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RAINFALL IN SOUTH AMERICA. SEASONAL TRENDS AND SPATIAL CORRELATIONS

With 4 figures

Cesar Caviedes

Meinem verehrten Lehrer,
Herrn Professor Dr. Wolfgang Weischet,
zu seinem 60. Geburtstag gewidmet

Zusammenfassung: Die jahreszeitliche Verteilung und der Jahresgang der Niederschläge in Südamerika.

Der Jahresgang der Niederschläge (Abb. 1) in den tropischen Tiefländern des Kontinents hat zenitalen Charakter. In der Äquatorzone sind die Regen nicht äquinoktialen Ursprungs, wie man erwarten würde. In den Küstengebieten im Norden, Nordosten und Süden des Kontinents werden die Niederschläge nicht vom Sonnenstand bestimmt, sondern von allochthonen Witterungsgeschehen und advektiven Luftmassenbewegungen. Regenfälle erfolgen bei niedrigem Sonnenstand. Die Amplitude der jährlichen *harmonic* der Niederschläge ist am besten in den Llanos von Kolumbien, im Tafelland der Guayanas, an den Küsten von Brasilien und Westkolumbien und in Südchile ausgeprägt (Abb. 2).

Die Amplituden der halbjährlichen *harmonic* zeigen sekundäre Maxima in den äquatorialen und tropischen Tiefländern Südamerikas (Abb. 3); am deutlichsten sind sie jedoch nicht am Äquator selbst, sondern zu beiden Seiten. Das Zusammenspiel von kontinentaler Konvektion und maritimer Advektion ist verantwortlich für die ausgeprägten halbjährlichen Niederschlagsmaxima im La Plata-Tiefland und entlang der nordbrasilianisch-guayanischen Küste.

Die jahreszeitliche Niederschlagsverteilung (Abb. 4) erlaubt Rückschlüsse auf die regenerzeugenden Mechanismen für die einzelnen Landschaften Südamerikas. Anomalien werden besonders deutlich, wenn man die Beziehungen von Regenschwankungen zwischen Nordperu und Nordostbrasilien, zwischen dem Hochland von Ecuador und dem Amazonastiefland und zwischen dem Amazonastiefland und den Llanos untersucht. In der Erklärung dieser Beziehungen und Anomalien spielen regionale monsunartige Luftmassenbewegungen und gewisse Zusammenhänge zwischen der tropischen zonalen Zirkulation von Südamerika und der globalen Walker Zirkulation eine besondere Rolle.

During the past three decades research on the patterns of precipitation over the South American continent has experienced its most dramatic phase of development. Investigations in all corners of the continent have expanded the knowledge and dissipated most of the inaccuracies and fallacies contained in the pioneer works of TRIPP (1889), VOSS (1907), REED (1910), HANN (1915), FRANZE (1927), KNOCH (1930), and P. E. JAMES (1939).

Recent surveys on the climatology of the continent or important parts of it by TREWARTHA (1966), EIDT (1968), AMIRAN and WILSON (1973), PEÑA and ROMERO (1975), SCHWERDTFEGER (1976), LAUER and BREUER (1976), and H. H. LETTAU and K. LETTAU (1978) have provided the basis from which a dynamic explanation of established precipitation patterns and climatic anomalies can be undertaken. Still, there remains much to be done in the field of relating weather singularities to regional patterns of atmospheric circulation over South America.

This article addresses, therefore, the question of how rain occurrence in one region of South America corresponds with rainfall or lack of it in another region, and what the trends are in the timely progression of precipitation across the continent. The basic assumption is that mechanisms that produce rain in one area may have the opposite effect in other areas and that, whenever climatic fluctuations occur, there is a widespread upset in the atmospheric circulation system that encompasses the equatorial, the tropical, the subtropical, and the mid-latitudinal zonal circulation of South America as well as the surrounding oceans.

