Spatial-temporal analysis of NOAA/AVHRR vegetation index and rainfall in the Northeast region of Brazil in 1982-85

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ABSTRACT

This work analyzes the spatial and temporal variation of Normalized Difference Vegetation Index (NDVI) and rainfall in the Northeast region of Brazil (NEB), between 1^0 to 18^0S and 35^0 to 47^0W. Studied were the dry years of 1982 and 1983 and the rainy years of 1984 and 1985, covering the intense El Niño-Southern Oscillation (ENSO) event of 1982-83. Ten test-areas representing prevailing and different phitophysiognomies of the region were used for temporal analysis. The spatial analysis was based on a grid of 5,571 rainfall data points spaced by $0{,}25^0$ in latitude and longitude, interpolated from the original rain-gauge measurements. In relation to previous NEB studies, the subdivision of the vegetation in classes and the use of correlations with time lags were introduced. The results showed that: *i)* NDVI and rainfall monthly data follow similar patterns on a temporal and spatial basis, being statistically correlated where the NDVI can depict the rainfall regime in periods of unusual droughts or rain in NEB; *ii)* the best correlation was found between the combined rainfall of two consecutive months with the NDVI of the latter these two months; *iii)* there was also an NDVI increase in the rainy season for the extremely dry year of 1983; *iv)* NDVI and rainfall better represented the vegetation hydric potential in the form of a ratio, or Rain Greenness Ration (RGR), rather than separately, and; *v)* the largest NDVI variation occurred for the urban area class. The results indicate the potential use of satellite NDVI imagery to monitor drought occurrences as well as to study climatic variability on a regional scale.

Keywords: NDVI (Normalized Difference Vegetation Index), rainfall, Northeast Brazil, phitophysiognomies, time lags, drought monitoring, climatic variability, regional scale.

1. INTRODUCTION

The Northeast region of Brazil (NEB), located on the main tropical zone, approximately 1^0 to 18^0S and 35^0 to 47^0W, with a territorial dimension of about 1.550.000 km², presents a high spatial and temporal rainfall variability rainfall, and encompasses diverse morphological types of vegetation cover. Approximately 60% of the NEB corresponds to the so called "Drought Polygon", which is one of the vast areas of semi-aridness of the Americas.

The causes of high climatic variability of NEB are not yet fully understood. Much research on the climate of this region has reinforced the hypothesis that rainfall variability is strictly related to the atmospheric and oceanic configurations on a grand scale in the tropics. These configurations act in relation to the inter-annual quantitative aspect and in respect to the spatial and temporal distribution of the rainfall. In general, most tropical rainfall falls within so-called 'tropical convergences zones', which often characterize moisture-laden near-surface winds that converge and rise, thus allowing the formation of convective clouds and intense but patchy rainfall. The most important convergence zones include the Inter-Tropical Convergence Zone (ITCZ), the South Pacific Convergence Zone (SPCZ), and the South Atlantic Convergence Zone (SACZ). The SACZ is very pronounced from October through March, and is linked directly to the November through February maximum seasonal rainfall in the southern and western parts of Northeast Brazil.

The vegetation cover of the semi-arid tropics presents a gradient of forms and variations that in one of the extremes is represented by *Caatinga Arbórea Densa* (Dense Arboreous Shrubbery), and in the other by *Caantinga Arbustiva Aberta* (Open Shrubs Shrubbery). The "*Caantinga*" is a type of vegetation that is characteristic of the semi-arid region occupying an area of 573.000 km², about 11% of the Brazilian national territory or 37% of NEB, and occurs throughout the states of Bahia, Sergipe, Alagoas, Pernambuco, Paraíba, Rio Grande do Norte, Ceará, Piauí,

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Maranhão, and Minas Gerais. In some states, however, this number is much greater. Approximately 90% of the state of Pernambuco is semi-arid; in Rio Grande do Norte this number is 91%, in Ceará 93%, and in Paraíba 80%.

Orbital remote sensing can be used to monitor climatic variabilities and the possible environmental impacts induced by climatic changes by accompanying its temporal and spatial evolutions. This condition is particularly important in such a vast and complex region like NEB where the density of the meteorological stations is very irregular. In order to detect time lags of natural vegetation due to the reduction of rainfall or other environmental effects such as dry areas, it becomes important to differentiate and quantify, from sensors on board satellites, the natural variability of the binomial vegetation/climate.

The multi-temporal series of the Normalized Difference Vegetation Index (NDVI) generated with data from satellites of the National Oceanic and Atmospheric Administration (NOAA) series have been utilized in the monitoring of vegetation covering on a regional or global scale. This data is related to the temporal evolution of the absorption of Photosynthetically Active Radiation (PAR), and at the phenological cycle of vegetation. There are studies of semi-arid regions in Africa[1] showed significant correlations between rainfall and Vegetation Indexes. The NDVI calculated from Advanced Very High Resolution Radiometer (AVHRR) imagery of the NOAA satellites has been utilized for global monitoring of vegetation due to the alterations caused by illumination, sloping surfaces, atmospheric opacity and geometric aim, and are partially compensated for with the overlap of the daily imagery in multi-temporal mosaics or with the composition of maximum values, where the highest pixel value is utilized in a period of one month[2]. The main advantage of the NOAA satellite is its high temporal resolution, which obtains data on a daily basis for the entire globe. The multi-temporal approach allows constant monitoring of various modifications occurring in the dynamic evolution of the vegetation on a regional scale.

