

## Inter-annual variability of some river stream-flows and rainfalls in the Amazon basin

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**सार** – अमेज़न नदी के चार स्थानों (सैम्युअल 9° द., 63° प., बलबिना, 1° द., 59° प. ; उरूआ उना 13° द., 54° प. युक्रूई, 4° द., 50° प.) पर मार्च, अप्रैल और/अथवा मई के महीने में नदी की धाराओं का प्रवाह (आर. एस. एफ.) अधिकतम था तथा सितंबर और अक्टूबर के महीनों में न्यूनतम था जबकि पहले इन्हीं क्षेत्रों में जनवरी से मार्च के महीनों में अधिकतम वर्षा हुई थी। इनमें प्रतिवर्ष काफी उतार चढ़ाव देखे गए हैं जो इन चारों स्थानों पर हमेशा एक समान नहीं पाए गए हैं। एल निनों की सबसे बड़ी दो परिघटनाओं (1982–83 और 1997–98) की जाँच से एल निनों के सक्रिय होने के समय, अंतरालों के दौरान कुछ स्थानों पर कुछ प्रभावों का पता चला है किंतु कुछ प्रभाव इन सक्रिय अंतरालों के बाहर भी दिखाई पड़ते हैं। नदी की कुछ धारा प्रवाहों का संबंध दक्षिणी अटलांटिक समुद्र सतह तापमान के साथ पाया गया है। अनुक्रम विश्लेषण ई. एन. एस. ओ. इनडाइसिस के 7–9, ~6 वर्षों और क्यू.टी.ओ. (अर्द्धवार्षिक दोलन, 3–4 वर्ष) की महत्वपूर्ण आवधिकताओं का पता चला है और क्यू.बी.ओ. (अर्द्धवार्षिक दोलन, 2–3 वर्ष) में आवधिकताएं इतनी महत्वपूर्ण नहीं होती है। ये केवल आंशिक रूप से नदी की कुछ धारा प्रवाहों में दिखाई देती है। ऐसा भी अनुमान है कि कुछ जल वैज्ञानिक क्यू.बी.ओ. समतापमंडलीय पवन क्यू.बी.ओ. से संबंधित हो सकती है। क्यू.बी.ओ. और क्यू.टी.ओ. के अलावा नदी के धारा प्रवाह में 7–14 वर्षों की अवधि ~22 वर्षों और ~55 वर्षों में महत्वपूर्ण आवधिकताएं हैं। दीर्घ अवधि प्रवृत्तियाँ (23 वर्ष गतिमान माध्य) रैखिक नहीं थी और विभिन्न स्थानों पर पूरी तरह से असमान थी। इससे ~0.2% दोलन का पता चला है।

**ABSTRACT.** For four locations (Samuel, 9° S, 63° W; Balbina, 1° S, 59° W; Curua-Una, 13° S, 54° W; Tucurui, 4° S, 50° W) in the Amazon, the river stream-flows (RSF) were maximum during March, April and/or May and minimum during September-October, while rainfalls in similar areas had maximum earlier, in January-March. There were considerable year-to-year fluctuations, not always similar at all the locations. An examination of the two largest El Niño events (1982-83 and 1997-98) showed some effects at some locations during intervals when the El Niños were active, but some effects were seen even outside these active intervals. Some RSFs showed relationship with South Atlantic SST. A spectral analysis showed that ENSO indices had prominent periodicities at 7-9, ~6 years and QTO (Quasi-triennial oscillation, 3-4 years) and not so prominent periodicities in the QBO (Quasi-biennial oscillation, 2-3 years). These were only partially reflected in some RSFs. There is an indication that some hydrological QBOs may be related to stratospheric wind QBO. Besides QBO and QTO, the RSFs had significant periodicities in 7-14 years range, ~22 years and ~55 years. Long-term trends (23-year running means) were not linear and showed oscillations of ~0.2%, grossly dissimilar at the different locations.

**Key words** – ENSO, QBO, QTO, Sea surface temperature, Decadal variation.

### 1. Introduction

The Amazon basin plays a very prominent role in the South American region. The land-use patterns there are changing rapidly (Richey *et al.*, 1989) and may modify the convective rainfall regime and cause downstream changes in river flow and nutrient and sediment transport. Whereas the precipitation may vary considerably from one small region to another in the same basin, river discharge is a robust integrator of the long-term hydrological properties of a drainage basin. For 1903-85, Richey *et al.* (1989)

examined the record of the stage of the Rio Negro at Manaus, which represented the runoff and ultimately, climatic conditions over  $3 \times 10^6$  km<sup>2</sup> of the Andean and western Amazon watershed. A power spectrum analysis of the deseasoned values revealed a pronounced spectral peak at 2.4 years. A cross-spectrum analysis with ENSO indices suggested a coupling to the tropical Pacific climate cycle.

In coastal Peru, heavy rainfall is considered as one of the criteria for identifying an El Niño (Quinn *et al.*, 1978,

1987; Quinn, 1992). Recently, Kane (2000) showed that the rainfall characteristics at Huancayo (central Peruvian Andes) were different from those of coastal Peru. On the other hand, ENSO effects on rainfall in South America are reported to be mostly droughts in NE Brazil and excess rains in the southern parts, including Chile (Quinn and Neal, 1983; Aceituno, 1988; Ropelewski and Halpert, 1987, 1989; Rutland and Fuenzalida, 1991; Pisciotano *et al.*, 1994; Diaz *et al.*, 1998; Grimm *et al.*, 1998; Robertson *et al.*, 2001; Kane, 2002). For the Amazon basin, Matsuyama (1992) studied the seasonal cycle, while Eltahir and Bras (1994) examined the role of precipitation cycling in the Amazon hydrological cycle. Marengo (1992) mentioned that whereas northern Amazônia showed strong El Niño signals, southern Amazônia seemed to be more independent of El Niño, and rainfall anomalies in northern Amazônia were associated with distinct circulation patterns in the tropical Atlantic. Also, ENSO effects may be different for different sizes of the basins. Marengo and Hastenrath (1993) presented case studies for the moderately wet year 1986 and the extremely dry El Niño year 1983 in northern Amazônia, where differences in locations of inter-tropical convergence zone (ITCZ), strength of subtropical westerly jets (STWJ), and vertical motions and convection over the Amazon basin were noticed. Zeng (1999) made an analysis of the Amazon basin hydrological cycle using data of rainfall and historical Amazon River discharge and reported a correlation with ENSO (El Niño/Southern Oscillation) of 0.8 for 1985-93 and 0.56 for 1979-96. Fu *et al.*, (1999) examined the influence of atmosphere and land surface on the seasonal changes of convection in the tropical Amazon, while Fu *et al.*, (2001) explored the influence of tropical SST on the seasonal distribution of precipitation in the equatorial Amazon. Marengo *et al.*, (1993) found that abundant rainy seasons in northern Amazônia were associated with cold SST in the tropical eastern Pacific and negative/positive anomalies in the tropical North/South Atlantic, accelerated Northeast trades and a southward displaced ITCZ. Marengo *et al.*, (1998) found strong long-term trends on flow data from the coast of northern Peru and the São Francisco River and positive significant trends in the Parnaíba River basin. Liebmann *et al.*, (1998) compared the rainfall, outgoing long wave radiation (OLR) and divergence over the Amazon basin and found moderate correlation (~0.6 or less). The major seasonal transitions from dry to rainy regimes were captured well by OLR while the mean diurnal cycle was represented reasonably well by the 150 hPa divergence. Marengo *et al.* (2001) studied the onset and end of the rainy season in the Brazilian Amazon basin and found an apparent association between SST anomalies in the tropical Atlantic and Pacific and the onset and end dates in parts of the Amazon. Liebmann and Marengo (2001) found that areas of rainfall exhibiting