Since this is an investigation into the progression of cyclical events or meteorological anomalies in the time dimension, it cannot be conducted with average values of meteorological parameters. It is indespensable that it relies on the analysis of time series.[1] Once the interregional linkages of rainfall occurrences are established, it is possible to recognize the mechanisms that explain relations between widely-separated precipitation regimes. This article approaches the question of rainfall synchronism and variability in different regions of South America.

The seasonal variations of precipitation

In a study of this kind, harmonic analysis is a most valuable tool for describing in an objective way the temporal and spatial variations of precipitation.[2]

For South America the annual harmonic curves reveal interesting patterns (Figure 1). In accordance with this continent having the greater part of its landmass in the southern hemisphere, most of the precipitation peaks of the South American lowlands occur during the mid-summer months of this hemisphere. The highlands of the Andes south of the equatorial line receive their annual maximum also during this time of the year. In the La Plata River lowlands, as well as in the Pampa, rainfall peaks during the late-summer months when the continental warming reaches its maximum. It is also because of this fact that the rains in the Amazon basin and northern Brazil have their highest peak during the equinox of March and not during the equinox of September (ALDAZ, 1971).

From March through July the march of precipitation follows the northward shift of the sun, as shown by the harmonic

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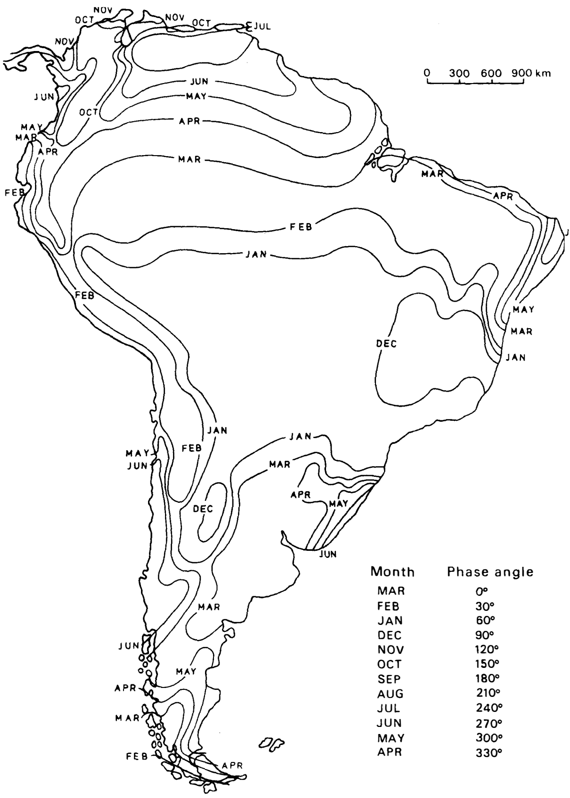
[1] Monthly values of precipitation, pressure, and temperature for 128 stations in South America were handled by the "Time Series Processor" program, Vanderbilt University, 1974. Autocorrelations, cross-correlation matrices, and Fourier (harmonic) analyses were computed from the data, using the computer facilities of the University of Regina. The monthly data proceeded from "World Weather Records, 1941–1950; 1951–1960," U. S. Department of Commerce, E.S.S.A. and from "Monthly Climatic Data for the World," for the years 1961 to 1970, published by the U. S. Department of Commerce, E.S.S.A. and the World Meteorological Organization at Asheville, North Carolina.

[2] The mathematical basis of this type of Fourier analysis is explained by J. N. RAYNER (1971). The method has been used by HORN and BRYSON (1960) for the United States, and by SABBAGH and BRYSON (1962) for Canada. Other case studies are available for Australia and New Zealand (RAYNER, 1971).

Phase angle denotes the adequation of a sinuous curve to the yearly march of precipitation of a certain station. The first harmonic, or annual harmonic, implies that a sinuous curve with one crest and one through fits well the precipitation curve of a station that has one yearly maximum and one yearly minimum occuring at six-months intervals. The name of the month and the phase angle describe the time of the maximum. The second harmonic, or semiannual harmonic, refers to a sinusoidal wave with two crests and two throughs that fits well the yearly precipitation curve of a station with two maxima and two minima, like those that characterize an equinoctial-rain regime.