The low rainfall indexes registered in NEB, especially in the semi-arids, have severely hurt the economy of this region. This high spatial-temporal irregularity of rainfall in the semi-arid northeastern region, makes monitoring and forecasting of the climatic variabilities and possible environmental impacts provoked by climatic changes difficult. In this context the temporal imagery of the Vegetation Indexes (NDVI) produced with the NOAA satellite data can be used to detect the natural variability of the binomial vegetation/climate. The general objective of this research is to determine the time lag of the NDVI data obtained from the AVHRR/NOAA imagery for different types of vegetation in Northeast Brazil due to rainfall, while focusing on the monitoring of extreme climatic events in this region. To accomplish this, NDVI and rainfall data from 1982-1985 was utilized encompassing the intense event of El Niño-Southern Oscillation (ENSO) of 1982-1983.

2. DATA BASE AND METHODS

Northeast Brazil is located between 1^0 to 18^0S and 35^0 to 47^0W just to the east of the Amazon rainforest, with an approximate area of 1.550.000 km^2. It is considered an anomalous region in the tropical continents because in contrast to other regions in this latitudinal range, it has semi-arid climate. There is also the existence of different atmospheric systems and scale time in the region. Although some eastern areas receive 1,600 mm or more of rainfall, some interior valley areas have an annual average of less than 400 mm. Spatial and temporal rainfall variability is high as is typical in other semi-arid regions of the world, e.g. the Sahel, Northeast Africa and parts of India. Using monthly mean rainfall data during the period of 1931-1960, [3] it was observed that rainfall reached a maximum in northern parts of the region during March and April. The southern and south-western parts received their maximum rainfall from December to January. Coastal areas from approximately 5^0 to 18^0S received their maximum rainfall during May to July. The data used in this study originated from the Global Normalized Difference Vegetation Index file furnished by the Global Inventory Monitoring and Modeling Studies (GIMMS), originating from a collaboration project between the National Institute of Space Research (INPE) and the National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC). The analysis period includes the four years, 1982-1985. The data is composed of NDVI monthly maximum obtained from daily data ascending crossings of the AVHRR sensor with a nominal resolution of 7.6 Km in the Equator, mapped in stereographic projection. The original data used for the calculation of the NDVI is the digital data from the Global Area Coverage (LAC), which represents a LAC window of 1.1 X 1.1 Km pixels taken from a 5 X 3 pixels LAC window. Our study is based on monthly rainfall totals and monthly composited NDVI. The analysis period includes the four years, 1982-1985. Superintendência do Desenvolvimento do Nordeste (SUDENE) of Brazil compiled and distributed monthly rainfall totals for 1,850 locations in Northeast Brazil. Each NDVI value represents an average of 7.6 X 7.6 pixels, with a resolution of around 7 Km by 7 Km. Time series plots of the average NDVI and total monthly rainfall values were computed for several locations in NEB.

Recent applications of NOAA AVHRR data to land surface monitoring were based on different to improve AVHRR data quality. Certainly, the cumulative influences of various procedures, ranging from sensor degradation correction[4], corrections for water vapor and aerosol effects[5], the bi-directional reflectance distribution model[6], and separation of soil influences[7], will greatly improve data quality. Nevertheless, a generally acceptable procedure for an operational system is still not available. In the present study we have not included any of these recently suggested quality improvement techniques because for a large-scale climatic variability study. The temporal and spatial variations of NDVI still allow us to perform the inter-annual comparison of drought evolution.

Based on the vegetation map published by the Instituto Brasileiro de Geografia e Estatística (IBGE, 1993)[10] as a basis, ten samples were selected from the following coverings: **Ea**, "Caatinga Arbórea Aberta" (Open Arboreous Shrubbery), **Ed**, "Caatinga Arbórea Densa" (Dense Arboreous Shrubbery), **Es**, "Caatinga Arbustiva Aberta" (Open Shrubbery), **Eu**, "Caatinga Arbustiva Densa" (Dense·Shrubbery), **D**, "Floresta Ombrófila Densa" (Dense Forest), A, "Floresta Ombrófila Aberta" (Open Forest), C, "Floresta Estacional Decidual" (woodland), S, "Cerrado" (Thicket), **F**, "Floresta Estacional Semidecidual" (Woodland), **T**, "Área Antropizada" (Human Activity Area). The NDVI monthly averages were obtained from a window of 3X3 pixels centered on the geographical co-ordinate samples previously selected. The NDVI monthly averages were integrated for each year studied to verify inter-annual variation due to the El Niño-Southern Oscillation (ENSO) phenomena.

The spatial analysis of monthly data placed in the form of NDVI images and punctual rainfall data refer to distinct sources of information. Geo-referencing of NDVI information between close pixels and rainfall for the same geographical position was needed, in this case pixels of an image and punctual data from pluviometric stations. The spatial coherence procedure was used in the first step which allowed the identification of pluviometric stations and was based on geographical co-ordinates within the NOAA image and the extraction of the NDVI average value of a 3X3 pixels window.

The inter-annual spatial variability of rainfall and NDVI were analyzed using compositions and monthly numeric fields in grid points. The spatial ordinance and distribution of the 1,850 pluviometric stations used and 17,000 NDVI values extracted from the Vegetation Index images were originally completed in latitude and longitude, saved in a file. The 1,850 pluviometric stations are distributed randomly within the entire NEB region. The objective analysis method[8] was applied.

The inter-annual temporal variability of rainfall and NDVI were analyzed using temporary series plots of the accumulated monthly rainfall observed in each location and NDVI monthly averages extracted from a window of 3X3 pixels centered on the geographical co-ordinates of the previously selected samples.

3. RESULTS AND DISCUSSION

The first step in analyzing the results was to obtain the rainfall from the 1,850 pluviometric stations in NEB, then organize this data by its respective latitude and longitude for use in the numeric fields analysis. From these stations, 130 were initially selected for more detailed studies due to their distance from areas with human activity. Of these, ten were selected for temporal monitoring.