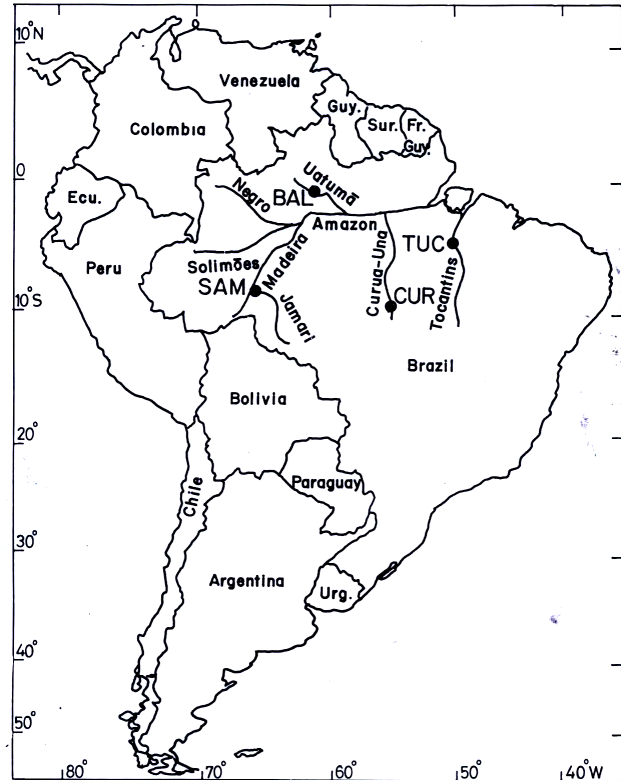


Fig. 1. Map of the Amazon basin, showing (dots) the locations Samuel (SAM), Balbina (BAL), Curua-Una (CUR), Tucuruí (TUC) for which RSF data are used

strong relationship with SST were confined to the equatorial region of the Brazilian Amazon.

Studies of river basins are generally of two types. In one, models try to estimate the effects of various circulation patterns on the hydrological characteristics (climatology etc.) of different parts of a basin. In another, specific effects like those of El Niño events or SST anomalies are examined. In the present communication, the study is of the second category and of a very limited scope, in that the river stream-flows (henceforth referred to as RSF) are examined for four rivers in the Amazon basin for their association with El Niño effects, particularly with those of the recent giant events of 1982-83 and 1997-98. Such long data (more than 60 years) are available for only a few locations including the four used here, which cover wide areas in different parts of the Amazon basin.

## 2. Data

Data for RSF (river stream-flow) were obtained from ONS (Operador Nacional do Sistema Elétrico, National Operator of the Electrical System), Brazil for River Jamari (at SAM, Samuel, 8° 45' S, 63° 25' W, nearest to

TABLE 1

Inter-correlations during 1930-99, between the series of RSFs (river stream-flows) at Samuel, Balbina, Curua-Una, Tucurui and rainfalls at the grid centers 7.5° S, 62.5° W (Grid-1, near Samuel), 7.5° S, 57.5° W (Grid-2, near Balbina), 7.5° S, 47.5° W (Grid-3, near Tucurui)

	Samuel	Grid-1	Balbina	Grid-2	Curua-Una	Grid-3	Tucurui
Samuel	1.00						
Grid-1	0.29	1.00					
Balbina	0.15	0.03	1.00				
Grid-2	0.23	0.05	0.23	1.00			
Curua-Una	0.20	0.13	0.56	0.33	1.00		
Grid-3	0.12	0.30	0.25	0.30	0.52	1.00	
Tucurui	0.15	0.14	-0.22	-0.08	0.01	0.33	1.00

the Peru-Ecuador coast, area ~14,000 km<sup>2</sup>), River Tocantins (at TUC, Tucurui, 3° 45' S, 49° 41' W, farthest from the Peru-Ecuador coast, area ~758,000 km<sup>2</sup>), River Uatumã (at BAL, Balbina, 0° 58' S, 59° 19' W, area ~17,000 km<sup>2</sup>) and River Curua-Una (at CUR, Curua-Una, 12° 47' S, 54° 16' W, area ~18,000 km<sup>2</sup>). The locations are shown in Fig. 1. Data for 5° × 5° gridded rainfall (Mitchell *et al.*, 2002) at grid centering 7.5° S, 62.5° W (Grid-1, near Samuel), 7.5° S, 57.5° W (Grid-2, near Balbina), 7.5° S and 47.5° W (Grid-3, near Tucurui) were obtained from the website <http://www.cru.uea.ac.uk/cru/data/hrg.htm>. Data for ENSO indices were obtained from the website <http://www.cpc.ncep.noaa.gov/data/indices/>, and for North Atlantic Oscillation Index from <http://www.cru.uea.ac.uk/ftpdata/nao.dat>.

### 3. Climatology

The average discharges were lowest (mean 183 m<sup>3</sup>s<sup>-1</sup>) in Curua-Una and largest (mean 11,124 m<sup>3</sup>s<sup>-1</sup>) in Tucurui and the percentage positive and negative deviations from means were very different, largest at Samuel (+136%, -83%), smallest in Curua-Una (+85%, -47%). However, the seasons were similar for all. The maximum values were in March, April and/or May and minimum values in September, October and/or November. Rainfalls were maximum during January, February and March. Details of the climatology are not studied here. Instead, the average monthly values (climatology) were subtracted from the monthly values and thus, deseasoned monthly values were obtained. For further smoothing, 12-month running means were calculated.

### 4. Year-to-year variations

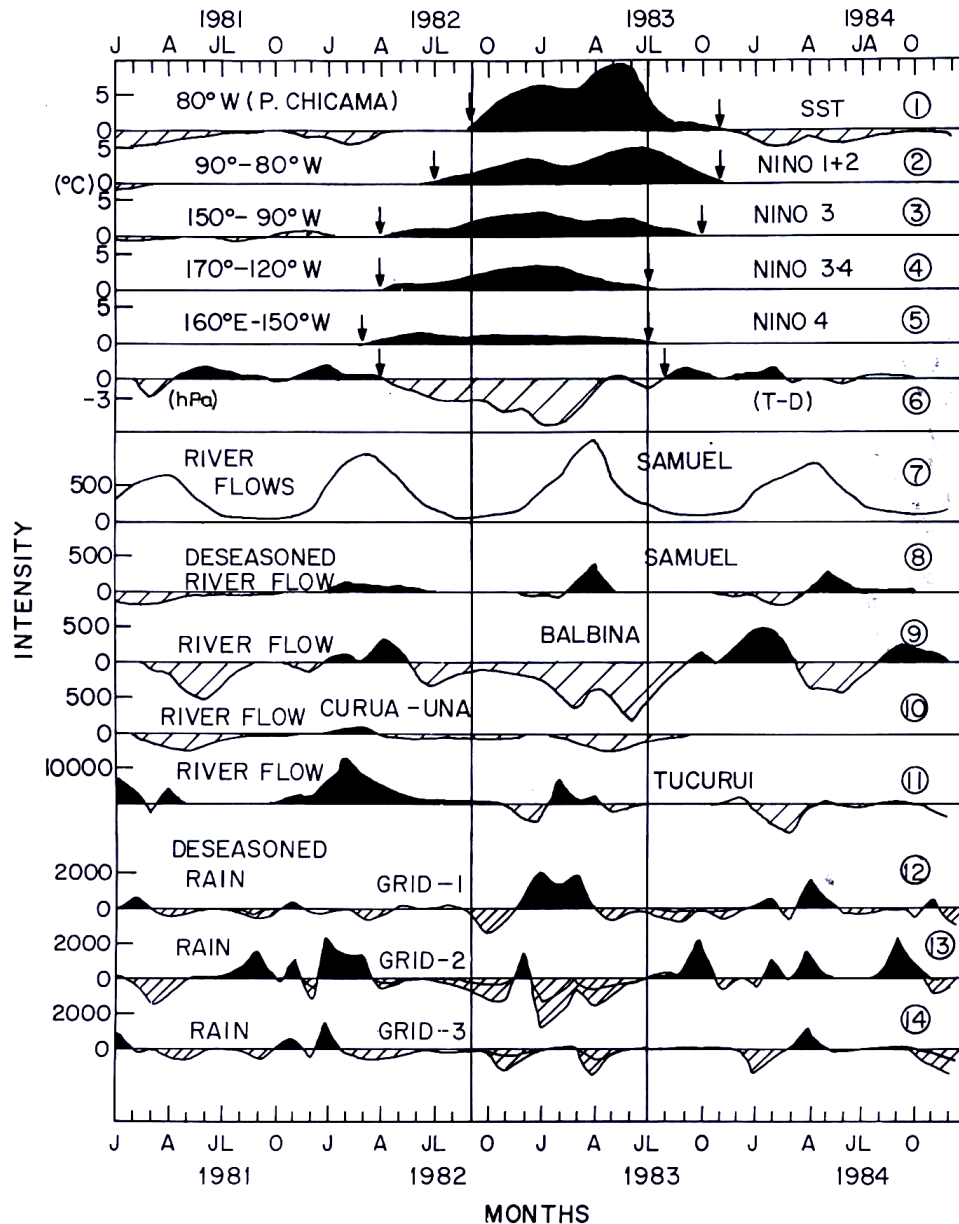
Plots of the various series of RSF and gridded rainfalls for 1930-99 (not shown here) indicated the following :

(i) The RSF variations at the four locations were not always alike.

