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RAINFALL EXTREMES IN SOME SELECTED PARTS OF CENTRAL AND SOUTH AMERICA: ENSO AND OTHER RELATIONSHIPS REEXAMINED

R.P. KANE*
Instituto Nacional de Pesquisas Espaciais (INPE), C.P. 515, 12201-970 São José dos Campos SP, Brazil

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ABSTRACT

El Niños and anti-El Niños (La Niñas) are known to be associated with rainfall extremes in several parts of the globe. However, not all El Niños show good associations. Recently, a finer classification of El Niño events was attempted. It was noticed that Unambiguous ENSOW (El Niño–Southern Oscillation, Warm) events (years when El Niño existed, and the Tahiti minus Darwin pressure difference (T – D) minima and equatorial eastern Pacific sea surface temperature (SST) maxima occurred *in the middle of the calendar year*) were very well associated with droughts in India and southeast Australia (Tasmania). In addition, C (cold SST, La Niña) events showed reverse effects (excess rains) in these regions. In the present paper, rainfall in selected regions in Central and South America are examined. For the Southern Oscillation Core Region (low latitudes, 155°W–167°E) and for the Gulf–Mexico region, no finer classification was necessary. All El Niños were associated with excess rains and all La Niñas with droughts. As in India and Tasmania, Unambiguous ENSOW years were associated with droughts in some parts of northeast Brazil (Ceara, Rio grande do Norte, Paraiba, Pernambuco) and excess rains in Chile and Peru. C events did not have good associations except in Chile and Peru, where droughts occurred. The effect of El Niños showed some dependence on the month of commencement. In years when El Niños showed no effect, considerable influence of other factors (e.g. Atlantic SST on northeast Brazil rainfall) was noticed. Thus, predictions based on El Niño alone are likely to be erroneous, a fact which should be noted by the mass media. Effects of the recent El Niño of 1997–1998 are discussed.

KEY WORDS: sea surface temperature; rainfall; drought; northeast Brazil; South America; El Niño; Southern Oscillation; ENSO; La Niña

1. INTRODUCTION

During certain years, excessively warm sea water appears off the Ecuador–Peru coast. Owing to its coincidence with the Christmas season, the phenomenon is known as El Niño (EN/the Child). It is also associated with the phenomenon of the Southern Oscillation (SO), where the atmospheric pressures in the southeast Pacific Ocean and the Indonesian region show a see-saw motion. For example, the pressure difference (T – D) between Tahiti (T; 18°S, 150°W) and Darwin (D; 12°S, 131°E) becomes small and goes through a minimum. The El Niño phenomenon is also associated with increases in the sea surface temperature (SST) in the equatorial eastern Pacific. However, El Niños and the SO Index (SOI) minima do not always occur simultaneously, there are phase lags (Deser and Wallace, 1987).

It is believed that El Niño–Southern Oscillation (ENSO) phenomena tend to coincide with droughts in northeast Brazil and floods in South Brazil (Caviedes, 1973; Hastenrath *et al.*, 1987; Rao and Hada, 1990). However, as was shown in earlier communications (Kane, 1989, 1992), this relationship is rather loose. Low correlations between SOI and northeast Brazil rainfall have also been reported by Ropelewski

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* Correspondence to: Instituto Nacional de Pesquisas Espaciais (INPE), C.P. 515, 12201-970 São José dos Campos SP, Brazil; e-mail: kane@laser.inpe.br

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and Halpert (1987), Aceituno (1988), Rogers (1988) and Rao *et al.* (1993). El Niño effects (even those of strong ones) are not always alike; Trenberth (1993) mentions different 'flavors' of El Niños. In recent papers (Kane, 1997b,c), a finer classification of El Niño events was attempted (details given below) and it was shown that for All-India summer monsoon rainfall, for some regions in Australia and for some regions elsewhere on the globe, rainfall deficits (droughts) showed a clear association with Unambiguous ENSOW (ENSOW-U) events (years when El Niño existed, and the $T-D$ minimum and equatorial eastern Pacific SST maximum occurred *in the middle of the calendar year*), while floods were clearly associated with cold (C) SST (La Niña) events (see section 3.2). In this paper, the rainfalls for Fortaleza and other locations in northeast, east and southeast Brazil, as well as for a part of Argentina and Chile near southern Brazil and some central American locations, are examined to determine whether any significant relationships can be obtained with this finer classification of El Niño events. In addition, for years when this classification has not proven to be satisfactory, attempts are made to check whether the discrepancies can be explained as being due to the effect of other parameters, notably the SST of the tropical Atlantic, first examined by Markham and McLain (1977) and recently by many other workers (e.g. Ward and Folland, 1991).

The purpose of the present communication is not to undertake a detailed study of the ENSO phenomenon, or to prove/disprove its being a single, coherent, global system. On the contrary the purpose is very limited, namely, to critically examine the ENSO associations with rainfall extremes in some regions in central and south America, mainly to check propaganda by local mass media (press, radio and television) regarding the so-called El Niño effects, and to emphasize that in some regions, other effects almost unrelated to the ENSO phenomenon can be equally, or more, important (e.g. the effects of Atlantic temperatures on rainfall in northeast Brazil), a fact known to some workers in this field but ignored by the mass media.

2. DATA

For purposes of classification, El Niño years were obtained from Quinn *et al.* (1978, 1987), SO index from Wright (1977, 1984) and Parker (1983) and equatorial eastern Pacific SST data from Angell (1981), as well as further private communication and Wright (1984). Data for SST at Puerto Chicama (Peruvian coast, 8°S, 80°W) from 1925 onwards were obtained privately from Dr Todd Mitchell and those for Pacific SST (El Niño regions 1 + 2, 3 and 4, from 1950 onwards) were obtained from the Climate Prediction Center (CPC) of the NOAA; Trenberth (1997) was also consulted. Rainfall data were obtained for northeast Brazil from SUDENE (Superintendencia do Desenvolvimento do Nordeste, Brazil; 'Dados Pluviometricos Mensais', Volumes I, II and III) for 224 stations. Data for locations near each other and having roughly similar average annual rainfalls were grouped together (A, B etc.), as shown by the dashed boundaries in Figure 1a, and separately for the states of Piaui, Ceara, Rio Grande do Norte, Paraiba, Pernambuco, Alagoas, Sergipe, Bahia and Minas Gerais. These were further grouped into eight regions (1, 2, ..., 8), as shown in Table I, having *annual* rainfall data for 1913–1978. The location Fortaleza in Ceara had a much longer data series (1849 onwards) and was considered separately (FT annual rainfall in Table I). In addition, for a restricted region (3–8°S, 36–41°W) in the northeast, Hastenrath (1990) gave a series (March–September rainfall; HT in Table I) combining data from 27 stations. For east-northeast (ENE) Brazil (6–11°S, 35–40°W), Rao *et al.* (1993) obtained a series (April–July rainfall; R in Table I) combining data from 63 stations. Outside the northeast region, annual rainfall data were supplied by CENACLI (Centro Nacional de Analises Climaticas, Brazil) for three individual locations: Rio de Janeiro, Sao Paulo (east Brazil) and Porto Alegre (southeast Brazil). For an average of eight stations in Central-East Argentina (30°S, 65°W; Figure 1b), annual data were obtained from Compagnucci and Vargas (1983). In Chile, rainfall data for Santiago (33.5°S, 70.7°W), located in a central plain between a coastal range and the Andes (altitude *ca.* 500 m), and for Valparaiso (33.0°S, 71.6°W), a coastal city, were obtained from Quinn and Neal (1983) and Rutllant and Fuenzalida (1991). For Peru, rainfall data were not immediately available; therefore, as a measure of the rainfall integrated over a drainage basin in Peru roughly 7500 km^2 in extent, the median discharge of the Piura River at Piura (5°S, 81°W) as given in Deser and Wallace (1987) was used. In low-latitude northern America, rainfall data for the Gulf and Mexican regions (Gulf–Mexico) from Ropelewski and Halpert (1986) and Karl *et al.* (1994) were used. The average rainfall data of seven stations in the Southern Oscillation Core Region (4°N–1°S, 155°W–167°E) given by Wright (1984) in the form of a rainfall index, were also used.

The rainfall data chosen are those which were easily available and may not necessarily be representative of large regions. Some are for single stations and local vagaries cannot be ruled out, while others are annual values only. Nonetheless, it is hoped that these locations display some characteristics of the regions in question.

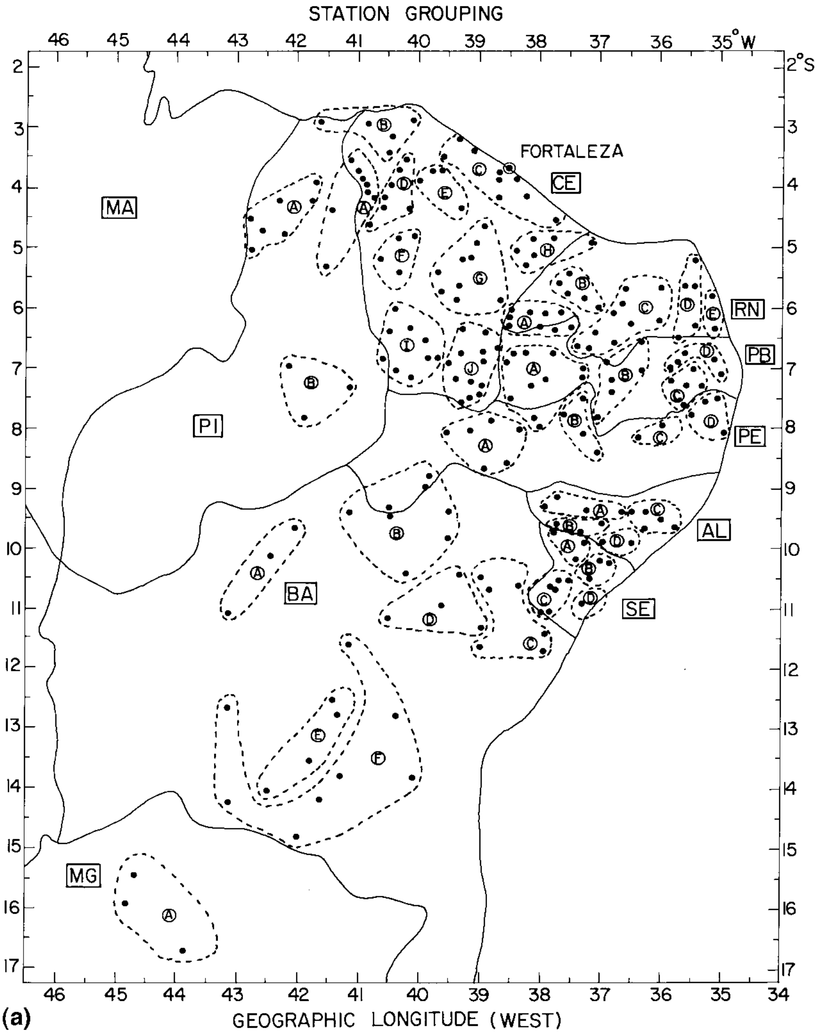

Figure 1. (a) Groupings of 224 stations in northeast Brazil: Piaui (PI), A–B; Ceara (CE), A–J; Rio Grande do Norte (RN), A–E; Paraiba (PB), A–D; Pernambuco (PE), A–D; Alagoas (AL), A–D; Sergipe (SE), A–D; Bahia (BA), A–F; Minas Gerais (MG), A. (b): Map of the South American continent

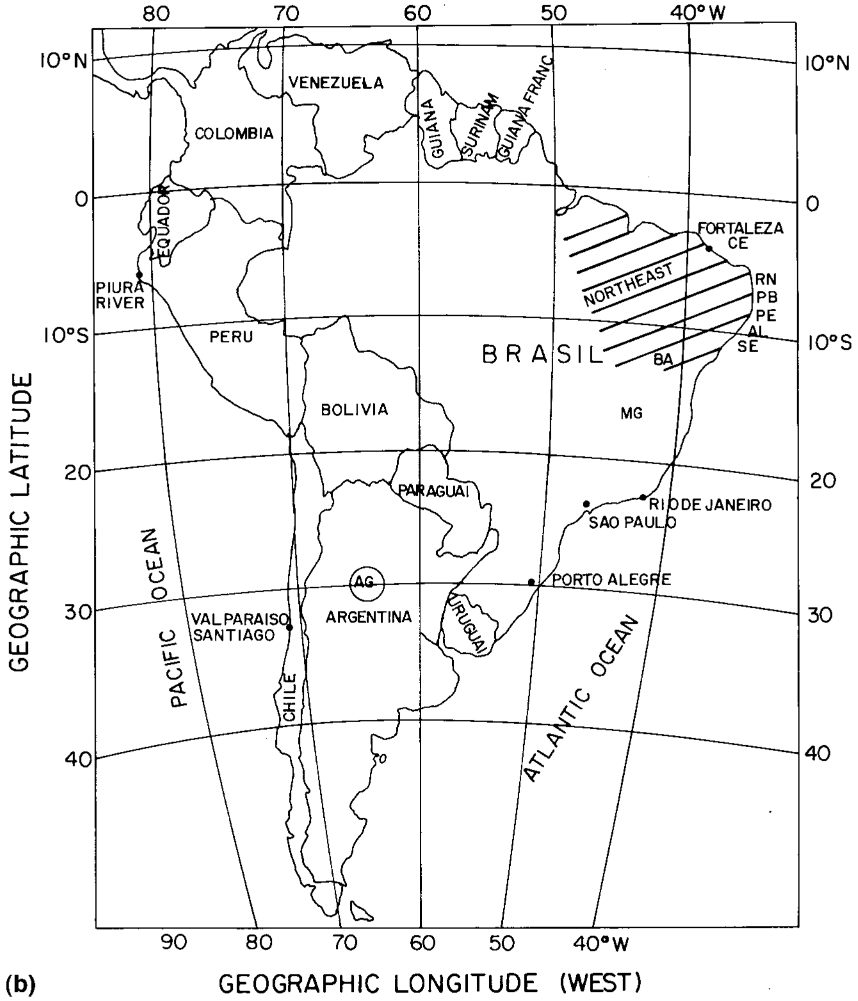

Figure 1 (*Continued*)

3. RELATIONSHIP WITH EL NIÑOS (PERU–ECUADOR COAST)

3.1. All El Niños

Kane (1997a) showed that for rainfall at Fortaleza, Ceara, in northeast Brazil, out of 46 strong and moderate El Niño events during 1849–1992, only 21 were associated with droughts, and only 26 with negative deviations of any magnitude (Quinn *et al.*, 1978, 1987 and private communication). Thus, all El Niños are not necessarily associated with droughts. In addition, in other parts of the world, e.g. India and Australia, not all El Niños show a clear association with droughts (Rasmusson and Carpenter, 1983). However, the finer classification outlined below showed better relationships (Kane 1997b,c).