The disturbance caused by El Niño, along with the normal variations, was striking in the various classes of vegetation covering, especially arboreal and shrubby vegetation: **Ea**, Caatinga Arbórea Aberta, **Ed**, Caatinga Arbórea Densa, **Eu**, Caatinga Arbustiva Aberta and **Es**, Caatinga Arbustiva Densa. In general, a high annual rainfall variability in the data was observed confirming the concept that the drought problem in NEB is due to irregular distribution of rainfall; this condition occurs due to the irregularity in the spatial-temporal covering by the synoptical meteorologic systems which are responsible for causing rainfall.

Using the NDVI as a good indicator of green biomass of surface vegetation[9], a low NDVI value may represent a surface with either less vegetation or with vegetation suffering from unfavorable growth conditions, such as drought, disease, or insect attack. The NDVI-rainfall relationship has not yet been investigated in great depth. For example, it remains to be established whether and under what conditions NDVI is a sensitive indicator of the internal variability of rainfall and what hydrologic variables, such as soil moisture, are most closely linked with NDVI. Similarly, little is known about the timing of NDVI response to rainfall. The focus of this work is to investigate the NDVI-rainfall relationship, especially the spatial-temporal variability of NDVI for various vegetation types and its dependence on rainfall variability.

3.1 Phenology of individual vegetation formations and the seasonal cycle of rainfall

The relationship between the phenology of vegetation and the seasonal cycle of rainfall is illustrated by temporal plots in the 1982-1985 analysis period. The sequence of plots represent the temporal variation of surface greenness from west (**C**, Imperatriz 5°32'S, 47°29'W; and **Ed**, Puca 8°03'S, 43°39'W) to east (**A**, Amaragi 8°23'S, 43°13'W and **F**, Macaparana 7°33'S, 37°27'W), and from south (**S**, Correntina 13°29'S, 44°38'W and **D**, Ponto Chique 14°33'S, 39°56'W) to north-west (**Ea**, Catunda 4°32'S, 40°13'W, **Eu**, Pedro II 4°25'S, 41°28'W, and **T**, Fortaleza 3°45'S, 38°32'W); with the driest center of the semi-arid region located at (**Es**, Casa Nova 9°24'S, 41°08'W; **Figure 1**).

It is of great relevance to note that in the comparison of time series plots for various vegetation types and its dependence on rainfall variability. It can be clearly observed that during 1982 and 1983 the NDVI values remained very low for most of the year. For the following years it was noted that the NDVI time series plots improved gradually at these locations, indicating that the severity of the drought was diminishing gradually. In contrast to this ENSO period for 1985, both locations had an average of approximately 8 months with NDVI above 0.3, indicating abundant water and potentially good crop yield. The phenology of vegetation in the bush land/thicket formations is considerably different (**Figure 1**). However, NDVI fluctuations closely correspond to rainfall fluctuations in both timing and magnitude. In the Caatinga a similar correspondence is evident in both the magnitude and timing of the fluctuations, but there is a more regular seasonal pattern of both NDVI and rainfall. The phenology of NDVI at the woodland stations differs from that of the forest in several ways (**Figure 1**). The month to month variations are less erratic and the period of minimum NDVI is longer and more pronounced, with monthly composited values often falling below 0.2. The peak monthly values seldom exceed 0.4 compared to 0.5 in the forest zones. Throughout the forest regions rainfall generally shows a distinctly bimodal seasonal cycle and two rainfall peaks manifest themselves as small, secondary NDVI peaks superimposed upon the basic unimodal pattern. NDVI shows a clear response to the cycle of rainfall, but there is little year-to-year change of NDVI even when rainfall varies significantly.