(ii) The correlations between the annual values of the four RSFs between themselves and with gridded rainfalls were as given in Table 1. As can be seen, most of the correlations are low (less than 0.35), the only exceptions being, 0.56 between RSFs at Balbina and Curua-Una and 0.52 between RSF at Curua-Una and rainfall in Grid-3. (The standard error is about ±0.10). Thus, the hydrological characteristics seem to have considerable local influences and large-scale common characteristics seem to have a minor influence.

(iii) Marengo (1992) had divided the Amazon roughly into three regions, namely NSA (Northern South America, excluding north-east Brazil), NA (northern Amazônia) and SA (southern Amazônia, 0-20° S, 45-70° W). One of our locations (Balbina) is in the bottom part of NA, while the others are inside the region SA within 0-10° S. Marengo (1992) had used data for six stations in SA and mentions that the correlations were not very large and explained only a small fraction of the total variance.

(iv) Particularly disconcerting is the low correlation between rainfalls and the RSFs in roughly the same area,



**Fig. 2.** Plots of monthly values for 1981-84, of (1-5) SST in five regions in the Pacific; (6) (T-D); (7) river flow at Samuel; (8-11) deseasoned RSF at Samuel, Balbina, Curua-Una, Tucurui; (12-14) deseasoned rainfalls in Grid-1, Grid-2, Grid-3

indicating that the rainfall variations are not reflected faithfully in the collection of water in the catchment area and that there are large latitude and longitude differences of rainfall characteristics. The catchment area may be larger than the  $5^{\circ} \times 5^{\circ}$  grid area. Marengo (1992) often mentions 'highly significant' correlations, but the values are mostly less than 0.50 (highly significant at a 95% or better level, because the standard error may be less than 0.15) and represent an explained variance of only

$(0.5)^2 = 25\%$ , leaving 75% to random causes, not a very encouraging situation for reliable predictions.

### 5. Giant El Niño events of 1982-83 and 1997-98

The El Niño events of 1982-83 and 1997-98 were stronger than any others in recorded history and were expected to show strongly their effects on RSFs and rainfalls.

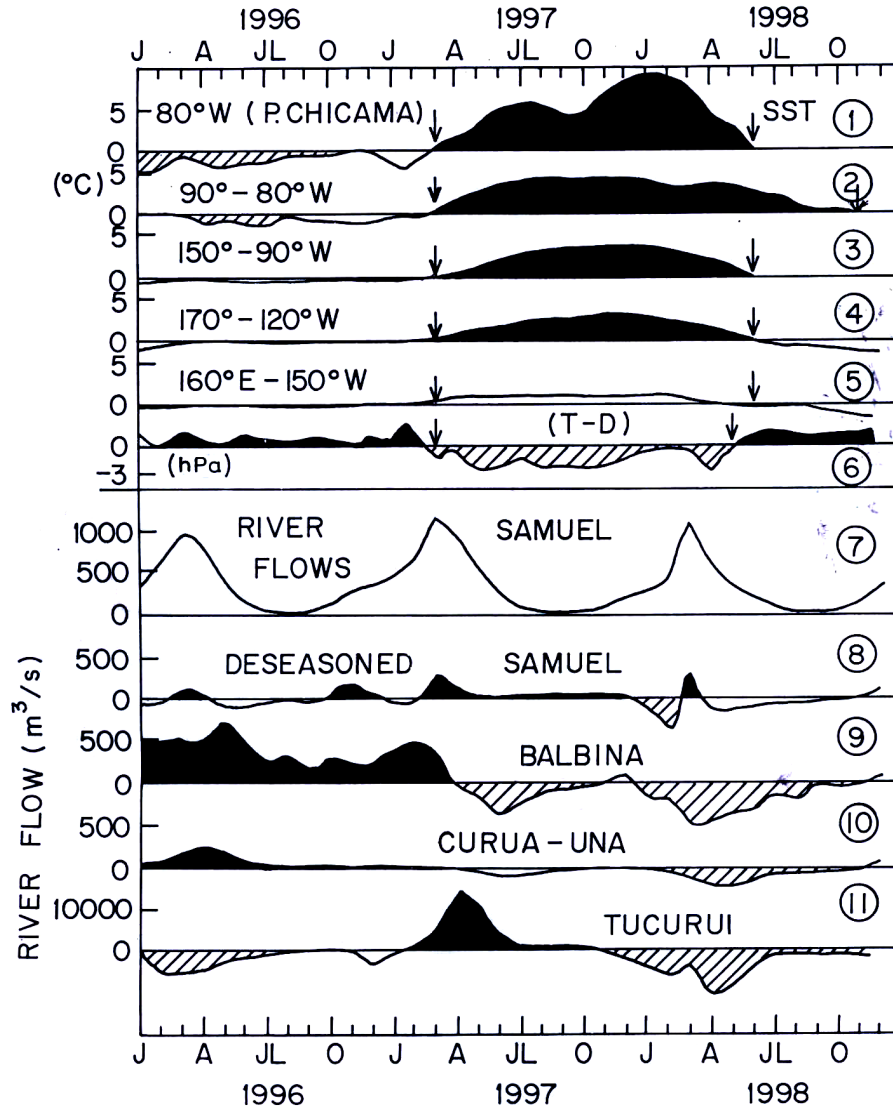


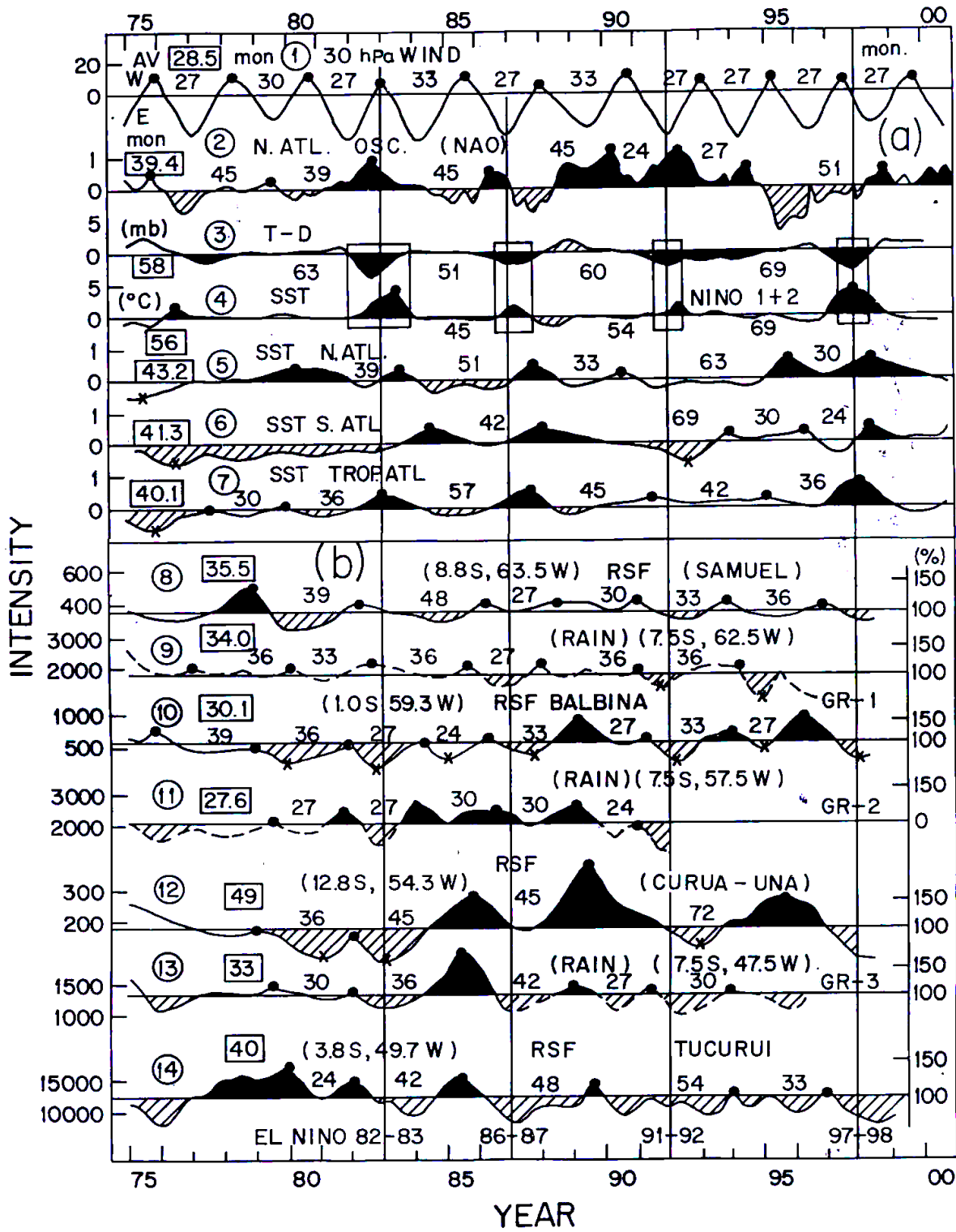
Fig. 3. Same as Fig. 2, for 1996-98 (no rainfall data available)