3.2. El Niños of the ENSOW types etc

The term ENSO is used nowadays to describe the general phenomenon of the El Niño–Southern Oscillation (see also p. 434 below). However, in the present paper, its components EN and SO are used in their *literal* sense. Thus, every year was examined to check whether it had El Niño (EN; as listed in Quinn *et al.* 1978, 1987), and/or SOI minimum (SO), and/or warm (W) or cold (C) equatorial eastern Pacific SST anomalies. For SO and SST, 12-month running means were used. For several years, ENSOW was present, the SOI showed minima and the Pacific SST was warmer. These were subdivided into two groups—*ENSOW-U* where El Niño was present and the *SOI minima and SST maxima were in the middle of the calendar year* (May–August), and *Ambiguous ENSOW* (ENSOW-A) where El Niño was present, but the *SOI minima and SST maxima were in the early or later part of the calendar year*. In addition to these, there were other years in which the following conditions prevailed: (i) ENSO (El Niño and SOI minima were present, but SST was neither warmer nor colder than normal); (ii) ENW, ENC (El Niño was present, SOI minima was not present, but SST was warm, W, or cold, C (before or after El Niño)); or (iii) EN (only El Niño was present, without SOI minima or SST maxima or minima). Some other years did not have an El Niño and were of the following types: (i) SOW (SOI minima existed and Pacific waters were warm); (ii) SOC, SO, W and C, where the last category C contains all anti-El Niños, i.e. La Niñas. The types ENC and SOC seem contradictory. In fact, during these years, EN and/or SO and C did not occur simultaneously. Either EN or SO occurred during part of the year, being *followed or preceded* by a cold Pacific SST, i.e. a C event. Years not falling into any of these categories were termed non-events. This classification has been prepared for all years from 1871 onwards.

With this classification, ENSOW-U events showed excellent association with droughts in All-India summer monsoon (June–September) rainfall, as well as for some regional rainfalls in Australia (Kane 1997b,c). Table IIa shows the rainfall characteristics for ENSOW-U, for the eight groups (1, 2, . . . , 8)—the Hastenrath (1990) group (HT) and Rao *et al.* (1993) group (R), located in northeast Brazil, and for individual locations: Fortaleza, Ceara in northeast Brazil, Rio de Janeiro, Sao Paulo and Porto Alegre in east and southeast Brazil, as well as Central Argentina, Santiago, Valparaiso, Piura River, the Core Region and the Gulf–Mexico Region. For comparison, All-India summer monsoon rainfall (Parthasarathy *et al.*, 1992) and Australian (Tasmanian) rainfalls (Srikanthan and Stewart, 1991) are also shown. Events marked as R were selected by Rasmusson and Carpenter (1983) and later by Ropelewski and Halpert (1987). All data were converted to normalised units. The symbols + and − indicate positive

Table I. Details of the rainfall locations

Symbol	Location	No. of stations	Geographic position		S.D. (%)	Period of data
			Latitude (S)	Longitude (W)		
1	PI (A)	7	4.5°	42.3°	27	1913–1978
2	PI (B)	3	7.4°	46.7°	26	1913–1978
3	CE (A, B, C, D, E, F, G, H); RN (A, B, C); PB (A, B); PE (B)	97	*ca.* 6.0°	*ca.* 39.0°	35	1913–1978
FT	Fortaleza	1	3.7°	38.6°	37	1849–1997
4	CE (I, J); PE (A)	28	*ca.* 7.5°	*ca.* 40.0°	26	1913–1978
5	RN (D, E); PB (C, D); PE (C, D)	24	*ca.* 7.0°	*ca.* 35.5°	22	1913–1978
HT	Hastenrath (1990)	27	*ca.* 5.0°	*ca.* 39.0°	Normal	1921–1987
6	AL (A, B, C, D); SE (A, B, C, D)	29	*ca.* 10°	*ca.* 37.5°	24	1913–1978
7	BA (A, B, C, D)	21	*ca.* 10.5°	*ca.* 40.0°	28	1913–1978
8	BA (E, F); MG (A)	15	*ca.* 14.0°	*ca.* 43.0°	24	1913–1978
R	Rao *et al.* (1993)	63	*ca.* 9.0°	*ca.* 36.0°	Normal	1914–1982
RI	Rio de Janeiro	1	22.7°	43.2°	22	1851–1976
SP	Sao Paulo	1	23.5°	46.0°	18	1903–1976
PA	Porto Alegre	1	30.0°	51.2°	21	1916–1985
AG	Central Argentina	8	*ca.* 30.0°	*ca.* 65.0°	32	1910–1977
ST	Santiago, Chile	1	33.5°	70.7°	Normal	1930–1988
VP	Valparaiso, Chile	1	33.0°	71.6°	Normal	1930–1980
PR	Piura, Peru	1	5°	81°	Normal	1930–1983
CR	Core Region	7	4°N–1°S	155°W–167°E	Normal	1930–1983
GM	Gulf–Mexico	*ca.* 10	*ca.* 30°N	*ca.* 90°W	Normal	1930–1988

For abbreviations see Figure 1.
Normal = normalised deviations.

Table II. Rainfall status during El Niño years of the types (a) ENSOW-U; (b) ENSOW-A; and (c) other types of El Niños

	India	Australia	Northeast Brazil																			
	AI	TA	1	2	3	FT	4	5	HT	6	7	8	R	RI	SP	PA	AG	ST	VP	PR	CR	GM
(a) ENSOW-U																						
S 1918 I R	○	–	△	–	–	△	–	–		△	+	△	–	–	○	○	△					
M 1930 I R	○	△	○	○	○	○	○	○	○	–	○	–	–	○	△	△	+					
S 1941 II 4	○	○	○	○	○	○	–	–	–	–	–	+	+	△	○	△	○	△	△	△	△	△
M 1951 R	○	–	○	○	○	○	○	○	○	+	○	○	△	–	○	○	–	+	+		+	–
S 1957 I R	○	–	△	△	–	–	+	○	△	+	+	△	+	+	△	+	+	–	+	△	△	△
M 1965 R	○	–	△	–	△	+	+	+	△	○	○	–	–	△	△	△	○	△	△	△	△	△
S 1972 I R	○	○	–	○	–	–	○	–	–	–	–	–	–	–	–	△	+	△	△	△	△	△
M 1976 R	+	+	○	+	–	–	–	–	○	○	○	○	○	△	△	△	△	–	–	+	△	△
S 1982 I R	○	○				○			○				○	+	△	△		△		+	△	+
M 1987	○	○				–			+				+		+			△				+
8–10 events																						
Positive deviation	1	2	3	2	1	2	2	1	3	3	2	3	4	5	6	7	5	6	5	6	7	7
Negative deviation	9	8	5	6	7	8	6	7	6	5	6	5	6	4	4	2	3	2	1	0	0	1
Positive/total	0.1	0.2	0.4	0.3	0.1	0.2	0.3	0.1	0.3	0.4	0.3	0.4	0.4	0.6	0.6	0.8	0.6	0.8	0.8	1.0	1.0	0.9
(b) ENSOW-A																						
M 1914 R	△	○	–	○	△	△	+	△		△	△	△	△	○	○		△					
M 1919 II	+	○	○	○	○	○	○	○		–	–	△	–	○	○	△	△					
M 1923 R	–	△	△	+	–	+	–	○	○	○	–	○	○	–	–	–						
S 1925 I R	○	○	△	+	+	–	+	–	+	○	○	○	○	○	+	○	+					
S 1926 II	△	–	–	△	△	+	△	+	△	–	△	△	–	○	–	+	△					
M 1931 II	+	+	–	○	○	○	○	△	○	○	○	○	–	+	△	–	–	–	–	–	△	+
S 1940 I	–	○	+	△	△	+	△	△	△	△	△	△	△	–	○	△	△	–	+	–	△	△
W 1948	+	–	+	○	–	–	–	+	+	△	+	△	△	–	○	○	–	+	–	–	+	+
M 1953 R	△	+	○	○	○	○	○	○	○	–	○	○	+	+	○	–	–	△	+	△	△	○
S 1958 II	+	△	○	○	○	○	○	○	○	○	○	+	○	△	–	+	△	+	+	+	△	+
W 1963	+	–	+	○	△	△	+	–	–	–	–	○	○	○	○	+	+	△	+	–	+	+
W 1969 R	–	+	○	–	–	△	+	△	+	△	△	△	△	+	○	○	+	○	–	–	+	△
S 1983 II	△	–				○			○				○	△	△	△		+		△	△	△
11–13 events																						
Positive deviation	9	5	5	4	5	6	6	6	5	4	5	7	5	5	3	6	8	5	4	3	8	7
Negative deviation	4	8	7	8	7	7	6	6	6	8	7	5	8	8	10	6	4	3	3	5	0	1
Positive/total	0.7	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.3	0.4	0.6	0.4	0.4	0.2	0.5	0.7	0.6	0.6	0.4	1.0	0.9
(c) Other El Niños																						
S 1932 EN R	○	–	○	○	○	○	○	–	○	○	○	○	○	○	△	+	–	–	+	△	+	+
M1939 EN R	○	△	○	○	–	△	○	–	–	–	○	○	○	○	○	+	△	–	–	△	+	○
M 1943 EN	+	–	○	–	○	○	○	○	○	○	–	–	○	△	○	○	△	–	–	△	–	△
3 events																						
Positive deviation	1	1	0	0	0	1	0	0	0	0	0	0	0	1	1	2	2	0	1	3	2	2
Negative deviation	2	2	3	3	3	2	3	3	3	3	3	3	3	2	2	1	1	3	2	0	1	1
Positive/total	0.3	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.6	0.6	0.0	0.3	1.0	0.7	0.7
S 1917 ENC	△	△	△	△	△	△	△	+		△	+	△	+	○	○	○	△					
S 1973 II ENC	△	+	△	△	△	△	△	△	△	○	+	○	–	–	+	+	△	○	–	+	+	○
2 events																						
Positive deviation	2	2	2	2	2	2	2	2	1	1	2	1	1	0	1	1	2	0	0	1	1	0
Negative deviation	0	0	0	0	0	0	0	0	0	1	0	1	1	2	1	1	0	1	1	0	0	1
Positive/total	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	1.0	0.5	0.5	0.0	0.5	0.5	1.0	0.0	0.0	1.0	1.0	0.0

Table II. (continued)

	India	Australia	Northeast Brazil																			
	AI	TA	1	2	3	FT	4	5	HT	6	7	8	R	RI	SP	PA	AG	ST	VP	PR	CR	GM
Other EN; 5 events																						
Positive deviation	3	3	2	2	2	3	2	2	1	1	2	1	1	1	2	3	4	0	1	4	3	2
Negative deviation	2	2	3	3	3	2	3	3	3	4	3	4	4	4	3	2	1	4	3	0	1	2
Positive/total	0.6	0.6	0.4	0.4	0.4	0.6	0.4	0.4	0.3	0.2	0.4	0.2	0.2	0.2	0.4	0.6	0.8	0.0	0.3	1.0	0.8	0.5
All EN; 28 events																						
Positive deviation	13	10	10	8	8	11	10	9	9	8	9	11	10	11	11	16	17	11	10	13	18	16
Negative deviation	15	18	15	17	17	17	15	16	15	17	16	14	18	16	16	10	8	9	7	5	1	4
Positive/total	0.5	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.6	0.7	0.6	0.6	0.7	0.9	0.8

The strengths of the El Niños involved are indicated by: S, strong; M, moderate; and W, weak. First and second years of double events (El Niños in two consecutive years) are indicated by I and II. The symbol R indicates that these events were also in the Rasmusson and Carpenter (1983) list. The columns show the rainfalls of: AI, All-India summer monsoon; TA, Tasmania (Australia); Regions 1, 2, 3, 4, 5, 6, 7, 8 and FT, Fortaleza; HT, the Hastenrath group; R, the Rao *et al.* group; all areas in northeast Brazil; RI, Rio de Janeiro; SP, Sao Paulo; PA, Porto Alegre; areas in east and southeast Brazil; AG, Central Argentina; ST, Santiago; VP, Valparaiso; PR, Piura River discharge; CR, Core Region; and GM, Gulf–Mexico Region. The symbols + and − indicate positive and negative deviations within 0 to $\pm 0.5\sigma$, respectively, while △ (positive) and ○ (negative) represent deviations $>0.5\sigma$.

and negative deviations within 0–0.5σ, while △ (positive) and ○ (negative) represent deviations $> 0.5\sigma$. As can be seen, *the Indian and Tasmanian rainfalls have a preponderance of negative deviations*. The only exception is 1976, probably because this El Niño began late (in April, as discussed below). Thus, ENSOW-U events show a close relationship with droughts. At the bottom of Table IIa, the numbers of positive and negative deviations are given. For All-India, among the ten events only one (1976) had a positive deviation and nine had negative deviations. The fraction of positive deviations was $(1/10) = 0.1$; this fraction was also low for Tasmania (0.2). Among the other locations and groups, Fortaleza and Ceara (region 3), as well as Rio Grande do Norte, Paraiba and Pernambuco (region 5) of northeast Brazil had low fractions (0.1 and 0.2, respectively), indicating a close relationship with droughts. Regions 2, 4 and 7 of northeast Brazil had a fraction of 0.3, indicating a mild association with droughts. Regions 1, 6 and 8 of northeast Brazil and Rio de Janeiro, Sao Paulo and Argentina had fractions of 0.4, 0.5 and 0.6 respectively, implying an almost equal number of positive and negative deviations, i.e. a poor relationship. Porto Alegre had a fraction of 0.8, implying an association with excess rainfall, unlike northeast Brazil. Incidentally, the deviations at Porto Alegre were not always similar to those of Argentina, indicating that the rainfalls in and near south Brazil are not always alike. For Santiago, Valparaiso, Piura River, the Core Region and the Gulf–Mexico Region, the positive fractions are ≥ 0.8, indicating that these places are prone to significantly higher rainfall.

