Roberts, J. and O. M. R. Cabral. 1993: ABRACOS: a comparison of climate, soil moisture and physiological properties of forest and pastures in the Amazon Basin. *Commonw. For. Rev.*, 72:310-315.

Sanchez, P. A. 1976: *Properties and management of soils in the tropics.* Wiley and Sons, 618 pp.

Smith-Ramirez, C. and J. J. Armesto. 1994: Flowering and fruiting patterns in the temperate rainforest of Chiloé, Chile — ecologies and climatic constraints. *J. Ecol.*, 82:353-365.

Soil Survey Staff. 1975: *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys.* Agric. Handb. No. 436. USDA. U. S. Government Printing Office.

Steel, R. G. D. and J. H. Torrie. 1980: *Principles and procedures of statistics: A biometrical approach.* 2d ed. McGraw-Hill, 633 pp.

Thornthwaite, C. W. 1948: An approach toward a rational classification of climate. *Geog. Rev.*, 38:55-94.

Unwin, G. I. and P. E. Kriedemann. 1990: Drought tolerance and rainforest tree growth on a North Queensland rainfall gradient. *For. Ecol. Manag.*, 30:113-123.

ANALYSIS OF RAINFALL DISTRIBUTION IN THE AMAZON BASIN USING KRIGING, NONPARAMETRIC STATISTICS, AND GIS TECHNIQUES. II. MONTHLY DEVIATIONS.

Elson D. Silva[1], Researcher Scientist, Ph. D.
Brazilian Enterprise for Agricultural Research, Satellite Monitoring Center (Embrapa-NMA)
Gary W. Petersen, Soil Scientist, Ph.D., Prof. of Soil and Land Resources
Agronomy Dept., The Pennsylvania State University.

The Amazon forest owes its existence, in part, to generous precipitation and, in turn, plays a pivotal role of its own in the functioning of the terrestrial-atmospheric hydrologic cycle. Assessing spatial and temporal variability of a water recharge by rainfall is important in hydrological studies of the Amazon Basin.

Rainfall characteristics can be assessed using nonparametric statistics. The median is the central tendency of nonparametrics and is protected from the displacing effects of outliers and skewness. Monthly rainfall is widely used as a partial measurement of a rainfall recharge during the tropical year. Usually it is important to know how much rainfall occurs during specific months, which is important in defining growing seasons, or determining water supply, and drought and flooding assessments. Measuring local rainfall departures from their medians and understanding their behavior can assess spatial rainfall variability and associate this pattern to climatic anomalies. This is a robust evaluation of rainfall variability and is vital when studying precipitation in the Amazon Basin.

Climate anomalies that affect the Amazon Basin are related to geographic position in the equatorial latitudes and to the orographic impact by the Andes Mountains. The Andes mountains extend through the entire South American continent along its western shore and serve as a barrier to the movement of moisture-bearing air masses (UNESCO, 1978). Equatorial sea surface temperature anomalies are believed to be related to changes in the tropical circulation systems (Rasmusson and Wallace, 1983). Anomalies have been linked to the occurrence of droughts and floods (Matalas, 1991). An improved understanding and ability to predict anomalies of rainfall are important for decision making.

Most meteorological studies designed to assess rainfall patterns try to rely on long-term rainfall data using normal distribution assumptions, and data transformations to correct skewness (Marengo and Hastenrath, 1993). However, a cube root employed to normalize the data in a study of seasonal variability of rainfall in the Pacific tropics was not successful. Weather stations reporting less than 16 years data or reporting erratic values were removed in a study by Hartmann and Gross (1988). Unfortunately, this procedure left large areas without estimated climatic references.

In the Amazon Basin, natural deviations in the hydrological cycle and the processes influencing those deviations must be determined before possible anthropogenic impacts can be assessed. For example, the El Niño-Southern Oscillation (ENSO) phenomenon in the tropical Pacific Ocean, has been linked to climate anomalies and

[1] Av. Dr. Júlio Soares de Arruda, 803, Parque São Quirino, 13088-300, Campinas, SP, email: silva@nma.embrapa.br.
Disclaim notice: The views expressed in this article are the author's and do not necessarily represent the official policy or interpretations of the Brazilian Enterprise for Agricultural Research (Embrapa).

river flow worldwide (Kiladiz and Diaz, 1989) and is one potential source of natural variability in the Amazon Basin (Bjerknes, 1969).