5.1. El Niño of 1982-83

Fig. 2 shows the plots of monthly values for four consecutive years 1981-84. The top five plots are for SST anomalies in Pacific regions: Puerto Chicama (Peru-Ecuador coast, 8° S), Niño 1+2 (0-10° S, 90° - 80° W), Niño 3 (5° N - 5° S, 150° - 90° W), Niño 3.4 (5° N - 5° S, 170° - 120° W, Niño 4 (5° N - 5° S, 160° E - 150° W). The arrows indicate the commencements and terminations of the El Niño and both are different in different parts of the Pacific. The sixth plot is for the Southern Oscillation Index (T-D), which shows the commencement in April 1982 and termination in August 1983, almost the same as for SST in western Pacific. (The vertical lines show the

interval in which El Niño was active in all regions). Plot 7 is for the RSF at Samuel, actual monthly values (not deseasoned) just to show that a large month-to-month variation (climatology) exists, which would camouflage any ENSO effects. Plot 8 shows the deseasoned RSF (climatology subtracted) for Samuel and plots 9, 10, 11 shows the deseasoned values for RSFs at Balbina, Curua-Una and Tucurui. Plots 12, 13, 14 are for the deseasoned monthly values of the rainfalls in Grids 1, 2, 3. The following may be noted :

- (i) During the interval April 1982-October 1983 when the El Niño was active, RSF at Samuel (Plot 8) showed a small increase and the rainfall in Grid-1 (Plot 12) showed



**Figs. 4(a&b).** Plots for 1975-99 for (a) climatic indices 1, 30 hPa wind; 2, North Atlantic Oscillation index; 3, ENSO index T-D; 4, ENSO index SST Nino 1+2 in Pacific; 5, 6, 7, SST in North, South and Tropical Atlantic and (b) hydrological indices 8, RSF Samuel; 9, rain Grid-1; 10, RSF Balbina ; 11, rain Grid-2; 12, RSF Curua-Una; 13, rain Grid-3; 14, RSF Tucurui. Positive deviations are painted black and negative deviations are shown hatched (for T-D plot 3, negative deviations implying El Niños are painted black and positive are shown hatched). Maxima are indicated by dots and numbers indicate spacings in months between successive maxima, while numbers in rectangles are average spacings, in months

a big increase, indicating that in this region, this El Niño was associated with excess rains. A small increase was observed in RSF at (far away) Tukurui also (Plot 11). On the other hand, RSF at Balbina (Plot 9) showed a strong decrease, which was seen in the rainfall in Grid-2 (Plot 13) and to a lesser extent in RSF at Curua-Una and rainfall in Grid-3. Thus, even in the region SA (southern Amazônia) delineated by Marengo (1992), highly dissimilar El Niño effects (excess rains in some parts, droughts in other parts, with no dependence on latitude or longitude) can occur.

(ii) There are considerable increases and decreases outside this interval at all locations (for example, a large increase followed by a large decrease in RSF at Balbina within ten months Nov 1983 - Aug 1984), indicating other influences unrelated to ENSO.

### 5.2. *El Niño of 1997-98*

Fig. 3 shows similar plots for 1996-98, which includes the El Niño event of 1997-98 (marked by vertical lines). The event started in March 1997 in all regions of the Pacific (Plots 1-5) and terminated in almost all regions in July 1998. The (T-D) (Plot 6) had the same pattern. Plot 7 is for the actual monthly values of RSF at Samuel and shows a prominent seasonal variation. Plots 8-11 are for the deseasoned values of RSF at Samuel, Balbina, Curua-Una and Tukurui. (Rainfall data were intermittent for these years and not useful for complete plots). The RSFs show decreases in the fall end of the ENSO active interval at all locations, more prominently at Balbina and Tukurui. However, large increases occurred in 1996 and early 1997 when there was neither an El Niño nor a La Niña.

## 6. Associations during the recent 25 years 1975-99

### 6.1. *Plots for 1975-99*

Fig. 4 shows plots of 12-month running means (four values per year, centered 3 months apart) of several parameters, climatic indices in Fig. 4(a), and RSF and rainfall data in Fig. 4(b). In Fig. 4(a), plots 1-7 are as follows:

(i) Plot 1 is for the low latitude stratospheric zonal wind at 30 mb level (positive values, westerly; negative values, easterly). A striking feature is a smooth oscillation with prominent peaks (marked by dots). Successive peak spacings are in the range 27-33 months (QBO, Quasi-biennial oscillation, discovered by Reed *et al.*, 1961 and Veryard and Ebdon, 1961). Some workers use the term QBO only for this stratospheric wind oscillation. However, we will use it only for its mathematical

meaning, namely, an oscillation of 2-3 year periodicity. For 1975-99, the average spacing of QBO (wind) is 28.5 months (indicated by the number in a rectangle).

(ii) Plot 2 is for NAO (North Atlantic Oscillation), traditionally defined as the normalized pressure difference between a station on the Azores and one on Iceland (Jones *et al.*, 1997). There are clear peaks here, but the spacing varies in a wide range 24-47 months. The average is 39.4 months (indicated in a rectangle), much larger than the average 28.5 months of QBO (Wind). NAO seems to have a QTO (Quasi-triennial oscillation, 3-4 years).

(iii) Plot 3 is for the Southern Oscillation Index, represented by the Tahiti (T) minus Darwin (D) atmospheric pressure difference (T-D). Portions painted black are El Niños (warmer waters, positive sea surface temperature (SST) anomalies in the Pacific). The spacing of these minima is large, 30-63 months, with an average of 58 months (number in the rectangle).

(iv) Plot 4 is for SST anomalies in the Niño 1+2 region (0-10° S, 90° - 80° W), with prominent positive anomalies (painted black) indicating El Niños. The average spacing of the maxima is 56 months, almost the same as for (T-D) minima, and both are very much larger than the QBO (Wind).

(v) Plots 5, 6, 7 are for the SST anomalies of North Atlantic, South Atlantic and Tropical Atlantic. There are peaks but with spacings in a wide range 24-63 months, but the average spacings are very similar, 43.2 months for North, 41.3 months for South and 40.1 months for Tropical Atlantic, all in a QTO (3-4 year) region.

