ANNUAL AND SEASONAL PATTERNS OF RAINFALL VARIABILITY OVER VENEZUELA

With 6 figures and 6 tables

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Zusammenfassung: Jährliche und jahreszeitliche Muster der Niederschlagsvariabilität in Venezuela

Für 60 Stationen in Venezuela wurden die monatlichen Niederschlagssummen der Periode 1972–1986 mittels Hauptkomponenten- und Cluster-Analyse untersucht und klassifiziert. Dabei ergeben sich drei Klassen von Klimaregionen mit insgesamt acht Untertypen. Es wurden mehrere Faktoren herausgearbeitet, die den jahreszeitlichen Niederschlagsgang in den verschiedenen Regionen des nördlichen Südamerika beeinflussen und abwandeln.

Synoptisch-klimatologische Voraussetzungen für eine überdurchschnittlich feuchte Regenzeit in Venezuela sind anscheinend Faktorenkombinationen von: positiven Werten des Southern Oscillation Index SOI, unterdurchschnittlichen Temperaturen der Meeresoberfläche (SSTs) im Ostpazifik südlich des Äquators sowie im Südatlantik, überdurchschnittlichen SSTs in der Karibik, kräftigen Ostwinden im 200 mb-Niveau zwischen 5°–15° N mit einem nordwärts verschobenen Südatlantischen Hoch (300 mb) im Winter, das in Brasilien bis in Äquatornähe reicht.

Im Juli–August können einige oder alle der genannten Voraussetzungen zu einem gesteigerten Regenmaximum in der großen Zentralregion führen, obwohl dann auch der Luftdruck am Boden seine höchsten Werte erreicht. In Regenzeiten mit unterschiedlichen Niederschlägen kehren sich die Voraussetzungen um: ein gut entwickelter El Niño zusammen mit kräftigen und beständigen Höhen-Westwinden, deren Zentrum über der südlichen Karibik und entlang der Nordküste von Venezuela liegt.

1 Introduction

The geography of northern South America with the Caribbean Sea to the north is reversed from that in South Asia and West Africa. Accordingly, the mean seasonal march of precipitation in Venezuela differs sharply from that in 'monsoon' areas. The main objective of this study is to investigate the nature and causes of interannual variability within the principal climatological rainfall regimes of Venezuela. Venezuela, which lies between latitudes 1° and 12° N and longitudes 60° and 73° W, can be divided into three major climatic sections of roughly equal size (SNOW 1976): (1) the north and west, comprising the Maracaibo basin, the east-west orientated Cordillera de la Costa (elevation <1500 m), and the prominent southwest-northeast orientated Cordillera de Merida (up to 5000 m); (2) the central area, known as the "Llanos", a vast, low-lying basin; and (3) the Guyana Highlands in the southeast, with elevations between 400 and 1400 m.

Previous research on precipitation in Venezuela has described its general characteristics (SNOW 1976, BARRIOS 1981, GOLDBRUNNER 1985). Explanations of the large-scale spatial features of rainfall have primarily invoked latitudinal shifts in the seasonal location of the Atlantic ITCZ (MOREAU a. DEFFIT 1979, HOFFMANN 1992), and the North Atlantic subtropical anticyclone (LAUER 1975).

The factors controlling interannual precipitation variability have been little investigated. The variability does not result from the simple passage of an equatorial trough. Emphasis is placed in this study on determining the causes and modulations of the well-known bimodal annual pattern (secondary minimum in July–August) west of about 70° W compared with the July–August maximum over the Llanos. In the eastern near-coastal region the fluctuations of the ITCZ over the western Atlantic must be taken into account. Additionally, a dry regime prevails north of the east-west Cordillera de la Costa which is related to low-level seasonal wind changes. The prevailing southeast winds of the main rainy season produce downslope winds and dryness north of the mountains. In the main dry season the northerly to easterly lowlevel winds produce an upslope component (LAHEY 1958). However, the precipitation remains so small that wide variations from any averaged climatic curve can occur at any time of the year.

Frequency distributions and statistics of cumulative precipitation show that tropical precipitation falls primarily during short episodes of a few hours duration. Nevertheless, these mesoscale episodes (see ZIPSER 1969) occur in association with various types of synoptic disturbance (e. g. surges in the easterlies) and are seldom determined by isolated convective activity. Investigations of rainfall in northern Venezuela during 1969 and 1972 by RIEHL (1977 a, 1977 b) and colleagues (RIEHL et al. 1973), suggest that intrusions of high tropospheric troughs from the Northern Hemisphere and their subsequent break-off from the extratropical portion near 20°–25° latitude can give rise to large 200-mb anticyclonic

Table 1a: List of stations used in regional classification and for calculating the all-Venezuela index C_i*. Characteristics of each class are discussed in Section 3*

Liste der Stationen, die für die regionale Klimaklassifikation und zur Berechnung des Index C_i für Gesamt-Venezuela benutzt wurden

Station	Latitude	Longitude	Altitude (m)	Annual precip. (mm)	Class
01 Acarigua	09° 35′	69° 14′	225	1540	2a
02 Amenadina	04° 09′	63° 41′	900	2810	3a
03 Barcelona	10° 08′	64° 41′	7	499	1a
04 Barquisimeto	10° 05′	69° 18′	528	690	2b
05 Banco San Pedro	08° 45′	67° 31′	100	1200	2a
06 Bruzual	08° 00′	69° 21′	80	1468	2a
07 Cagigal	10° 30′	66° 51′	1035	791	2b
08 Canal Voc	10° 03′	71° 12′	2	934	1b
09 Cararabo	06° 10′	69° 16′	77	2313	3b
10 Cariaco	10° 30′	63° 36′	12	824	2a
11 Ciudad Bolivar	08° 08′	65° 32′	43	765	2a
12 Coro	11° 25′	69° 41′	21	345	1a
13 Elorza	07° 03′	69° 29′	90	1886	2a
14 El Tigre	08° 54′	64° 15′	280	860	2a
15 Guanare	09° 01′	69° 44′	163	1675	2a
16 Guasdualito	07° 15′	70° 45′	101	1750	2a
17 La Asuncion	11° 01′	62° 31′	100	588	1a
18 La Corcovada	10° 05′	64° 34′	90	1149	2a
19 La Orchila	11° 48′	66° 11′	3	277	1a
20 La Vergerena	06° 46′	63° 36′	222	1709	2a
21 La Vitera	07° 17′	65° 48′	90	1447	2a
22 Machiques	10° 03′	72° 34′	99	1463	1b
23 Maracaibo	10° 38′	71° 36′	40	581	1b
24 Maracay	10° 15′	67° 38′	442	927	2b
25 Maripa	07° 26′	65° 11′	35	2010	2a
26 Maturin	09° 45′	63° 12′	66	1391	2a
27 Mene Grande	09° 49′	70° 56′	18	1185	1b
28 Merida	08° 36′	71° 09′	1470	1801	1c
29 Moroturo	10° 33′	69° 14′	190	1111	2b
30 Musinacio	07° 42′	74° 21′	52	1483	2a
31 Palmira	07° 51′	72° 14′	1100	949	1c
32 Puerto Ayacucho	05° 37′	67° 37′	74	2335	3b
33 Puerto Cabello	10° 29′	68° 04′	15	450	1a
34 San Antonio	09° 44′	70° 22′	237	745	1b
35 San Antonio Tachira	07° 51′	72° 27′	404	1174	1b
36 San Carlos	01° 56′	67° 03′	119	3449	3a
37 San Fernando Apure	07° 54′	67° 28′	48	1353	2a
38 San Juan los Morros	09° 55′	67° 22′	434	1169	2b
39 San Juan Manapiare	05° 14′	66° 10′	140	2557	3b
40 Santa Barbara	07° 49′	71° 11′	200	2080	1b
41 St. Barbara Orinoco	03° 56′	67° 08′	120	3230	3a
42 St. Elena Uairen	04° 36′	61° 07′	907	1646	1d
43 St. Maria Guaicas	02° 48′	65° 15′	16	2487	3a
44 Santiago Trujillo	09° 15′	70° 31′	1180	729	1c
45 Tachira	08° 07′	72° 15′	340	2587	1c
46 Toro Negro	08° 22′	66° 14′	88	1227	2a
47 Tovar	08° 21′	71° 45′	952	1106	1b
48 Tucupita	09° 03′	62° 03′	10	1384	1d
49 Tumeremo	07° 15′	61° 31′	180	1303	1d
50 Upata	08° 01′	62° 23′	327	1094	1d

Source: Ministerio del Ambiente y Recursos Naturales, Caracas and Servicio de Meteorologia FAV, Maracay.