The amplitude is half the height between a trough and a crest. It is usually expressed in centimeters or inches of precipitation. High amplitude values in both first and second harmonics indicate precipitation regimes with two clearly defined peaks. High values in only the first harmonic indicate one pronounced maximum and one minimum yearly.



Month	Phase angle
MAR	0°
FEB	30°
JAN	60°
DEC	90°
NOV	120°
OCT	150°
SEP	180°
AUG	210°
JUL	240°
JUN	270°
MAY	300°
APR	330°

Figure 1: Annual harmonic of precipitation

lines in the northern Amazon basin and in the Venezuelan-Colombian Llanos. Conspicuous exceptions to this pattern are the northern Andes and the areas facing the Caribbean Sea, where the yearly precipitation peaks follow the autumnal equinox and coincide with the maximum summer heating of the sea.

A remarkable feature in the yearly march of precipitation over South America – and very well portrayed by the annual harmonic figure – is that the annual lull in precipitation for the whole continent occurs in August and September, that is, shortly before the autumnal equinox. This is the time of the year when the high sun strikes the Caribbean Sea, or the northern part of South America, and when, in the southern portion of the continent, the winter frontal rains are receding.

Apart from depicting accurately the seasonal variations of precipitation over tropical lowlands and tropical high mountains, the annual harmonics provide clues about the climatic controls that operate on some coastal areas of South America. The coast of temperate Chile, the east coast of Uruguay and southern Brazil, the coast of northeastern Brazil and, finally, the Carribbean coasts of Colombia and Venezuela have precipitation patterns that are very different from those of contiguous continental areas. These regional disparities in rainfall patterns stem not only from maritime influences or frontal activity, but also from orographic controls that play additional roles in explaining temporal and regional variations of precipitation.

The map of the annual harmonic amplitude (Figure 2) reveals spatial patterns which are of great significance in a study on the temporal and spatial linkages of precipitation. On the one hand, the contrast between regions of high and low amplitudes becomes very visual and, on the other, the yearly variations of precipitation are greatly emphasized. So, for example, the yearly variations of rainfall in the Andes of Colombia and the Llanos are strongly contrasted as shown by the crowding of isoamplitudes. The same can be observed in the highlands of Peru and the tropical eastern lowlands, particularly the region of La Montaña.

In yet another example the Pampean Sierras west of Cordoba (Argentina) stand out also as areas of greater yearly variation than the surrounding Pampa and the Andes to the west. Conversely, areas of relatively low yearly amplitudes, like the dry interior of northeastern Brazil and the arid Pampa on the eastern slopes of the Andes, appear as islands of dryness amidst areas of relatively high amplitudes.

In the yearly variations of precipitation depicted by the isoamplitude lines, three types of high annual amplitudes can be identified: First, equatorial and subequatorial lowlands, like the Amazon basin and the Colombian Llanos, which are characterized by large amplitudes at relatively high allyear round precipitation. Although the amount of rainfall in the sixth month following the annual peak is still high, the difference produces a large yearly amplitude. Thus, it is obvious that in areas like these the rain-generating mechanisms function almost all year round and that they are reinforced during periods of high sun elevation.

Second, highlands where the orographic effect adds to the advection of air masses during particular months also have a large annual amplitude. This is the case in the uplands of the southern Guianas and, to a lesser extent, of the Pampean Sierras. A map of isohyets clearly reveals the differences between these highlands and their surroundings, but a graphic of the amplitude of the annual harmonic is richer in scope, since it blends the temporal component and the magnitude of the yearly variations of precipitation.

Third, high yearly amplitudes occur in coastal areas under the influence of maritime air masses of seasonal character. This has a particularly strong effect on the coast of French Guiana, which receives its maximum rains during the March equinox and when the northern trade winds are intensified; on the coast of southern Chile, which is battered by the westerlies of the southern hemisphere; and on tracts of the coast of Brazil which receive humid winds from the South Atlantic.

