The Pacific El Niño Phenomenon and the Atlantic Circulation

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ABSTRACT

Atmospheric-oceanic departure patterns in the tropical Atlantic and eastern Pacific associated with the Ecuador/Peru El Niño and its antithesis are studied on the basis of long-term ship observations during 1911–71. Departure maps of sea level pressure (SLP), wind speed and sea surface temperature (SST) in March/April are presented for composites of ten extreme years of either regime. The evolution of SLP anomalies from the preceding to the event year is traced for large ocean areas. Gaussian and binomial probabilities are calculated as a measure of the importance of SLP departures.

El Niño years are characterized by abnormally low SLP over the eastern South Pacific and positive SLP anomalies over the Atlantic; winds are weaker than normal over the Pacific, and stronger over the Atlantic; SST anomalies are positive in the Pacific, but negative in a band of the Atlantic extending from West Africa toward the South American coast. During counter-El Niño years, departure patterns are approximately inverse. Departure patterns during droughts and floods in northeast Brazil are similar to, but not identical with, the ones obtained by stratification with regard to the Ecuador/Peru El Niño and counter-El Niño, respectively.

El Niño has a tendency to occur in a series of successive years, as does its antithesis. The seasonal development of departure patterns in *initial* El Niño years (a single event or the first in a sequence) and *sequential* years (the second or later years in a sequence) differs, in that an initial El Niño tends to be heralded by anomalously high SLP and cold waters in the eastern South Pacific. In sequential years, the pre-season exhibits anomalies of the same sign as the peak season. Statistical probabilities indicate the possibility of foreshadowing initial El Niño from SLP anomalies in the Atlantic.

1. Introduction

A general understanding of the El Niño phenomenon along the South American west coast has been reached in the context of the atmospheric-hydrospheric dynamics of the greater Pacific basin (Quinn, 1974; Wyrtki, 1975; Hurlburt *et al.*, 1976; McCreary, 1976; Barnett, 1977). Based on the early work of Walker (Walker and Bliss, 1937), Berlage (1957, 1966) studied the "Southern Oscillation" in particular, defining it as an exchange of air between centers in the eastern South Pacific and the Indonesian-North Australian area, with a time scale of the order of 1–5 years. Pressure variations over the South Atlantic were found to be broadly in phase with Indonesia and out of phase with the eastern South Pacific, a nodal line being located in the South American sector. Berlage (1966) also discovered that the warm-water El Niño events off the Ecuador/Peru coast tend to be associated with low pressure over the eastern South Pacific. Bjerknes (1969) suggested linkages between the Southern Oscillation, equatorial sea temperature anomalies and the extratropical circulation. Lettau (1976) hypothesized that El Niño may be caused by strictly regional factors. Caviedes (1973) noted the occasional simultaneity of the Ecuador/Peru El Niño and the northeast Brazil Sêca. Wyrtki (1975), Hurlburt *et al.* (1976), McCreary (1976) and Barnett (1977) explained the appearance of the warm water characteristics of the El Niño in terms of an oceanic response to the relaxation of wind stress over the open equatorial Pacific. The wind stress pattern, in turn, is controlled by the altered pressure distribution.

Large-scale pressure variations encompassing the South Atlantic were also found to be instrumental for climatic hazards in northeast Brazil (Hastenrath and Heller, 1977; Markham and McLain, 1977), and for the positive coupling between the northeast Brazil Sêcas and the Ecuador/Peru El Niño. Expanding on earlier work on Pacific anomalies, the present paper explores the anomaly patterns of key atmospheric-hydrospheric fields in the Atlantic region, in particular, that are associated with the Pacific El Niño and its antithesis.