The goals of this study are to figure out whether monthly rainfall extremes are localized in the Amazon Basin, to develop kriged interpolation surfaces to show spatial distribution of monthly rainfall deviations across the Amazon Basin for months having higher deviations, and to identify persistences of monthly rainfall deviations in the Amazon Basin from 1950 to 1990.

This work was carried out using rainfall data reported by 533 weather stations. Considering the rainfall reported in a specific month, each weather station reporting data had a calculated deviation from its own median. Since the median separates half of observed values below and half above it, then it is expected that each event will have 50% probability of being negative or positive. When rainfall is totally random, the number of negative and positive deviations will be almost similar and resulted median of deviations equals to zero. Then, the medians of median deviations were tested statistically to confirm if they were different from zero ($P<.05$). The statistical hypothesis was that months experiencing precipitation extremes are spatially uniform across the Amazon Basin (Gibbons, 1985). Over the 492-month period analyzed, deviations significantly different from zero occurred in 210 of the months ($P<.05$).

The spatial analyses of monthly rainfall deviation were divided into three major groups. The analysis allowed comparisons of spatial structure among negative deviations, positive deviations, and no deviations. (1.) Negative rainfall deviations were assigned to the three largest negative median deviations from monthly medians ($P<.05$): January 1983 (-90.9 mm), April 1981 (-51.3 mm), and February 1983 (-44.2 mm). (2.) No rainfall deviation was assigned arbitrarily to a month with median deviations equal to zero ($P>.05$): January 1986 (0.0 mm). (3.) Positive rainfall deviations were assigned to the three largest positive median deviations from monthly medians ($P<.05$): February 1988 (41.1 mm), April 1984 (41.7 mm), and January 1982 (63.9 mm).

Climatic deviations are defined as spatially correlated median deviations of monthly rainfall. Deviation phenomena were assessed by their continuity and intensity. Persistences were defined as periods having only continuously positive or continuously negative deviations. If more than twelve months of rainfall records show only statistically significant deviations, either negative or positive, it was considered a persistent effect whose length can be determined.

Spatial distribution of monthly rainfall deviations was described by surface interpolation analysis using geostatistics. Geostatistical analyses including exploratory analysis, variography, kriging interpolation, and cross-validation were carried out using GS$^+$ - Geostatistics for the Environmental Sciences (Gamma Design Software, 1994).

GIS techniques were used to manipulate spatial features. Rasterized outputs from the interpolation routines were overlaid by vectorial information representing the weather stations, rivers, and boundaries. This procedure helps to relate departure patterns to local weather stations and geographical features for that location.

Box plot analysis is an important exploratory tool for understanding the natural variation of monthly rainfall. To understand monthly variability, data from Parintins weather station are discussed. The medians of

monthly rainfall show the typical value in a tropical yearly cycle, while the outliers describe erratic values. The frequency, timing and deviation size of outliers can be significant clues for oscillatory phenomena if they are spatially correlated with nearby weather stations that are reporting similar data patterns. The direction of the skewness suggests potential persistency of distribution since rainfalls are expected to be right skewed.

The basin-wide deviation analysis of monthly rainfall is from 1950 to 1990 ($P<.05$). Deviations for January show a diversified behavior. It was left skewed in 1983 (-90.9 mm), no skewed in 1986 (0.0 mm), and right skewed in 1982 (63.9 mm). Sometimes, most of the weather stations receive less rainfall than normal, and other times they receive more rainfall than normal rainfall. On some occasions, there is no deviation effect in the whole basin. Since the medians of deviations are used, any singular large deviation does not affect the overall analysis. A statistically significant median of the deviations means that the weather stations in the Amazon Basin are being affected by a climatic anomaly which displaces rainfall events from typical values ($P<.05$).

An important feature of monthly rainfall deviation analysis is its potential to detect persistence longer than 12 months of continuously repeating deviation phenomena, either positive or negative. Positive persistences of rainfall anomalies have been called warm events, and are related with the extremes of the Southern Oscillation (SO) phenomena and are associated with above normal sea surface temperature (SST) in eastern equatorial Pacific. Negative persistences are correspondingly called cold events and are associated with below normal SST (Kiladiz and Diaz, 1989). The SO was initially established as a connection between eastward shifts in equatorial convection over the tropical Pacific and a deepened wintertime Aleutian low over the North Pacific (Bjerknes, 1969). Climatic anomalies associated with the SO are intimately tied to planetary-scale climatic effects on the global climate system. Other studies have focused on regional anomalies over Latin America during both warm and cold events (Aceituno, 1988).