The map of semiannual harmonics and their amplitudes stresses the precipitation regimes that are characterized by two yearly peaks of precipitation (Figure 3). A comparison of the amplitudes of the semiannual variations with the annual variations shows that the former are not of the same intensity. Thus, it can be stated that yearly cycles rather than semi-

Figure 2: Amplitudes of the annual harmonic, in centimeters

annual cycles of precipitation are spatially dominant in South America[3] and that, therefore, in the explanation of rainfall seasonality in South America those factors that cause only one yearly oscillation deserve more attention than those that bring about two cyclical recurrences of rainfall.

The semiannual variations of precipitation reveal two strong nuclei located in the interior of the continent, on each side of the equator. One stretches from the Peruvian Oriente to the Bolivian tropical lowlands, and the other embraces most of the Colombian Llanos. The fact that in these two regions the second annual peak occurs shortly before or after the equinox of autumn indicates the zenithal character of this peak. A third conspicuous nucleus of semiannual variations is located in the La Plata River lowlands, with its axis running from Misiones to Corrientes in northeastern Argentina. The amplitude of the second harmonic is close to the first harmonic indicating that the second peak, between November and December, is almost of the same intensity as the mid-summer peak. A fourth and a fifth nucleus of semiannual variations lie in the Planaltos of Matto Grosso and in the Serras of Minas Gerais. These continental highlands receive maximum precipitation during the summer solstice and the following autumn equinox. Obviously this maximum is controlled by the position of the sun.

Two peaks and two lows in precipitation are also discernible in the highlands of Colombia and western Venezuela and, if one compares Figure 2 and Figure 3, the magnitude of the

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[3] To appreciate the validity of this statement the reader is invited to compare Figures 1 and 3 of this paper with the climate diagrams of South America contained in H. WALTER and H. LIETH's "Klimadiagramm Weltatlas," 1961.