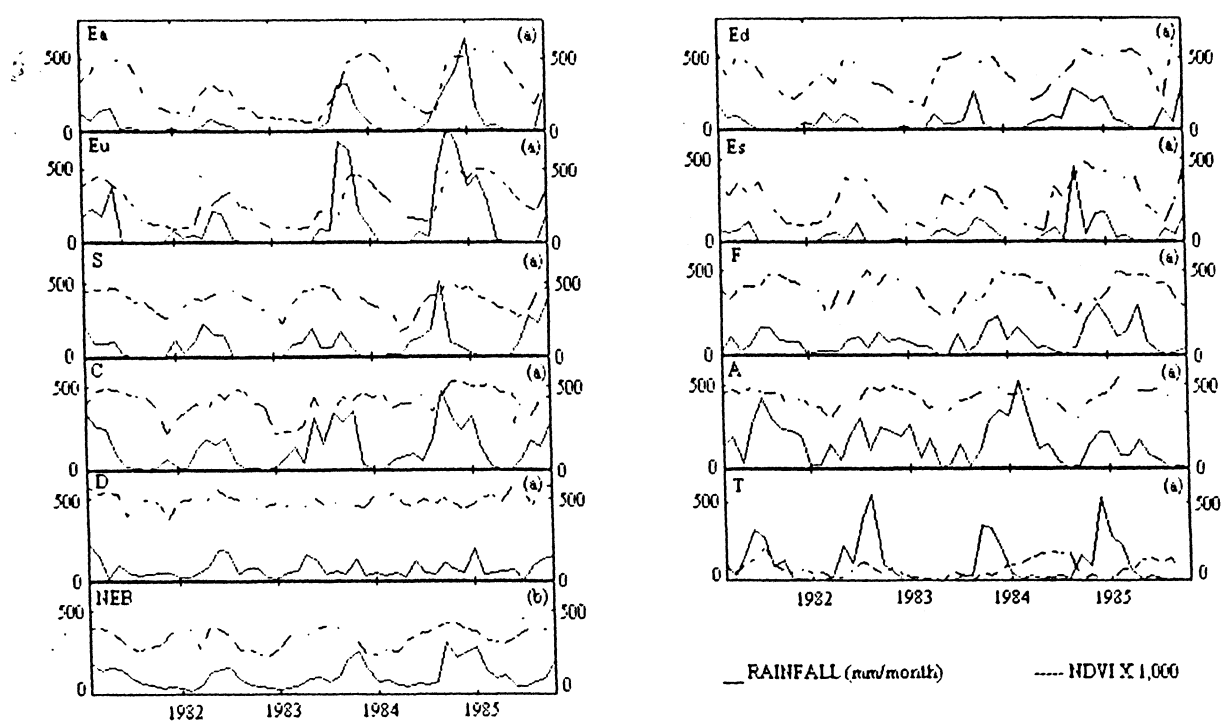

Fig. 1. Temporal plots of monthly composites of NDVI (dashed) versus rainfall (solid line, in mm). (a) Ten vegetation formations in Northeast Brazil (data for one typical station within the formation); (b) Northeast Brazil - NEB (each point represents a mean for 5,571 points).

The relationship between the phenology of vegetation and the cycle of rainfall is illustrated by temporal plots for the 1982-1985 analysis period. **Figure 1** presents station plots for each vegetation formation; each figure summarizes one major physiognomic category. Notice the minimum values which occur during the months of August and September, then there is a gradual increase up to the maximum values occurring in April and May, and once again, NDVI indicates a decrease until September. The seasonal component exerts influences in the low production of phytomass when the dry season arrives, reflecting a decrease in the NDVI values in moments of hydric excess to moments of hydric deficit. Observing the average NDVI values by vegetation type, it was verified that the months of March-May represent the lowest coefficients of variation, while the months of October-December represent the highest. This clearly demonstrates that the drought conditions tend to be more favorable for the separation of small differences between the various types of vegetation. The rainy season, with small NDVI variations, provokes a uniformity in the spectral responses causing difficulties in the separation of the various typologies. The effect of the rainfall distribution variability can be observed in the NDVI variability.

When analyzing the temporal evolution of the NDVI profile in the **(D)** Floresta Ombrófila Densa it is perceived that the small NDVI random variations occur slowly with an increase or a decrease in rainfall. This suggests that the NDVI variations can occur due to the humidity in the soil and not from the rainfall. Besides, when the storage capacity of water in the soil reaches the maximum value, the alterations arising from the rainfall are considered null, regardless of its intensity. In tropical forests where there is abundant rainfall through-out the year the NDVI loses its sensibility to rainfall due to the saturation effect. The correlations are almost null due to the absence of a defined cycle of those variables.

The **Figure 1** presents a temporal evolution of NDVI and rainfall for the **(T)** Fortaleza station where an area of human activity prevails. The urban areas have their own natural covering which is modified by various types of construction and pavements, of which the immediate consequence is a climatic alteration resulting from the urbanization process. In the case of NDVI, high instability was found with variation co-effecients of 85.8% overshadowing the seasonal behavior of this index due to the rainfall. The drought periods of 1984 and 1985, in particular show surprising highs. For this reason, necessary caution is needed when interpreting results arising from human activity in the NDVI and rainfall values due to the existence of the multiple factors involved.

Rainfall causes diverse effects in the NDVI, depending on the type of climate and vegetation that predominates in the area being studied. To detect the responses of the natural vegetation due to decrease in rainfall or other natural environmental effects, correlations were obtained between NDVI and rainfall. The correlations are based on a the NDVI average taken from a sample area of 520 km^2 and on the rainfall data obtained at the pluviometric station which is located in the center of the sample. The correlations between the NDVI and rainfall in a semi-arid region present positive values because the rainfall in this region is a determining factor in the beginning of the growth season of the vegetation covering. Based on the temporal analysis of the results, it was verified that the NDVI values increase after heavy rainfall, presenting time lags between the rainfall occurrence and the absorption of the available water by vegetation, increasing its photosynthesis and evapotranspirative activities, which are registered by the increase in the NDVI.

Simultaneous linear correlations were determined with lags between the NDVI and rainfall for the various types of vegetation of the region, identified in this study using vegetation maps. In analyzing correlations between the variables, 0, 1, 2, 3 and 1+2 month lags were used. The results of these correlations showed that there existsa relationship between the NDVI and rainfall data for the different vegetation types in NEB, proving a significant correlation with a 1+2 month time lag, in other words, the accumulated rainfall within two consecutive months with the latter of NDVI of these two months. The correlation obtained for the human activity class revealed a non-existent dependence of NDVI in relation to rainfall. The urban effect provokes distortions in the representation of NDVI in terms of vegetation covering due to the existence of multiple factors involved; especially paved grounds, the influence of rivers and buildings, etc., impeding the capture of the real reflection of vegetation by the sensor. In fact, extreme caution is required when interpreting the results of NDVI modifications due to the various factors that may be involved such as urbanization and climatic reasons on a global scale. In addition, the intense urbanization in this sample introduces other variable factors not considered in this study.

The above analysis shows that shifts in the semi-arid region, as evidenced by surface vegetation, is closely parallel to shifts in rainfall patterns. The RGR is a better parameter for characterizing arid and semi-arid regions like the Northeast Brazil.