Table 1 b: Additional stations used in regional classification. A total of 60 stations were thus used for the regional classification. Characteristics of each class are discussed in Section 3

Zusätzliche Stationen, die für die Klimaklassifikation benutzt wurden

Station	Latitude	Longitude	Altitude (m)	Annual precip. (mm)	Class
01 Agua Viva	09° 36′	70° 36′	404	973	1 b
02 Cua Tovar	10° 06′	66° 54′	230	1042	2 a
03 El Cobre	08° 00′	72° 06′	2100	842	1 c
04 Guiria	10° 36′	62° 18′	8	928	1 d
05 Jajo	09° 06′	70° 42′	1693	847	1 c
06 Las Cruces	09° 24′	70° 49′	756	882	1 c
07 Los Laureles	07° 54′	72° 06′	1520	1194	1 c
08 Puente Villegas	09° 48′	70° 12′	621	1040	1 c
09 San Cristobal-Et.	07° 56′	72° 12′	992	1514	1 c
10 Valle Hondo	09° 42′	70° 18′	800	862	1 c

circulation centres in the southern Caribbean and northern South America. The absolute vorticity of these centres approaches zero over Venezuela and may lead to anomalous (counter-gradient) winds (see for e. g. Fultz 1991). When, under these circumstances, a weak upper divergence field develops in conjunction with compensating low-level convergence, rapid development of a substantial and propagating rainfall area can occur. This in turn will greatly strengthen the high tropospheric anticyclone and provide a mechanism for converting potential to kinetic energy through energy release by convection. Alternatively, remnants of old cyclonic systems over Argentina and southern Brazil occasionally penetrate north of the equator. These systems, visible as large satellite cloud centres, move northward at about 5-10 degrees latitude per day just east of the Andes (see Barry et al. 1990) and can give rise to heavy precipitation events when they reach latitudes 5°-10° N over the Llanos and even into the eastern Caribbean. These earlier studies provide the basis for the present investigations.

2 Data and methods of analysis

Monthly totals of rainfall at 50 stations (Table 1 a a. Fig. 1) and monthly mean station level pressures (22 stations) are used to calculate means and departures during the periods 1972-1986 and 1972-1985, respectively. Regional variation of rainfall is examined at 32 long-term stations (Section 3) for 1951-1985. An all-Venezuela index of precipitation anomalies at 50 stations, with the most complete rainy season records during 1972-1986, was calculated as deviations from the median rainfall (Eqn. 1), in view of the wide range of monthly totals. At each station the deviation is:

$$x = (P_{ij}/P_{mi}) - 1 \qquad \text{Eqn. 1}$$

where P_{ij} = precip. in month i, year j
P_{mi} = median precip. for month i over j years.

Frome these anomalies a rainfall index, C_i, for each map was derived from:

$$C_i = (a + b)/(a - b) \qquad \text{Eqn. 2}$$

where a = number of stations in (i, j) with $x > 0.2$
b = number of stations in (i, j) with $x < -0.2$

The defined threshold of $-0.2 < n < 0.2$ excludes near average months. Values range from near +100% (extremely wet month) to − 100% (extremely dry month). Note however, that this index is unusable in regions having little or no rainfall for most of the year. In addition to the all-Venezuela rainfall index, C_i, in the regional analyses the term 'anomaly' (for area-averaged data), refers to differences from the mean expressed in units of standard deviation (i. e. a rainfall anomaly for a particular month refers to the rainfall total for that month minus its respective monthly mean and divided by the standard deviation for that month). Anomalies are calculated over the following three-month seasons: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and, September-October-November (SON). To delineate objectively appropriate regions for study, a two-stage multivariate analysis was performed on the median monthly precipitation totals at 60 stations (Tables 1 a, b). First, a Principal Components Analysis (PCA)

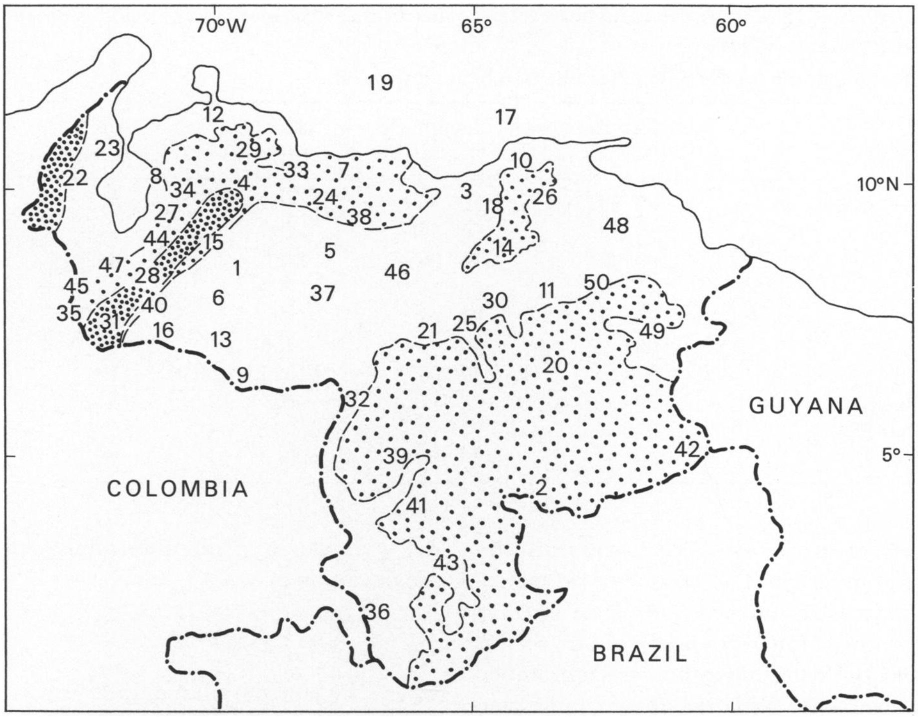

Fig. 1: Location of rainfall stations used in analysis. Lighter and heavely shaded areas are >100 m and >1000 m altitude respectively. See Table 1 for key to station names

Lage der in die Untersuchung einbezogenen Niederschlagsstationen. Durch Punktierung hervorgehoben sind die Gebiete über 100 m bzw. 1000 m Meereshöhe. Namen der Stationen vgl. Tab. 1

was applied to the original matrix $A = I \times J$ of the rainfall data, where I is the number of stations (60) and J contains the monthly (12) median values of precipitation. The components are orthogonally rotated using the Varimax procedure. Second, an automatic classification (cluster analysis) is applied to the matrix $A_{PC} = I \times J_{PC}$, where $I = 50$ as before, but with $J_{PC} = 4$; the first four sets of principal component scores. Different classes or groups of stations were thus determined. The similarity measure used is the standardized m-space Euclidian distance (Davis 1986).