Four positive persistences were detected between 1950 and 1990. The first persistence was a 25-month period of positive deviations (October 1954 to November 1957). The second persistence was a very uniform positive persistence phenomena that lasted for 41 months (February 1973 to June 1976). The third persistence was from December 1983 to January 1985. This was followed by a short interruption of one month, then continued as the fourth persistence from March 1985 to November 1986. These last two persistent anomalies could have been joined which would have resulted in three continuous years of positive deviations.

Monthly surface interpolation of these positive persistences can reveal spatial patterns of rainfall anomalies. Further studies will help to evaluate how these anomalies develop and their potential to affect spatially the landscape. One important factor to understand is the distribution and intensity of these spatially correlated excessive rainfall. Flooding events may be associated with higher prone spot areas of the basin.

Negative persistences can have important effects on the hydrology of the ecosystem especially if extreme deviations result in an accumulative water deficit. Four negative anomalous persistences of rainfall were detected in the Amazon Basin from 1950 to 1990. The first two persistences occurred almost successively; one period of 15 months from March 1963 to July 1964, followed by a longer period of 46 months, from November 1964 to August

1968. If both persistences had been joined, a very long persistence of 64 months would have resulted. A 13 month-period of short negative deviations occurred from March 1976 to April 1977.

The last anomaly was a very important persistence of negative deviations that occurred from May 1982 to November 1983 and has been called El Niño phenomena (Cane, 1983). These strong negative deviations are related to global climate circulation and produced two months (January and February of 1983) with very large negative deviations. This negative persistence registered the lowest median rainfall of -90.9 mm in January 1983.

These negative and positive deviations agree in some extent with indices produced by studies on atmospheric-oceanic deviations associated with wind, temperature, rainfall and other hydrometeorological indices (Kousky et al., 1984; Ropelewski and Halpert, 1987; Marengo, 1992; Marengo and Hastenrath, 1993). However, a full comparison is restricted by the different methodology applied regarding basic statistical assumptions. Since this is a combination of nonparametric statistics plus kriging and GIS, some analytical power needs to be explored and expanded to connect to other important climatic parameters.

There have been some speculations in the literature about a 'biennial tendency' of alternate cycles between warm and cold events associated with the anomalies of the Southern Oscillation. However, this research agrees with Kiladiz and Diaz (1989) and does not support any regular frequency of alternating warm and cold events in the Amazon Basin.

January 1983 was the largest monthly median deviation analyzed in the period from 1950 to 1990. A maximum deviation effect may have occurred in January 1983 as the center of an 18-month persistence. The median of rainfall deviations for January 1983 was -90.9 mm, according to rainfall reported by 291 weather stations. At this time, about 4.5% of the Amazon Basin area received more than 200 mm of rainfall below their medians, and 70.8% of the basin received rainfall between 0 and 200 mm below the medians. Even with a negative anomaly, 24.6% of the Basin area still reported rainfall above the medians. This occurred in the headwaters of the River Araguaia and Tocantins in the southern part of the basin, where a center of strong rainfall developed and 5.2% of the area had more than 100 mm of rainfall above medians.

Three drier spots of negative rainfall deviations occurred parallel to the equator and followed the Amazon River's main course and increased in size eastwards. This variability mode started in January 1983 and still had some sequential time features in the following month. The portion of the basin having positive rainfall deviations decreased in quantity and intensity compared to the previous month. However, two more wetter areas developed in the central and northwestern portions of the basin.

This study is the first attempt to explain a possible 30-50 day peak of deviations in monthly precipitation records for the Amazon Basin in the equatorial Atlantic. A similar phenomenon has already been described in the equatorial Pacific (Madden and Julian, 1972; Hartmann and Gross, 1988), where a steady meridional propagation of troughs and ridges seemed to form near the equator and dissipate near the Himalayas. As displayed by the January 1983 deviations, the Amazon Basin shows a strong track of deviations entering the basin at the mouth of the river and repeating in two more drier areas that dissipate toward the Andes. For the equatorial Pacific, the meridional of this mode is around 3000 km, and its propagation moves about 0.75° latitude per day (Krishnamurti and Subrahmanyam, 1982).