2. Data

The observational basis of the project has been described in detail elsewhere (Hastenrath, 1976;

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Hastenrath and Heller, 1977; Hastenrath and Lamb, 1977). Ship data comprising more than 7 000 000 individual observations for the period 1911–72 were obtained on magnetic tape from the National Climatic Center at Asheville, NC. These were in the form of individual monthly averages of various meteorological parameters in 1° square areas of the tropical Atlantic and eastern Pacific Oceans (30°N–30°S). Parameters include surface wind speed and direction, sea level pressure (SLP) and sea surface temperature (SST). Data were subjected to quality control checks, with values beyond physically reasonable limits being excluded. Wind speed was converted from original Beaufort estimates. Sixty-year mean and individual monthly fields are stored on magnetic tape, and computer programs have been developed to access and analyze the various data decks, including machine plotting of scalar and vector quantities. Fields were subjected to a filter designed by Bleck (Hantel, 1970).

Time series of various meteorological elements were compiled from this data set for large ocean areas, with the aim of compacting the information and enhancing data stability. Elements of interest here are SLP and SST. The blocks were delineated from our earlier experience with climatic mean and anomaly patterns.

As an indicator of pressure variations over the eastern South Pacific, a time series of monthly mean SLP values during 1942–74 at Easter Island has been used (courtesy of Dr. W. Quinn). SST observations are available for several ports along the Ecuador/Peru coast, the longest series being 1925–69 for Puerto Chicama. The aforementioned ocean blocks and stations are shown in Fig. 1.

A time series of an index of SST off the Ecuador/Peru coast (Ec/Peru SST) was constructed from calendar-year averages of SST at the ports of La Libertad, Puerto Chicama and Chancay, and ship observations in the coastal strip 0–10°S, 78–82°W. The three ports are contained within this rectangle. Half of the weight was assigned to the ship observations, and the other half to the average of the port data. Although other weighting schemes are conceivable, the compositing scheme seems adequate for the present purposes of identifying El Niño and counter-El Niño years. Fig. 2 is a time series plot of this SST index.

3. Regional extreme events

The time series plot of annual Ec/Peru SST in Fig. 2 shows an alternation of extremely warm ("El Niño") and cold years ("counter-El Niño"). From this series ten extremely warm and cold years shall be selected. It may appear plausible to choose the ten years of largest departure of either sign. However, it was also found desirable to include the highly interesting counter-El Niño sequence 1935–36–37–38,

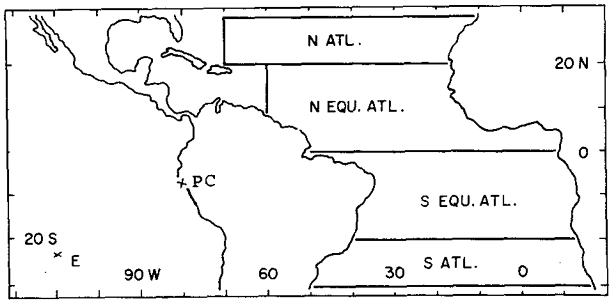

FIG. 1. Orientation map. Atlantic ocean blocks of SLP time series: E = Easter Island; PC = Puerto Chicama.

and the El Niño sequence 1939–40–41, although 1936 and 1940–41 were not among the ten most extreme years. In fact, 1964 and 1967–68 were slightly colder than 1936, and 1951 and 1969 were slightly warmer than 1940–41. Extreme years along the Ecuador/Peru littoral were thus chosen for further analysis as follows: 1925, 26, 39, 40, 41, 43, 53, 57, 58 and 65 as El Niño; and 1922, 24, 35, 36, 37, 38, 50, 54, 55 and 62 as counter-El Niño. Departure of these years from the long-term mean is at least 0.75 σ.

A composite rainfall time series for northeast Brazil (NE BRAZIL) is of interest here, because of its significant negative correlation with Ec/Peru SST (Hastenrath, 1976; Hastenrath and Heller, 1977). In a plot similar to the present Fig. 2, this series is exhibited as Fig. 2 in Hastenrath and Heller (1977). From that time series, the ten most extreme years in northeast Brazil were identified as 1915, 19, 30, 31, 32, 36, 42, 51, 53, 58, as dry; and 1917, 21, 22, 24, 26, 34, 35, 40, 64, 67, as wet.

