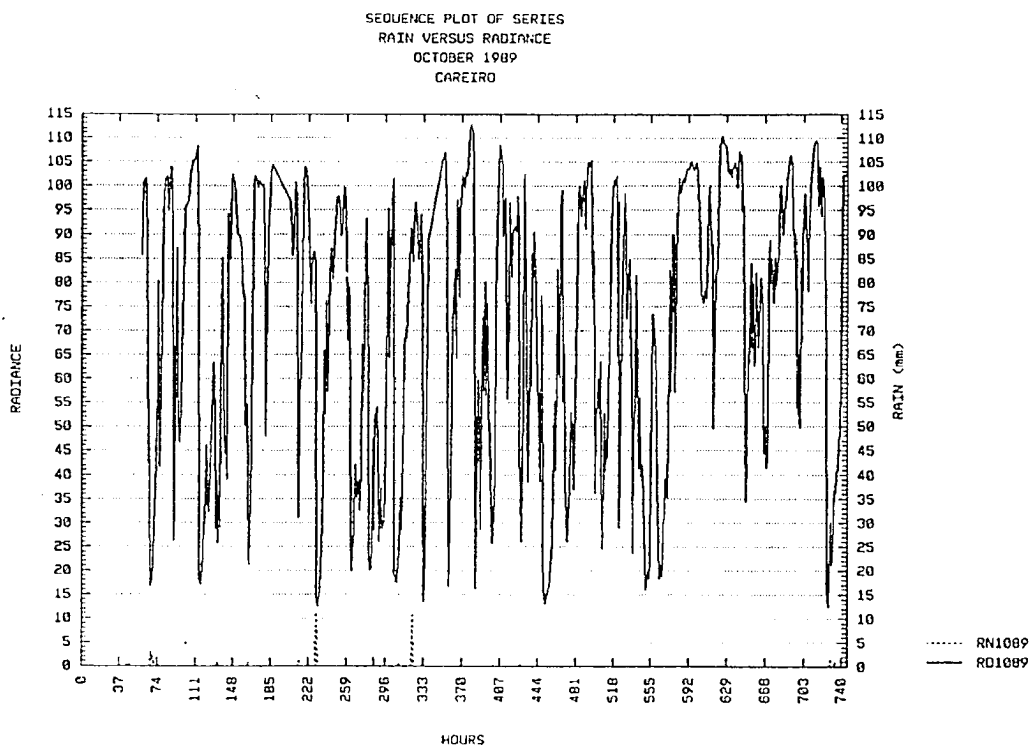
Time From Peak of Event to end of Event
in Hours

January 1988-December 1990				July 1989-July 1990		
	UFPa	Careiro	Ceplac	UFPa	Careiro	Ceplac
Mean	1.75	2.01	1.86	1.81	2.05	1.77
Median	1.00	1.00	1.00	1.00	1.00	1.00
Mode	1.00	1.00	1.00	1.00	1.00	1.00
Maximum	12.00	14.00	16.00	11.00	14.00	9.00
SD	1.31	1.68	1.46	1.41	1.77	1.24
Variance	1.71	2.83	2.12	1.98	3.13	1.55
Skewnes	3.23	2.71	2.92	2.91	2.64	2.28
Kurtosis	15.12	10.30	13.67	10.57	9.51	6.42
Sum/ yr	787.00	581.33	695.67	732.00	606.00	644.00