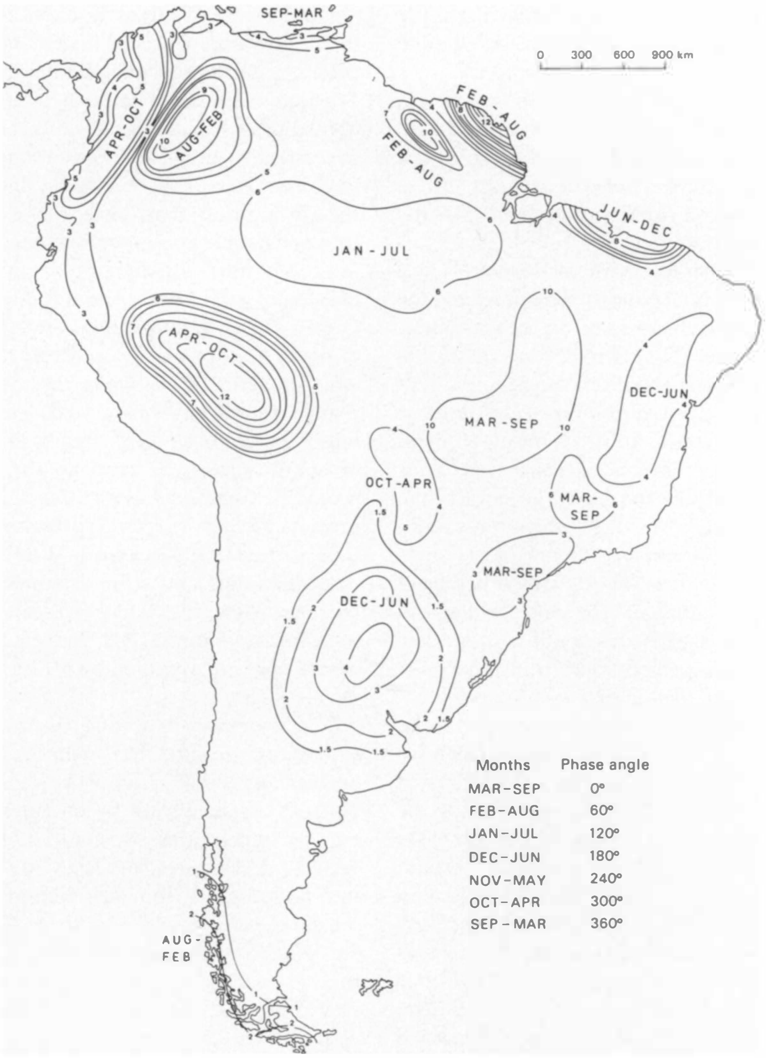


Figure 3: Semiannual harmonic of precipitation and amplitudes in centimeters

semiannual harmonic is very close to the annual harmonic amplitude. It is evident that the amount of the equinoctial rains in these tropical highlands is balanced by orographic controls and advection, so that one peak does not become larger than the other. In the Andes of Ecuador, where a second maximum of precipitation also occurs, though not with the intensity of that of the Colombian Andes, the values of the second harmonic are visibly smaller than those of the first. As in the case of the Colombian Andes the two peaks occur close to the equinoxes.

The amplitude of the semiannual harmonic in the lower Amazon basin merits particular reference, for it does not match the amplitude of the annual harmonic. This means that, although the basin runs almost coincident with the equatorial line, the rain regime of the area is not characterized by equinoctial rain – as one might expect – and that, therefore, other climatic controls have to be taken into account to explain the seasonal variations of precipitation in the lower Amazon basin.

The case of the northern Serras of Brazil is where the harmonic analysis clearly proves its efficacy in unveiling secondary periodicities. In fact, the semiannual harmonics reveal the existence of a second peak of precipitation in early summer (December) that comes very close to the main yearly peak in late summer (March). This second oscillation might well go unnoticed if only the annual variation of precipitation, which in this part of Brazil is very large indeed, is considered.

The timely correspondence of precipitation

Once the time of occurrence of the peaks of precipitation has been ascertained by means of harmonic analysis, the question of how these peaks relate to others occurring at the same time, but at different places, can be considered more effectively.[4]

A study of the seasonal march of precipitation in South America can conveniently be initiated with the JAS and ASO triads which are, for most parts of South America, the driest ones. Only in certain tracts of the Venezuelan coast and on Panama's Pacific coast, one of these two triads includes the rainiest months of the year.

In extratropical South America – particularly central Chile and southern Brazil – the winter rains are in decline, and the same is happening to the summer rains on the Caribbean slopes of the northern Andes. The scattered rains that fall in the arid coastal belt of Venezuela during August and September are associated with deep waves in the easterlies over the Caribbean Sea which appear in the form of a trough extending from the western Atlantic across the central Caribbean (LAHEY, 1973). Meanwhile, the central lowlands of the continent experience, during JAS or ASO, their yearly minimum of precipitation. The widespread cooling of the continent by the end of the southern winter, the strengthening of anticyclonic conditions on adjacent seas, and the low sun elevation seem to be the chief factors conducive to a late winter/summer minimum precipitation which becomes more evident in August and September.

Precipitation maximum during mid-autumn (SON) occurs along the coastal areas of Colombia facing the Caribbean Sea and on the Pacific coast. Local air flow from an overheated ocean contributes to the rainfall in these areas during the autumn months. In the highlands of Ecuador a second peak, of equinoctial character, takes place during the SON triad. This precipitation in Ecuador correlates well with rainfall in the upper Amazon basin, which probably shares the effects of that season's higher insolation. Also during this triad, as the result of the progressive warming of the central lowlands south of the equator, the territories around the La Plata River receive so much precipitation that there is a second annual peak (WÖLCKEN, 1962).

September, October, and November are the months of minimum rainfall for the coastal belt of the Guianas and for the northern coast of Brazil between French Guiana and Cape Sao Roque. Good correlation coefficients of pressure values for stations in northeastern Brazil and Paramaribo underline the influence of the northeast trades on the precipitation in northern South America during this time of year.