A comparison of the aforementioned years shows some tendency for El Niño, counter-El Niño, and drought/flood years in northeast Brazil to occur in short sequences or "regimes."

4. The onset of El Niño and its antithesis at Puerto Chicama

The evolution of extreme SST regimes is exemplified in Table 1 by Puerto Chicama. Separate collectives are considered for *initial* El Niño/counter-El Niño (a single event, or the first in a sequence), and for *sequential* years (the second or later years in a sequence). Values are listed for all twelve months of the year preceding, and the first seven months of the respective event years themselves. Departures from the 1925–69 monthly mean are expressed in terms of standard deviation.

Table 1a shows that *initial* El Niño years tend to be preceded by particularly strong negative SST anomalies, with an abrupt switch of the departure sign occurring from December of the preceding to February of the El Niño year. This state of affairs has been noted before (Hastenrath, 1976; Wright,

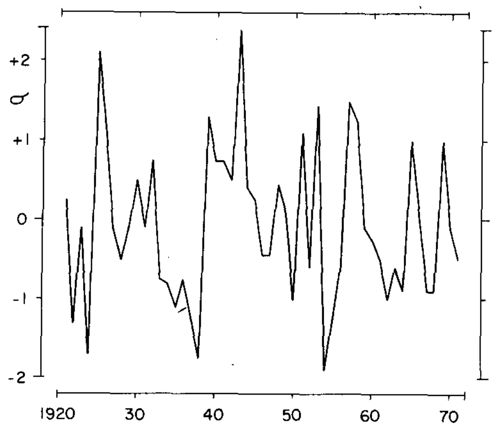

FIG. 2. Normalized departures of calendar-year mean SST along the Ecuador/Peru coast ($\sigma = 0.8°C$).

1977), and is consistent with evidence presented by Quinn (1974) to the effect that major El Niño events tend to follow an abrupt change in atmospheric pressure distribution over the eastern South Pacific.

Table 1b shows rather different characteristics for counter-El Niño, in that initial years are not preceded by marked departures. The strong negative SST anomalies instead develop rather gradually. A similar contrast in the development of El Niño as compared to counter-El Niño years has been noted by Namias (1976).

5. Circulation patterns of El Niño and counter-El Niño

Large-scale circulation characteristics in March/April are illustrated in Figs. 3 and 4 by mean departure charts for the ten extreme El Niño and counter-El Niño years, respectively, as discussed in Section 3. These months were chosen because they seem to comprise the season with highest coastal SST and greatest likelihood of precipitation in the otherwise desertic littoral strip of Ecuador and Peru. Maps for the preceding September/October were also constructed, but are not shown here. Sea level pressure, wind and SST are the key elements chosen for representation in the form of departure maps; departures being understood as the mean of the selected years minus the 60-year mean.

During the El Niño years on the Ecuador/Peru coast (Fig. 3), pressure is anomalously low over the eastern Pacific, a feature familiar from earlier studies (Quinn, 1974; Hastenrath, 1976; Hastenrath and Heller, 1977). More remarkable is the concurrent positive pressure departure over essentially all of the tropical Atlantic. The wind field is somewhat slack over the eastern Pacific, but not the Atlantic. A very slight southward displacement of the near-equatorial wind discontinuity is indicated over the Pacific during El Niño years. The SST chart shows anomalously warm waters in the eastern Pacific especially to the south of the equator. In the Atlantic a cold water band is apparent from West Africa to the coast of Brazil.

During the counter-El Niño years (Fig. 4), patterns are approximately inverse to the ones shown in Fig. 3: pressure is anomalously high over the eastern Pacific, but not the Atlantic; winds are rather slack over much of the Atlantic; and cold waters prevail in the eastern Pacific and most of the Atlantic, except for a band of positive anomaly extending from West Africa toward the coast of South America. A very slight northward displacement of the near-equatorial wind discontinuity is indicated over the Pacific during counter-El Niño years.

6. Evolution and statistical significance of SLP departure patterns

Figs. 3 and 4 illustrate that Pacific El Niño events and their antithesis are concomitant with marked atmospheric–hydrospheric departures in the Atlantic region. In the present section an attempt is made to trace the gradual evolution of SLP departure configurations, and to apply statistical criteria to the observed anomalies.