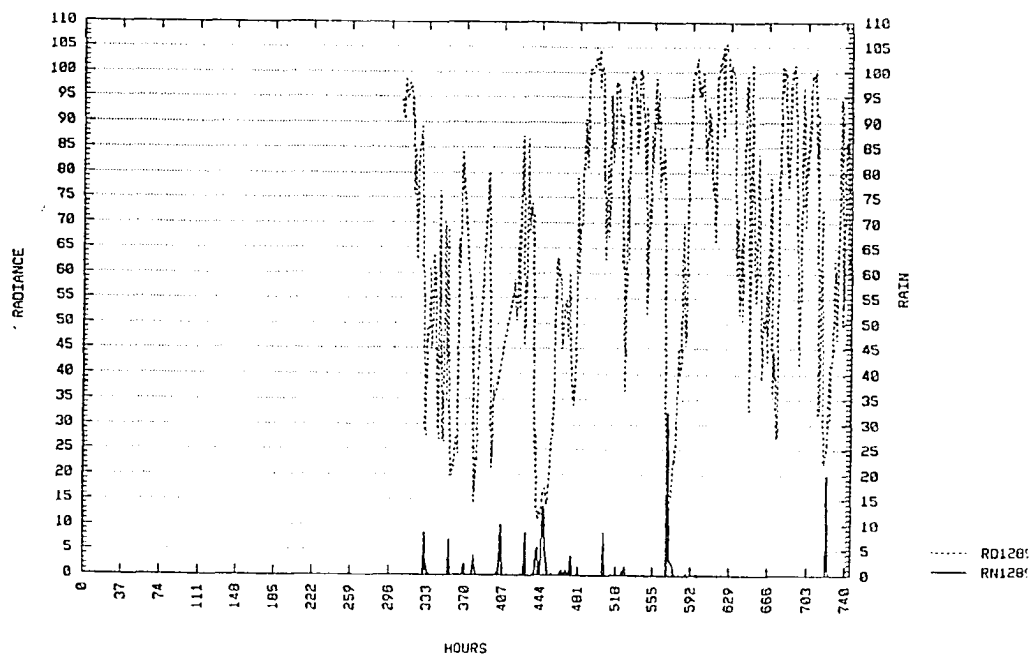
Appendix C

Monthly Radiances and Rainfall Time Series Figures
for Careiro for the Period June 1989 to July 1990