Table IIb shows results for ENSOW-A. Here, Indian rainfall shows a fraction of 0.7, implying a mild affinity for excess rains rather than for droughts. It is interesting to note that most of the II year of El Niños fall within this group, which for India resulted in excess rainfall. Among the others, regions 2 and 6 in northeast Brazil had a fraction of 0.3, i.e. a mild association with droughts. Sao Paulo had a fraction of 0.2, indicating an association with droughts. The Core and Gulf–Mexico regions showed a tendency to flooding. All others had fractions of 0.4, 0.5 and 0.6, implying poor relationships, with the exception of Argentina, which had a fraction of 0.7, implying a mild tendency for excessive rainfall.

Table II(c) shows results for El Niños of the types EN (i.e. only El Niño was present, but there were no SOI minima or warm Pacific waters, W), and ENC (El Niño was present, but there were cold waters in the Pacific before or after the El Niño). Of the three EN events, at least two showed droughts in all regions except Porto Alegre and Argentina, where two showed excessive rainfall. At Santiago, all three showed a deficit in rainfall, while at Piura, all showed excessive rainfall. Thus, the pattern of droughts in northeast Brazil associated with excess rains in the south of Brazil cannot be clearly seen. In addition, the relationship with El Niños is not invariably seen. For the two ENC-type events, a large number of locations showed positive deviations, which for the northeast would imply an effect of C rather than EN.

At the bottom of Table II, the statistics for all 28 El Niños types or less, indicates that only regions 2, 3 and 6 of the northeast show a mild association with droughts (fraction of positives, 0.3), Argentina and Piura River for excessive rainfall (fraction of positives, 0.7) and the Core and Gulf–Mexico regions for significantly excessive rainfall. All other regions show poor relationships (fractions 0.4, 0.5 and 0.6).

The statistics for the various El Niño groups (a, b and c) as well as their total are given in Table V. Summarizing:

(i) The rainfall in the Core and Gulf–Mexico regions is excessive for all types of El Niño events.
(ii) Only the ENSOW-U seems to show a good relationship with droughts in India, Tasmania and Ceara, as well as nearby regions in northeast Brazil. It also shows a mild association with excess rainfall in the south of Brazil, and a clear association with excess rainfall in Chile and Peru (Piura River discharge). Thus, ENSOW-U certainly has a ‘flavor’ for more consistent ENSO relationships than do other El Niño events.
(iii) However, out of 24 El Niño years, Porto Alegre and Argentina had similar deviations for only 15 years and dissimilar deviations for 9 years. Thus, rainfall may not be similar in Argentina and nearby South Brazil.

In northeast Brazil, Fortaleza, Ceara, has the longest rainfall record. Thus far, only data from about 1913 onwards were considered. For Fortaleza alone, the results for earlier periods were as follows:

ENSOW-U	ENSOW-A	Other El Niños	
S 1877 I ○	S 1878 II ○	ENSO S 1871+	ENW S 1884 ○
M 1896 △		ENSO W 1873 △	EN M 1897 △
S 1899 △		ENSO M 1880+	ENC M 1874+
M 1902 ○		ENSO S 1891 ○	ENC M 1887−
M 1905−		ENSO S 1990 ○	ENC M 1889 ○
S 1911+		ENSO S 1912 △	ENC M 1907○

As can be seen, out of the six ENSOW-U, three show positive deviations and three show negative deviations; not a satisfactory score, considering that for the later period (1914–1990), out of ten such events, eight showed negative deviations (association with droughts) for Fortaleza. For these six events (1877, 1896, 1899, 1902, 1905 and 1911), Indian summer monsoon rainfall showed (○, −, ○, ○, ○, ○) and Tasmania showed (○, −, ○, −, − ○), i.e. an overwhelming association with severe droughts (○) or deficit rains (−). For the other 13 events above, Fortaleza had six positive and seven negative deviations, again an unsatisfactory score. Thus, the association of El Niños with droughts seems to be *better in recent decades only for Fortaleza and nearby regions*. However, it may be noted that occasionally, Fortaleza deviations were dissimilar to those of the Ceara average (3), indicating that in some years, Fortaleza may have a different rainfall than the rest of Ceara. Thus, using data from one station only could sometimes be misleading.

3.3. Relationship with El Niño timings

In the finer classification above, ENSOW-U and Ambiguous ENSOW-A are distinguished by the timing of the occurrence of the SOI minima and equatorial eastern SST maxima, i.e. in the middle of the calendar year (May–August) for ENSOW-U and in the earlier or later part (not in the middle) of the calendar year for ENSOW-A. For the El Niño itself, only its existence at Puerto Chicama (8°S, 80°W) on the Peruvian coast was required and it was tacitly assumed that El Niño started and strengthened in the early part of the calendar year. However, as pointed out by Deser and Wallace (1987), some El Niños may begin later in the year and their durations could be from a few months to a full year. Thus, for some regions like northeast Brazil where main rainfall occurs in March, April and May, a late El Niño may not be significant. In order to check whether some of the weaker relationships could have occurred because of such a lag, SST monthly anomalies for Puerto Chicama for 1925–1949 and SST for El Niño region 3.4 for 1950–1997 (running means over five consecutive months for both) were examined and the months of El Niño commencements (positive temperature anomaly exceeding + 0.4°C) were located. If the El Niño had started in November or December and was already developed in the succeeding January, then that January was considered as the El Niño commencement for that year. Table III shows the rainfall characteristics for the El Niño events which started (or were strengthened, anomaly exceeding + 0.4°C) in January, February etc. and their durations in months (given in parentheses).

The first 11 events in Table III started in January (or a month or two earlier) and hence, should be appropriate for effects in northeast Brazil, where rainfall occurs mainly in March, April and May. All six second-year events (II) are included in this group for the obvious reason that these are continuations of 1-year events (I) and therefore must be present even in the January of the year following the years of (I). The following may be noted:

(i) Among the I-year (or 1-year) events, the 1925 event, an ENSOW-A, was long-lasting (14 months, overflowing in 1926). It was associated with droughts in India and Tasmania, but only in some areas (regions 6–8) of northeast Brazil—droughts in Porto Alegre, but excess rains in Argentina. The 1930 event was also long-lasting (15 months, overflowing in 1931) and was associated with droughts in India (but not in Tasmania, where there were severe floods) and northeast Brazil, and with excess rains in Porto

Table III. Rainfalls for El Niño years when El Niño was strong in January, February etc.

		India	Australia	Northeast Brazil																			
		AI	TA	1	2	3	FT	4	5	HT	6	7	8	R	RI	SP	PA	AG	ST	VP	PR	CR	GM
January (14) 1925 I	A	○	○	△	+	+	−	+	−	+	○	○	○	○	○	+	○	+					
January (2) 1926 II	A	△	−	−	△	△	+	△	+	△	−	△	△	−	○	−	+	△					
January (15) 1930 I	U	○	△	○	○	○	○	○	○	○	−	○	−	−	○	△	△	+					
January (2) 1931 II	A	+	+	−	○	○	○	○	△	○	○	○	○	−	+	△	−	−	−	−	−	△	+
January (2) 1939		○	△	○	○	−	△	○	−	−	−	○	○	○	○	○	+	△	−	−	△	+	○
January (5) 1941 II	U	○	○	○	○	○	○	−	−	−	−	−	+	+	△	○	△	○	△	△	△	△	△
January (3) 1943		+	−	○	−	○	○	○	○	○	○	−	−	○	△	○	○	△	−	−	△	−	△
January (3) 1958 II	A	+	△	○	○	○	○	○	○	○	○	○	+	○	△	△	+	△	+	+	+	△	+
January (2) 1973 II	C	△	+	△	△	△	△	△	△	△	○	+	○	−	−	+	+	△	○	−	+	+	○
January (10) 1983 II	A	△	−				○			○				○	△	△	△		+		△	△	△
January (6) 1987	U	○	○				−			+				+					△				+
February (5) 1932		○	−	○	○	○	○	○	−	○	○	○	○	○	○	△	+	−	−	+	△	+	+
February (17) 1940	A	−	○	+	△	△	+	△	△	△	△	△	△	△	−	○	△	△	−	+	−	△	△
February (6) 1948	A	+	−	+	○	−	−	−	+	+	△	+	△	△	−	○	○	−	+	−	−	+	+
February (9) 1953	A	△	+	○	○	○	○	○	○	○	−	○	○	+	+	○	−	−	△	+	△	△	○
February (11) 1969	A	−	+	○	−	−	△	+	△	+	△	△	△	△	+	○	○	+	○	−	−	+	△
February (13)1972 I	U	○	○	−	○	−	−	○	−	−	−	−	−	−	−	−	△	+	△	△	△	△	△
March (17) 1957 I	U	○	−	△	△	−	−	+	○	△	+	+	△	+	+	△	+	+	−	+	△	△	△
March (11) 1965	U	○	−	△	−	△	+	+	+	△	○	○	−	−	△	△	△	○	△	△	△	△	△
April (10) 1951	U	○	−	○	○	○	○	○	○	○	+	○	○	△	−	○	○	−	+	+		+	−
April (11) 1976	U	+	+	○	+	−	−	−	−	○	○	○	○	○	△	△	△	△	−	−	+	△	△
July (5) 1963	A	+	−	+	○	△	△	+	−	−	−	−	○	○	○	○	+	+	△	+	−	+	+
July (17) 1982 I	U	○	○				○			○				○	+	△	△		△		+	△	+

Duration in months is given in parentheses. U, Unambiguous ENSOW; A, Ambiguous ENSOW; C, ENC; Blank, EN only.

Alegre and Argentina. The 1939 event was a very short-lived event (2 months) and yet was associated with droughts in India, northeast Brazil (excluding Fortaleza proper), Chile and the Gulf–Mexico region (but not in Tasmania), and with excess rains in Porto Alegre, Argentina, Peru and the Core Region. The 1943 event was also short-lived (3 months) but caused droughts in northeast Brazil (but not in India) and Porto Alegre, and floods in Argentina, Peru and the Gulf–Mexico region. The 1987 event was relatively long-lasting (6 months), causing droughts in India and Tasmania, but not in northeast Brazil (Fortaleza, HT, R), and floods in Chile and the Gulf–Mexico region. Thus, while some relationship with the timing of El Niño is indicated, it is not a clear-cut relationship. Opposite rainfall patterns in northeast and South Brazil are sometimes seen, but on other occasions, these patterns are similar.

(ii) The other events were all II-year events, four of which were short-lived. The 1926 event (2 months) rather than leading to droughts, caused flooding in many areas, including Argentina. The 1931 event (2 months) did not cause droughts in India and Tasmania, but did lead to droughts in northeast Brazil and deficit rains in the south of Brazil, and even in Chile and Peru, as well as to excess rains in the Core and Gulf–Mexico regions. The 1958 event (3 months) did not result in droughts in India and Tasmania, but did give rise to drought in northeast Brazil and to excess rains in Porto Alegre, Argentina, Chile, Peru and the Core and Gulf–Mexico regions. The 1973 event (2 months, considered by some workers as an *aborted* El Niño), rather than producing droughts, lead instead to excess rains in nearly every region, including Porto Alegre and Argentina, Peru and the Core Region, and to deficit rains in Chile and the Gulf–Mexico region. The 1941 event was relatively long-lived (5 months) and gave droughts at all locations (India, Tasmania, northeast Brazil), perhaps because this was an ENSOW-U (the only one of type II); however, it also led to droughts in Argentina, although not in Porto Alegre, while Chile, Peru and the Core and Gulf–Mexico regions had very heavy rains. The 1983 event was also long-lived (10 months), causing droughts in Tasmania and northeast Brazil (but not in India), as well as excess rains in Chile and heavy rains in Peru and the Core and Gulf–Mexico regions. Thus, ENSOW-A II-year events do not cause drought in Tasmania and India (possibly even giving rise to excess rains); however, they may cause droughts in northeast Brazil—but not necessarily excess rains in South Brazil—while Chile, Peru and the Core and and Gulf–Mexico regions have heavy rains.

The next six events in Table III began in February; the 1932 and 1972 events were relatively long-lived (5 and 13 months, respectively) and gave rise to droughts in India, Tasmania and northeast Brazil, as well as to excess rains in Porto Alegre; however, there was no extreme rainfall in Argentina. In 1932, Santiago had deficit rains, while Valparaiso, Peru, and the Core and Gulf–Mexico regions had excess rains. In 1972, all of these regions had heavy rains. The 1953 event, although long-lived (9 months), gave excess rains in India, Chile, Peru, the Core and Gulf–Mexico regions and Tasmania, and droughts in northeast Brazil; however, there were no excess rains in South Brazil. The event of 1940 was long-lived (17 months), resulting in deficit rains in India and Tasmania and in excess rains in northeast and South Brazil, as well as the Core and Gulf–Mexico regions. The 1948 and 1969 events, relatively long-lived (6 and 11 months, respectively), showed small deviations in India, Tasmania, northeast Brazil, Chile, Peru and Argentina, droughts in Porto Alegre, and excess rains in the Core and Gulf–Mexico regions.

The next two events in Table III began in March, were long-lasting, and caused deficit rains in India and Tasmania, heavy rains in Chile, Peru and the Core and Gulf–Mexico regions, and mixed rainfalls in other places. The next two events, in 1951 and 1976, started in April; the 1951 event caused droughts almost everywhere, while 1976 caused excess rains in India and Tasmania, deficit rains in northeast Brazil and floods in South Brazil, Argentina and the Core and Gulf–Mexico regions. Finally, for the two events starting in July, 1963 gave mixed results, while 1982, although starting so late, caused droughts in northeast Brazil, India and Tasmania and flooding in Porto Alegre, Chile, Peru and the Core and Gulf–Mexico regions. *Thus, northeast Brazilian and Indian droughts preceded El Niño.*

Overall, there seems to be some connection between the starting months of El Niño and the rainfall events occurring in the next few months; however, there are some disconcerting exceptions (rainfalls being affected before El Niño events). In addition, whereas rainfalls are generally opposite in northeast and South Brazil, sometimes both regions have similar rainfalls.