First, monthly departures were expressed as standard deviations from the long-term mean. This procedure may be affected by spuriously large values in one or a few individual years. Independently, values above and below the long-term average can be counted and evaluated in terms of binomial probability (Brooks

TABLE 1. Puerto Chicama SST for composites of El Niño and its antithesis, and corresponding preceding years, expressed as normalized departure (tenths of σ) from 1925–69 mean. March/April of the event year is italicized. For El Niño, *initial* years are 1939, 43, 53, 57, 65; and *sequential* years 1926, 40, 41, 58. For counter-El Niño, *initial* years are 1935, 50, 54, 62; and *sequential* years 1936, 37, 38, 55.

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	*M*	*A*	M	J	J
a. El Niño																			
1. Initial	−2	−6	−5	−10	−8	−7	−9	−14	−7	−8	−8	−8	+1	+9	+7	+11	+11	+12	+9
2. Sequential	+3	+7	+14	+10	+12	+11	+10	+16	+7	+9	+7	+19	+17	+12	+13	+8	+8	+6	+4
b. Counter-El Niño																			
1. Initial	−3	+1	+1	0	0	+1	0	0	0	−2	−2	−6	−6	−13	−11	−10	−9	−11	−11
2. Sequential	−10	−7	−5	−5	−5	−11	−10	−17	−12	−11	−8	−6	−9	−5	−4	−7	−8	−10	−10