Precipitation from cumulonimbus clouds is produced mainly in deep convective synoptic systems passing through the region with outflow concentrated in the upper troposphere. Accordingly, kinematic parameters at 200 mb as well as satellite-derived data on highly reflective clouds and outgoing longwave radiation were compared with rainfall data. Monthly relative vorticity and divergence (1976–1986) fields at 200 mb on a 5° × 5° grid were obtained from the National Meteorological Center (NMC) global analyses. The number of days per month with highly reflective clouds (HRC) was obtained from the atlas of Garcia (1986) for all months of 1971 through 1983. Twice-daily outgoing longwave radiation (OLR) data (1975–1990) on 2.5 degree square grid, were obtained from the Climate Analysis Center. Seasonal climatologies of observed cloud cover (Warren et al. 1986) were compared with seasonal OLR. West of 70° W the amount of cumulus and cumulonimbus decreases by 20% (weaker rain episodes) during JJA. As expected, maximum amount-when-present (AWP) of cumulus and cumulonimbus occur to the east of 70° W during JJA. Cirrus AWP is constant during the rainy season on both sides of 70° W. A low OLR value (≤ 200 Wm^{-2}) should thus provide an adequate indicator of deep convection over the region. Daily OLR values were averaged within 2.5° × 2.5° boxes over the region 30° N to 30° S and 50° W – 120° W. The existence of deep convection, at grid location ij for any month M, was determined using a binary valued convection flag. Any gridpoint having OLR ≤ 200 Wm^{-2} for more than 10 days within any month is assigned a value of 1, and 0 otherwise. Each ij location is then weighted by this assigned value and the cosine of its latitude. The centroid of convection for that month is then found by averaging over the weighted locations.

The Southern Oscillation Index (SOI) used here is the normalized Tahiti minus Darwin monthly pressure. Sea surface temperatures (SSTs) in the Atlantic and Pacific were obtained from the Comprehensive Ocean-Atmosphere Data Set or COADS (SLUTZ et al. 1985). Sea surface temperatures are averaged over two regions of the eastern Pacific, the NIÑO1 and NIÑO2 regions off the coasts of Ecuador and Peru, bounded by 0°-10° S and 80°-90° W. SSTs within this region (hereafter called PSST) provide an indication of 'warm' (El Niño) and 'cold' events which can occur independently of SOI fluctuations (DESER a. WALLACE 1987, DIAZ a. PULWARTY 1992).

The autoregressive nature of the data must be accounted for in order to avoid spurious correlations between time series. The effective number of degrees of freedom in the time domain, reduced due to persistence, is calculated using QUENNOUILLE's (1952) method.

3 *Classification of regions by rainfall*

The first three principal components (PCs), accounting for 74, 15, and 5 percent of the total variance of rainfall respectively, provide significant information concerning: (a) the relation between months, (b) the relation between stations, and (c) the relation between rainfall months and stations (MAHERAS 1985). Cluster analyses of the first four PCs identify three major classes, with 8 subclasses.

The main characteristic of the first class is a bimodal annual course of rainfall. This category, containing 29 stations, can be subdivided into 4 subclasses. Stations in Class 1a are situated along the dry coastal region and on islands (annual rainfall total 432 mm with July-August and November-December maxima). Included in Class 1b are most of the stations at low elevations west of 70° W (annual rainfall 1020 mm). Maximum rainfall occurs in autumn (SON) months. The stations identified by Classes 1c and 1d have larger annual rainfall totals than Class 1a or 1b primarily because of increased altitude. These 16 stations are located in two seemingly diverse regions, the Venezuelan Andes (Class 1c, annual rainfall 1204 mm) and the eastern Guyana Highlands (Class 1d, annual rainfall 1271 mm). Rainfall variability in the Venezuelan Andes, including the location of rainfall maxima, has been shown to be highly dependent on aspect as well as altitude (MONASTERIO 1980, LAUER 1981). The early season maximum, at Andes stations, occurs during April-May-early June, followed by a late June-July-August minimum, and a second maximum of greater magnitude during SON. The eastern stations, more directly influenced by the Atlantic ITCZ, have their primary maximum in the early rainy season (JJA), followed by a relative minimum during September-October. These peaks vary according to latitude and rate of excursion of the equatorial trough.

In subclass 2a are most of the stations (19) in the Llanos (annual rainfall 1414 mm). These have a single midsummer peak or broad maximum (JJA) of rainfall. Class 2b contains those stations (5) along the Cordillera de La Costa (annual rainfall 938 mm), adjoining the Llanos. Of interest is the station of El Tigre (No. 14 in Fig. 1); in most years, its rainfall has a unimodal distribution (August maximum approx. 210 mm) but in other years (e. g. 1973, 1975, 1978, 1981, 1982) there is a clear bimodal (July minimum) distribution. Suppression of rainfall in July does occur in a few years but for the most part the double maximum is due to the enhancement of June rainfall (equivalent to the August maximum). In still other years a single June maximum dominates. The rainfall patterns and distribution occurring on this north-south highland region, on which El Tigre is located, have not been investigated in detail although study of regional surface conditions (RENNE 1970) has been undertaken.

The third category of stations represents the wet continental regime south of 6° N, characterized by large annual precipitation totals. Stations (4) in subgroup 3a (annual rainfall 2993 mm) have rainfall minima in DJF which still exceed the maxima of some coastal stations by 50-100 mm. The three stations of 3b (annual rainfall 2401 mm) situated further north, are less strongly influenced by convection over the Amazon Basin during southern summer. The rainfall totals for January-February are 90 mm and 250 mm for class 3b and 3a respectively. The mean annual rainfall total over all 60 stations is 1301 mm reflecting the large totals of the interior stations.

From the above classification we define the following regions for study on longer timescales, MARACAIBO (stations west of 70° W (including those in coastal areas) but <800 m altitude), ANDES (>800 m altitude west of 70° W), LLANOS (as defined above), CORDCOSTA (Cordillera de la Costa excluding the dry coastal region), EASTVEN (east of 63° W), and AMAZONAS (interior south of 5° N). The regional rainfall climatologies (1972-1986) shown in Fig. 2 include the dry coast and island stations (COSTA, east of 70° W). As a tradeoff between the number of stations available and the length of record, we employ the concepts of fractional common

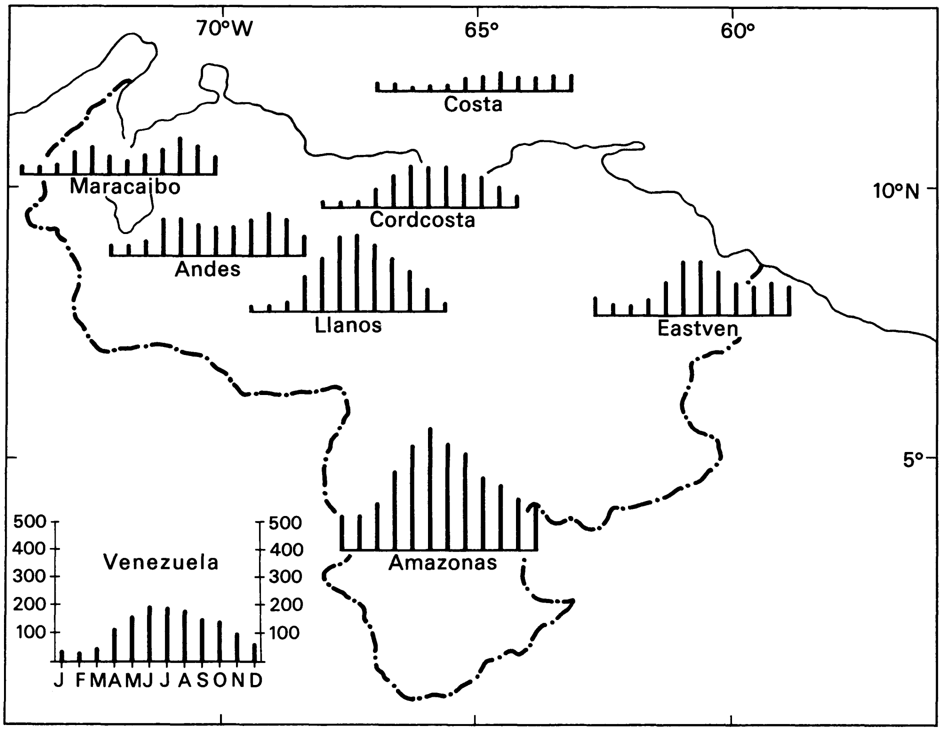

Fig. 2: Mean monthly rainfall by region. Regions are based on principal components and cluster analyses of rainfall at 60 stations