The term El Niño has evolved in its meaning over the years. The original reference was to the annual weak, warm ocean current that runs southwards along the Peru–Ecuador coast (e.g. represented by Puerto Chicama SSTs). However, this coastal warming is often associated with a much more extensive anomalous ocean warming up to the International Date Line. The atmospheric component tied to El Niño is the Southern Oscillation and the joint phenomenon is termed ENSO. El Niño corresponds to the warm phase of ENSO, while the cold phase is termed La Niña. There is, however, considerable confusion in regard to the usage of these terms, with some using the term El Niño to represent the whole phenomenon, while others restrict it to the Peru–Ecuador coastal temperature increases. Aceituno (1992) gave a general review of the confusion in the terminology and Glantz (1996) gave dictionary-type definitions reflecting the multitude of uses of the term El Niño. At present, temperatures in four geographical regions are considered: El Niño $1+2$ near the Peru–Ecuador coast (0°–10°S, 90°–80°W), El Niño 3 in the region (5°N–5°S, 150°–90°W) and El Niño 4 in the region (5°N–5°S, 160°–150°W). The SSTs most-involved in ENSO are those of the Central Pacific, not those of Peru–Ecuador (Trenberth and Shea, 1987; Deser and Wallace, 1987; Ropelewski *et al.*, 1992). In recent years, Trenberth and Hoar (1996) showed that the negative correlations between SOI and SSTs exceeded -0.80 only throughout a broad region (5°N–10°S, 180°–120°W) and called this the El Niño 3.5 region. Meanwhile, the CPC (Climate Prediction Center, NOAA National Centers for Environmental Prediction) also introduced in their monthly Climate Diagnostic Bulletin, a new SST index called El Niño 3.4 for the region (5°N–5°S, 170°–120°W). Using $+0.4$°C as a threshold for the SSTs in the El Niño 3.4 region, Trenberth (1997) gave a list of El Niño and La Niña events since 1950. It would be interesting to compare these with the SST anomalies in the El Niño $1+2$ region. Different workers seem to use El Niño years in different ways. Some consider single years, while others consider these only as double events: 1957–1958, 1982–1983 etc. In addition, some use the first years while others use the second years (Rasmusson and Carpenter, 1983; Andrade and Sellers, 1988; Heerden *et al.*, 1988; Xavier *et al.*, 1995). Quinn *et al.* (1978, 1987) mention only some of these as double events (events marked as I and II in Table II). Depending upon the timing of the parameter considered (e.g. rainfalls occurring early or late in the calendar year), the first or second year may or may not be meaningful. Table IV compares the El Niño $1+2$ region SST anomaly beginnings and durations (CPC) with those of the El Niño 3.4 region as given by Trenberth (1997), using the same threshold of $+0.4$°C for both.

As can be seen, in almost all cases the El Niño $1+2$ signal comes earlier by 0–5 months, and mainly by 0–2 months. Exceptions were June 1963, September 1968, April 1982, August 1986 and June 1994, when El Niño 3.4 was reported to have started earlier (Trenberth, 1997). In addition, in some cases no El Niño was reported near the Peru–Ecuador coast, but El Niño 3.4 developed nonetheless. These are W events (or, if associated with SOI decreases SO, SOW events). Thus, El Niño 3.4 is a better and more comprehensive representation of the ENSO phenomenon. Nevertheless, in spite of their frequent waxing and waning, the El Niño $1+2$ SST anomalies (or traditional El Niños as judged from SST anomalies at Puerto Chicama) seem to be useful as early warnings. The above list of Trenberth (1997) shows only events from 1950 onwards. For our classification, the SOI used was that of Wright (1977), obtained from a principle component analysis of atmospheric pressures at eight low latitude stations around the globe, as well as on the $T-D$ pressure difference. For SST, the Wright (1984) index for the equatorial eastern Pacific (6°N–6°S, 180°–90°W), a similar index given by Angell (1981) and further private communication, were used. These seem to be very similar to the El Niño 3.4 anomaly indices. For 1925–1949, the El Niño occurrences at Puerto Chicama were as shown in Table III. For earlier periods, Quinn *et al.* (1978) mention that the month of onset was not available for most of the early cases (during 1864–1976), and a study of recent cases showed onset times to range from January to May.

4. EVENTS NOT INVOLVING EL NIÑO AT PUERTO CHICAMA

As mentioned by Deser and Wallace (1987), there were some years when the SOI showed minima (SO) and/or equatorial eastern Pacific waters were warmer (W) but there was no El Niño at Puerto Chicama

Table IV. Temperature anomalies exceeding +0.4°C (from 5-month running means) since 1950: starting month, ending month and duration, for the El Niño 3.4 region (5°N–5°S, 170°–120°W) and for the El Niño 1+2 region, near the Peru–Ecuador coast. The classification from this paper for the years involved (ENSOW etc.) is also given

El Niño 1+2	Duration (months)	El Niño 3.4	Duration (months)	Classifications from this paper	
April 1951–January 1952	10	August 1951–February 1952	7	1951, ENSOW-U	1952, non-event
February 1953–October 1953	9	March 1953–November 1953	9	1953, ENSOW-A	
March 1957–July 1958	17	April 1957–June 1958	15	1957 I, ENSOW-U	1958 II, ENSOW-A
July 1963–November 1963	5	June 1963–February 1964	9	1963, ENSOW-A	1964, C(La Niña)
March 1965–January 1966	11	May 1965–June 1966	14	1965, ENSOW-U	1966, non-event
February 1969–December 1969	11	September 1968–March 1970	19	1968, W	1969, ENSOW-A
February 1972–February 1973	13	April 1972–March 1973	12	1972 I, ENSOW-U	1973 II, ENC
April 1976–February 1977	11	August 1976–March 1977	8	1976, ENSOW-U	1977
No El Niño		July 1977–January 1978	7	1977, SOW	1978, non-event
July 1979–January 1980	7	October 1979–April 1980	7	1979, SOW	1980, non-event
July 1982–November 1983	17	April 1982–July 1983	16	1982 I, ENSOW-U	1983 II, ENSOW-A
October 1986–January 1988	16	August 1986–February 1988	19	1986, W	1987, ENSOW-U
December 1990–July 1992	20	March 1991–July 1992	17	1991, ENSOW-A	1992, ENSOW-A
March 1993–July 1993	5	February 1993–September 1993	8	1993, ENSOW-A	
October 1994–January 1995	4	June 1994–March 1995	10	1994, ENSOW-A	1995, ENSOW-A

(Peru–Ecuador coast). Workers have often also included such events for ENSO studies (Shukla and Paolino, 1983; Khandekar and Neralla, 1984; Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Mooley and Paolino, 1989; Ropelewski and Halpert, 1989). The results for such events are not shown individually here. The general statistics are shown in Table V, with those of other types of years. If all the SOW etc. events are considered together, there is a slight bias for positives (association with floods) in northeast Brazil.

5. NON-EVENTS

If some events give results opposite to expectations, a doubt arises as to whether the relationships found in other cases could be obtained by fluke. An important method of verification would be to observe what happens in years when there were no ENSO effects (no El Niño, no SOI minima, no warmer (W) or colder (C) waters in the Pacific). These years, termed as non-events, showed average results (Table V). As can be seen, the fractions are mainly around 0.3–0.7, indicating that such mild associations can occur randomly, or owing to factors unrelated with ENSO. Particularly disconcerting is the fact that for many individual events (not shown here), many deviations were extremes (△ and ○). Thus, extreme rainfalls can occur without any connection with ENSO. These facts place in doubt the veracity of some of the ENSO relationships discussed above.

6. COLD EVENTS (LA NIÑAS)

In some years, Pacific waters are colder than normal. These are La Niña years, interspersed between El Niño years. The average results for these C events are shown in Table V. An examination of individual events (not shown here) revealed that out of the 21 events, 19 were associated with positive deviations (excess rains) in India (positive/total ratio 0.9), a very good association indeed. It also confirms that the events chosen are real cold events, many of which were also selected by Ropelewski and Halpert (1989). However, for many other rainfalls, including those in Tasmania, the fractions are 0.4, 0.5 and 0.6, i.e. there is an almost equal number of positive and negative deviations, thus implying a poor relationship. In contrast, Chile, Peru and the Core and Gulf–Mexico regions had very low ratios of positives, indicating severe drought conditions during La Niñas, which is the converse of the excess rains expected during El Niños. A strange fact was that in the years 1921, 1924, 1964 and 1967, there were widespread *floods in northeast Brazil and Argentina*; in 1938, 1942, 1954 and 1970, there were widespread *droughts in northeast Brazil and Argentina*; in 1922, 1934, 1971 and 1975, there were *floods in northeast Brazil and droughts in Argentina*; and in 1955 and 1956, there were *droughts in northeast Brazil and floods in Argentina*. All of these conditions prevailed during C events when only floods in the northeast and droughts in Argentina are believed to occur, thus calling into question the veracity of this popular belief. During a 20-year period, Porto Alegre and Argentina had similar deviations in only 7 years (both negative in 6 years, both positive in 1 year). In the other 13 years, there were opposite deviations (Porto Alegre, positive; Argentina, negative in 7 years and vice versa in 6 years). Thus, the ENSO relationship during the cold phase is very weak indeed in the Brazilian and Argentinian regions considered here.

For the period from 1950 onwards, Trenberth (1997) listed the periods of La Niña as follows:

March 1950–February 1951, 12 months	1950 C
June 1954–March 1956, 22 months	1954 C, 1955 C
May 1956–November 1956, 7 months	1956 C
May 1964–January 1965, 9 months	1964 C
July 1970–January 1972, 19 months	1970 C, 1971 C
June 1973–June 1974, 13 months	1973 ENC (EN aborted early), 1974 SO
September 1974–April 1976, 20 months	1975 C, 1976 ENSOW-U

Table V. Average rainfall status during years of the types (a) ENSOW-U; (b) ENSOW-A; (c) other types of El Niños; (d) all El Niños; (e) SOW etc.; (f) non-events; and (g) C events

Positive/Total	India	Australia	Northeast Brazil																			
	AI	TA	1	2	3	FT	4	5	HT	6	7	8	R	RI	SP	PA	AG	ST	VP	PR	CR	GM
(a) ENSOW-U	0.1	0.2	0.4	0.3	0.1	0.2	0.3	0.1	0.3	0.4	0.3	0.4	0.4	0.6	0.6	0.8	0.6	0.8	0.8	1.0	1.0	0.9
(b) ENSOW-A	0.7	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.3	0.4	0.6	0.4	0.4	0.2	0.5	0.7	0.6	0.6	0.4	1.1	0.9
(c) Other El Niños	0.6	0.6	0.4	0.4	0.4	0.6	0.4	0.4	0.3	0.2	0.4	0.2	0.2	0.2	0.4	0.6	0.8	0.0	0.3	1.0	0.8	0.5
(d) All El Niños	0.5	0.4	0.4	0.3	0.3	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.4	0.6	0.7	0.6	0.6	0.7	0.9	0.8
(e) SOW etc.	0.5	0.4	0.6	0.7	0.5	0.7	0.5	0.4	0.6	0.6	0.7	0.7	0.7	0.3	0.3	0.5	0.5	0.6	0.3	0.4	0.4	0.4
(f) Non-events	0.5	0.6	0.5	0.7	0.5	0.4	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.3	0.4	0.4	0.1	0.4	0.5
(g) C (cold SST)	0.9	0.5	0.7	0.5	0.5	0.6	0.6	0.4	0.6	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4	0.2	0.2	0.3	0.1	0.1

The columns show the rainfalls of: AI, All-India summer monsoon; TA, Tasmania (Australia); Regions 1, 2, 3, 4, 5, 6, 7, 8 and FT, Fortaleza; HT, the Hastenrath group; R, the Rao *et al*. group; all areas in northeast Brazil; RI, Rio de Janeiro; SP, Sao Paulo; PA, Porto Alegre; areas in east and southeast Brazil; AG, Central Argentina; ST, Santiago; VP, Valparaiso; PR, Piura River discharge; CR, Core Region; and GM, Gulf–Mexico Region.

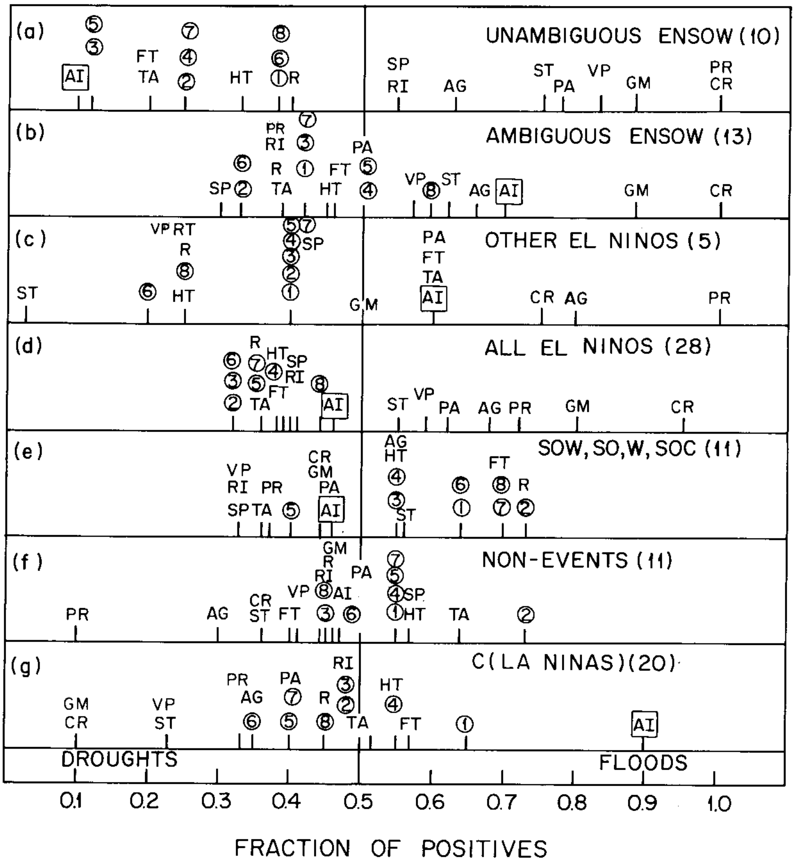

Figure 2. Plot of positive fractions for various rainfalls for different types of events: (a) ENSOW-U; (b) ENSOW-A; (c) other El Niños; (d) all El Niños; (e) SOW, SO, W and SOC; (f) non-events; and (g) C, i.e. La Niñas. The central vertical line is for a fraction of 0.5, i.e. an equal number of positive and negative deviations, implying a poor relationship. Values to the far-right imply an excess of positive deviations, i.e. an association with excess rains, while those to the far-left imply an excess of negative deviations, i.e. an association with droughts

September 1984–June 1985, 10 months	1984 non-event, 1985 Non-event
May 1988–June 1989, 14 months	1988 C, 1989 Non-event

Our classification for years in these intervals is also mainly C (occasionally 'non-event'). Thus, the C events selected here are genuine La Niñas.