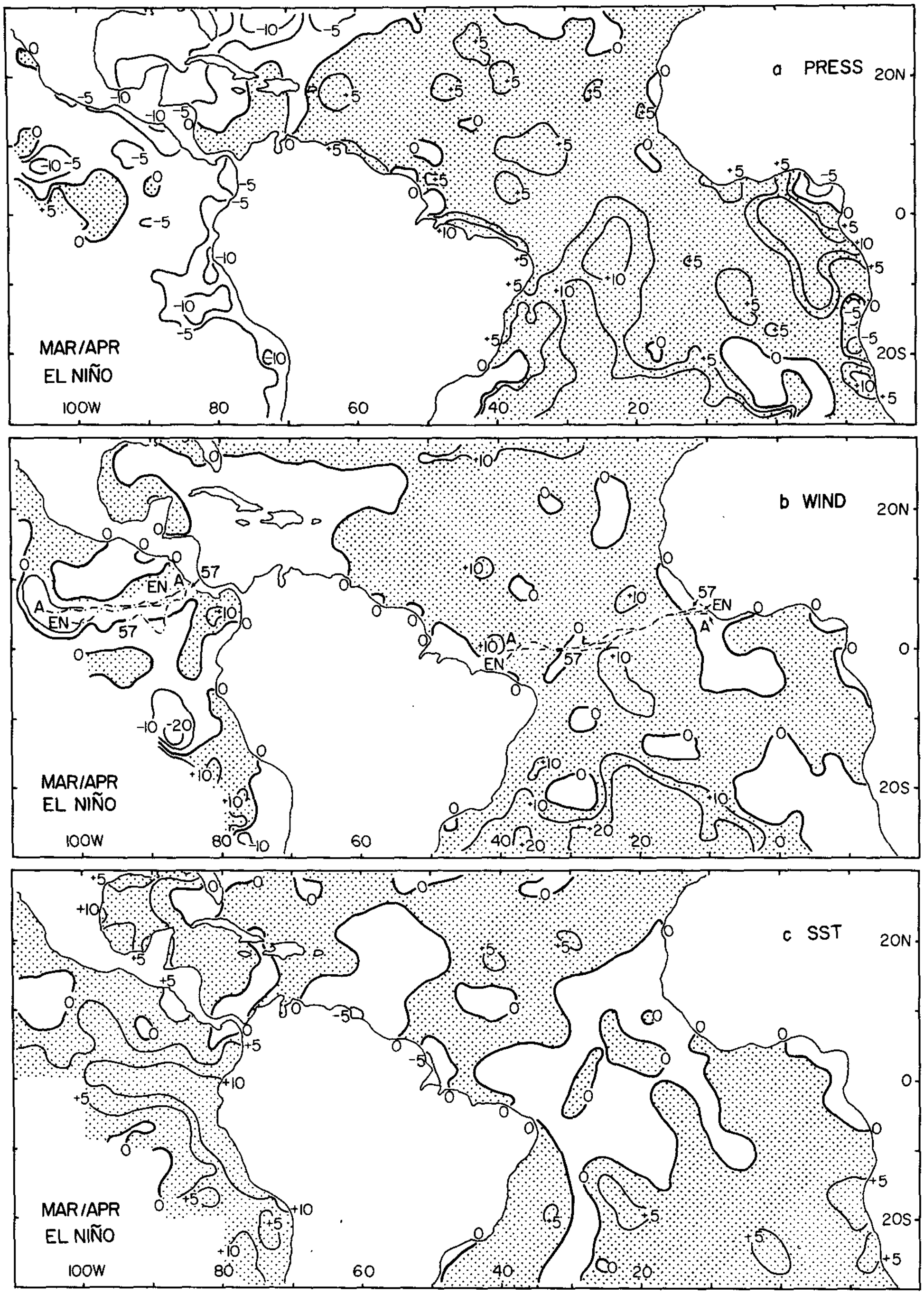

FIG. 3. March/April composite of ten El Niño years expressed as departure (zero line heavy, positive areas shaded) from 60-year mean pattern: (a) sea level pressure, isopleth interval 0.5 mb; (b) resultant wind isotachs (0.1 m s^{-1}), position of confluence axis dash-dotted with A, EN and 57 denoting 60-year mean, 10-year El Niño composite and El Niño year 1957, respectively; (c) SST (0.1°C).

and Carruthers, 1953, pp. 70–84; Panofsky and Brier, 1968, pp. 33–35). The binomial count in part circumvents the problem of spuriously large departure values in individual years. The evaluation in terms of Gaussian probabilities yields results similar to the binomial counts. Only the binomial probabilities are presented in Tables 2–4. In the light of the different seasonal development borne out by Table 1, Tables 2–4 also distinguish between *initial* and *sequential* years.

It will be noted that statistical probabilities cited in the following discussion are mostly outside conventional significance limits. The term "significance"