During the OND triad the numerous basins of the Colombian Andes experience the higher of the two annual peaks of precipitation. Rainfall there correlates closely with that of the Ecuadorian highlands and to a lesser extent with that of the highlands of Venezuela. Good correlations of pressure between Bogota and other Andean stations such as Caracas, La Paz, or La Quiaca (but remarkably not Quito) lend support to the assumption that, during the southern mid-spring, thermodynamic conditions over the tropical Andes are spread uniformly and, consequently, rainfall is also distributed evenly along the Andes. The only deviation from this norm is Quito, whose pressure values correlate negatively with those of other Andean stations and relate only to stations in the Amazon basin. This suggests that Quito shares the pressure characteristics of stations located along the equatorial trough rather than those of sister stations in the tropical mountains of South America. Therefore, the highlands of Ecuador should be considered as a kind of "watershed" in terms of pressure patterns and wind circulation between Andean stations located north and south of the equatorial line.

Under strong anticyclonic dominance, the arid plains of southern Argentina (Patagonia) experience their minimum precipitation during OND. Indeed, at that time of year the winter rains are over and the convective summer rains have not set in yet.

The same rain-inhibiting circumstances that prevail in early spring are also effective during November, December, and January (NDJ). Rainfree periods in extratropical South America are paralleled by lower precipitation in tropical regions, which otherwise are humid all through the year. NDJ is, nevertheless, the triad, with the greatest rainfall, in certain areas of the Parana basin where the continental warming increases as the southern summer approaches and on the coast of the Guianas, which is being affected at that time of year by steadier northeast trades. In fact, during November, the precipitation in Paramaribo correlates well with that in Asuncion, but only slightly with that in the Amazon basin, which continues to warm up as the summer progresses.

In the month of the summer solstice (December), as well as in the following two months (DJF triad), rainfall is abundant in the Andean highlands, in the Altiplano, in the southern Llanos[5], in the Pampa, and in northern Peru. In terms of spatial patterns intensive early-summer rains are concentrated in the subtropical belt and in the widest part of the Andes, whereas the Brazilian highlands and the Atlantic coast experience only a slow increase of seasonal precipitation. The west coast of South America, however, under the influence of the Peru Current, records its yearly precipitation minimum since the southeastern Pacific is, during this period, under the influence of the subtropical anticyclone and the polar front retreats to its southernmost position.

[4] To establish the genetical linkages between the different rainfall regimes determined by the annual and semiannual harmonics, correlation tests of the monthly precipitation for all the stations were performed. Once the correlation coefficients were computed, the months were grouped in triads (Figure 4). The three months with the highest precipitation or around the yearly maximum are referred to as the rainy season, whereas the months of the lowest or around the minimum precipitation are called the dry season. When referring to semiannual variations reference will be made to the triad of the first or the triad of the second peak.

[5] "Southern Llanos" in this paper refers to the complex of lowlands between the Beni and the Pilcomayo rivers, like the Llanos de Mojos, Llanos de Guarayos, Llanos de Chiquitos, and the Chaco Boreal.

The best rainfall correlations for the DJF triad are found between the Altiplano and the southern Llanos and between the southern edge of the Altiplano (La Quiaca) and the central coast of Brazil (Rio de Janeiro). These places correlate negatively with northeastern Brazil, the lower Amazon basin, central Chile, and the Ecuadorian highlands, a pattern which emerges also in the correlation coefficients of pressures. In fact, while the Altiplano, the adjacent southern Llanos, and the Pampa lowlands experience a summer thermal depression, the regions with which their correlation is negative are dominated by drying anticyclones. Very indicative of the major split that exists along the equatorial line between the pressure fields and the rain producing mechanisms of both halves of South America is the fact that Quito correlates negatively in precipitation and pressures with stations in the northern Andes and in the Altiplano during the DJF triad. Conversely, in both respects Quito and other stations of the Ecuadorian highlands correlate well with stations in the Amazon basin (Manaus and Uaupes). These patterns indicate that in the months of early summer there is an intensification of thermo-convective processes along the Andean heights south of the equator, whereas stabilizing oceanic and anticyclonic action account for the dryness of coastal regions. The intense convection coincides with the maximum insolation over the South American continent, which, at this time of the year, has its center precisely between the Altiplano and the southern Llanos (HIRSCHMANN, 1973).