In Fig. 4(b), plots 8, 10, 12, 14 are for RSFs at Samuel, Balbina, Curua-Una and Tukurui and the in between plots 9, 11, 13 are for the rainfalls in Grids 1, 2, 3. Since each point is a 12-month mean, it is automatically deseasoned. There are peaks in wide ranges 24-72 months, but the averages seem to be in the QBO (2-3 year) range for some locations and in the QTO (3-4 year) range for other locations. Since Pacific SST and (T-D) spacings are of more than 50 months (almost 4 years), the smaller spacings at some locations can be compared only with QBO (Wind). Thus, an association between hydrological parameters and stratospheric wind is indicated. This has not been suggested before for any part of Amazônia, but in some rainfalls in other parts of the globe, such an association has been hinted (for example, in summer monsoon rainfall in India, Mukherjee *et al.*, 1985; Kane, 1995). In the Parametric model of the long range forecasting of southwest monsoon rainfall in India, one of the 16 parameters used is the 50 hPa wind (Thapliyal and Kulshrestha, 1992).

TABLE 2

Inter-correlations between the climatic indices and hydrological parameters (RSF and rainfalls), calculated from about 100 values of each parameter (12-month running means, centered 3 months apart, 4 values per year, for 25 years 1975-99)

	30 hPa	NAO	T-D	SST Pac	SST N.At	SST S.At	SST T.At	Sam	Gr-1	Bal	Gr-2	C.Un	Gr-3	Tuc
30 hPa	1.00													
NÃO	-0.19	1.00												
T-D	0.05	-0.16	1.00											
SST Paci.	0.05	-0.01	-0.54	1.00										
SST N.At	0.10	-0.38	-0.07	0.37	1.00									
SST S.At	-0.15	-0.20	0.21	-0.07	0.21	1.00								
SST TrAt	-0.06	0.01	-0.69	0.67	0.59	0.29	1.00							
Samuel	0.02	0.19	0.08	-0.15	-0.11	0.17	0.03	1.00						
Grid-1	0.15	-0.22	0.06	-0.23	-0.15	-0.07	-0.30	0.00	1.00					
Balbina	-0.12	-0.06	0.56	-0.51	-0.13	0.32	-0.37	0.30	0.14	1.00				
Grid-2	-0.20	-0.21	0.44	-0.27	-0.02	0.62	-0.17	0.23	0.07	0.39	1.00			
Curua-Una	-0.01	-0.08	0.57	-0.53	-0.29	0.62	-0.36	0.28	0.19	0.66	0.47	1.00		
Grid-3	0.08	-0.35	0.42	-0.46	-0.27	0.52	-0.36	0.13	0.12	0.25	0.53	0.61	1.00	
Tucuruí	-0.02	-0.06	0.02	-0.17	0.12	-0.18	-0.15	0.08	0.04	-0.32	-0.01	-0.13	0.44	1.00

## 6.2. Relationship of RSF and rainfall with individual climatic indices

### 6.2.1. El Niños (Plots 3 and 4)

The relationship seems uncertain. Whereas increases or decreases are seen during El Niños, such changes seem to occur even without an El Niño.

### 6.2.2. NAO (plot 2)

The NAO (North Atlantic Oscillation) had prominent maxima in 1982, 1986, 1990, 1992. Three of these coincide with El Niños and hence, their effects are not distinguishable from those of El Niños. In others, there is no consistency of effects on RSF.

### 6.2.3. SST North Atlantic (Plot 5)

Lack of consistency.

### 6.2.4. SST South Atlantic (Plot 6)

Lack of consistency.

### 6.2.5. SST Tropical Atlantic (Plot 7)

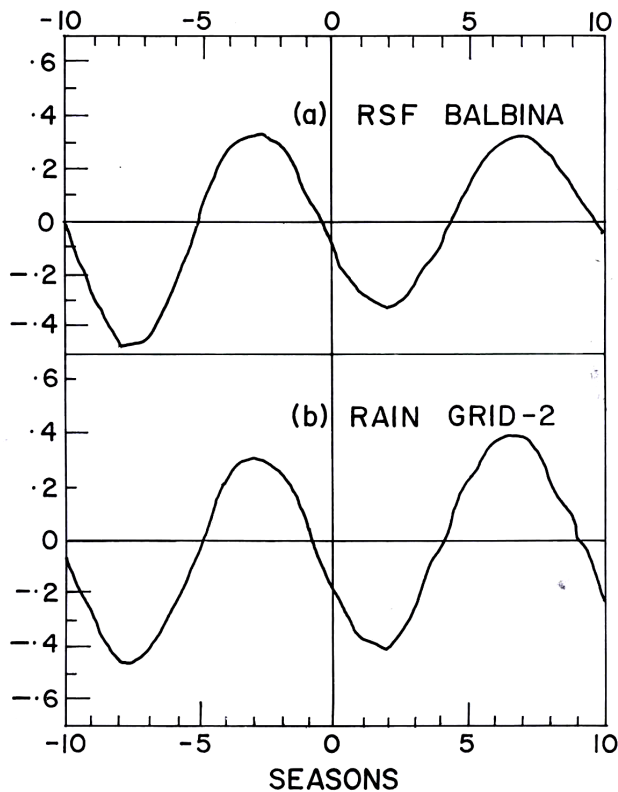
This had major maxima in 1982-83, 1987 and 1997-98, all mixed up with El Niños.

## 6.3. Relationship of climatic indices with individual rainfalls and RSFs

The RSF changes were sometimes related to some parameters but sometimes not related to any parameter. Thus, the relationships are obscure. Table 2 gives the inter-correlations between the climatic indices themselves, the hydrological parameters (RSF and rainfalls) themselves, and hydrological and climatic indices, calculated from about 100 values of each parameter (12-month running means, centered 3 months apart, 4 values per year, for 25 years). The following may be noted:

(i) The 30 hPa wind is poorly correlated with all parameters. RSF at Balbina and rainfall in Grid-2 which had QBOs, should have had a good correlation with 30 hPa wind, but the correlations are only  $-0.12$  with RSF Balbina and  $-0.20$  with Rainfall Grid-2. It happens that the phases (maxima with maxima) are not tallying and





**Figs. 5(a&b).** Cross correlation between 30 hPa wind and (a) RSF Balbina, (b) rainfall in Grid-2, for phase differences -10 to +10 seasons

there are considerable lags. To estimate the lags, a cross-correlation was done with lags of -10 to +10 seasons (3 months). The plot of correlations is shown in Fig. 5. The correlations oscillate between about -0.50 and +0.40, with the maxima of wind occurring 3 seasons later than maxima of RSF and rainfall, or 2 seasons earlier than the minima of RSF and rainfall. However, the maximum correlations are not very high (only ~0.50), indicating only an approximate relationship.

(ii) NAO is also poorly correlated. Maximum correlations are -0.38 with North Atlantic SST and -0.35 with rainfall in Grid-3.

(iii) (T-D) has a good correlation with Pacific SST (obvious, El Niño indices) but it is only -0.54 because the (T-D) minima do not coincide exactly with the SST maxima and occur earlier by 1-2 seasons (observed before by Deser and Wallace, 1987). A good correlation exists with Tropical Atlantic SST (-0.69). Reasonable correlations are obtained with RSF at Balbina (+0.56) and Curua-Una (+0.57) and rainfalls in Grid-2 (+0.44) and Grid-3 (+0.42), but poor correlations with RSF at Samuel

(+0.08) and Tucurui (+0.02) and with rainfall in Grid-1 (+0.06).

(iv) North Atlantic SST is well correlated with Tropical Atlantic SST (+0.59) but poorly correlated with South Atlantic SST (+0.21) and with all other parameters.

(v) South Atlantic SST is well correlated with RSF at Curua-Una (+0.62) and rainfalls in Grid-2 (+0.62) and Grid-3 (+0.52).

(vi) Tropical Atlantic SST has moderately negative correlations (0.36 or less) with the hydrological parameters.

(vii) RSF at Samuel is poorly correlated with other hydrological parameters, maximum correlation being with RSF at Balbina (+0.30).

(viii) Rainfall in Grid-1 is also poorly correlated with other hydrological parameters, including RSF at Samuel (0.00).

(ix) RSF at Balbina has a moderate correlation with rainfall in Grid-2 (+0.39), a good correlation with RSF at Curua-Una (+0.66), and a moderate negative correlation with RSF at Tucurui (-0.32).