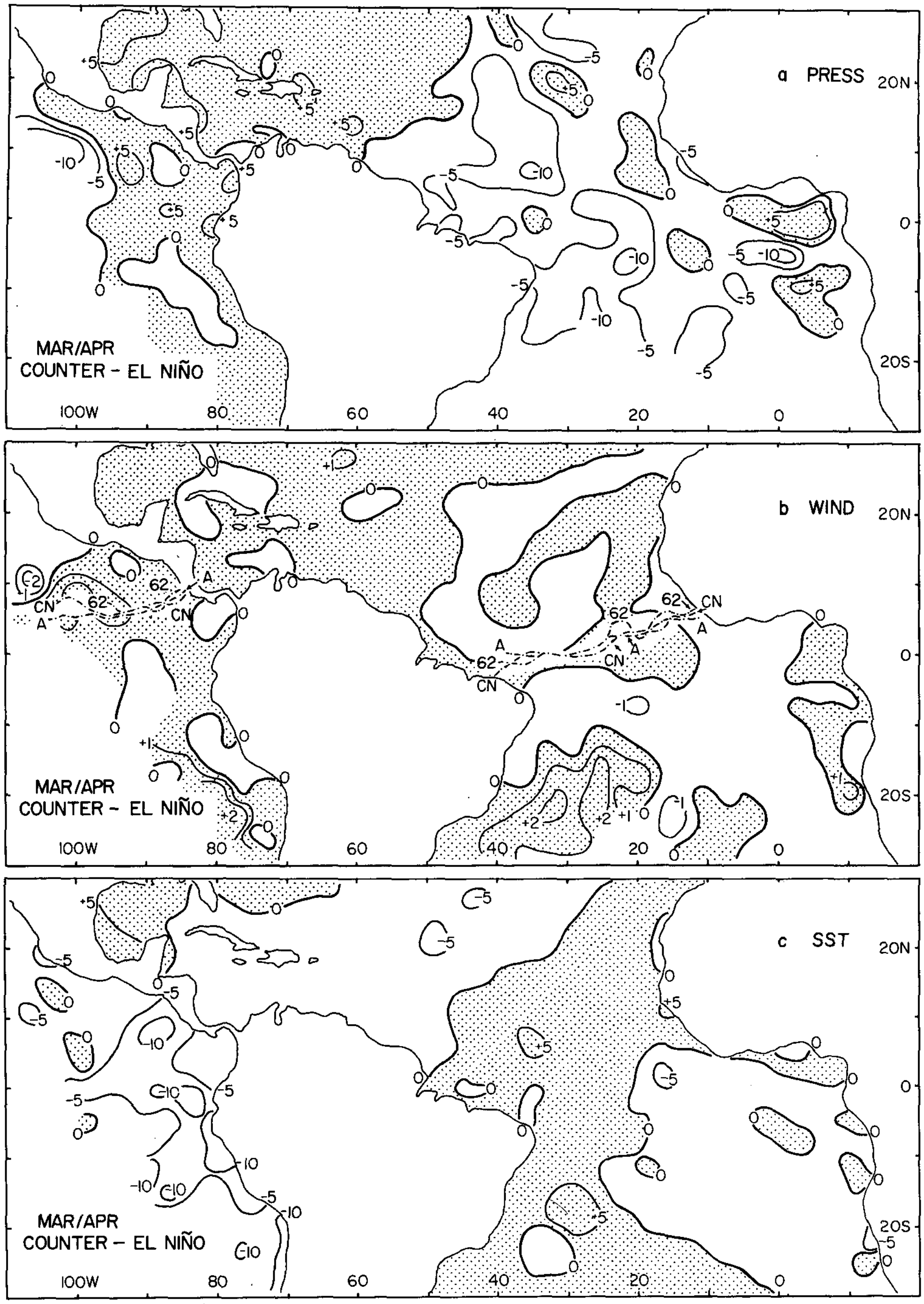

FIG. 4. As in Fig. 3 except for ten counter-El Niño years. CN and 62 denote 10-year counter-El Niño composite, and counter-El Niño year 1962, respectively.

will be used only for statistical probabilities of 5% or less.

For the evolution of El Niño refer to Table 2. Initial El Niño (Table 2a) is preceded by a transition from positive to negative departure signs at Easter Island around September and a switch in the opposite sense in most of the tropical Atlantic in December/January. The predominance of negative departures for Easter Island reaches a minimum statistical probability of 6% in November and in February of the initial El Niño year. Similar patterns appear also for sequential El Niño in Table 2b.

For the evolution of counter-El Niño refer to Table 3. For the collective of initial years (Table 3a) the positive SLP departures at Easter Island reach their minimum statistical probability in April/May

TABLE 2. Monthly SLP departure signs (p for positive and n for negative) most often observed in the El Niño years of Table 1, and corresponding preceding years, for sea areas shown in Fig. 1. p, P, *P* and n, N, *N*, respectively, denote binomial probability <40, <20 and <10%. March/April of El Niño year is italicized.

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	*M*	*A*	M	J	J
a. Initial years																			
N Atlantic	p	n		n	p	p		p		p		p		*P*	p		p		p
N Equatorial Atlantic		*N*					n	*P*		n	n	*N*	*P*	p	p	*P*	n		*P*
S Equatorial Atlantic	*N*	*N*		n		p		p	p			n	p	n	p	p		p	*N*
S Atlantic		*N*	p		*P*		*N*	p		p		n	*P*					*P*	n
Easter Island	p			p				p		n	*N*			*N*	n	n	n		n
b. Sequential years																			
N Atlantic	P	*P*	n		p	*N*		n	*N*	p	*P*		*N*		*N*		n	n	
N Equatorial Atlantic		p	n	p	n	n		n	n		*P*	*P*	n			p			
S Equatorial Atlantic	p			p	n		*N*		n	n	*P*	*P*	p		p	*P*	p	p	
S Atlantic			n	p			*N*	n	n	n	p			n		p	p	p	
Easter Island*	n	n	n	n	n	n	n	p	n	p	n	n	p	p	n	n	n	p	n