Table I: Correlation between monthly NDVI and rainfall in various time intervals for each vegetation formation and for one representative station within each formation. Columns, from left to right, denote correlation of NDVI with rainfall in concurrent (0), one month earlier (1), two months earlier (2), three months earlier (3), and accumulated rainfall within two consecutive months with the last NDVI of these two months (1+2)

Vegetation Classification in Northeast of Brazil			*Correlations (r)*				
			Time Lag				
Vegetation Formation/Typical Station			*0*	*1*	*2*	*3*	*1+2*
Ea	Catunda	CE	0.43	0.62	0.68	0.65	0.68
Ed	Puca	PI	0.43	0.57	0.63	0.57	0.66
Es	Casa Nova	BA	0.52	0.62	0.52	0.52	0.62
Eu	Pedro II	PI	0.63	0.77	0.73	0.58	0.80
F	Macaparana	PE	0.46	0.65	0.49	0.34	0.62
C	Imperatriz	MA	0.17	0.46	0.60	0.61	0.58
S	Correntina	BA	0.28	0.64	0.61	0.51	0.68
A	Amaragi	PE	0.53	0.56	0.36	0.07	0.49
D	Ponto Chique	BA	0.25	0.33	0.23	0.04	0.34
T	Fortaleza	CE	0.01	0.01	0.14	0.11	0.08

The seasonal influence in the phonological cycle can drive the different correlations between the dry and wet season during the year or for specific cycle phases. Most of the time lag correlations in **Table I** should be analyzed with this point of view, thus, if these correlations are considered in shorter times spans it would result in even more insignificant correlation coefficients.

The "Rain Greenness Ratio" (RGR) index provides an approximate quantitative to evaluate the ground hydric availability in relation to the vegetation type. This is defined as the ratio of mean annual integrated NDVI to mean annual rainfall, multiplied by 1,000 to produce values greater than unity. The driest regions appear to be the most efficient with respect to moisture utilization. The ratios for the NEB are considerably higher on the whole than those for comparable conditions in Sahel and East Africa[1]. Such differences can be attributed to NEB formations being more arboreous rather than herbaceous (**Table II**). In East African regions where the same synoptic atmospheric systems as NEB prevail, herbaceous formations appear.

Table II: Annual integrated NDVI (four-year mean), annual rainfall (four-year mean in mm), and Rain-Greenness Ratio (RGR) for vegetations in Northeast Brazil - NEB

Vegetation Classification in Northeast of Brazil			*Mean Year 1982-85*		
Vegetation Formation/Typical Station			*NDVI*	*RAIN*	*RGR*
Ea	Catunda	CE	3.48	897.2	3.88
Ed	Puca	PI	4.73	770.9	6.13
Es	Casa Nova	BA	2.90	582.7	5.00
Eu	Pedro II	PI	3.37	1,694.4	1.99
F	Macaparana	PE	4.73	1,013.6	4.66
C	Imperatriz	MA	4.95	1,529.8	3.23
S	Correntina	BA	4.55	983.5	4.62
A	Amaragi	PE	5.20	1,862.4	2.79
D	Ponto Chique	BA	5.94	874.7	6.79
T	Fortaleza	CE	0.82	1,255.0	0.65

3.2 The Spatial Variability of NDVI and rainfall

The spatial variability of NDVI and its association with rainfall patterns are illustrated in **Figure 2**. Monthly drought evolutions of a dry and wet year were compared in order to analyze the seasonal migration of the drought area from region to region. Most of NEB suffers from recurrent droughts. The lack of real-time climatic and environmental data makes it difficult to monitor its development, intensity and impact. Our analyses suggest that vegetation is directly responding to the inter-annual variability of rainfall in many regions. Rainfall isopleths over NEB (**Figure 2**) for each of the four years, 1982 -1985, indicate that 1983 and 1984 were considerably drier than 1982 and 1985. In general, the spatial patterns of NDVI departures in the four years closely correspond to those of rainfall, except in the northeastern areas of NEB where NDVI values are too low to represent cloud cover amounts during the rainy season. However, NDVI was generally about the same in both 1985 and 1982, despite higher rainfall in 1985. This may indicate an incomplete recovery of vegetation from the extreme drought conditions of the two previous years. The NDVI shows some variation with rainfall because the duration of the low-growth period and in the minimum NDVI values attained during the period change in response to rainfall. It can be observed that, for NEB, the drought areas decreased from October 1982 to its minimum in April 1983 (**Figure 1**). This indicates that even at the peak of the rainy season the occurrence of drought areas was still high in the Northeast region of Brazil. This is due mostly to the fact that rainfall events are of high spatial variations, being generated from small convective rain cells and producing irregular rainfall distribution in the area. As the evolution of the drought areas is followed to the end of the rainy season, the drought areas in NEB return to their maximum extend by September 1983. It is also interesting to observe that the drought area of the northeast and of the southwest regions of the continent seemed to expand towards each other during the dry season and to retreat during the rainy season as a result of the regional weather system dynamics. In the driest vegetation formations there is a clear and immediate response to rainfall variability; it is apparent in both the maximum monthly values of NDVI which are attained during the year. Each rainfall peak clearly manifests itself in the NDVI cycle. There is no apparent change in the minimum NDVI, however, this seems reasonable since in this formation there is little green vegetation during the dry season.

The rainfall analysis shows that during the rain season of the dry years there is an abundance of rainfall over the southern section of NEB and a deficiency over the northern section. The cold fronts are the main causes of rain during November-January in the southern section of NEB. This region was the one least affected by the ENSO event of 1982-1983 and remained over the influence of the convection associated to SACZ (South Atlantic Convergence Zone) resulting in a rainy period beginning a month prior to the northern section. The western and northwestern areas of NEB were the least affected by ENSO and their rainy season was intensified in January 1983, possibly due to the direct influences of the summer rains caused by the convective activity associated with SACZ. The monthly sequences in **Figure 3** show that the displacement of rainfall at the northern and southern sections of NEB occurs in the opposite direction in both the dry and wet seasons. In the northern section the drought progresses from the east to the west, while in the southern section it progresses from the south to the north. It is probable that the orientation of the cold fronts that occur in the southern section of NEB and that the southwestern trade-winds, breezes, and eastern disturbances that affect the eastern section of NEB are responsible for these displacements.