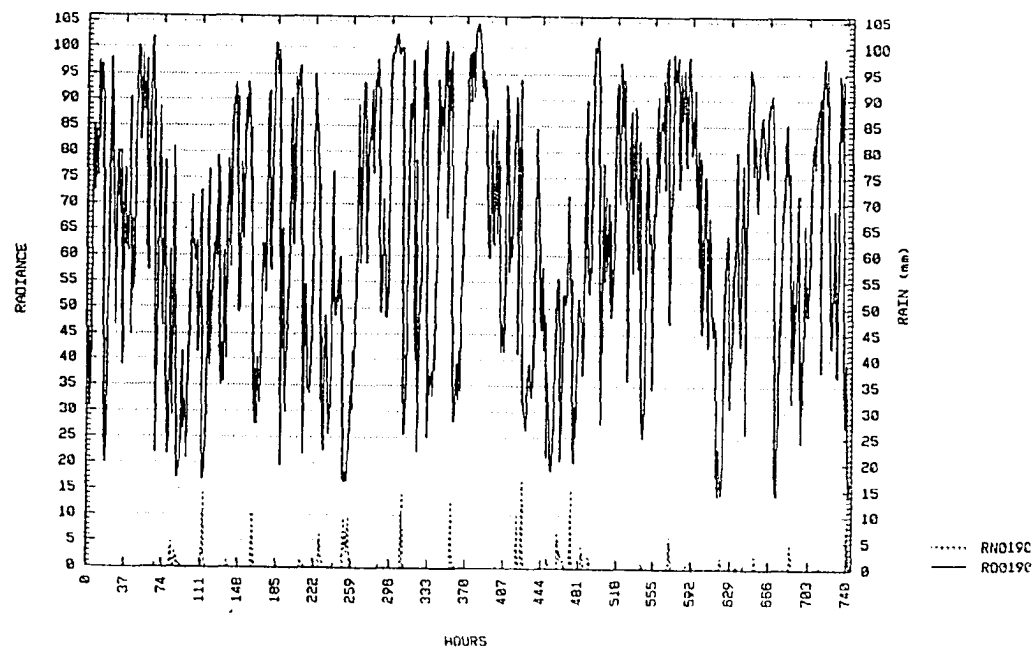




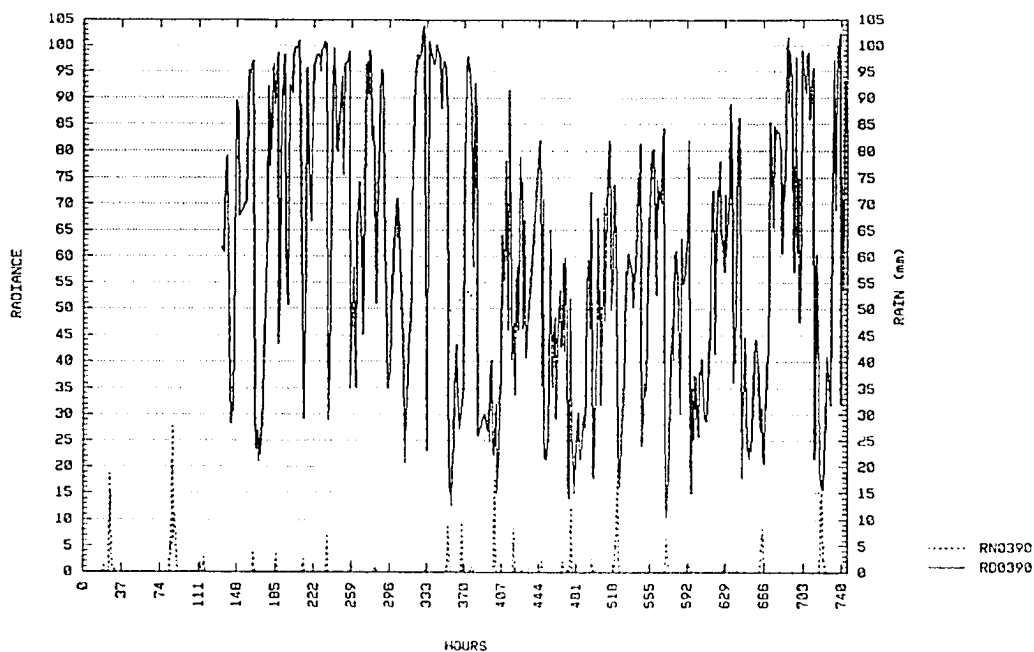
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RAIN VERSUS RADIANCE
DECEMBER 1989
CAREIRO



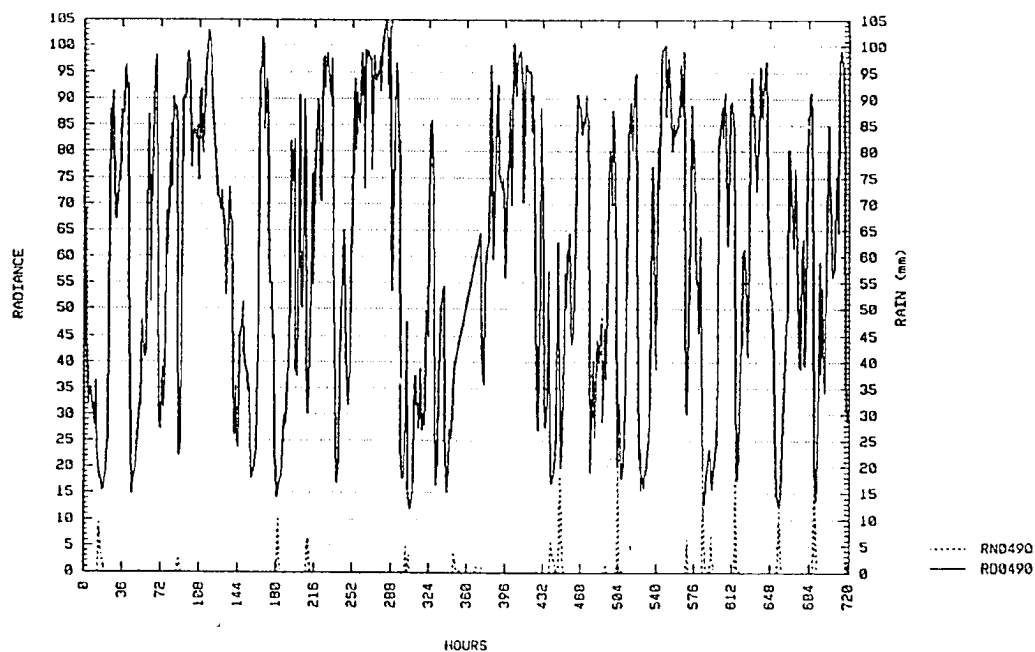
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RAIN VERSUS RADIANCE
JANUARY 1990
CAREIRO