Mittlerer monatlicher Niederschlag nach Regionen. Die Regionalisierung stützt sich auf Hauptkomponenten- und Cluster-Analysen der Niederschläge von 60 Stationen

variance and inter-series correlation (see Wigley et al. 1984) to arrive at the minimum number of stations required for a regionally representative composite, over time. For 1951-1985, the number of stations available is 7 in MARACAIBO, 10 in ANDES, and 5 in each of LLANOS, CORDCOSTA, and EASTVEN. From these regions, an all-Venezuela seasonal anomaly time series (VENCOMP), excluding AMAZONAS, was composited. This series is not expected to be as accurate in representing variability over the entire Venezuelan region as the shorter (1972-1986) Venezuela index C_i, described above. AMAZONAS is excluded since it has no long rainfall record but comparisons with variability in the Brazilian Amazon Basin can be made (Eischeid a. Pulwarty 1991).

4 Large-scale departures of circulation and rainfall over Venezuela

Interannual differences in circulation modes may cause major changes in rainy season characteristics. For example, maps of monthly precipitation anomalies show that in a few individual months most of Venezuela has anomalies of predominantly one sign, whereas in other months/years the anomaly pattern consists of two to four alternating zones (east-west) of opposite sign. Factors contributing to these changes in regime are examined here using circulation analyses and station precipitation data for the period 1975-1986.

Regional circulation

The tropical Americas have no major monsoon system. For South America, this results from the combined effects of reduced cross-equatorial flow due to the meridional orientation of the Andes, and the usually cold waters in the eastern Pacific (see Webster 1981). The near-symmetric distribution of land between 10° S-0 and 0-10° N, in the region of the Americas, allows for a wet season of comparable duration in both hemispheres (Horel et al. 1989). For this region, the nearest conceivable analogue to a monsoon model, so prominent in other tropical regions, could be a three-element pattern with heating of northern (25°–35° N) and southern (0°–10° N) continental areas versus relatively cold air over cold water residing between them (12°–25° N). For near steady-state conditions, a tropospheric cold layer should lead to an upper tropospheric large-scale cold cyclone centred at 200 mb. Because of latitude, a belt of strong upper westerly winds then must overlie at least latitudes 5°–15° N. Our analysis of the upper air charts for 1976–1986 indicates that this situation occurs in 40 percent of rainy seasons and persists for 1–3 months, often with a connection to the mid-Atlantic upper air trough (BARRY et al. 1990).

This three-element model is, of course, more vulnerable to outside interference than flow regimes in the 'normal' monsoon regions. Three factors create differences from the monsoon model. Firstly, SSTs, at their maximum during the Indian monsoon onset, rise slowly through the West Atlantic-Caribbean warm season. Thus model mechanisms should preferentially operate early in the 'rainy season' and weaken or disappear later as the dynamical structure cannot be maintained. Long rainy seasons, of a half a year or more, with mean rainfall gradually increasing, are indeed observed over the Greater Antilles (PORTIG 1976). At San Juan, Puerto Rico, for instance, mean rainfall rises from 100 mm in April to almost 200 mm in November. The clear precipitation peaks of Venezuela (Fig. 2) are not observed. The frequent occurrence of late season November maxima, including parts of Venezuela, is related to the great lag of mean temperature with respect to the sun in many areas. Secondly, the general circulation is variable at latitude 30° N, associated with intermittent or persistent extratropical westerly incursions, including, but not limited to, the well documented oscillations of the Bermuda High. Strong subtropical jet streams, or feeders to them, occur mainly in April–early May and November. Large precipitation amounts can be stimulated by such baroclinic mechanisms, as, for instance, in April 1981 discussed below. Thirdly, there are encroachments of the Southern Hemisphere winter upper tropospheric anticyclone to the equator. This leads to deep easterlies over the region 0°–12° N and northward (see below). Other thermal and dynamical factors leading to deep easterly currents at least on an intermittent basis remain to be explored.

Lack of a reliable dynamic solution for precipitation stimulation is a problem that had not been fully anticipated and still lacks a solution. Upper anticyclones are now generally depicted as thermal outflow circulations while the 'dynamic high' has been relegated to the eastern parts of the subtropical anticyclones. It is surprising that a 200-mb clockwise flow over all Venezuela, centred over the north coast, can occur with severe dry months of the whole region. This clearly 'dynamic' high, with upper convergence (hardly measurable with the available data), may thus overlay the area where in a monsoon regime a rainy equatorial (low pressure) trough at the surface, with convergence, could be expected. Some of the westerly wind parts of these anticyclones may be reinforced during ENSOs as a result of enhanced warming in the equatorial zone and associated strengthening of the meridional temperature gradient.

Information on dynamic processes is most reliable for deficient rainfall cases. Westerly components bring dryness, except early and late in the season when strong rains may occur from a mixture of baroclinic (late season subtropical jet stream feeders) and convective processes. Most other situations, excluding the large high level anticyclones just discussed, have the potential for short or long rain stimulations.

Rainfall variability

From VENCOMP, the 1972–1985 period had, for the most part, above average rainfall, with 1977 and 1981 being the driest year (847 mm) and wettest year (1300 mm) respectively. The seasonal rainfall climatology over all 50 stations in Fig. 1 shows that 9, 23, 40 and 28 percent of the annual rainfall is carried by DJF, MAM, JJA and SON, respectively. The April–November season carries 88% of the mean annual rainfall (1347 mm). All rainy season months were investigated using C_i but only discussions of April (rainy season onset, 8%), August (mid-season, 13%), and November (rainy season retreat, 7%), are presented here (see Table 2).

Interestingly, no "average" April was recorded. Four Aprils had an index (C_i) < -80 and > 70. The mean kinematic circulation fields of April 1984 (the second driest April during 1972–1986) and April 1981 (the wettest April in the record) are compared since the proximity of these years lessens the extent of any changes in the NMC global analyses (TRENBERTH a. OLSON 1987). Of the 50 stations analysed for April 1984, 12 reported little or no precipitation with only 3 stations reporting rainfall above the median. In contrast, April 1981 had only two stations reporting below median rainfall. In April 1984 only a small 200-mb level divergence centre of 2×10^{-6} s^{-1} was

Table 2: Classification of all-Venezuela rainfall index C_i for April (rainy season onset), August (mid-season), and November (retreat) for 1972–1986

Klassifikation des Niederschlagsindex C_i für Gesamt-Venezuela im April (Beginn der Regenzeit), August (Höhepunkt der Regenzeit) und November (ausklingende Regenzeit), Periode 1972–1986

	April	August	November
Extremely dry $C_i < -70$	1974–75, 1977 1984, 1986	1982	1982–83
Dry $-70 < C_i < -10$	1973, 1980	1972, 1976 1986	1972, 1977 1981
$-10 < C_i < 10$		1977	1975
Wet $10 < C_i < 70$	1972, 1976 1979, 1985	1973–75, 1978 1980–81, 1983	1974, 1976 1978–80, 1984, 1986
Extremely wet $C_i > 70$	1978, 1981–83	1984–85	1973, 1985

located over Venezuela, with lower values both towards the north-east and south-west. In April 1981, however, an intense divergence maximum of greater than 4×10^{-6} s^{-1} occupied the bulk of northern South America except for the north coastal zone. Defense Meteorological Satellite Program (DMSP) images reveal a total of five synoptic systems with extensive cumulonimbus activity passing over Venezuela in this month.