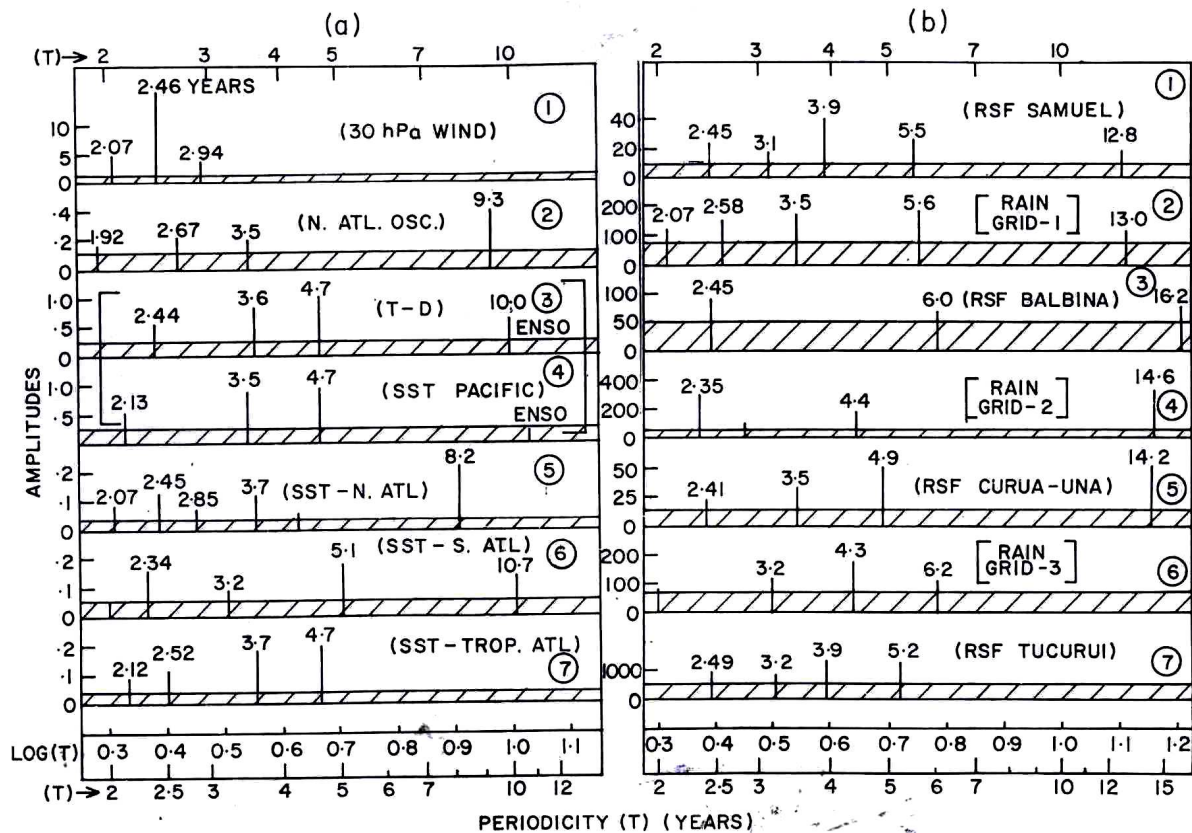
(x) Rainfall in Grid-2 is moderately correlated with RSF at Curua-Una (+0.47) and rainfall in Grid-3 (+0.53), but poorly correlated with RSF at Tucurui (-0.01).

(xi) RSF at Curua-Una is well correlated with rainfall in Grid-3 (+0.61) but poorly correlated with RSF at Tucurui.

(xii) Rainfall in Grid-3 is moderately correlated with RSF at Tucurui (+0.44).

Overall, RSF at Samuel and rainfall in Grid-1 are dissimilar to each other and dissimilar to other hydrological parameters and have poor relationship with climatic indices, while RSF at Balbina and Curua-Una and rainfalls in Grid-2, 3 are reasonably interrelated and have moderate to good relationship with climatic indices, notably ENSO.

If more than one climatic indices are involved in affecting any hydrological parameter, the direct correlation would be reduced, but a multiple regression analysis should show higher multiple correlations. In case of RSF at Curua-Una, reasonably good correlations were: +0.57 with (T-D) and +0.62 with South Atlantic SST. A regression analysis considering RSF at Curua-Una as the dependent variable and (T-D) and South Atlantic SST as two independent variables yielded a multiple correlation coefficient as +0.76, larger than the individual correlations



Figs. 6(a&b). Spectra (amplitudes versus periodicities  $T$  detected by MEM for 1975-99) for (a) climatic indices and (b) hydrological indices. Numbers are periodicities in years. Note that the abscissa scale is logarithm of periodicity  $T$

+0.57 and +0.62. Using rainfall in Grid-2 as a dependent variable and (T-D) and South Atlantic SST as two independent variables, the individual correlations +0.44 with (T-D) and +0.62 with South Atlantic SST improved to a multiple correlation of +0.69 (not a large improvement). Thus, for some hydrological parameters, a few climatic indices (notably ENSO and South Atlantic SST) operating in unison seem to explain a substantial part of the total variance (more than ~60%). Nevertheless, considerable variance (40% or more) remains unexplained and hence unpredictable.

## 7. Spectral analysis

To obtain quantitative estimates of the spectral characteristics of the inter-annual variability, the series in Fig. 2 (about 100 seasonal values) were subjected to spectral analysis by MEM (Maximum Entropy Method, Burg, 1967; Ulrych and Bishop, 1975), which locates peaks much more accurately than the conventional BT (Blackman and Tukey, 1958) method. However, the amplitude (Power) estimates in MEM are not very reliable (Kane, 1977, 1979; Kane and Trivedi, 1982). Hence, MEM was used only for detecting all the possible peaks

$T_k$  ( $k = 1$  to  $n$ ), using LPEF (Length of the Prediction Error Filter) as 50% of the data length. These  $T_k$  were then used in the expression :

$$f(t) = A_0 + \sum_{k=1}^n [a_k \sin(2\pi t/T_k) + b_k \cos(2\pi t/T_k)] + E$$

$$= A_0 + \sum_{k=1}^n r_k \sin(2\pi t/T_k + \phi_k) + E$$

where  $f(t)$  is the observed series and  $E$  the error factor. A Multiple Regression Analysis (MRA, Bevington, 1969) was then carried out to estimate  $A_0$  ( $a_k$ ,  $b_k$ ), and their standard errors (by a least-square fit). From these, amplitudes  $r_k$  and their standard error  $\sigma_k$  (common for all  $r_k$  in this methodology, which assumes white noise) were calculated. Any  $r_k$  exceeding  $2\sigma$  is significant at a 95% (a priori) confidence level.

Figs. 6(a&b) shows the spectra (amplitudes, versus periodicities  $T$  detected by MEM) in (a) for climatic