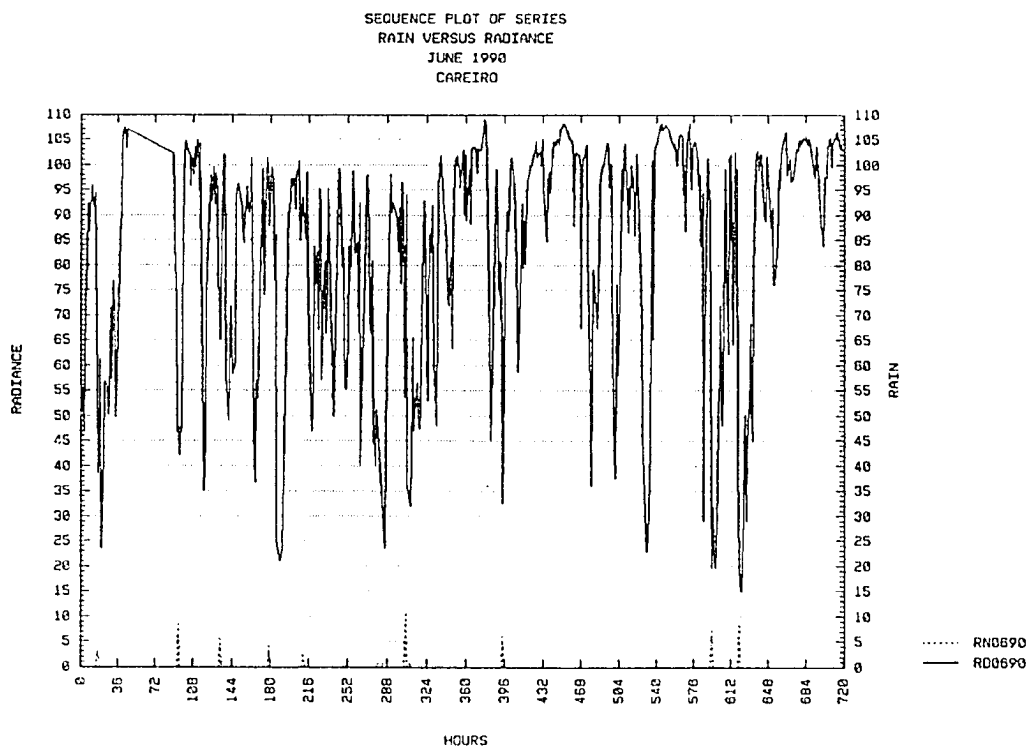
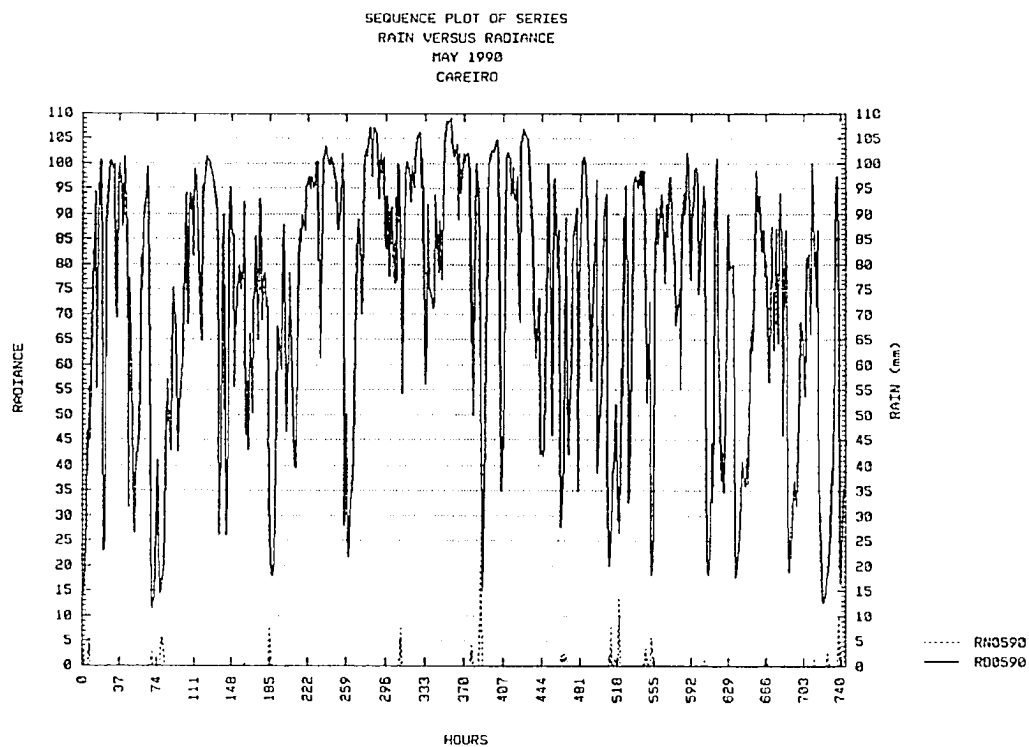


SEQUENCE PLOT OF SERIES
RAIN VERSUS RADIANCE
MARCH 1990
CAREIRO



SEQUENCE PLOT OF SERIES
RAIN VERSUS RADIANCE
APRIL 1990
CAREIRO





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