*Since only one sequential El Niño year was included within the Easter Island SLP series, monthly departure signs shown are not significant beyond the 40% level.

of the initial year. For the South Atlantic and the equatorial North Atlantic, negative departure signs are indicated in most months after October. Positive SLP departures prevail in the North Atlantic during the larger part of the 19-month period, with the positive SLP departure in September being significant at the 2% level.

Prominent features of sequential years (Table 3b) include strong positive SLP departures at Easter Island especially from September onward, concomitant with negative SLP departures in much of the Atlantic from around December. The predominance of negative departures reaches a minimum statistical probability of 6% in the North Atlantic in December; and in the equatorial North Atlantic in March of the sequential counter-El Niño year.

Binomial probabilities of SLP departures are presented in Table 4 for drought and flood in northeast Brazil. For drought in northeast Brazil (Table 4a) predominant departure signs in most of the 19 months are negative at Easter Island, and positive in the equatorial North Atlantic and the South Atlantic. In the North Atlantic, dominant departures are generally positive in January–November of the preceding year, and negative in January–May of the drought year. The predominance of negative SLP departures in the North Atlantic reaches significance at the 3% level in March and a statistical probability of 7% in April and May of the drought year.

Predominant SLP departure signs for floods in northeast Brazil are shown in Table 4b. Negative SLP departures prevail in most of the 19 months in the equatorial North Atlantic and the South Atlantic.

7. Conclusions

El Niño events along the west coast of South America have come to be understood in the context

TABLE 3. As in Table 2 except for the counter-El Niño years of Table 1. March/April of counter-El Niño year is italicized.

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	*M*	*A*	M	J	J
a. Initial years																			
N Atlantic		*P*	p	p				*P*	*P*	p	n		p	p	p	p	p	p	*P*
N Equatorial Atlantic		p		*P*		p	*N*	p	n	n			n	p			n	n	n
S Equatorial Atlantic		n		p			p	n		n	n	N			p	n			n
S Atlantic	n	n	n		n	n		p			n	*N*		n	n	p		p	
Easter Island	p	n	p	n	p	p	n	n	p	n	p	p	p	p	n	P	P	n	p
b. Sequential years																			
N Atlantic			p	p	n	p	p	n		*P*		*N*		n					n
N Equatorial Atlantic		p	n	p	n		n	*N*	p	p	p		n	n	*N*		n		n
S Equatorial Atlantic	p	p	p	p	p	p	n			n		n		n	n				
S Atlantic	p	n			p		N		P				p	n	n	n			n
Easter Island*	p	p	n	p	p	n	p	n	p	p	p	p	p	p	p	p	p	p	p

* Since only one sequential CEN year was included within the Easter Island SLP series, monthly departure signs shown are not significant beyond the 40% level.

TABLE 4. Monthly SLP departure signs (p for positive and n for negative) most often observed in the extreme years in northeast Brazil of Table 1, and corresponding preceding years, for sea areas shown in Fig. 1. Otherwise notation as in Table 1.