In analyzing the monthly numeric fields for the four years studied, during the months of October- March the displacement of the highest NDVI values of the isolines occurs in a southern to northern direction, regressing once again in April-September. These geographical displacements are most likely related to the preferential course of the convective activity associated to SACZ and to lines of instability responsible for the occurrence of rain during that period. It was also observed that in the monthly numeric fields, the irregular spatial distribution of the nucleus with high NDVI values persist throughout the year. It was verified that the monthly NDVI values for the rainiest months show high variability throughout the year, thus identifying a pronounced annual cycle and a high reduction in the variability of the rainiest months to the driest months.

In addition to the quantitative analysis of the numeric fields for the spatial distribution of NDVI and rainfall, a temporal evolution of the respective monthly spatial averages for the entire NEB region was also obtained. The temporal evolution of **Figure 1** indicates a dependence of the NDVI numeric field to the monthly rainfall variations during the four years studied. While observing the temporal evolution of NDVI in **Figure 2**, a seasonal period of oscillation in the phenological cycle of NEB was noticed. This cycle reaches its maximum evolution in November - March, with an increase of the NDVI values in the rainy season, corresponding to the beginning of the phenological cycle. On the other hand, a dry spell prevails in the remaining months of that year, and thus a retrogression in the

NDVI values occurs as a response to the hydric stress by the vegetation covering. The monthly spatial average NDVI temporal value from January 1982 to December 1985 was 0.34 with a coefficient variation of approximately 17%. All the previous results show that the NDVI field is a good indicator of the rainfall field, especially in an vast region like NEB.

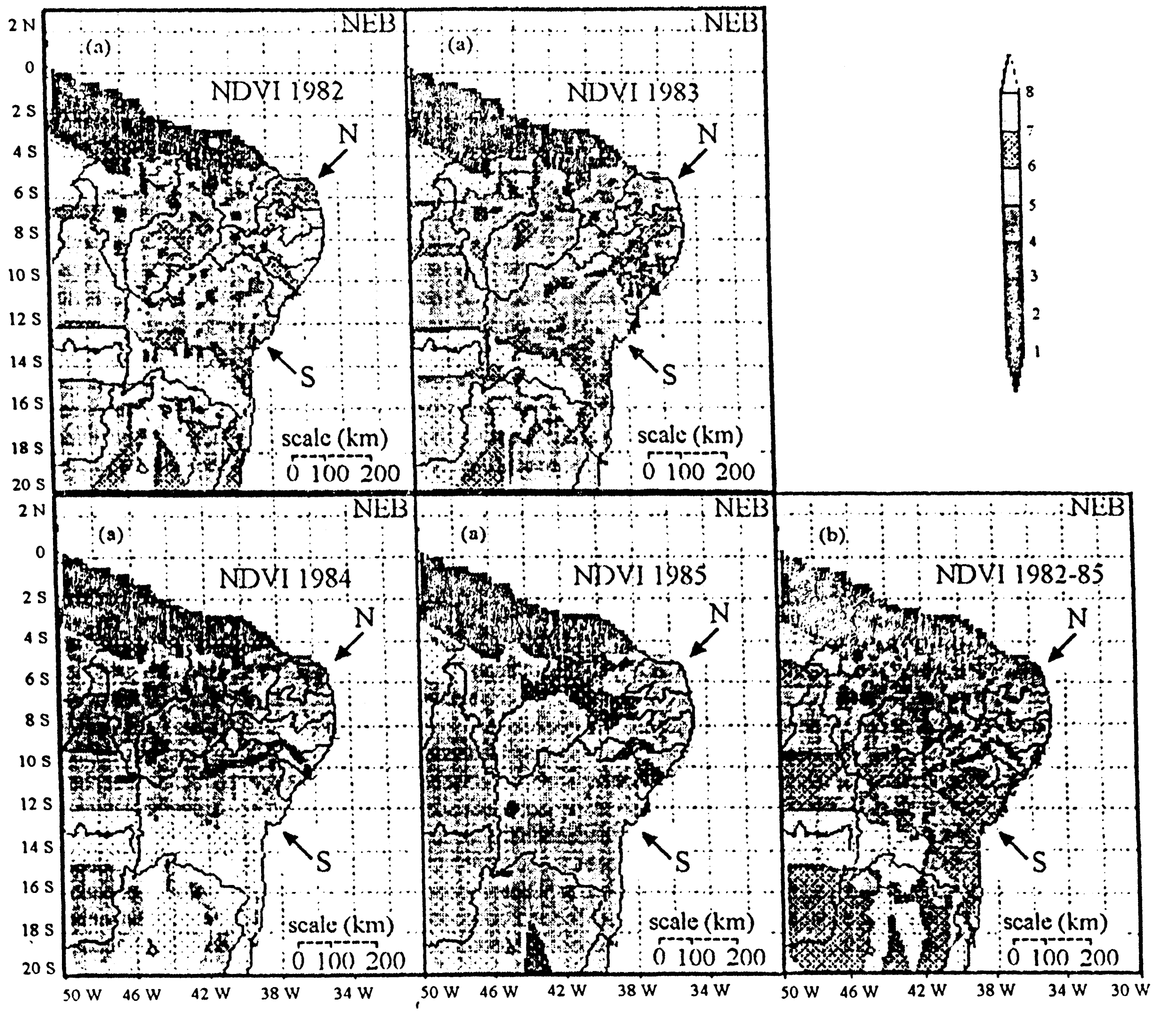

Fig. 2. Annual integrated NDVI for Northeast Brazil - NEB (white, NDVI greater than 7.0; black, NDVI less than 1.0). (a) Years 1982-1985 in NEB; (b) Four-year mean for 1982-85.