No specific patterns of August rainfall indices were delineated in relation to whether the August of a particular year was dry or wet. The spatial distribution of rainfall anomalies usually represented some variant of the four-part longitudinal pattern of positive and negative anomalies as observed in August 1980 (Fig. 3). In some cases most of Venezuela displayed a large positive anomaly (e. g. August 1985) or a large negative anomaly (e. g. August 1986) with minor regions carrying different signs. Apart from extreme cases, the controls of these patterns could not be discerned from analysis of the large-scale circulation. There was no indication of a gradual movement of regional rainfall regimes from the preceding July or to the following September. It is of interest to note that all the negative values of C_i during August occurred during the development of warm ENSO events.

For November 1972–1986, only 1981 and 1982 had strongly negative indices. In 1981 only October and November had negative indices for that year even though it is the wettest year in the 1951–1985 record. This dry October–November appears related to the rapid retreat of the centre of convection southward into the continent during the latter part of 1981. The high November 1985 index ($C_i = 95$) resulted from heavy and widespread rainfall particularly over CORDCOSTA and EASTVEN. Large deficits during November 1983 ($C_i = -95$) were recorded in MARACAIBO, ANDES, and LLANOS (2.0σ) but with positive anomalies in CORDCOSTA and EASTVEN (1.8σ). The regional conditions associated with these anomalies are investigated below.

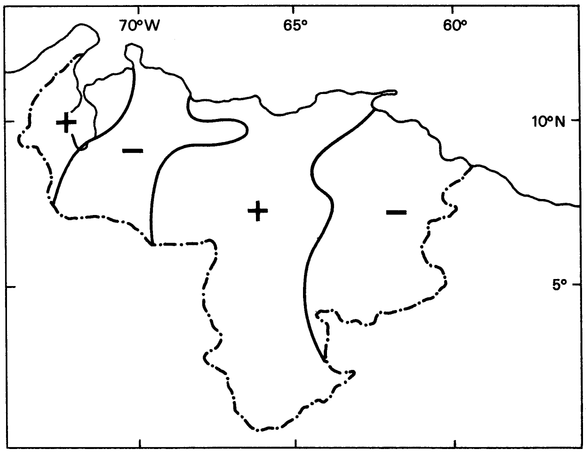

Fig. 3: Areas in Venezuela with large rainfall anomalies during August 1980. Departures based on median rainfall at 50 stations from 1972 to 1986

Gebiete in Venezuela mit erheblichen Niederschlagsanomalien im August 1980. Die Abweichungen beziehen sich auf den Medianwert des Niederschlages von 50 Stationen 1972–1986

5 *Relationships with El Niño-Southern Oscillation events and Atlantic SSTs*

Gray (1984), among others, suggests that during El Niño years, enhanced deep convection over the

*Table 3: Correlations of rainfall against SOI, PSST and tropical N. Atlantic (NATL) for seasons within the same year. All correlations are at lag zero with symbols indicated as * and ** for 95% and 99% significance, respectively. A composite of the five regions is averaged to give the all-Venezuela anomaly index*

Korrelationen zwischen den Niederschlägen und dem Southern Oscillation Index SOI, den Meeresoberflächentemperaturen des Pazifik PSST und des tropischen Nordatlantik NATL für die einzelnen Jahreszeiten des gleichen Jahres

		DJF	MAM	JJA	SON
ALL VENEZUELA					
	SOI	47**	-10	14	38*
	PSST	-27	12	-35*	-38*
	NATL	-26	18	45**	-33
MARACAIBO					
	SOI	53**	7	38*	29
	PSST	-34	12	-25	-29
	NATL	-21	7	15	-19
ANDES					
	SOI	50**	-2	13	35*
	PSST	-29	9	-39**	-33
	NATL	-28	9	53**	-30
LLANOS					
	SOI	23	-25	13	31
	PSST	4	8	-34*	-48**
	NATL	5	39*	47*	-34*
CORDCOSTA					
	SOI	27	-16	3	34*
	PSST	-19	4	-16	-19
	NATL	-20	34	38*	-26
EASTVEN					
	SOI	34*	8	9	23
	PSST	-18	15	-17	-17
	NATL	-26	7	14	-23

eastern Pacific develops anomalous upper tropospheric outflow patterns which act to enhance upper westerly winds over the Caribbean and western equatorial Atlantic, creating conditions different from those of a non-El Niño year.

Table 3 shows the correlation of regional rainfall on a seasonal basis with SOI, PSST and a tropical North Atlantic SST index. For VENCOMP, JJA and SON rainfall anomalies have significantly negative correlations (-0.36 at 95%) with PSST. This suggests that a colder sea surface in the eastern Pacific is related to higher rainfall amounts over Venezuela during JJA. Only DJF (0.48 at 99%) and SON (0.38 at 95%) have significant correlation with SOI. For JJA, LLANOS and ANDES have significant correlations with PSST but not with SOI, the opposite to that for MARACAIBO. Correlation of rainfall with Atlantic SSTs is discussed below.

As a test of the longer term relationships of rainfall with ENSO, PULWARTY a. BARRY (1988) used eight coastal or near coastal stations which had at least 60 years of record. Using the VAN LOON a. MADDEN (1981) chronology of Low/Wet (warm event) and High/Dry (cold event) modes, correlations of rainfall anomalies and the Southern Oscillation Index (SOI) were made for the entire rainy season (April-November) and, the subseasons April-May-June (AMJ) and July-August-September (JAS). In general, large positive 850-200 mb thickness occurs over the northern South America/Caribbean sector during warm events. Rainfall over the April-November period has low and negative correlations (-0.20) with coincident and preceding SOI values. For AMJ, correlations with SOI modes are also low and negative, whereas for JAS they are significantly positive (0.40 at 99%). While the coastal region is considered climatologically homogeneous, enough variability occurs to indicate an inconsistent local response to the Southern Oscillation (PULWARTY a. BARRY 1988, ROGERS 1988).

A superposed-epoch analysis, with key event dates obtained from Kiladis a. Diaz (1989), shows that, in general, rainfall over VENMCOMP during El Niño (warm event) years, is low (-0.50σ), with greater than average (0.75σ) rainfall during a cold event for JJA of event year 0 through MAM of event year 1. There have, however, been exceptions to this general rule for both types of events (Rogers 1988, Pulwarty a. Barry 1988). For instance, the wettest year in the record (1981, with 1184 mm in MARACAIBO) occurred without any exceptional cooling in the eastern Pacific.

Anomalies in MARACAIBO, ANDES, and CORDCOSTA, reach their maxima (approximately +1.0σ) in August-October of the year of an event. Rainfall anomalies in LLANOS and EASTVEN do not exceed +0.50σ. The exceptional 1982-1983 warm event was associated with JJA 1982 rainfall deficits over MARACAIBO (-1.5σ), LLANOS (-1.0σ) and CORDCOSTA (-0.5σ). In the ANDES, however, deficits were observed in June and August 1982 but July was the wettest over the period (>2.0σ). In contrast, ANDES, CORDCOSTA and LLANOS all had large deficits (-2.0σ) in JJA 1972 indicating that there may be no seasonally consistent deficits of regional rainfall associated with ENSO in Venezuela, since each ENSO event develops differently.