By mid-summer (JFM) the estival patterns of precipitation and pressure are already established over the central part of the continent. The La Plata River lowlands, a large part of the Peruvian Andes, the central highlands of Brazil, and the northern coast of Peru receive their annual precipitation maximum in the January-February-March triad. The best precipitation correlations during JFM are those of the southern Llanos, the La Plata River lowlands, and the southern portion of the Altiplano. There are negative correlations between these regions and central Chile, northeastern Brazil, the northern Andes, and the Guianas. While the subtropical mass of the continent is under the influence of a vigorous turbulent exchange – which is exported into the Peruvian Andes, the Altiplano, and the Pampa – the western slopes of the Andes, the northern coast of Brazil, and the Guianas are under the drying influence of subtropical anticyclones. An exception to the general dryness along the west coast of South America is the coast of northern Peru, which records irregular rainfall during the JFM triad. The Peruvian littoral between 3° S and about 10° S receives isolated summer showers in normal years, but experiences torrential rains during years that are affected by El Niño phenomenon (CAVIEDES, 1975). Modest correlations (never higher than .500) were computed for Talara – a typical station in northern Peru – Manaus in the lower Amazon basin and Paramaribo, suggesting some linkages between the rainfall of these stations. Negative correlation coefficients result when the precipitation amounts of Talara during February and March are run against those of northeastern Brazil, Bogota, Caracas, and La Paz. Thus, northern Peru experiences rainfall during JFM which correlates well with that of the coast of the Guianas (the amount need not be the same) but negatively with that of Andean stations and northeastern Brazil. It has been proposed that summer rainfall in arid northern Peru is caused by an invasion of equatorial air masses whose southward advance is supported by a seasonal slackening of the Peru Current, a process which intensifies during El Niño years. At about the same time – slightly before or after – a summer persistence of anticyclonic blocking results in a lessening or absence of summer rains in northeastern Brazil, on the other side of the continent (CAVIEDES, 1973). In correspondence with this trend, pressures at Talara and at stations in northeastern Brazil correlate negatively during the summer months, a tendency which is particularly pronounced in January. During February and March, however, correlations are only slightly negative, but they mount again in April. It seems, then, that during the summer a kind of seesaw occurs in the form of a southward shift of humid air masses in the equatorial Pacific off South America and a northward displacement of drying winds in the equatorial Atlantic off northeastern Brazil. There must, therefore, exist a pivotal center somewhere in the Amazon basin, as both northeastern Brazil and northern Peru lie on the same latitude. Since the precipitation as well as the pressure values of Talara and Uaupes (in the upper Amazon basin, lat. 0°, long. 67°W) correlate well, but not so the values of Talara and Manaus (lat. 3°S, 60°W), it can be assumed that the area along the equatorial belt of South America where precipitation and pressure fields reverse their character is located between 60° and 67°W. This is an aspect of the regional climatology of South America that awaits further investigation.

In the late-summer triad (FMA), and coinciding with the maximum continental heating, the precipitation peak moves from the South American lowlands south of the equator into the lower Amazon basin. Manaus and Belem correlate well with the highlands of Ecuador indicating that a second period of rains is affecting the central Andes. Good correlations exist also with the northern Andes (Bogota and Caracas), where the increasing elevation of the sun and occasional southward flexions of an upper trough over the Caribbean Sea (LAHEY, 1973) lead to widespread spring rains.