The drought area observed over the northwestern section of Northeast Brazil may be sometimes due to the cloud contamination effect, which was even more pronounced during the high rainfall months caused by the daily cycle of strong convective ativity. The NDVI maximum value composite procedure for a 1-month period may not effectively remove the persistence of cloud contamination. An interannual variability comparison of the drought area during a wet year (1984-1985) is presented in **Figure 2**. The general patterns of the drought area over the northwestern part of NEB remained the same as observed during 1982-1983. The NDVI maps for each of the four years 1982-1985 indicate that vegetation growth in 1983 and 1984 were considerably lower than 1982 and 1985. This is also an indication of the higher water availability in the region during the wet year. This was favoured by precipitating systems associated with the location of the ITCZ, which remained around 8^0S from March through May of 1985. In contrast to this, during 1983, the ITCZ remained above the equator from January to March, and retreated further north afterwards, exposing the region to a large-scale subsidence, inhibiting the development of rigorous precipitation systems.

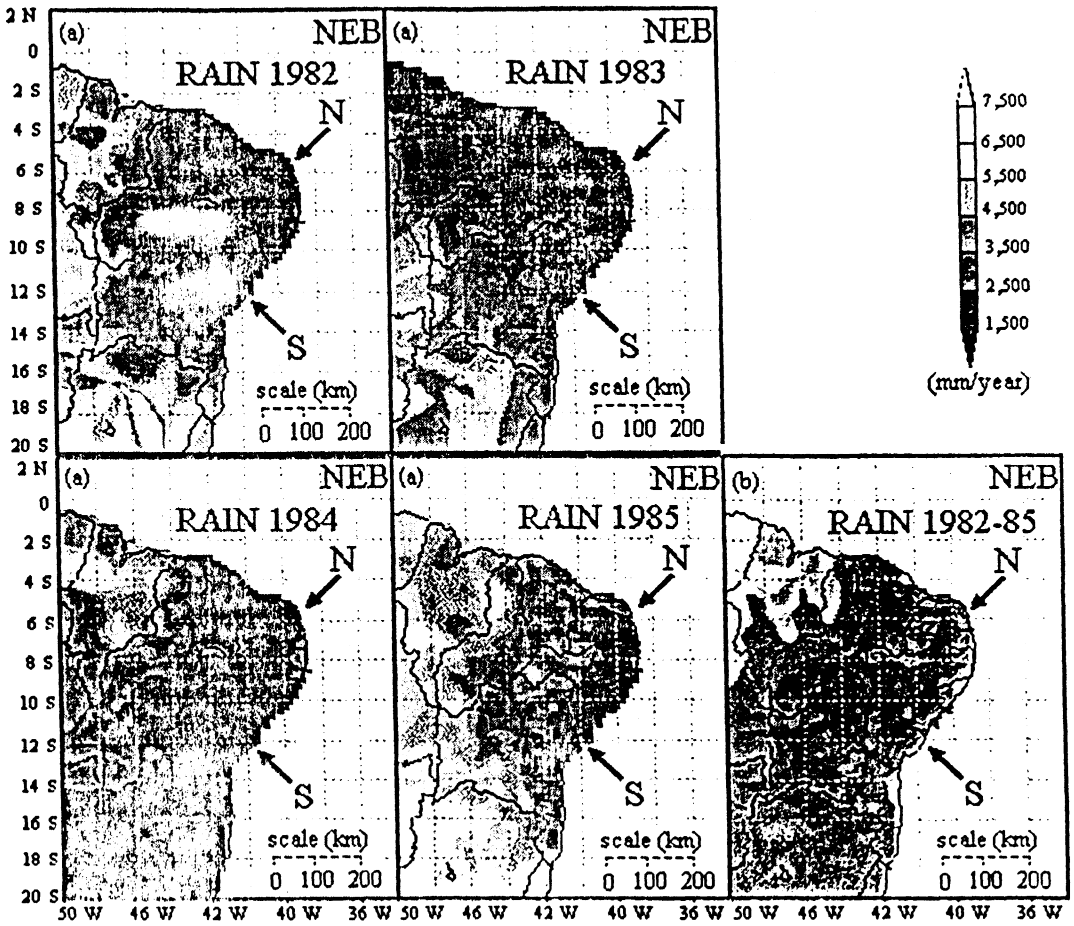

Fig. 3. Annual accumulated rainfall (mm) for Northeast Brazil - NEB (white, rainfall above 7,500 mm/year; black, rainfall below 2,500 mm/year). (a) Years 1982-1985 in NEB; (b) Four-year mean for 1982-85.

3.3 Relationships between NDVI and rainfall

Figure 3 shows the correlated numeric fields dephased by a one-month lag between the average monthly NDVI and rainfall fields in NEB obtained from the 5,571 grid point data during the four years studied. Only the months of September-December which cover the early rain season were analyzed, being that this period shows a greater scope of variation in a shorter period of time. Positive correlations indicate a direct NDVI variation of a particular month in relation to the rainfall value of the previous month.