At the height of the northern summer during the positive SO phase, the near equatorial trough and associated confluence zone over the eastern Pacific and southwestern Caribbean are displaced northward, the Northeast Trades and cross-equatorial flow from the Southern Hemisphere are reduced (Hastenrath et al. 1985).Drought in Central America and the Caribbean tends to be associated with an equatorward expansion of the North Atlantic High and a band of anomalously cold water extending from the coast of Africa across the North Atlantic (Hastenrath 1976). Hastenrath a. Kaczmarczyk (1981) show that in much of the Atlantic north of 10° N, the correlation between SST and the SOI for July-August is negative (similar to, but not as strong as for the eastern Pacific ($r > 0.40$)), and generally positive south of 10° N over the tropical Atlantic. During austral summer, the negative SO phase is associated with decreased pressure in the tropical North Atlantic and relatively high pressure in the tropical South Atlantic (Aceituno 1988, 1989). However, during boreal summer, the negative SO phase is associated with increased pressure and anomalously cold waters in the tropical North Atlantic with reversed conditions in the tropical South Atlantic.

SSTs were averaged over a region of the Atlantic bounded by 10°-20° N, 40°-50° W, (hereafter designated ASST) and shown by Hastenrath et al. (1985) to have positive correlations with the SOI. Correlations between ASST and rainfall are strongly positive for ANDES, LLANOS and CORDCOSTA. In addition, correlation between DJF and MAM ASSTs with JJA rainfall in these regions are >0.40 (0.57 at 99% in LLANOS). MARACAIBO and EASTVEN have no strongly significant correlation with ASST. Correlations are similar in magnitude but opposite in sign with SSTs in the tropical South Atlantic, but with MARACAIBO having a correlation of -0.46 at 99%. Table 3 shows the clearly inconsistent regional response to forcing on the seasonal timescale. While the correlation structure is similar for LLANOS and ANDES, differences in other regions may produce the monthly plus/minus anomaly pattern shown in Fig. 3 and evident in other months. Since the forcing of SST patterns on monthly timescales by sea level pressure in the Atlantic appears to be more important than vice versa (Lough 1986), more detailed studies of these patterns in relation to forcings on the monthly to seasonal timescale, with consideration of the statistical field significance, are necessary.

6 *Southern Hemisphere influences*

The western end of the South Atlantic High is not as positionally stable with respect to South America as its Pacific counterpart (Trewartha 1981). During austral winter it pushes westward deep into Brazil, while in austral summer it retreats seaward. Vigorous westerly circulation in the Southern Hemisphere results in the longitudinal axis of the South Atlantic High lying closer to the equator than its Northern Hemisphere counterpart. Hastenrath (1985 p. 128) shows that the South Atlantic High reaches farthest north and west during June (27.5° S, 12° W), July (28° S, 12° W), and August (26° S, 14° W). The North Atlantic High reaches its farthest westward extent during June (33° N, 37° W), and August (36° N, 37° W); its July position is (37° N, 34° W).

The monthly course of station pressure averaged for 22 first order weather stations of Venezuela provides evidence of forcing from the Southern Hemisphere. Each of these stations participates in the double pressure wave with maxima in December-February during the northern winter and in June-August during the southern winter (see also Hoffmann 1992). The annual pressure cycle over San

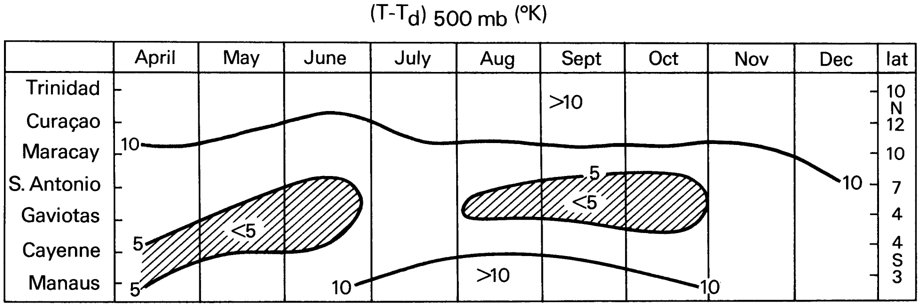

Fig. 4: Latitudinal cross-section of 500 mb monthly dew-point depression temperatures (i. e. $T_{ambient} - T_{dewpoint}$) for 1979
Source: Barry et al 1990

Meridionalprofil der monatlichen Taupunktsdifferenz im 500 mb-Niveau für 1979

Antonio, Merida and Coro (all west of 70° W) show a bimodal distribution with one minimum during April-May-June and a second deeper minimum during September-October-November (approx. -0.9 mb). During the dry season months and June-July-August, pressure maxima are observed (+ 0.6 mb in the latter case). Similar distributions are evident over all of Venezuela. Although this suggests an extended North Atlantic anticyclone during mid-summer with associated subsidence, Portig (1976) notes that throughout the Caribbean, summer pressure is not in phase with rainfall. Extremes of pressure, but not of rainfall, occur throughout the region at the same time. In some years with July-August rainfall maxima, the atmospheric pressure distribution shows a concurrent maximum. The pressure maximum is even observed in the Llanos where the rainfall maximum is consistently during JJA. As pointed out by Trewartha (1981) for the Caribbean, and confirmed for Venezuela, the hypothesis that the mid-summer pressure maximum acts to reduce summer rainfall is not satisfactory.

The depth of the moist layer in the lower troposphere (as expressed by the dewpoint depression at 500 mb) tends to vary inversely across the Equator (Fig. 4). The minimum difference (highest moisture) is located in northern Colombia (Gaviotas) and southern Venezuela (San Antonio) in May-June and then again in September-October, precisely following the OLR minimum (not shown). The cross section is, however, highly variable from year to year. There is the strong impression of a truncated attempt at monsoon generation, as discussed in Section 4. One may infer influences such as frontal incursions (Serra a. Ratisbona 1941, Myers, 1964) from the southern winter circulation to account for the observed aperiodic variations.

Upper-level circulation over South America during northern summer

Monthly streamfunction and relative vorticity charts for 1976-1986 were analyzed at 300 mb between latitudes 10° N and 40° S and longitudes 90° W and 40° W. This level was chosen since the colder part of the austral year and a lower layer of maximum wind are involved. Uncertainty as to the quality of the 300 mb vorticity charts limited the analysis to qualitative procedures. The subtropical anticyclone appears most frequently between 0°-10° S in the

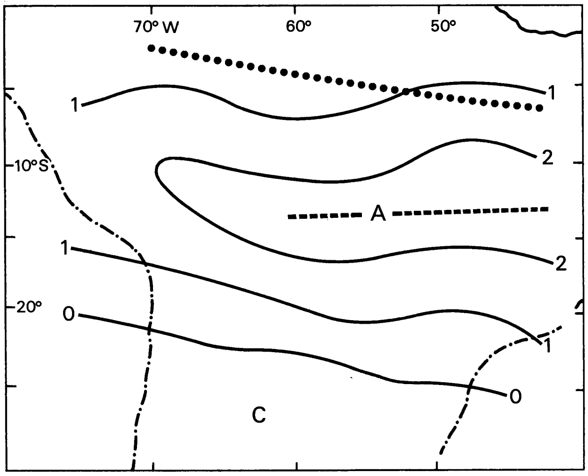

Fig. 5: Relative vorticity (10^{-5} s^{-1}) at 300 mb over tropical South America for August 1984. Note the broad anticyclonic (A) vorticity centre. Dots indicate location of the center of the subtropical ridge

Relative Vorticity (10^{-5} s^{-1}) im 300 mb-Niveau über dem tropischen Südamerika für August 1984. Gestrichelt das antizyklonale Vorticity-Zentrum (A), punktiert die Kernlage des subtropischen Rückens

Southern Hemisphere mid-winter (Fig. 5). During the transition seasons it is also present in most months in the latitude range 10–15° S. Frequently an east-west ridge, without a closed centre, dominates northern Brazil with easterlies persisting to about 10° N. A summer pattern (i. e. no 300 mb anticyclone and no easterlies 0°–10° N) occurred at times in all months but with such high frequency in November that this month was discarded for the present analysis.