From a practical point of view, a precise detection of this mode in the deviation phenomena is important because of the large impact of the tropical atmospheric disturbances repeating over localized regions. An indication of this variability was shown by the box plot analysis indicating a high climatic disturbance in intercalated months of the year. Savanna, common in arid regions, occurs with some frequency in the dry areas of lowlands near the mouth of the Amazon River. This suggests that rare climatic deviations events would cause high water stress and restrict colonization of dense forests in these regions.

January 1986 had a median rainfall deviation of zero. This month is part of a 20-month period of positive deviations. The deviations, however, were not statistically significant ($P>.05$). The Amazon Basin had positive deviations in 50.5% of the area and negative deviations in 49.5% of the area. 32% of the basin had positive rainfall deviations between 0 and 50 mm, while 30% of the basin had negative rainfall deviations between -50 and 0 mm. The spatial correlation of rainfall phenomena shows a pattern of negative and positive deviations in distinct areas. For January 1986, the positive deviations seem to follow the path of humidity influx to the basin mainly in a northwestern to southeastern direction.

Even for months without any deviation, a spatial correlation was observed between median deviations. When the entire basin was receiving regular rainfall, some uniform regions had positive deviations and others had negative deviations. When the deviations occurred, these positive or negative regions were enlarged. Negative deviations seemed to be more spatially continuous and intense than positive deviations. These diagnostics indicate that the enhancements and reductions of the typical annual cycle may form the major general circulation mechanism for the interannual variability of rainfall in distinctive regions of the Amazon Basin (Hastenrath, 1984).

The largest positive monthly deviations recorded between 1950 and 1990 occurred in January 1982. At this time 90.4% of the basin was receiving rainfall above medians, with only 0.2% of the area reporting rainfall of more than 200 mm above local medians. The most intense deviations occurred in the southeastern part of the basin, the high plains of Mato Grosso Shield, and decreased toward the central core. A large area of negative deviations developed in the central-northwestern portion of the Amazon Basin. Positive deviations that resulted in higher rainfall in the southeastern part of the basin agrees with findings relating rainfall variability to Southern Oscillation (Rao and Hada, 1990; Kousky and Chu, 1978; Kayano et al., 1988).

These positive and negative deviations reports a description of extremes months. However, for climatic evaluation, a full time sequence of a persistence will give more insights because of temporal connectivity of the anomaly. More understanding will be provided if this guidelines are followed and better way to assess the problems are tried.

Combining nonparametric statistics with geostatistical analysis and GIS techniques is a reasonable approach to detect monthly deviation patterns of rainfall in the Amazon Basin. Because of its large size and geographic position, there are no totally dry or wet years in the Amazon Basin — only spatially localized regional departures from median rainfall. The underlying effect that triggers the onset of rainfall events is highly seasonal, and is dependent on the global circulation dynamics. When deviation effects occur, these positive or negative regions enlarge.

Deviations were detected in approximately 50% of the months ($P<.05$). The negative deviations are more intense and more continuous spatially, while the positive deviations are wider and weaker and more randomly distributed. A high spatial correlation of monthly rainfall was found. Even for months with no evidence of deviations, some continuous regions received rainfall above medians and were balanced by another region receiving rainfall below medians.

REFERENCES

Aceituno, P. 1988: On the functioning of the Southern Oscillation in the South American sector. Part I: Surface Climate.

Mon. Wea. Rev., 116:505-524. Bjerknes, J. 1969: Atmospheric teleconnection from the Equatorial Pacific.

Mon. Wea. Rev., 97:163-172. Cane, M. A. 1983: Oceanographic events during El Niño. *Science*, 222:1189-1195.

Gamma Design Software. 1994. *Gs+: Geostatistics for the environmental science*. Gamma Design Software, 133 pp.

Gibbons, J. D. 1985: *Nonparametric Methods for Quantitative Analysis*. 2d ed. American Sciences Press, 481 pp. Hartmann, D. L. 1994: *Global physical climatology*.

Academic Press, San Diego, CA. Hartmann, D. and J. R. Gross. 1988: Seasonal variability of the 40-50 day oscillation in wind and rainfall in the tropics. *J. Atmos. Sc.*, 45:2680-2702.

Hastenrath, S. 1984: Interannual variability and annual cycle: Mechanisms of circulation and climate in the Tropical Atlantic Sector.