The fractions of positive deviations shown in Table V are plotted in Figure 2. The vertical line in the middle represents a fraction of 0.5, implying equal numbers of positive and negative rainfall deviations and hence, a poor relationship. Values falling to the far-right imply a large fraction of positive deviations, i.e. an association with floods. Values falling to the far-left imply a small fraction of positive deviations (large fraction of negative deviations), i.e. an association with droughts. The top panel (a) is for ENSOW-U and the Indian summer monsoon (AI, shown with a rectangle) shows a great affinity for droughts. Tasmania (Australia) and some parts of northeast Brazil (Fortaleza, and regions 2, 4 and 7) also show an affinity for droughts, while Porto Alegre in South Brazil, Chile (Santiago, Valparaiso) and the Core and Gulf–Mexico regions all show an affinity for floods. The second panel (b) for ENSOW-A shows fractions of 0.3–0.7, i.e. only mild relationships, except for the Core and Gulf–Mexico regions, which show a great affinity for floods. Panel (c) for other El Niños does not show good relationships for India or Tasmania, but some regions in northeast Brazil (6, 8, HT and R), Rio de Janeiro and Chile

(Santiago, Valparaiso) show an affinity for droughts, while Core and Gulf–Mexico regions show an affinity for floods. In Panel (d) for all 28 El Niños, all effects are diluted (fractions 0.3–0.7, mild or poor relationship) except for the Core and Gulf–Mexico regions, which show floods for all El Niños. In Panel (e) for events when there were no El Niños, but there were events of the types SOW, SO, W and SOC, Rio de Janeiro and Sao Paulo show a mild association with droughts, while some parts of northeast Brazil (R, Fortaleza, regions 2, 7 and 8) show a mild association with floods. Panel (f) for non-events shows an affinity for floods in region 2 of northeast Brazil and droughts in Argentina and Peru, indicating that these can occur for reasons unrelated to ENSO. Finally, Panel (g) for C events (La Niña) shows a good association with floods in India (AI) and droughts in Chile, Peru and the Gulf–Mexico region, but no clear associations in other areas. Thus, only ENSOW-U events show good associations with droughts in northeast Brazil and floods in South Brazil (Porto Alegre). For all other types of events, the relationships are poor. However, the core and Gulf–Mexico regions show excess rains for all El Niños and droughts for all La Niñas.

The classification used in this study (ENSOW etc.) was made by a visual inspection of the plots (12-month running means), as shown in Kane (1997b,c), and is somewhat subjective. Thus, some events where SO minima or W were considered as being late or early in the calendar year (not in the middle) and therefore were termed as ENSOW-A could just as well have been ENSOW-U. Some events in C may deserve to be termed non-events; by and large however, the classification seems clear enough and the main conclusion that only some parts of northeast Brazil show an association with droughts during ENSOW-U only and that during all other events the effects are uncertain, seems valid. This indicates that other factors unrelated to ENSO must be causing considerable interference, except in the Core and Gulf–Mexico regions, where the ENSO relationship is very strong.

7. INTERCORRELATION

Since the different series show different results, it is obvious that these are not well related to each other. To obtain a quantitative estimate of their interrelationships, correlation coefficients were calculated between the various locations in Brazil and Argentina and the matrix is shown in Table VI.

As can be seen, the northeast Brazil series are fairly well correlated ($+0.5$ or more) between each other; however they have a low positive correlation with Rio de Janeiro, a low negative correlation with Sao Paulo, a slightly more negative correlation with Porto Alegre, and a low positive correlation with Argentina. Rio de Janeiro has a correlation of $+0.35$ with Sao Paulo, -0.14 with Porto Alegre and $+0.13$ with Argentina. Sao Paulo has a correlation of $+0.19$ with Porto Algere and -0.19 with Argentina. Porto Alegre has a correlation of -0.25 with Argentina. Thus, in eastern and southern Brazil, the rainfall characteristics change rapidly with latitude, have very small intercorrelations and cannot possibly have similar relationships with any phenomenon like ENSO.

8. RELATIONSHIP WITH FACTORS OTHER THAN ENSO

In every part of the globe, rainfalls are affected by factors which may not be related to ENSO, such as local conditions (circulations, topography), SSTs in nearby regions etc. For central Chile (30–35°S), Rubin (1955) found that the precipitation was below normal during the positive phase of the SO, i.e. when the southeast Pacific subtropical anticyclone was stronger than average (see also Pittock 1980). Quinn and Neal (1983) reported a good correlation between Chilean rainfall and SSTs in the southeastern Tropical Pacific. Aceituno (1987) concluded that the excess rainfall in Chile during the negative phase of the SO was associated with a weak and northerly displaced southeast Pacific subtropical anticyclone. Rutllant and Fuenzalida (1991) reported that the winter (June, July, August; JJA) rainfall in central Chile showed positive anomalies during the developing stage of warm events of the SO and dry conditions during the cold events. They also presented a synoptic characterization of major storms during some warm events

Table VI. Correlations between the various rainfall series in Brazil and Argentina

	1	2	3	FT	4	5	HT	6	7	8	R	RI	SP	PA	AG
1	1.00														
2	0.60	1.00													
3	0.82	0.70	1.00												
FT	0.66	0.43	0.83	1.00											
4	0.78	0.87	0.90	0.67	1.00										
5	0.55	0.51	0.70	0.58	0.65	1.00									
HT	0.78	0.68	0.90	0.72	0.89	0.64	1.00								
6	0.49	0.51	0.58	0.44	0.66	0.56	0.62	1.00							
7	0.50	0.74	0.61	0.43	0.80	0.57	0.65	0.80	1.00						
8	0.18	0.54	0.26	0.06	0.49	0.31	0.32	0.55	0.75	1.00					
R	0.40	0.38	0.53	0.41	0.54	0.60	0.55	0.87	0.62	0.44	1.00				
RI	0.08	0.14	−0.05	−0.05	0.08	0.10	0.05	0.10	0.21	0.19	0.13	1.00			
SP	−0.11	−0.08	−0.21	−0.19	−0.18	−0.10	−0.15	−0.30	−0.12	−0.10	0.27	0.35	1.00		
PA	−0.38	−0.31	−0.24	−0.21	−0.31	−0.14	−0.24	−0.24	−0.26	−0.23	−0.25	−0.14	0.19	1.00	
AG	0.16	0.24	0.22	0.22	0.22	0.28	0.18	0.19	0.20	0.12	0.11	0.13	−0.19	−0.25	1.00

For abbreviations see Table II.

and described dry months during cold events in terms of average 500 hPa contour anomaly fields, but in some cases found significant departures from the general behaviour. For central Chile, Rutllant and Fuenzalida (1991) mention that the precipitation is almost exclusively a southern winter phenomenon, associated with the extratropical disturbances penetrating the area of influence of the southeast Pacific subtropical anticyclone. About 80% of the annual precipitation occurs during May–August, distributed into relatively few large events, particularly in wet winters. Regarding latitudes further south, Quinn and Neal (1983) mention that the prominent ENSO-related rainfall departures are primarily confined to the Chilean subtropics, and that at times, stations near 40°S latitude register these changes, but to a lesser degree.

For India, relationships were reported with Eurasian snow cover (Hahn and Shukla, 1976; Dey and Bhanukumar, 1983), the state of the troposphere at middle and upper levels (Bhalme *et al.*, 1986), stratospheric wind quasi-biennial oscillation (Bhalme *et al.*, 1987 and references therein), and latitudinal location of the axis of the 500 hPa ridge along 75°E (Krishna Kumar *et al.*, 1992 and references therein). For Australia, a relationship was found with SST in the Indonesian region and Central Indian Ocean (Streten, 1983; Nicholls, 1989).

For rainfall in Brazil, particularly in the northeast, east and southern region, several factors are known to be relevant. Markham and McLain (1977) reported considerable influence of tropical Atlantic SST. Other factors are, the 700 mb circulation pattern over the North Atlantic (Namias, 1977), the meridional displacement and strength of the Inter-tropical Convergence Zone (ITCZ) (Hastenrath and Heller, 1977), Atlantic trade winds (Chung, 1982), rainfall systems associated with tropical disturbances moving westward from the Atlantic towards northeast Brazil (Ramos, 1975; Yamazaki and Rao, 1977; Rao *et al.*, 1993), and Southern Hemisphere cold fronts or their remains moving northward along the eastern and northeast coast of Brazil (Kousky and Chu, 1978; Kousky, 1979). There is a well-defined large-scale atmospheric circulation pattern related to the SST anomalies in the Tropical Atlantic (Hastenrath and Heller, 1977; Moura and Shukla, 1981). According to Hastenrath (1990), droughts in northeast Brazil can be due to an anomalously far northerly position of the ITCZ, reduced northeast trades and accelerated cross-equatorial flow from the Southern Hemisphere, and anomalously warm surface waters in a zonal band across the Tropical North Atlantic, contrasting with negative SST anomalies south of the equator. The association with SO minima may come about through the displacement of the near-equatorial trough northward. Hastenrath *et al.* (1984) and Hastenrath (1990) formulated prediction schemes involving zonal and meridional wind components over limited areas of the Equatorial Atlantic, SST in Tropical North and South Atlantic, SOI and preseason rainfall itself in northeast Brazil as predictors. A particularly interesting aspect is the relationship between the rainfall in northeast Brazil and the coastal wind in that region, through its effect on the positioning of the ITCZ. Servain and Seva (1987) indicated that the position of ITCZ was well-related to the minimum of the meridional component of the wind stress. Xavier and Xavier (1997) utilised this relationship for locating the position of the ITCZ in individual months and for the predictions of rainfall. Since years when El Niño and cold events did not yield the expected results (droughts and floods, respectively) have been isolated here, the possibility of whether in these years other factors played a more important role will now be examined.

Figure 3 shows a plot of various parameters for 1913–1951 in Figure 3a and for 1952–1990 in Figure 3b. The rectangles at the top show the category of the year (ENSOW etc.) allotted for this work, and in the case of El Niño being present, the symbols above the rectangles (S, strong; M, moderate; W, weak) indicate the strength of the El Niño.

The next three plots are for rainfall at Fortaleza and for the average series by Hastenrath (1990) for northeast Brazil and Rao *et al.* (1993) for east-northeast Brazil. Following these are plots of SST and zonal (U) and meridional (V) wind components in the Atlantic. Hastenrath (1990) presented indices of January values of SST, as well as and meridional and zonal wind components obtained by an Empirical Orthogonal Function (EOF) analysis of data for the entire Tropical Atlantic (30°N–30°S, 0–50°W). Rao *et al.* (1993) studied SST in the whole Atlantic and found the best correlation for a region near 10°S, 10°W. They also found good correlations with the meridional wind component at Abrolhos (18°S, 39°W). Both of these sets of data have been used here, as have SST data given in Servain (1991) for the North

Atlantic (28–5°N, 10–60°W) and South Atlantic (5°N–20°S, 10°E–40°W) and SST data for (8°S–0°W) and SST and wind stress data near the northeast Brazil coast (*ca.* 5°S, 40°W; Servain and Lukas (1990) and Drs Vianna and Servain, private communication). A large part of the Atlantic data were available from 1964 onwards only (Figure 3b).