The wet April of 1981 in Venezuela (rainfall over all areas $< 2.5\sigma$; see also Table 2) was associated with a dominant high at 300 mb located at 10° S over the centre of the continent. During the dry April of 1984, however, the high extended from the South Atlantic into South America at 15° S. Conditions, similar to that of April 1981, were observed during the wet months of May and June 1981 and May 1982. Wet JAS months were associated with the upper high over Brazil, but the dry JAS of 1982 occurred with two small highs straddling east-west on the equator over South America.

Examination of the 1976–1986 record reveals a positive relation between Venezuelan precipitation (positive anomalies) and months with strong 300 mb anticyclonic relative vorticity near 15° S. The large anticyclonic vorticity maximum lies 5°–7° latitude south of the subtropical ridge line (marked by dots in Fig. 5). When the vorticity band was not present, or when it was strongly oriented toward the southeast and reached 40° W at 18° S and further south, the relation with Venezuelan rainfall was negative. Surprisingly enough, no relation was discerned between the anticyclone (and its vorticity) and the strength of the southern westerlies at 300 mb (at 20°–30° S and 50°–80° W).

For a more quantitative test of the Venezuelan rainfall-Southern Anticyclone relationship, the latitude of the band with relative vorticity values in excess of 10^{-5} s^{-1} more or less oriented east-west, and extending to 45°–40° W has been determined. Three categories are differentiated: the band extends down to 15° S (positive), is located between 16°–17° S (zero), and occurs at 18° S or lower (negative). The anticyclone is given a positive rating when present, zero when there is only a ridge, and negative for a summer (SH) pattern. However, because the anticyclone is a rather arbitrary feature, except for summer patterns, relative vorticity is used only qualitatively. The all-Venezuela precipitation index was modified for this purpose. The difference (a–b), where $a > 0.3$ and $b < -0.3$, was assigned the value of zero for absolute values of (a-b) in the range 0 to 0.8 with larger differences being positive and differences less than zero being negative. Altogether $n = 67$ (Table 4); four values are missing in the data (starting after July 1976). Six values coincide with deep easterlies extending above 300 mb north of the equator. There are 11 months with positive departures of the rainfall index in all instances. Five of these support the results for the southern vorticity, but in the other six cases the deep easterlies supercede any other relationships. The Cramer's V and contingency correlation measures of association for Table 4, at 99% significance, are 0.40 and 0.49 respectively. The degree of association is from zero to one (perfect association). It is surprising that this result for southern hemisphere circulation features is not matched by any correlation of Venezuelan rainfall with a northern hemisphere circulation feature.

Close proximity of the 300-mb southern anticyclone centre to the equator and continuous 300-mb easterlies from there across the equator to the northern coast of Venezuela or beyond appear to be very favourable for stimulating precipitation in any low-level equatorial trough in Venezuela or forming a new convective band. This subject is still under consideration.

Table 4: Associations between 300 mb relative vorticity over Brazil and the all-Venezuela rainfall index for April–November 1975–1986 (except where noted in text)

Beziehungen zwischen der relativen Vorticity im 300 mb-Niveau über Brasilien und dem Niederschlagsindex C_i für Gesamt-Venezuela im April bis November 1975–1986

All-Venezuela Index C_i Sign	Latitudinal band of southern anticyclone over Brazil + North of 15° S	0 16° S–17° S	– South of 18° S
+	22	0	7 (6E)
0	4	2	8
–	5	1	18

E: Upper easterlies 0°–10° N

Table 5: Rainfall at Maracaibo during four selected years and the 1951–1985 mean. These years were chosen to illustrate the interannual variability of monthly rainfall distribution; 1975: small primary maximum, very large secondary; 1977: both maxima suppressed; 1981: wettest year over 1951–1985 period, very large primary maximum; 1983: suppressed secondary maximum

Niederschläge in Maracaibo in vier ausgewählten Jahren und im Mittel der Periode 1951–1985. Diese Jahre wurden ausgewählt, um die interannuelle Variabilität der Niederschläge zu veranschaulichen

	J	F	M	A	M	J	J	A	S	O	N	D	Total
1975	11	11	26	33	74	56	72	41	125	122	123	126	820
1977	22	15	31	39	62	44	43	55	72	97	53	13	546
1981	12	43	27	213	162	114	60	76	136	157	106	79	1184
1983	19	5	17	137	84	74	33	43	60	104	23	16	615
Mean	28	24	28	74	94	61	45	63	86	119	93	55	770

7 The mid-season rainfall minimum west of 70° W: the Maracaibo region

Table 5 shows the monthly rainfall and annual totals in MARACAIBO, for 4 selected years and the 1951–1985 mean. It is clear that 1975 had a very wet SON season (SOND carried 60% annual rainfall) in comparison with the 35 year mean. Following a relatively dry April and May, 1977 had lower than average rainfall over all months of the rainy season except June and August. During 1981 higher than average rainfall was recorded over all months of the rainy season but with the primary maximum being the larger, while 1983 had a larger than average primary maximum and a smaller than average secondary one. Correlations between seasonal rainfall in MARACAIBO and the same seasons in the other four regions show that only JJA is consistently less than 0.40. In fact, while as may be expected, the correlation between seasonal rainfall in MARACAIBO with that in ANDES for DJF, MAM and SON is high (> 0.80 at 99%), a low JJA correlation (0.28 at 90%) indicates that the modulations of the JJA minimum in ANDES and MARACAIBO may have dissimilar origins or different (subseasonal) timescales.

For MARACAIBO, years with anomalously high rainfall appear to be associated with a positive SOI phase, below normal Pacific SSTs, and weak 200 mb flow between northern South America and the Caribbean (i.e. weaker upper easterlies or upper westerlies, between 10°–15° N). This is indicative of a northward-displaced ITCZ, characteristic of a high SO

Table 6: Interannual variability during July–August 1975–1985 of: C_i = all-Venezuela index; MCBO = Maracaibo rainfall anomaly × 100; SOI = Tahiti minus Darwin pressure SOI; PSST = eastern Pacific SST anomaly; $d\xi/dy$ (NH) = vorticity shear along 70° W and between 10°–20° N; $d\xi/dy$ (SH) = same as before but between 10° N–10° S; AXIS = intersection of $d\xi/dy$ (SH) axis with 40° W longitude above (+) or below (–) 10° S; LOC = the location of the centre of convection associated with the equatorial trough relative to its mean July–August position of 6.25° N, 95.0° W. Note: Asterisks denote mean positions. OLR data are unavailable for 1978

Interannuelle Variabilität des Niederschlagsindex C_i für Gesamt-Venezuela und verschiedene Einflußfaktoren für Juli–August 1976–1985

	C_i	MCBO	SOI	PSST	$d\xi/dy$ NH	$d\xi/dy$ SH	AXIS	LOC	
1975	19	21	2.05	-0.55				E	*
1976	-15	4	-1.50	1.89	27.5	14.7	1.3	W^{+}	*
1977	0	-30	-1.45	-0.14	33.0	15.0	-13.8	W^{++}	S^{++}
1978	17	164	-0.25	-0.52	22.0	11.3	-6.3		
1979	-3	16	0.30	-0.39	18.0	6.5	2.5	E^{+}	N^{+}
1980	42	51	-0.15	-0.22	17.5	11.0	-5.0	*	N^{+}
1981	48	101	0.60	-0.48	6.3	7.3	2.5	E^{+}	N^{++}
1982	-63	-179	-2.35	1.15	23.8	9.5	1.3	*	S^{++}
1983	15	-104	-0.65	3.62	26.3	10.0	-10.0	*	S^{++}
1984	23	47	0.05	-0.04	20.0	11.9	-2.5	E^{+}	N^{+}
1985	30	-98	-0.20	-0.69	19.0	12.3	-12.5	W	*