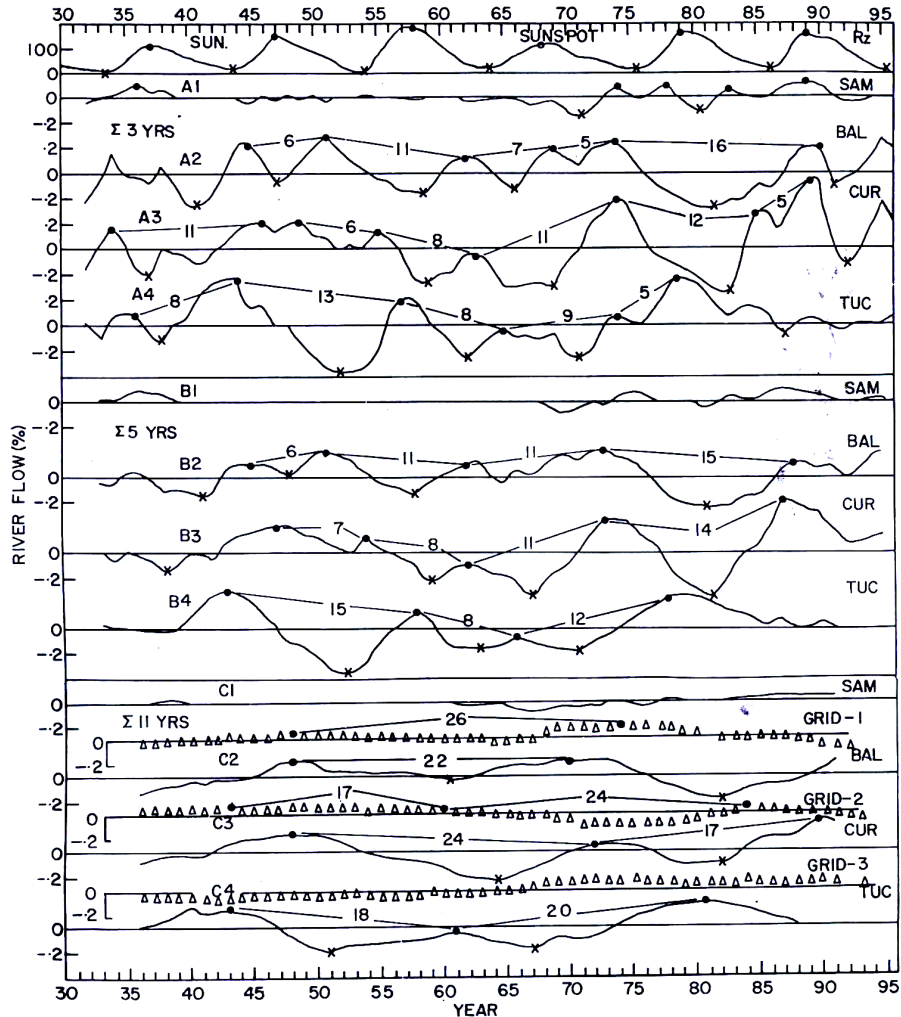


Fig. 7. Plots of yearly values. Top, sunspot number; next, river flows at Samuel, Balbina, Curuauna, Tucuui. (A1-A4), 3-year moving averages; (B1-B4), 5-year moving averages; (C1-C4), 11-year moving averages (in between triangles are for rainfalls in Grids 1, 2, 3). Peaks (maxima) are marked by dots and troughs (minima) by crosses. The numbers indicate peak spacings in years

indices and in (b) for hydrological parameters. The hatched portion shows the  $2\sigma$  limits and lines protruding above this limit are significant at a better than 95% confidence level. The following may be noted:

(i) In Fig. 6(a) for climatic indices, the 30 hPa wind and shows one very prominent peak in the QBO region, at 2.46 years ( $\sim 29.5$  months). This peak is seen very weakly in other climatic indices (including ENSO indices), which show instead prominent peaks near 3.5 and 4.5 years. Thus, the 30 hPa wind has virtually no relation with the other climatic indices.

(ii) In Fig. 6(b) for hydrological indices, almost all indices (notably RSF Balbina) have a small peak near  $\sim 2.40$  years, which could be identified with the 30 hPa peak but could also be the weak peak in ENSO. All indices have prominent peaks in the 3-5 year range, indicating some relation with ENSO and/or North Atlantic SST.

Thus, a complex picture emerges. The 30 hPa wind has a very prominent QBO at  $\sim 30$  months, while the ENSO indices have most prominent periodicities at 3.5 and 4.7 years. However, ENSO has also small QBOs. If

any hydrological parameter shows prominent QBO, the association should be considered with stratospheric wind or with ENSO? We feel that the conclusion should be based on relative proportions. RSF Balbina and rainfall in Grid-2 do not show any peak near 3.5 years and show only small peaks at 4.4 and 6.0 years, indicating lack of ENSO influence. On the other hand, both show very strong QBOs near 2.4 years. Hence, association with stratospheric winds is more likely. In other hydrological parameters, ENSO does seem to be effective, but QBO is very prominent in all of them and hence, some association with stratospheric wind is also indicated.

### 8. Long-term (decadal) variations

To reduce the contribution of QBO, QTO etc., 3-year moving averages were calculated. The results are shown in Fig. 7. The top plot is for sunspot numbers  $R_z$  and the sunspot maxima are marked by dots and minima by crosses. The succeeding plots A1, A2, A3, A4 are for the 3-year moving averages of percentage RSF deviations from mean, for Samuel, Balbina, Curua-Una and Tukurui. Peaks (maxima) are marked by dots and the numbers indicate the spacings (in years) between successive peaks. Troughs (minima) are marked by crosses. As can be seen, the spacings of the maxima are not constant and vary in a large range 5-16 years, and the peaks at different locations do not match (variations at Samuel are negligibly small). Thus, these features are not common for all locations. The inter-correlations are :

3-year runn.mean	Balbina	Curua	Samuel	Tukurui
Balbina	1,00			
Curua-Una	0,57	1,00		
Samuel	0,08	0,39	1,00	
Tukurui	-0,47	-0,07	0,16	1,00

The plots B1, B2, B3, and B4 are for 5-year moving averages. Here again, different locations show different variations. Some spacings are ~11 years and it is tempting to attribute these to sunspot cycles. The inter-correlations are :

5-year runn.mean	Balbina	Curua	Samuel	Tukurui
Balbina	1,00			
Curua-Una	0,52	1,00		
Samuel	-0,08	0,49	1,00	
Tukurui	-0,62	-0,10	0,19	1,00

The plots C1, C2, C3, and C4 are 11-year moving averages for RSFs. The in between plots (triangles) are for

rainfalls in Grids-1, 2, 3. Here, a 22-year (Hale magnetic cycle of sunspots?) oscillation is indicated. Thus, though some long-term variations are indicated, there is no consistency between different locations and between RSF and rainfall. The inter-correlations are :

11 year runn.mean	Samuel	Grid-1	Balbina	Grid-2	Curua-Una	Grid-3	Tukurui
Samuel	1,00						
Grid-1	-0,19	1,00					
Balbina	-0,46	0,13	1,00				
Grid-2	0,40	-0,42	-0,18	1,00			
Curua-Una	0,52	0,09	0,24	0,18	1,00		
Grid-3	-0,07	0,14	-0,09	-0,70	0,13	1,00	
Tukurui	0,51	0,07	-0,71	-0,04	0,12	0,28	1,00

A spectral analysis of the series revealed the following:

(i) In the 3-year moving averages, there was a periodicity of ~5.5 years present at all locations. Further, there were periodicities in a wide range 7.7-13.8 years, dissimilar at the four locations (these would reduce the inter-correlations). Tukurui had 18.2 years, not seen at other locations, while other locations had ~22 years, not seen at Tukurui.  $T = \sim 55$  years was seen at all locations.

(ii) In the 5-year moving averages, periodicities were seen in a wide range 7.6-13.8 years remains wide. The 18.1 years was seen at Tukurui, ~22 years at the other locations, and ~55 years at all locations.

(iii) In the 11-year moving averages, the 18.2 years at Tukurui, ~22 years at other locations and ~55 years at all locations were seen. In rainfalls, Grid-1 showed 25.1 years, Grid-2 showed 22.8 and 50 years, and Grid-3 showed 21.4 and 57 years.

A 55-year periodicity in a sample of 56 years seems unbelievable, but MEM is capable of detecting it, albeit with large errors. Hence, the conclusion would be that a periodicity of ~50-60 years is roughly indicated, in all the series.

Since ENSO effects are eliminated, solar cycle effects could be playing a role. Besides the 11-year cycle, sunspot numbers have larger periodicities also, for example, the Hale magnetic cycle of ~22 years, the 80-year periodicity (Gleissberg, 1965) and others (60 years, etc., mentioned in Kane and Trivedi, 1985). Some of these larger periodicities (notably 20-25 years and 50-60 years) are reflected in our RSF and rainfalls (by whatever mechanism), raising an embarrassing question, namely, why is the most prominent periodicity of ~11 years in

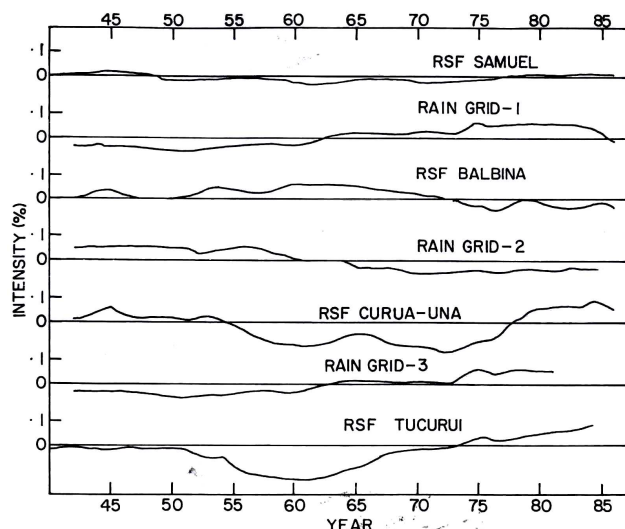


Fig. 8. Plots of 22-year running means of percentage RSF and rainfalls for 1942-86

sunspot numbers not reflected clearly and accurately in river flows. Constain and Bollinger (1996) observed a statistically significant peak for the surface stream-flow in the seismic zones bisected by the Mississippi River, Illinois, and James River, Virginia (USA) in the range 11-13 years but could not resolve it with any better accuracy. They also noted an 18-20 year periodicity, which could be a Hale magnetic cycle effect or a lunar tidal effect. Burroughs (1992) mentions that meteorological records show fairly regularly the periodicities: QBO, 3-4 years, 5-7 years, 11 years and 20 years.