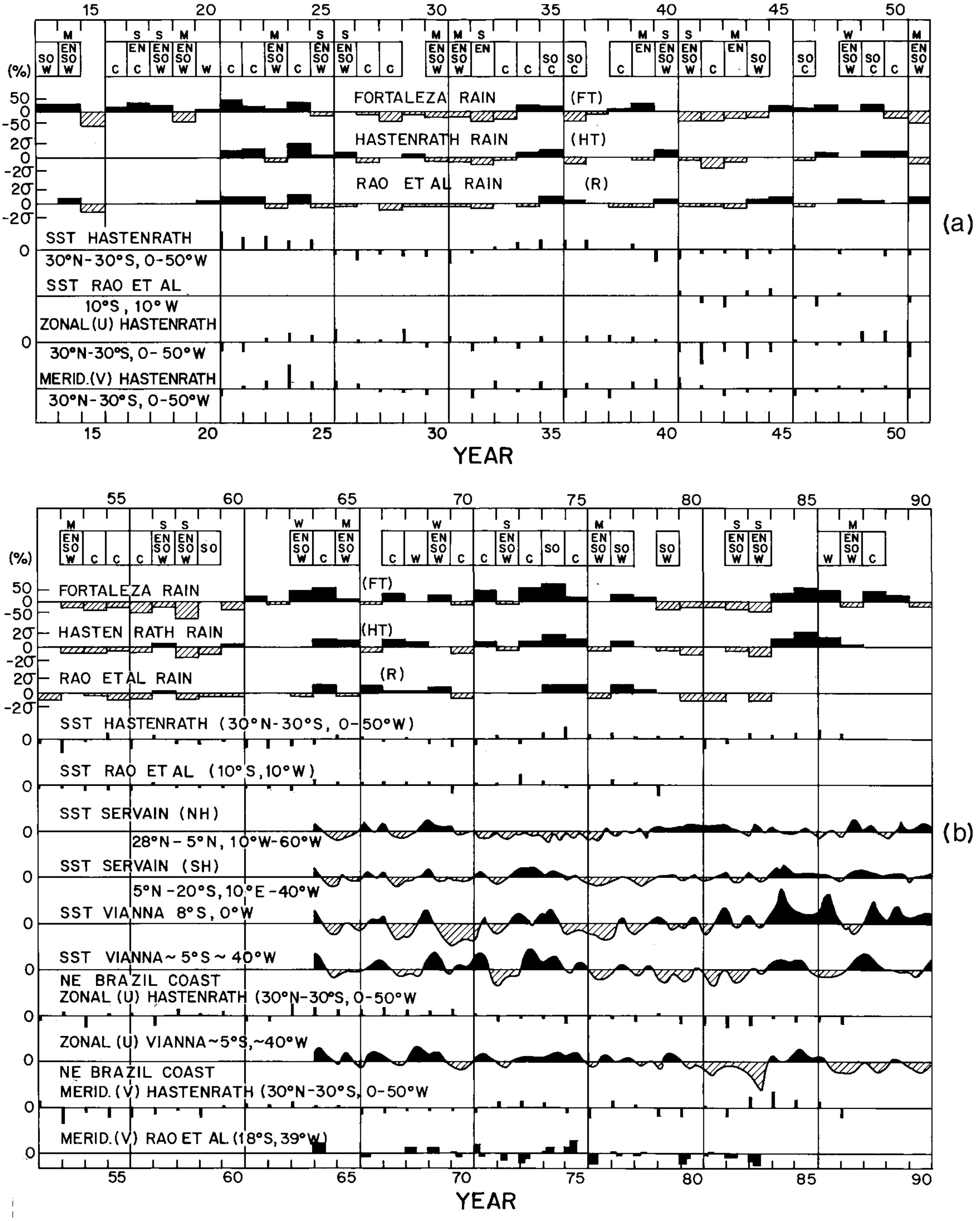

Figure 3. Categories of years (EN, SO etc.), rainfalls for Fortaleza (FT), the Hastenrath (1990) group (HT), and the Rao *et al.* (1993) group (R), and Atlantic SST and wind components (zonal, U; meridional, V) for (a) 1913–1951 and (b) 1952–1990

As mentioned earlier, among the 24 events involving El Niño and another seven involving SO and/or W, all of which were expected to be associated with droughts, at least eight were associated with unexpected flooding in northeast Brazil. These were 1914, 1926 II, 1940 I and 1969 in the El Niño group (Table II) and 1913, 1977, 1974 and 1968 in the SO/W group. These years should be examined individually for associations with SST and wind components in the Atlantic. Similarly, from the 21 C events which were expected to be associated with floods, 7 years (1928, 1938, 1942, 1954, 1955, 1956 and 1970) were associated with droughts and require similar examination, as do some non-events which rather than giving rise to normal rainfall as expected, caused droughts or floods.

Table VII shows the results. The years, their categories (EN, SO etc.) and the expected and observed rainfalls are indicated. The symbols (+ +), (+), (0), (−) and (− −) indicate the status of the various SST and wind components. Thus, (+ +) in SST (HT) means that for that year, the SST plot of Hastenrath (1990), reproduced in Figure 3, had a large positive deviation in Atlantic SST, which is favourable for excess rainfall in northeast Brazil. A (+ +) result also implies large positive deviations for all other SSTs except the Servain SST for the North Atlantic, for which—because of its dipole nature with respect to the South Atlantic—a reverse convention, i.e. *negative* temperature deviations are considered as having a (+) or (+ +) effect, are adopted. Since data for many of these parameters are available only from 1964 onwards, there are many gaps in the data in Figure 3a. However, in general, when floods and droughts were observed, there was a preponderance of (+) and (−) respectively, thus confirming that in cases where El Niños and cold events did not give the expected results, the effects of Atlantic (particularly South Atlantic) SST and winds comprised a predominant contribution.

Figure 3 shows rainfall data for Fortaleza, HT and R for years up to 1987. During 1979–1987, years 1979 (SOW), 1982 (ENSOW), 1983 (ENSOW) and 1987 (ENSOW) were expected to yield droughts and did so. However, 1980, 1981, 1984 and 1985 were non-events and 1986 was a late W; these were associated with droughts and floods, respectively. The lower part of Table VII shows a preponderance of negatives (−) for droughts and positives (+) for floods, again indicating the prominent roles of South Atlantic SSTs and winds.

Since 1964 when copious data for the various parameters are available, only 3 years of the C type (1964, 1967 and 1973) expected to have floods, did have floods and only 2 years of the ENSOW type (1982 and 1983) expected to have droughts, did have droughts. Table VII (bottom) shows the contribution of other parameters. The floods were associated mostly with (+) and the droughts mostly with (−) thus accentuating the El Niño and La Niña effects.

Therefore, it would seem that on occasions when El Niños and La Niñas did not yield the expected results, considerable complications from the Atlantic region were involved. Hence, predictions in relation to rainfall anomalies in northeast Brazil must be made by taking into account the conditions in both the Pacific and the Atlantic, although the media seems to be concerned only by the Pacific events (El Niños). Such efforts are underway at present and involve correlation analysis discussed in the next section.

9. CORRELATIONS WITH PACIFIC AND ATLANTIC PARAMETERS

Ward and Folland (1991) investigated the relationship between northeast rainfall and SST in various regions. For the Atlantic, they reported correlations similar to those reported earlier by Markham and McLain (1977), i.e. positive correlation with SST in the South Tropical Atlantic and negative correlation with SST in the North Tropical Atlantic. For the Tropical Pacific, negative correlations extended over a wide area, thus implying a relationship with the ENSO phenomenon, reported earlier by Covey and Hastenrath (1978). Furthermore, they calculated the covariance eigenvectors for SST in the Atlantic and Pacific Oceans, with the main purpose being to derive a few time series which would express much of the large-scale variability in the SST in these two oceans. They also studied the relationship of the various eigenvectors with north northeast Brazil rainfall. Atlantic eigenvector 3 and Pacific eigenvector 1 showed the best correlations and together explained about 55% of the rainfall variance. When SST data were averaged over November–January, 35–50% of the variance was explained, sufficient to provide a

Table VII. Indications as to whether the signs and strengths of the various Atlantic SST and wind components (zonal, U; meridional, V) for January, February and March were favourable for heavy floods (++), mild floods (+), normal rainfall (0), mild droughts (−), severe droughts (−−) in northeast Brazil

Year	Type	Rainfall		SST						U		V	
		Expected	Observed	HT	R	SER, N	SER, S	VIA Off	VIA Coast	HT	VIA	HT	R
1913	SOW	Drought	Flood										
1914	ENSOW	Drought	Flood										
1926 II	ENSOW	Drought	Flood	−									
1940 I	ENSOW	Drought	Flood	−−	0								
1965	ENS OW	Drought	Flood	0	+	+	0	−−	−	+	+	−	++
1969	ENSOW	Drought	Flood	−	+	−	+	+	+	+	+	0	++
1974	SO	Drought	Flood	+	+	+	+	+	+	0	+	+	+
1977	SOW	Drought	Flood	+	+	+	−	0	+	0	+	+	0
1917	ENC	Normal	Flood										
1935	SOC	Normal	Flood	++						+		+	
1947	X	Normal	Flood	0	−					0		0	
1915	X	Normal	Drought										
1928	C	Floods	Drought	−									
1938	C	Flood	Drought	0									
1942	C	Flood	Drought	−	−								
1954	C	Flood	Drought	0	−								
1955	C	Flood	Drought	+	−								
1956	C	Flood	Drought	−−	−								
1970	C	Flood	Drought	−	−	−	−	−	+	+	−	−	0
1980	X	Normal	Drought	0		−	−	−	−	−	−	−	−
1981	X	Normal	Drought	−		−	−	−	−	−	−	0	0
1984	X	Normal	Flood	+		0	+	+	+	0	+	++	
1985	X	Normal	Flood	+		0	+	+	+	−	+	+	
1986	W	Normal	Flood	+		+	0	+	−	−	+	+	
1964	C	Flood	Flood	−	+	−	+	+	+	+	+	0	+
1967	C	Flood	Flood	−	+	−	+	+	+	+	+	−	+
1973	C	Flood	Flood	−	++	0	+	+	+	0	+	+	−
1982	ENSOW	Drought	Drought	−		−	−	±	−	−−	−	−	−
1983	ENSOW	Drought	Drought	+		−	−	±	−	−	−	+	−

HT, Hastenrath (1990); R, Rao *et al.* (1993); SER (N, S), northern and southern Atlantic, Servain (1991); VIA (Off, Coast), coastal and off-coast, Dr Vianna (private communication). X, Non-event.

preliminary forecast of the March–April rainfall over northeast Brazil. Using two statistical techniques, namely multiple linear regression (MIR) and linear discriminant analysis (LDA), forecasts were made for 1987, 1988, 1989 and 1990 which were subsequently found to be good. Since 1990, forecasts have been available in February. Here, the results of a simplistic correlation analysis are reported.

In the Atlantic region, SST variations are dissimilar in the northern and southern hemispheres. SST indices for the northern (N; 28°–5°N) and southern (S; 5°N–20°S) Atlantic were obtained from Servain (1991). Their average $(N+S)/2$ represents the average Tropical Atlantic SST, while their difference (N–S) represents the dipole inducing a meridional circulation cell with subsidence over northeast Brazil, as envisaged by Moura and Shukla (1981). Two additional parameters were also considered, namely SST variations near the northeast Brazil coast and the zonal pseudo-wind stress (product of the intensity of the eastward wind velocity and the total wind speed) in the same region. A cross-correlation between Fortaleza rainfall (12-month running means, centered 3 months apart) showed maximum correlations 0.30 with North Atlantic SST N, 0.45 with South Atlantic SST S, 0.40 with $(N+S)$ and $(N-S)$, 0.50 with Brazil coastal SST and 0.40 with coastal wind stress. Thus, all of these parameters have some relationship with northeast Brazil rainfall. Most of these had a zero lag with rainfall, and therefore could not be used for prediction. However, N and S showed maximum correlation not at zero lag, but a lag of few (two to three) seasons, with the parameters preceding the rainfall. Thus, the December–January Atlantic SST warming could be indicative of excess rainfall later in northeast Brazil. The equatorial eastern Pacific SST showed a good correlation (0.65 ± 0.05) with North Atlantic SST N, a smaller correlation (0.45 ± 0.06) with South Atlantic SST S and a moderate correlation with northeast coastal Brazil SST $(-0.5$, with a lag of three to four seasons).

The maximum correlations (at a *ca.* two-season shift) between Fortaleza rainfall and Atlantic S, Atlantic N, SOI $(T-D)$, and equatorial eastern Pacific SST were 0.52, 0.32, 0.25 and 0.18, respectively. When the Fortaleza rainfall values were shifted by two seasons and a multiple regression analysis was carried out, the single variable correlation $+0.52$ between rainfall and South Atlantic SST S increased to a multiple correlation $+0.69$ when North Atlantic SST N was also included, but remained near $+0.69$ when $(T-D)$ and equatorial eastern Pacific SST were included one by one. Thus, Atlantic SST (both N and S) seem to be the parameters of major influence, the effects of $(T-D)$ and Pacific SST being almost insignificant. When rainfall was correlated with northesat coastal SST and wind stress, the bivariate analysis gave a multiple correlation $+0.76$, which increased to $+0.80$ when SST Atlantic S was also included. However, as mentioned earlier, the coastal parameters attain maximum correlations during the rainfall regime and hence have no prediction potential. Overall, above-average temperatures in the Tropical South Atlantic can cause excess rains in northeast Brazil and, if there is a simultaneous El Niño effect (droughts), normal rainfall may be the net result. However, below-normal temperatures in the Tropical South Atlantic accompanied by El Niño could cause disastrous droughts in northeast Brazil.

Since the correlations are only *ca.* 0.7, the variance explained is *ca.* 50%, leaving almost 50% as a random component. Therefore, quantitative predictions based only on Atlantic temperatures may not be very accurate or reliable. Hastenrath *et al.* (1984) and Hastenrath (1990) conducted a stepwise multiple regression analysis, using October–January northeast rainfall, January values of SO $(T-D$ pressure), Pacific and Tropical Atlantic SST and Tropical Atlantic wind components as predictors for the March–September northeast rainfall. In the Atlantic, the area chosen by the above authors is rather large (30°N–30°S) and EOF analysis was used; among the first five EOFs, those with the best correlation were selected. However, the SST patterns in the North and South Atlantic are not alike; as illustrated in Servain (1991), there is a meridional dipole structure, but the north (28°–5°N) and the south (5°N–20°S) series are not out of phase simultaneously. From the patterns seen in Table VII, it seems that use of SST and winds in the South Atlantic only would be more appropriate. However, in their earlier publication, Hastenrath and Heller (1977) reported that the rainfall anomalies in northeast Brazil were associated with meridional surface *pressure gradients* and the associated interhemispheric *SST gradients*, rather than with pressure and SST over either the Tropical North or South Atlantic alone. In a recent communication, Hastenrath and Greischar (1993) elaborated their list of predictors and showed that whereas excess rainfall in northeast Brazil was related both to anomalously cold SST and high pressure in the North

Atlantic, and to anomalously warm SST and low pressure in the South Atlantic, the relationship of northeast rainfall extremes with the interhemispheric gradients of SST and pressure was even stronger. Servain (1991) gave the indices for SST variability separately for the North (NB) and South (SB) Atlantic, as well as for their difference (NB − SB) as a dipole index. However, the main feature of this dipole index was not a large year-to-year variation but a slow variation on a *decadal* time scale, i.e. positive during 1964–1970 and 1976–1983 and negative during 1971–1975 and after 1984. It is clear that such a slow variation cannot be related to the abrupt year-to-year changes in rainfall (Figure 3) seen in northeast Brazil. Earlier, Hastenrath (1990) mentioned that a model involving October–January rainfall Atlantic meridional wind and equatorial Pacific SST as predictors captured *ca.* 70% of the March–September rainfall variance. It would be interesting to see whether the modified list of predictors used by Hastenrath and Greischar (1993) (including N–S gradients) explains variance exceeding 70%. A major difficulty is to decide the relative weights of the different parameters, which seem to vary from time to time. For example, strong El Niños do not always seem to be equally effective. For the 1980–1991 period, these authors acquired global upper air analysis from the European Center for Medium-Range Weather Forecasts (ECMWF) and studied the circulation differences between the four most wet (1984, 1985, 1986 and 1989) and the four most dry (1980, 1982, 1983 and 1990) years of northeast Brazil rainfall and found that during the wet years, North Atlantic SST was cooler and south Atlantic SST warmer; a schematic summary of thermal and hydrostatic mechanisms of SST forcing on lower atmosphere was given. Hastenrath and Druyan (1993) complemented this study by evaluating the output of a 7-year run of the general circulation model (GCM) of the Goddard Institute of Space Studies (GISS). Whereas the response of lower tropospheric thickness and near-surface pressure to SST was reasonably well produced, *the simulation of wind and rainfall was somewhat deficient*. For predicting the HT rainfall series (March–June precipitation, average of 27 stations in northeast Brazil), Hastenrath and Greischar (1993) used five potential predictors which had correlations with HT over the training period 1921–1957 as follows:

(i) October–January HT rainfall (pre-season rain), + 0.55**.
(ii) January meridional surface wind over the Tropical Atlantic (30°N–30°S), − 0.35*.
(iii) January SST in the Equatorial Pacific, − 0.11.
(iv) January SST in the Tropical Atlantic, − 0.57.
(v) November–December–January SST in the Tropical Atlantic, − 0.70**.