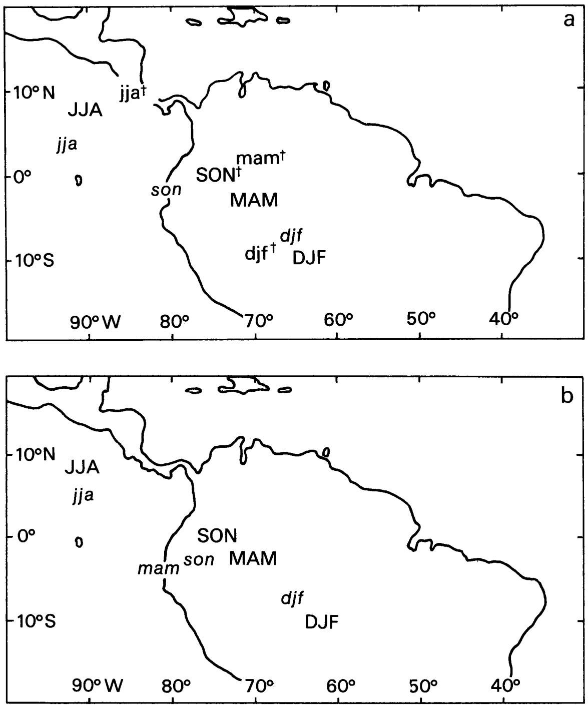

Fig. 6: Seasonal location of centroids of deep convection for the 1975–1990 mean (capital letters) and (a) 1977 (lower case) and 1981 (†) and (b) JJA 1982–MAM 1983 (lower case). Note: SON 1981 is at the same location as in the mean. OLR values ≤ 200 Wm^{-2} are used to indicate deep convection within a grid box. Only grid boxes (over 30° N, 120° W and 30° S, 30° W), with >10 days of convection in any given month are considered

Jahreszeitliche Lage der Zentren hochreichender Konvektion im Mittel der Periode 1975–1990 (Großbuchstaben) sowie (a) 1977 (Kleinbuchstaben) und 1981 (†) und (b) JJA 1982–MAM 1983 (Kleinbuchstaben)

phase during northern summer (Hastenrath 1990). Table 6 summarizes these features for July–August. During 1975, the SOI was positive (deviations $>1.0\sigma$ from MAM through SON). SST anomalies along the Pacific South American coast were negative with a maximum deviation of 1.0 °C during SON. Thus, a cold phase was occurring in the eastern Pacific, particularly during the latter half of 1975. Heavy rainfall was recorded during these months in MARACAIBO but with deficits over LLANOS. During 1975, the SON centre was displaced significantly northward. Fig. 6 shows the seasonal location of centres of convection for the 1975–1990 climatology (capital letters); Fig. 6a includes 1977 and 1981, and Fig. 6b JJA 1982 to MAM 1983. The above normal rainfall during the first half of the rainy season in 1981 is reflected in the northward displaced MAM centre. The major precipitation during these months in 1981 occurred over the LLANOS and MARACAIBO regions. The April 1981 centre alone was displaced almost 6° further northward than in the mean. On retreat, the centre of convection moved back over the southern Llanos. In 1977, these centres are displaced almost 3° further south and east. In 1982, the south and westward displacement of convection centres provides less rainfall during JJA.

Based on all charts considered, the location during advance of the centre of convection from April to May offers a good indication of the strength of the first peak of the MARACAIBO rainy season, with the September to October retreat controlling the second peak. In 1982, the advance of April to May convection centres was further north than in the mean (producing MAM rainfall $>1.0\sigma$) whereas the JJA rainfall was deficient (-1.0σ). The convection centre during this season was located further west than in the mean, coinciding with a rise in east Pacific SSTs and a negative SOI. In MAM 1983, SSTs were still above normal with a weakly positive SOI. The April 1983 centre of convection was displaced 7° further west than in the mean, leaving the source of high rainfall recorded in that month in question. The locus of convection centres was similar to that for 1986–87. Above normal SSTs in the eastern Pacific may displace the centre of convection further west and south from the South American landmass to the Pacific resulting in weaker rainfall over northern South America during those months. During cold episodes, the northward and eastward displacement of the centre is associated with positive rainfall anomalies over MARACAIBO, ANDES and northern Venezuela in general.

Thus, modulation of the mid-summer precipitation minimum over this region appears to be related to moderate Southern Oscillation events as well as fully coupled ENSO events (as reflected in the superposed-epoch analysis). During 1972 (a very strong ENSO year) the mid-summer equatorial convergence was restricted to the south over the Orinoco while during 1969 (a weak ENSO year) strong convection was established near the north coast (Riehl 1973). As in 1975, the strong cold-event/positive SOI conditions of 1988–1989 were related to heavy summer rainfall in northern Venezuela with discharge deficits from the Orinoco and its savannah tributaries further south (in the Llanos) reaching 40% (Caviedes 1989). OLR maps show the locus of the centre of convection to be displaced further north from August throught October 1988 than in the mean. This is precisely the response that would be expected from the present analysis.

In general, high eastern Pacific SSTs and/or low SOIs result in the southward and westward displacement of centres of convection, with some modulation by variations in the Atlantic Subtropical Anticyclones. In the mean, both highs reach their northernmost and westernmost positions during July and August (Hastenrath 1985). However, variations in the location of these anticyclones have also been shown to be related to conditions in the eastern Pacific.

8 Conclusions

Rainfall in Venezuela has high seasonal and regional dependence. The controls of rainy season precipitation are shown to involve the seasonal displacement of the convection centre, modulated by other influences. In the transition months, March-April and October-November, incursions of westerly perturbations play a significant role. Earlier views held that the temporal and spatial rainfall anomalies over Venezuela result from westward and southward excursions of the Bermuda High, and the regular passage of the equatorial trough. Our results suggest that these simple models should be rejected in favour of multi-component explanations of variability appropriate to such a climatically complex area.

The annual cycle of convection over northern South America controls the bimodal distribution of monthly rainfall west of 70° W in lowland areas while at higher elevations a combination of the annual cycle and orographic controls appear to dominate. Modulation of the annual cycle can result from changes in tropical Atlantic and eastern Pacific SSTs, the Southern Oscillation, and the South Atlantic upper-tropospheric High.

The conditions for a wetter than average rainy season (for 3 month seasons) in Venezuela appear to include: a positive SOI, below normal SSTs in the east Pacific and in the tropical South Atlantic, above normal SSTs in the Caribbean, easterlies between 10° N and 20° N at 200 mb, and a northward displaced South Atlantic High reaching into Brazil. During July and August these conditions can, in concert, lead to above average rainfall over Maracaibo, raising the mid-summer minimum. Moreover, during the development of strong cold (positive SOI) events, heavy rainfall in northern Venezuela may occur with simultaneous rainfall deficits in the southern Llanos, while very strong El Niños (negative SOIs) usually result in widespread dryness. These large rainfall differences result from a further northward and eastward displacement of the centre of convection associated with the equatorial trough. Correlations of rainfall with SOI and eastern Pacific SSTs indicate that a warm ENSO phase can result in a further southward and westward displacement of convection associated with the equatorial trough, with below average rainfall over northern and western Venezuela during summer. However, a negative SOI with a negative eastern Pacific SST anomaly may still coincide with large rainfall deficits over Maracaibo, but with near-average rainfall over most of Venezuela (as in 1985, Table 6). This implies that east Pacific SSTs can provide significant forcing of rainfall over Venezuela during July-August, independent of the direction of the Southern Oscillation signal.

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