Regarding long-term trends, the plots of the 11-year moving averages are dominated by the ~22 year fluctuations. When linear trends were fitted, the total variations over 56 values (1936-91) of 11-year moving averages were, Samuel,  $(-0.22 \pm 0.39)\%$ ; Balbina,  $(+1.34 \pm 1.29)\%$ ; Curua-Una,  $(-1.62 \pm 1.79)\%$ ; Tucurui,  $(+1.18 \pm 1.18)\%$ , essentially negligible, insignificant linear trends. If the fact that moving averages are used is taken into account, the degrees of freedom would be reduced and the standard errors mentioned above would increase by almost a factor of 2. Hence, all these trend estimates are grossly unreliable, and linear trends are negligible. However, the possibility remained that the trends may not be linear at all. Fig. 8 shows the plots of 22-year running means. As can be seen, the trends are not linear and are not alike at all locations, even qualitatively. We suspect that local conditions (terrain, orography etc.) have a considerable influence on these dissimilar patterns.

After 1976, the El Niño events have been stronger and recent IPCC reports present evidence of decadal scale

changes in circulation in the Pacific, which seem to have affected rainfall in Southern Brazil-Northern Argentina. In our plots, nothing unusual was found in recent years.

## 9. Conclusions and discussion

A comparison of the characteristics of the river stream-flows (RSFs) at four locations (Samuel, 9° S, 63° W; Balbina, 1° S, 59° W; Curua-Una, 13° S, 54° W; Tucurui, 4° S, 50° W) and rainfalls in similar areas (Grids 1, 2, 3) in the Amazon region indicated the following:

(i) The RSFs were maximum during March, April and/or May and minimum near September-October. Rainfalls were maximum earlier, during January, February, and March.

(ii) There were considerable year-to-year fluctuations but these were not similar at all the locations.

(iii) An examination of the two largest El Niño events (1982-83 and 1997-98) showed some effects during intervals when the El Niños were active, but some effects were seen even outside these active intervals.

(iv) Other climatic indices, notably the South Atlantic SST seemed to be effective in their own way, independent of the ENSO.

(v) A spectral analysis of stratospheric wind (30 hPa) showed a very prominent periodicity at 2.46 years and minor periodicities at 2.07 and 2.94 years (all QBOs). ENSO indices showed prominent periodicities at 7-9, ~6, ~4, ~3.5 years and minor periodicities in the QBO region (2-3 years). The larger periodicities were reflected in some RSFs.

(vi) For some locations, the QBO in RSF was very prominent and resembled the QBO of stratospheric winds.

Thus, for the four regions examined here, the hydrological variations were different. This is not necessarily in contradiction with Marengo (1992) who examined broad divisions namely, Northern Amazônia (NA) and Southern Amazônia (SA) and found that whereas NA showed strong El Niño signals, SA was more independent of El Niños. Here we find that SA is by no means a homogeneously unresponsive region by itself. Some parts of it can be responsive to El Niños and/or other climatic indices, while others are not responsive. We suspect that this may be true for NA also. In fact, not broad regions but some strips in these regions may have good ENSO and/or other responses, while neighboring strips may be unresponsive, probably due to highly localized circulation patterns interacting differently with



ENSO etc. This is, of course, speculation and needs to be checked by examining rainfalls in small grids all over the Amazon. We propose to do that in near future. In a broad way, as envisaged in Marengo (1992), the circulation mechanisms of anomalously wet and dry years in the Amazon basin are probably associated with distinct circulation patterns in the tropical Atlantic (strong North Atlantic high, steep meridional pressure gradient on its equatorial side, accelerated North-east trades and cool surface waters in the tropical North Atlantic) and this ensemble of atmospheric and oceanic anomalies is characteristic of (but not limited to) the positive phase of Southern Oscillation. In finer details, some local circulation patterns may create complications and deviations from the general pattern. For the same reason, RSF and rainfall in the same region may not show similar characteristics.

ENSO effects in different parts of the globe have been reported since long (Ropelewski and Halpert, 1987, 1989) but these are never one-to-one. Also, these are often distorted by other effects. For example, in southern part of South America (including southern Brazil), El Niños are very well related to excess rains, but in NE Brazil, low latitude Atlantic temperature increases combined with favorable winds towards the Brazilian coast can bring in moisture which may neutralize the drought-like conditions caused by El Niños. In other parts of the world too, other factors complicate the ENSO relationship. In the Amazon basin, one would have expected that the vicinity to the Peru-Ecuador coast (birth place of El Niño) would result in strong ENSO effects. This does not seem to happen, probably because of other interfering effects like those related to tropical Atlantic, or local circulation patterns related to orographic effects etc.

Because of the prominence of the El Niño phenomenon, the QBO in hydrological parameters is popularly attributed to ENSO, in spite of the fact that QBO is not a major part of ENSO, which has major contributions in the 3-5 year region. However, if some hydrological parameter has only QBO as a prominent periodicity, with no substantial periodicities in the 3-5 year region, an association with ENSO only should be considered as suspect. No attention seems to be paid to stratospheric QBO, because a physical mechanism is claimed as not obvious. However, a relationship between stratospheric QBO and tropospheric QBO has been already investigated. True, there are contradictory opinions. For the troposphere, Yasunari (1985), Gutzler and Harrison (1987), Kawamura (1988) reported a tropospheric QBO. In addition to the ENSO mode (40-60 month period), the zonal wind in the troposphere has a component of transient east-west circulation with the QBO time scale, which shows a totally eastward

propagation (Yasunari, 1989). Thus, there is some evidence that the stratospheric and tropospheric QBO are coupled and these are, in turn, coupled to the QBO of the equatorial eastern Pacific SST, suggesting a dynamical link between stratospheric QBO and the large scale coupled atmosphere/ocean system. Trenberth (1980) mentions that the QBO shown by tropospheric ultra-long waves of the Southern Hemisphere does not match with stratospheric QBO. Meehl (1987) identified a biennial signal in the coupled ocean-atmosphere system in the tropical Indian and Pacific regions, which does not seem to be related to stratospheric QBO (Rasmusson *et al.*, 1990). In any case, the ENSO mode (40-60 months) present in SST seems to be an independent parameter. Gray *et al.* (1992) have hypothesized a mechanism by which stratospheric QBO influences ENSO variability while Geller and Zhang (1991) and Geller *et al.* (1997) illustrate a mechanism by which SST variations can modulate tropical wave activity and finally, the SST QBO would tend to force a stratospheric zonal flow oscillation with the same period as the oceanic QBO. Ropelewski *et al.* (1992) feel that tropospheric QBO is mainly related to ENSO. However, recently Hamilton and Fan (2000) noted a relationship between stratospheric winds at Singapore and the growth rate of surface methane while Giorgetta and Bengtsson (1999) reported a potential role of QBO in the STE (stratosphere-troposphere exchange) as found in water vapor in GCM experiments. A possible mechanism suggested is a QBO modulation of stratosphere-troposphere exchange *via* the QBO modulation of the upwelling through the tropical tropopause. Coughlin and Tung (2001) found a QBO (Wind) signal in the Northern Hemisphere surface air temperatures and concluded that the equatorial QBO (Wind) signal is transmitted to the extratropical latitudes not only in the upper atmosphere but also to the surface (Kane and Buriti, 1997). Thus, a relationship between stratospheric QBO and hydrological parameters should receive serious attention, and efforts should not be confined to relate the QBO in hydrological parameters to ENSO only.

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