Mon. Wea. Rev., 112:1097-1107. Kiladiz, G. N. and H. F. Diaz. 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate*, 2:1069-1090.

Kousky, V. E., M. T. Kagano, and I. F. A. Cavalcanti. 1984: A review of the Southern Oscillation: oceanic-atmospheric circulation changes and related rainfall anomalies. *Tellus*, 36A:490-504.

Krishnamurti, T. N. and D. Subrahmanyam. 1982: The 30-50 day mode at 850 mb during MONEX. *J. Atmos. Sc.*, 39:2088-2095.

Madden, R. A. and P. R. Julian. 1972. Description of global-scale circulation cells in the tropics with a 40-50 day period. *J. Atmos. Sci.*, 29:1109-1123.

Marengo, J. A. 1992: Interannual variability of surface climate in the Amazon basin. *Int. J. climatol.*, 12:853-863.

Marengo, J. A. and S. Hastenrath. 1993: Case studies of extreme climatic events in the Amazon basin. *J. Climate*, 6:617-627.

Matalas, N. C. 1991: Drought description. *Stoch. Hydrol. Hydraul.*, 5:255-260.

Rao, V. B. and K. Hada. 1990: Characteristics of rainfall over Brazil: Annual variations and connections with the Southern Oscillation. *Theor. Appl. Climatol.*, 42:81-91.

Rasmusson, E. M. and J. M. Wallace. 1983. Meteorological aspects of the El Niño/Southern Oscillation. *Science*, 222:1195-1202.

Ropelewski, C. F. and M. S. Halpert. 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.*, 115:1606-1626.

UNESCO. 1978: *World water balance and water resources of the earth*.

UNESCO Press, Paris. Wyrtki, K. 1975: El Niño—The dynamic response of the Equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, 5:572-584.

ANALYSIS OF RAINFALL DISTRIBUTION IN THE AMAZON BASIN USING KRIGING, NONPARAMETRIC STATISTICS, AND GIS TECHNIQUES. III. ATMOSPHERIC WATER BALANCE.

Elson D. Silva[1], Researcher Scientist, Ph. D.
Brazilian Enterprise for Agricultural Research, Satellite Monitoring Center (Embrapa-NMA)
Gary W. Petersen, Soil Scientist, Ph.D., Prof. of Soil and Land Resources
Agronomy Dept., The Pennsylvania State University.

A water balance refers to the balance that must exist among water entering the basin (input), water leaving the basin (output), and water being stored. The main components of the water balance are precipitation (P), evapotranspiration (ET), and streamflow (R).

River flow is calculated using measurements at gauging stations situated close to the river mouths. Measurement of stream flow at the mouth of the Amazon River is almost impossible, however, because it has multiple distributary branches, a large delta, and is influenced by ocean tides. Most studies in the Amazon River gauge streamflow near the city of Óbidos, around 800 km upstream from the mouth, and extrapolate to the entire basin.

Precipitation within the Amazon Basin is known to originate from the recycling of water vapor released during ET ~~and from the moisture influx into the basin~~. It is suggested that a reduction in tropical forests may result in reduced evaporation and rainfall.

UNESCO (1978) has developed one of the most accurate water budgets for the Amazon Basin. This water budget reports a total of 2150 mm y^{-1} of precipitation, 1060 mm y^{-1} of evaporation, and 1000 mm y^{-1} of river discharge for an area of 6,915,000 km^2. These estimates can be improved using a more sophisticated data analysis of more extensive rainfall data sets. Nonparametric statistics can be used to assess typical values (medians), to protect against potential mistakes, or erratic values, and to detect centrality in skewed distribution. GIS techniques handle raster and vector spatial information and its gridding capabilities allow partitioning of water balance components into squared cells. The goal of this study was to develop an atmospheric water balance for the Amazon Basin (6,860,350 km^2) using 533 weather stations, more advanced geostatistical techniques for surface interpolation (kriging), and a robust nonparametric statistical analysis.

This work can be used as a reference base for any scientific application concerning the water cycle in the Amazon Basin. The spatial distribution of the water balance components can be useful in the study of ecosystem dynamics in the tropics and can allow for a comparison of spatial water balance to the vegetation distribution in the Brazilian Amazon.

[1] Av. Dr. Júlio Soares de Arruda, 803, Parque São Quirino, 13088-300, Campinas, SP, email: silva@nma.embrapa.br.