One/two asterisks indicate significance at the 5 and 1% levels, respectively. These predictors are used with stepwise multiple regression analysis and linear discriminate analysis and the forecasts are made at a 1-month lead, i.e. using data no later than January. Eight prediction models are used, each using a different combination of the five predictors listed above.

In addition to these empirical techniques, dynamical model forecasts and forecasts using GCM forced with persisted or model-forecast SST anomalies are also used (discussed later).

10. PREDICTIONS FOR 1987–1996

Following the methodology outlined in Ward and Folland (1991), experimental forecasts of northeast Brazil rainfall at 1- and 0-month leads are issued using November–January and January–February predictor data. The two predictors used are: (i) the 30°N–30°S third EOF eigenvector of Atlantic SST for all seasons, reflecting the SST anomaly immediately off the north-northeast coast of Brazil and the large-scale north–south SST gradient structure in the Atlantic; and (ii) the first EOF of Pacific SST for December–January–February, serving mainly as an ENSO index. Both multiple regression analysis and discriminant analysis are used and their results combined to predict the HT rainfall (March–April), as well as Fortaleza/Quixeramobim (FQ) rainfall (March–May). The forecasts and observed values for FQ for the 10 years from 1987 to 1996 given by Colman *et al.* (1997) in the form of five broad Quintile (Q) categories, namely: Q1, very dry; Q2, dry; Q3, normal; Q4, wet; and Q5, very wet, were as follows:

Year	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
Preliminary	*1*	*4*	*5*	*2*	*4*	*1.5*	2	5	4	2.5
Updated	*1*	5	5	3	4	2	2	4	4.5	3.5
Observed	*1*	*4*	*5*	*2*	*4*	*1.5*	1	4.5	5	5

As can be seen, the preliminary forecasts matched very well with the observed rainfall for FQ in the earlier years and approximately in recent years. The worst forecast was for 1996, probably due to a sharp change in Atlantic SST throughout the forecast season. These forecasts are *statistical* predictions. In the same group (UK Meteorological Office (UKMO), Bracknell), Harrison *et al.* (1997) makes a *dynamical* prediction of northeast Brazil rainfall using a version of the UKMO climate atmospheric general circulation model (AGCM). Colman *et al.* (1996) mention that the 1994 and 1995 dynamical AGCM forecasts were in good agreement with the statistical predictions. For 1996, the AGCM forecast was also for rainfall about 10% below average, thus agreeing with the statistical forecast (Q2.5); however, both these forecasts were found to be in *disagreement* with the observed rainfall (Q5).

Using an atmospheric GCM with persisted SST anomalies, Graham (1996) has been forecasting northeast Brazil rainfall since 1993. For 1993, a continued severe drought was forecast which proved to be accurate (Q1 in the above table). According to Graham (1994, 1996), the information was given beforehand to the local agency (FUNCEME, in the state of Ceara, northeast Brazil), resulting in the construction of hydrological facilities that prevented severe shortages later in the year. Similarly, in 1994, a forecast of normal to slightly wetter-than-normal conditions was issued, which allowed agricultural managers to devise a planting strategy that resulted in record agricultural production in the state of Ceara. It is not known what forecast was made for 1995, but that for 1996 (Graham, 1996) mentions dry (− 50% of normal) conditions over the 'nordeste'. Thus, this forecast proved to be erroneous (observed, Q5).

Using the method of five predictors, Greischar and Hastenrath (1996) predicted *near-average* conditions for March–April–May–June 1996 rainfall. Therefore, this forecast also proved to be erroneous.

In summary, whereas forecasts for earlier years were reasonably correct, forecasts for 1996 were miserably poor using all of these methods, because of the rapid changes in Atlantic SST during the forecast season, as mentioned by Colman *et al.* (1997).

11. PREDICTIONS FOR 1997–1998

During 1997, a strong El Niño developed. The forecasts for northeast Brazil rainfall issued in January 1997 using different methods were mostly for below-average rainfall (Colman *et al.*, 1997; Graham 1997; Greischar and Hastenrath, 1997; Harrison *et al.*, 1997). *The observed rainfall in northeast Brazil during March–May 1997 was 15–30% below normal, thus basically conforming to the above predictions*. Regarding the evolution of the 1997 El Niño itself, several predictions were made.

Different models predicted slightly different evolution patterns. However, the consensus seemed to be for a peak intensity in the northern autumn–winter (October, November, December) of 1997 and a decline after January 1998. With regard to the effect on rainfalls, the predicted deficit rainfall in northeast Brazil for 1997 did occur. For other regions, it may be interesting to examine the evolutions in earlier El Niño events in order to have some idea what to expect. Figure 4 shows plots of the temperature anomalies (deviations from the mean) in the El Niño $1+2$ region near the Peru–Ecuador coast (full lines) and the El Niño 3.4 region in the eastern Equatorial Pacific (crosses) and the SOI, represented by the $T-D$ pressure difference (negative values hatched). The arrows indicate the commencements of El Niños. In each event, data for three complete years are plotted and the El Niño commences in the first year. The duration of the Pacific El Niño 3.4 is shown black. For each year, our designation (ENSOW etc.) is

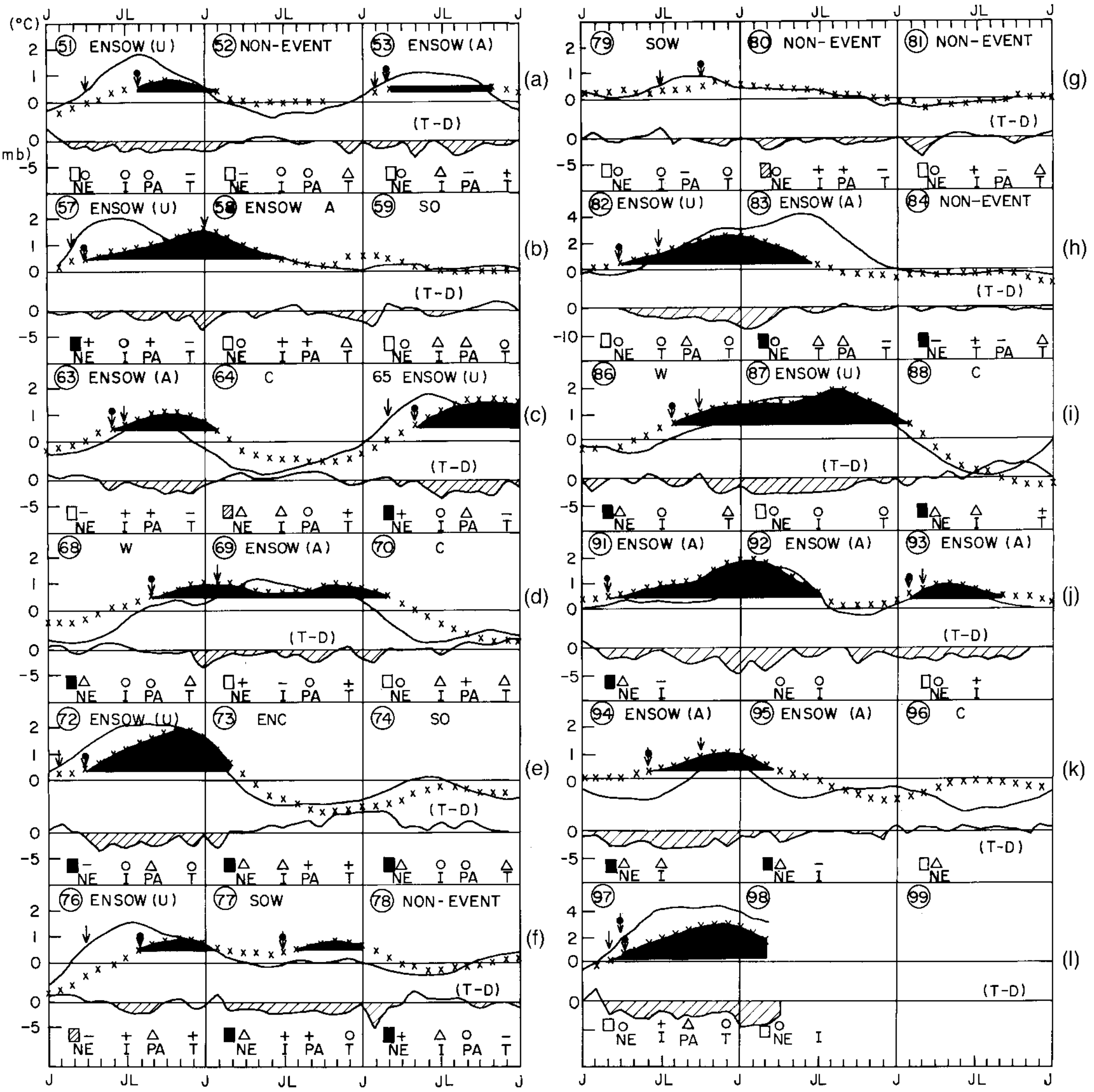

Figure 4. Plots of the 5-month running averages of SSTs in the El Niño 1 + 2 region (full lines) and the El Niño 3.4 region (crosses), and monthly mean SOI, represented by the T − D atmospheric pressure difference (negative values hatched), for panels of 3-year intervals in which El Niño started in the first year. Vertical lines indicate Januaries; durations of strong El Niños 3.4 (anomaly exceeding + 0.4°C) are shaded black; arrows indicate commencements of strong El Niños. At the bottom of each 3-year panel, symbols (−, +, ○, △) indicate rainfall status at the various locations: northeast Brazil (NE); All-India (I); Porto Alegre, south Brazil (PA); and Tasmania, Australia (T). The rectangles near NE show the status of Atlantic SST in the January of that year (full rectangles, positive SST, cause of excess rains in northeast; blank rectangles, negative SST, cause of deficit rains in NE)

indicated. Vertical lines indicate Januaries. At the bottom of each 3-year panel, the symbols (+, △, excess rain; −, ○, deficit rain) indicate rainfall status for northeast Brazil, NE (centered in April), All-India (I) summer monsoon (July), Porto Alegre, PA (September), Tasmania, T (December). Since the northeast Brazil rainfall is considerably affected by Atlantic parameters, one measurement of the same, namely the SST anomaly (shown in Figure 3 as SST Hastenrath and SST Rao *et al.*), is shown in Figure 4 in each panel as a rectangle adjacent to the rainfall symbol of northeast Brazil, a full rectangle representing positive Atlantic SST anomalies (expected to give excess rainfall in northeast Brazil), and a blank rectangle representing negative Atlantic SST anomalies (expected to give deficit rainfall in northeast Brazil). Figure 4 shows events from 1950 onwards only; these and many others before 1950 were discussed earlier. However, the main features may be restated as follows:

(i) El Niño 1 + 2 generally starts 0–5 months earlier than El Niño 3.4. However, notable exceptions were 1963, 1968, 1982, 1986, 1991, 1993 and 1994.

(ii) Among the I-year events.

  (a) In 1951, 1953, 1957, 1965, 1972, 1976 and 1993, El Niño 1 + 2 started before April and northeast Brazil had deficit rainfall in all of these years, except in 1957 and 1965, when there were excess rains. *This discrepancy in 1957 and 1965 is due to the effect of Atlantic SSTs*, which were above normal (full rectangles near NE) and hence appropriate for excess rains in northeast Brazil.

  (b) In 1963, 1968, 1979, 1986 and 1994, both El Niño 1 + 2 and El Niño 3.4 started late (June or later), but 1963 and 1979 brought droughts in northeast Brazil, because the Atlantic SSTs were below normal (blank rectangles near NE); 1968, 1986 and 1994 brought floods, because Atlantic SSTs were above normal (full rectangles near NE). For 1987 onwards, the rectangles represent the predictions based on the Ward and Folland (1991) methodology, as depicted in Colman *et al.* (1997). Since Pacific SST effects are small in January, the Ward and Folland (1991) predictions are based mainly on Atlantic SST anomalies). Thus, in the absence of properly timed El Niños (and perhaps even otherwise), the Atlantic SST anomalies dictate the rainfall patterns of northeast Brazil.

  (c) In 1982, El Niño 1 + 2 started late (July) but El Niño 3.4 started earlier (April) and northeast Brazil had droughts. The Atlantic SST was below normal (blank rectangle near NE) and hence, favourable for droughts. However, in 1991, when El Niño 1 + 2 started late (December) but El Niño 3.4 started early (March), northeast Brazil had floods, probably because the Atlantic SST was above normal (full rectangle near NE).

(iii) Among the II-year events, 1958, 1983 and 1992 had strong El Niños (both 1 + 2 and 3.4) in January which lasted for at least 2–3 months, and the northeast Brazil rainfall showed a deficit. The Atlantic SST was below normal (blank rectangles) for 1958 and 1992 January, which helped the droughts, while in 1983, Atlantic SST was above normal (full rectangle), which was conducive to floods; however, droughts were seen. (1983 is one of the rare examples when Atlantic SST predictions did not match northeast Brazil rainfall). However, 1969, 1973 and 1995 had a strong El Niño 3.4 but weak a El Niño 1 + 2 in January and the northeast Brazil rainfall was in excess, probably because the Atlantic SST was above normal (full rectangles near NE).