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	*M*	*A*	M	J	J
a. Dry years																			
N Atlantic	p	p	n	p	P	*P*	p	p	n	p	p	n	n	N	*N*	*N*	*N*		P
N Equatorial Atlantic	p	N	*P*	p	P	P	n	P	n	p	N	p	p	n		p	p	P	
S Equatorial Atlantic	p	N	P	n	P	P	n		p	p		P	P	n	P	P	P	P	p
S Atlantic	p	N		p	P	n		p	p		n	P	P		P	p	*P*	p	
Easter Island	p	n	n	n	p	n	p	n	N	p	n	n	P	n	p	N	n	p	N
b. Wet years																			
N Atlantic		p	*P*	n	p	*N*	N		p		P	p	n	P	P	n	P	*N*	n
N Equatioral Atlantic	n	p	N		N	N	*N*	n	n	n	P	p	n	n	*N*	p	N	*N*	*N*
S Equatorial Atlantic	n	n	N	N	n	N	n	N	n	n	n	n	N	*N*	P	n	p	n	*N*
S Atlantic	n		N	*N*	N	N	n	n	*N*	N	n	N	N	*N*	n	P	n	n	N
Easter Island		p		n	n					n				p	p			p	

of the atmospheric–hydrospheric dynamics of the greater Pacific basin. The present study shows that extreme events of Ecuador/Peru are also associated with distinct departure configurations in the tropical Atlantic. A prominent feature already suggested by Hastenrath and Heller (1977), and substantiated in the present paper, is an inverse pressure variation over the eastern Pacific and the Atlantic: during El Niño, for example, SLP is low over the eastern South Pacific but high over the Atlantic, especially the South. This SLP configuration favors Sêcas in northeast Brazil concurrent with El Niño off Ecuador/Peru, although simultaneity of these regional extreme events is not universal. The study further shows that initial El Niño years are preceded by anomaly configurations that are approximately inverse to those of the peak season—a circumstance not found with sequential El Niño years.

Only broad probability intervals are considered in Tables 2–4. With a view toward seasonal prognosis, more detailed figures shall be given here for the critical ocean areas and months.

Initial El Niño (Table 2) is heralded by negative SLP departures at Easter Island in the preceding November with 94% frequency. The associated SLP departure of 1.1 σ is, on the basis of a Gaussian distribution, to be expected with a probability of 14%. Positive SLP departures in the South Atlantic and equatorial North Atlantic (Fig. 1) during the preceding January would be expected with 91% frequency.

Initial counter-El Niño (Table 3) is foreshadowed only poorly by events at Easter Island. However, negative SLP departures in the South Atlantic and equatorial South Atlantic (Fig. 1) in the preceding December can be expected with 91 and 84% frequency, respectively. That is, SLP in the Atlantic seems to provide a better predictor for counter-El Niño than SLP at Easter Island.

The climatic hazards in northeast Brazil (Table 4) appear to be preceded more strongly by events in the tropical Atlantic than in the eastern Pacific. Markham and McLain (1977) have noted that the SST departure sign in a specified area of the eastern South Atlantic is followed approximately 70% of the time by similar departure signs of rainfall during the following January–March in northeast Brazil. In the present study it was found that positive SLP departures in the tropical Atlantic during May preceding the drought year can be expected with 84–89% frequency. In addition, negative SLP departures at Easter Island in September preceding the drought year is expected with 87% frequency. The associated SLP departure of 0.8 σ would on the basis of a Gaussian distribution correspond to a probability of occurrence of 21%.

Extremely wet years in northeast Brazil are heralded by negative SLP departures in the tropical Atlantic (Fig. 1) during June of the preceding year with 89–93% frequency. The associated SLP departures of 0.7 and 0.6 σ are on the basis of a Gaussian distribution to be expected with probabilities of 24 and 27%, respectively. Positive SLP departures at Easter Island during February of the extremely wet year are expected with 75% frequency. The typical associated SLP departure of 0.5 σ would on the basis of a Gaussian distribution correspond to a probability of occurrence of 31%.

The tendency for the linkage of climatic hazards in northeast Brazil and along the Ecuador/Peru coast appears related to inverse large-scale SLP variations over the tropical Atlantic and eastern Pacific Oceans. The implied anomaly mechanisms offer the prospect of foreshadowing the Pacific El Niño and its antithesis, as well as the hydrometeorological extreme events in northeast Brazil from SLP developments in the South Atlantic. The inverse SLP tendencies in the subtropical highs of the two Southern Oceans in turn seem to be part of mass exchange processes on the scale of the near global tropics.

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