In this figure observe how the arrangement and the numeric value of the correlation fields for the 4 months are very similar when compared from one month to the other, inclusively in the negative correlations. Positive correlations indicates that the resprouting and regrowth of vegetation occurs after the rainfall, which is expected. On the other hand, the negative correlations, some close to -0.8 which are considered very low, require individual consideration. It was observed that these latter cases had almost zero rainfall, thus negative correlation would indicate that the vegetation possesses a seasonal cycle independent of rainfall. In other words, the resprouting and regrowth would be initiated during a certain time of the year, even with a delay of rain, due to the humidity found in the deeper layers of the soil. Areas with the highest positive correlation coefficients, such as r greater than 0.8, are found in the northern, southern, central-west and southeastern regions of the NEB. In addition, small nuclei with r between 0.8 and 1.0 were observed through-out the entire NEB.

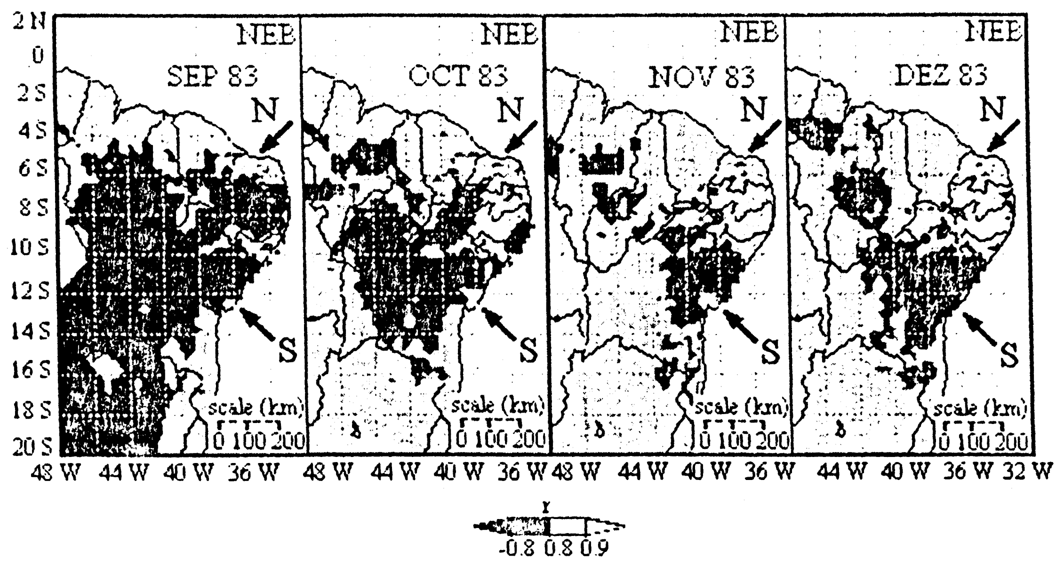

Fig. 3. Correlation maps of NDVI with rainfall one month earlier during a four month period beginning in September of 1983; areas in white correspond to correlations of 90%; areas in grey correspond to correlations of 80%; areas in black correspond to negative correlations of 80%.

4. CONCLUSIONS

The temporal evolution for the various types of phytophysiognomy of NEB indicated that in the drought years of 1982-1983, monthly NDVI values with a growth tendency in the Summer and Autumn, or from October-May, did not reach high values (0.4 to 0.5); during the Winter and Spring , or from June to September, when the tendency is for the values to decrease, these reached very low levels(0.08 to 0.12). During the rainy years of 1984-1985, the NDVI monthly values during the Summer and Autumn reached high levels, between 0.5 and 0.6, while in the Winter and Spring they remained relatively normal, 0.1 to 0.3.

The NDVI also varied during the fours years according to the various morphological patterns of the NEB vegetation covering. In one extreme, the **(D)** *Floresta Ombrófila Densa* showed an average value of 0.49 with a coefficient variation of 8.8%, and in the other, the **(Es)***Caatinga Arbustiva Densa* with 0.25 and 48.86%, respectively. For the former, the NDVI showed extremely slow or non-existent responses to the rainfall variations, thus in this case not being suitable for the monitoring of vegetation. The **(T)** *Área Antropizada* (areas with Human Activity) with an average value of 0.08, presented the highest NDVI instability with a coefficient variation of 86% due to the high ground exposure, the presence of various constructions and the lack of vegetation covering; in the Spring of the rainy years of 1984-1985 the NDVI unexpectedly increased.

In the fours years studied, it was verified that during the January-May and September - December periods the contribution for the annual spatial average of 5,571 points were 60% and 18% respectively over the NEB region. The analysis of NDVI monthly numeric fields showed a spatial progression in a southern-northern direction in October -March, and with a return in April-September. It is probable that this geographical displacement occurs in the path similar to the convection caused by the South Atlantic Convergence Zone (SACZ) and the lines of instability related to them. In the same way, isolated nuclei with high NDVI values observed in NEB for the duration of a few months, must be related to SACZ and in particular, to local atmospheric convections. The only interruption in the NDVI displacement occurred in December/82, in the beginning of the great ENSO (El Niño-Oscillation) event of 1982-83.

The correlations obtained from the temporal analysis for the ten test areas revealed a relationship of dependency between NDVI and rainfall, with an "r" correlation level of 0.2 to 0.6, and prevailing with a lag of 1+2 months with more significant values, between 0.3 to 0.8. The rainfall of a month relates better to the NDVI of that same month and the previous month combined. For the numeric fields, this time lag in NEB was one month.

The regions where the monthly numeric fields of NDVI and rainfall presented a higher correlation in the September-December period of the four years studied, correspond in a general way to the performance areas of the main patterns of meteorological systems of NEB. In the dry years, from August - November, the rainfall fields were uniform, contrary to the rainy months of January - May.

This study showed that the NDVI can be utilized as an indicator of the pluviometric condition during extreme rainy and dry periods, on a local as well as a regional level. It is recommended that continuity be given to this line of research, improving the temporal-spatial resolution of the satellite data used, as well as the density of pluviometric observation, especially in the *Caatinga* region.

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