It seems, therefore, that whereas some El Niño effects may exist, deviations from the expected pattern are almost always explainable by the influence of Atlantic SST anomalies. A curious aspect is that among 14 I-year El Niño events, all but two (1972 and 1976) had Atlantic SST matching with the northeast Brazil rainfall anomaly (full rectangles with △ and blank rectangles with ○). In all these events, although El Niño existed, its strength (anomaly) in January was negligible. Thus, even in the absence of El Niño in January, the Atlantic SST anomaly during this month was sufficiently large to correctly predict the northeast rainfall. If so, was the existence of El Niño superfluous? Or, were the Atlantic SSTs harbingers of El Niño activity? In addition, in the eight II-year El Niños (which were strong in January), the Atlantic predictions matched with northeast rainfall in seven cases (only 1983 was an exception), and among these seven cases, three were of droughts (El Niño effect?), but three were of floods (El Niño ignored?). Overall therefore, the effect of January Atlantic SST anomalies on northeast Brazil rainfall (positive SST anomaly leading to floods and negative SST anomaly leading to droughts) seems to be sufficiently overpowering to neutralise the effects of El Niños in some cases. It also raises another question: do the Atlantic SST anomalies act independently or are they (even partially) related to Pacific SST? As mentioned earlier, a correlation analysis between equatorial eastern Pacific SST and Atlantic SSTs showed a correlation with North Atlantic SST (0.65 ± 0.05) and with South Atlantic SST (0.45 ± 0.06), both relatively large and significant. Hameed *et al.* (1993) suggested that atmospheric and ocean conditions in the Atlantic sector are related to conditions in the Pacific, not via an oceanic signal from the Pacific, but by changes in the atmospheric Walker circulation and the meridional circulation envisaged by Moura and Shukla (1981); SST gradients in the Atlantic are at least partially due to SO changes. Delecluse *et al.* (1994) also suggested that changes in the Walker circulation appear to connect the Central Equatorial Pacific and Equatorial Atlantic. Nobre and Shukla (1996) pointed out that the ENSO-related anomalous atmospheric patterns contribute to the genesis of dipole patterns in SST over the Atlantic. Thus, some connection between the Pacific and the Atlantic is envisaged, but it is by no means perfect.

Figure 4(l) is for 1997, 1998 and 1999, where the El Niño 1 + 2 started (exceeded the threshold of + 0.4°C) in March 1997 and El Niño 3.4 started in April 1997. The event is, therefore, comparable to 1951, 1953, 1957, 1965, 1972, 1976 and 1993, when El Niño 1 + 2 started before April. The following may be noted:

(i) The observed below-normal rainfall in northeast Brazil during March–May 1997 could be due to an El Niño effect, but the Atlantic SST anomaly was also favourable for droughts and all models predicted deficit rains in northeast Brazil (Colman *et al.* 1997; Graham, 1997; Greischar and Hastenrath, 1997; Harrison *et al.*, 1997). The prediction was based on Atlantic SST data of January 1997 when there was no trace of El Niño. Therefore, the effect of Atlantic SST is assumed to have prevailed and the role of El Niño seems dubious.
(ii) The Indian rainfall should have shown deficits; however, in June, July and August 1997, there were *severe floods in many parts of India*, and the final rainfall was only marginally in deficit in some areas and in excess in others (overall, positive). Incidentally, the India Meteorological Department (IMD) issues long-range forecasts for the southwest monsoon rainfall during the Indian summer (June–September) every May, based on the statistical models outlined by Thapliyal and Kulshrestha (1992). For 1997 summer monsoon, their prediction was for near-normal rainfall, which proved to be correct in spite of the strong El Niño. For the 1998 summer monsoon, the IMD predicted normal rainfall for the eleventh year in succession. Actually, the rainfall turned out to be in excess in many parts of India.
(iii) In 1997, there were excess rains in South Brazil and in Chile, where heavy excess rains caused the deserts to bloom.
(iv) For Australia, The Bureau of Meteorology, Australia, mentions that from 1 March 1997 to 30 April 1998, serious to severe deficiencies in rainfall occurred across southern and eastern Victoria and eastern Tasmania.

El Niño was still strong in January 1998 but was showing signs of weakening. Meanwhile, a dipole was developing in the Atlantic and hence, the January 1998 forecast by Andrew Colman of the Hadley Center, UKMO for northeast Brazil was for slightly wet conditions (private communication). However, an updated forecast given in the Experimental Long-Lead Forecast Bulletin (Colman *et al.*, 1998) prepared in early March 1998 using February 1998 SST seemed to indicate *drier conditions*. It was also mentioned that given the continuing strong El Niño, and the fact that the atmospheric model placed positive (wet) anomalies over the northeast, the *possibility of a dry or very dry season should also be considered*. Evans *et al.* (1998) gave a dynamical prediction of below-average rainfall for north-eastern South America, but above-average rainfall for northeast Brazil. Greischar and Hastenrath (1998) predicted wetter-than-normal conditions, but pointed out that whereas the pre-season northeast rainfall and the meridional SST gradient in the Atlantic sector point to abundant March–June 1998 precipitation, the Equatorial Pacific SST and the field of the meridional wind component in the Atlantic sector favour drier conditions. Hence, the precipitation should be only *slightly above average*. Cavalcanti *et al.* (1998) reported predictions from CPTEC, INPE, BRAZIL, based on the CPTEC version of the COLA AGCM, derived from the NCEP model (Kinter *et al.*, 1988) and a sophisticated biosphere model (Xue *et al.*, 1991). Their prediction was for *below-average* precipitation over much of northeast Brazil. During the main rainy season in northeast North Brazil (March, April and May, 1998), the region suffered one of the *most severe droughts in recorded history*. It will naturally be attributed to the 1997–1998 El Niño, again the strongest in recorded history. Thus, in spite of the progress in understanding the mechanisms which affect rainfall in northeast Brazil, predictions are still hazardous and could be greatly in error.

In India, 1998 will be a II-year El Niño event (like 1958 and 1983) and normal or excess rainfall is expected in 1998. Incidentally, for the 1997–1998 El Niño, the 12-monthly running averages show that the SO minima and Equatorial Eastern Pacific SST maxima were *not in the middle of 1997*, and although data are not yet complete, the SO minima and SST maxima will probably be *centered* towards the *end of 1997*.

Hence, 1997 and 1998 are both ENSOW-A events, and therefore not suitable for droughts in India. In Tasmania, the II-year events of 1958 and 1973 were also associated with excess rains; but 1983 showed deficit rainfall, as did 1997. It is interesting to note that 1991, 1992, 1993 and 1994 all had El Niños, a unique situation (according to Trenberth and Hoar, 1996, the longest on record), but droughts in northeast Brazil occurred only in 1992 and 1993, when El Niños occurred early in the year, while in 1991 and 1994, there were excess rains, since the El Niños started late in the year. However, all of this could also be due to the Atlantic SST anomalies which were favourable for just such situations (full rectangles in 1991, 1994; blank rectangles in 1992, 1993).

In south Brazil, a considerable influence arises from cold fronts originating in the Antarctic region. Their advance northwards is unpredictable and certainly not related to ENSO. Often, these cold fronts bring rain to Porto Alegre (South Brazil), but their advance northwards is obstructed by warmer air masses ahead and the fronts either linger over South Brazil, giving excess rains, or deviate to the Atlantic Ocean, sparing the rest of Brazil from their effects. When the cold fronts do manage to move northward, rainfall occurs in Sao Paulo and Rio de Janeiro, and even in Bahia. Thus, on occasion, all these regions have similar rainfall; more often however, the rainfalls are dissimilar, resulting in low correlations. In El Niño years, warm fronts in central Brazil may obstruct the southern cold fronts more effectively, resulting in drier conditions in the north and wetter conditions in the south of Brazil, but this pattern is very uncertain and irregular, resulting in the very low correlations between the rainfalls of Rio de Janeiro, Sao Paulo, Porto Alegre and Central Argentina. Therefore, predictions based upon El Niño effects alone in South Brazil are very often erroneous. In addition, SST in coastal South Brazil also seems to play an important local role in the rainfall of south Brazil and may not have any relationship with ENSO.

12. CONCLUSIONS

The El Niño phenomenon is popularly known to be associated with rainfall extremes in many regions of the globe. However, serious workers have long known that this relationship is not one-to-one, with some El Niños seeming to to have an almost negligible effect. Trenberth (1993) mentions the possibility that El Niños have different ‘flavors’. Recently, Kane (1997b,c) attempted a finer classification of El Niño events and noted that El Niños of the ENSOW-U type (El Niño years in which the SOI $T-D$ atmospheric pressure difference is minimum, and equatorial eastern Pacific SSTs are maximum in the middle of the calendar year, i.e. May–August) were overwhelmingly associated with droughts in India and some parts of Australia (e.g. Tasmania), while years of type C (La Niñas) were associated with excess rains. In this paper, this relationship is examined for some selected regions in Central and South America. The following was observed:

(i) For the SO Core Region (4°N–1°S, 155°W–167°E) and for the Gulf–Mexico Region (9°N, 90°W), all types of El Niños are effective in producing excess rains, while La Niñas produce droughts.

(ii) ENSOW-U events, which are very clearly associated with droughts in India and southeast Australia (Tasmania), were also associated with droughts in some parts of northeast Brazil (Ceara, Rio Grande do Norte, Paraiba, Pernambuco) and excess rains in Chile and Peru (river discharge data).

(iii) For C-type events (negative SST anomalies in the Pacific), which were clearly associated with excess rains in India and Tasmania, the relationship with northeast Brazil rainfall was not clear-cut. Chile and Peru had droughts during C events.

(iv) Other parts of Brazil and Argentina did not have clear relationships with either ENSOW or C events.

(v) Since northeast Brazil rainfall is known to be affected by Tropical Atlantic SST, all events when El Niños were not associated with droughts in northeast Brazil and when the C events were not associated with excess rains in northeast Brazil, were examined for the status of SST and wind components in the Tropical Atlantic. It was noticed that in each case, the Atlantic parameter anomalies had interfered to spoil the El Niño or C relationships with rainfalls. Thus, predictions of rainfall anomalies in northeast Brazil must be based on conditions in the Pacific as well as the Atlantic, although Atlantic SST seems to play a dominant role.

(vi) All El Niños did not start in the same month. The starting month had some relevance in the sense that events occurring soon after the starting of the El Niño had a better chance of feeling the effect (El Niño starting in January affecting northeast Brazil rainfall occurring during March–May etc.). However, some embarrassing situations occurred when the effects were felt before the El Niño started (northeast Brazil rainfall during March–May showing droughts while El Niño started in April and strengthened in July). A closer examination revealed that these droughts occurred because the Atlantic SST in January (before the rainfall season) was below normal.

(vii) The expectation that El Niños would be associated with droughts in northeast Brazil and floods in South Brazil was often belied. The correlation between northeast Brazil and South Brazil rainfalls was not highly negative. In addition, rainfalls in Sao Paulo, Rio de Janeiro, Porto Alegre and Central Argentina were poorly interrelated. Thus, in each case local effects and/or different mechanisms appear to be interfering. For northeast Brazil, the Atlantic SST is very important. In the case of south Brazil, cold fronts from the Antarctic seem to play a prominent role. These fronts advance northwards in an irregular, unpredictable manner, mainly unrelated to El Niños, although the presence of a strong El Niño sometimes seems to inhibit the northward advance of the cold fronts.

(viii) A strong El Niño developed in March 1997. The rainfall in northeast Brazil during March–April–May, 1997 was below normal (15–30%). However, such a deficit was predicted on the basis of Atlantic SST anomalies in January 1997, when there was no sign of El Niño. Thus, the role of this El Niño in causing the deficit rains in northeast Brazil in 1997 was dubious. The El Niño continued strong in January 1998. Since an SST dipole was also developing in the Atlantic, initial predictions were for slightly above-average rainfall in northeast Brazil. However, Atlantic conditions changed rapidly thereafter; the El Niño did not weaken, and the prediction had to be revised, to below-average rainfall. What followed was a disaster. In northeast Brazil, rains in the main season March–April–May, 1998 did not occur and very severe drought conditions prevailed.

(ix) On the basis of El Niño alone, droughts were expected in India in 1997. Instead, only slightly deficit rains occurred in some regions and excess rains in others (overall, rains were slightly in excess). In 1998, continuation of the El Niño would indicate the II-year of a double event (1997–1998) and previous experience indicates a possibility of floods or normal rains (not droughts) in 1998. The India Meteorological Department (IMD) predicted normal rains in All-India for the 1997 summer monsoon, which proved to be correct. The IMD also predicted normal rains for the All-India summer monsoon in 1998. Actually, rainfall was in excess.

For the prediction of rainfall anomalies in northeast and other parts of Brazil, several models are currently in use. The forecasts from these do not always correspond with each other, nor do any of them give correct predictions in all years. Clearly, some factors have escaped notice. With more experience, these deficiencies should be overcome.

The finer classification in this paper—ENSOW-U and ENSOW-A—is based on the occurrence of the SO index minima and Pacific SST maxima in the *middle of the calendar year*. Does this have any physical significance? A clue comes from the analysis of Ward *et al.* (1994), where years were classified as to whether they were wet (excess rains) or dry (droughts) in the Sahel and India, and their average characteristics were studied in terms of SST anomalies in the Pacific. They found that years of type I which were associated with a near-global rainfall teleconnection, including a tropic-wide oscillation, showed a strong contrast in SST anomalies between the central/eastern Tropical Pacific and western Tropical Pacific, leading to a strong perturbation in the longitude of the maximum in the zonal SST profile at 0–10°S in the western Pacific. Earlier, Fu *et al.* (1986) identified two distinct patterns in Pacific SST. In one, the Pacific was warmer east of the dateline, warmer in the Central Pacific, and slightly below normal west of the dateline (examples 1957, 1965, 1972 and 1982). In another, the Pacific was warmer everywhere (examples 1963 and 1969). In cases like 1976, there was a mixture of the two patterns. These different SST patterns in the Pacific (different El Niño flavors?) could have different effects on the world climate.

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