The FMA triad is also the period of greatest rainfall in the plains around the La Plata River estuary as well as those of the southern Pampa and Patagonia. In the La Plata River region the rainfall peak during FMA is caused by convective rains which, in the course of summer, have been moving from the northwest of Argentina towards Uruguay. The progressive eastward shift of the precipitation peak reaches Uruguay in April/May and is enhanced by the instability of a warm subtropical Atlantic Ocean. Thus, the autumn peak in the La Plata River lowlands can be considered the result of the convergence of two rain-producing circumstances (PROHASKA, 1976). The late-summer rains in the southern Pampa and Patagonia are associated with the frequent passing of subpolar depressions during this time of the year in a track that is disturbed in the winter time by the establishment of a blocking anticyclonic ridge across the Andes (CAPITANELLI, 1967).

Aside from the areas of southern South America which receive rains during FMA because of convective activity and the passage of depressions, dryness is widespread in the regions under the influence of anticyclones. Nevertheless, as the sun, the pressures, and the wind systems progress northward, autumn precipitation begins to increase in the higher latitudes of the continent because of frequent frontal activity. Observe, for instance, the march of precipitation along the coast of southern Chile (Figure 4).

The MAM triad brings about a complete change in the patterns of maximum precipitation. Rainfall intensification occurs along the equatorial line, from Ecuador to northeastern Brazil, as the sun reaches its zenith. The highlands of Colombia also experience stronger heat influx and convection as evinced by a second peak of precipitation during MAM. Rainfall in Quito during this triad correlates well with that of the Amazon basin, with northeastern Brazil, and with Bogota, confirming the trend mentioned above.

March and April are the months of maximum yearly precipitation in northeastern Brazil in correspondence with the southernmost position of the Intertropical Convergence (RATISBONA, 1976). Consequently, rainfall at stations in Brazil's northeast correlate well during these months with stations in the lower Amazon and on the east coast of Brazil (Recife, Salvador). However, the correlations between northeastern Brazil and the upper Amazon (Uaupes) are much weaker, showing clearly that the rainfall mechanisms at work in northern Brazil, east of longitude 60°W, are different from those of the interior Amazon. When comparing the pressure values of all the mentioned stations, one discovers that northeastern Brazil and lower Amazon stations correlate well during MAM, but that the correlations between northeastern Brazil and the upper Amazon as well as between the two segments of the Amazon basin are negative, in spite of their proximity. It is evident that during this time of the year pressures and wind systems together with rain-generating processes in the upper Amazon are not in phase with those of the rest of the Amazon and of northeastern Brazil.

By mid-spring in the northern hemisphere (AMJ) the precipitation maximum shifts north of the line of the equator to the coast of the Guianas, the southern portion of the Venezuelan-Colombian Llanos, and the eastern slopes of the Andes in Colombia. Rainfall in the Llanos and the Guianas is the result of convective activity, whereby the latter receive also advective moisture from the sea. At Paramaribo and Georgetown, where AMJ is the triad of maximum precipitation and where exists a secondary peak in autumn (NDJ), the passage of the sun over the Guianas is not accompanied by a northward translation of the equatorial trough – as contended by some authors (SNOW, 1976) – but the rains occur under strong dominance of the trade winds and at comparatively high pressure values.

While the heaviest rainfall during the AMJ triad is concentrated in a belt from 5° to 8°N and in the tract of northern Brazil that is exposed to the maritime winds from the south Atlantic in most of the South American lowlands south of the equator, in the Altiplano, and in northeastern Brazil a dry period of autumn and winter begins. This trend is demonstrated by the negative correlations of precipitation between stations in the Guianas and in the southern Llanos, in the Altiplano, and in northeastern Brazil. At the same time, over the southern tip of the continent, the seasonal northward shifting of the polar front causes a peak of rains in mid-autumn which heralds the return of the winter precipitation to temperate South America.

The late-autumn triad (MJJ) brings a rainfall maximum to temperate middle Chile. This area on the western coast of South America falls under the influence of frontal rains and maritime air masses whose effects also extend into Argentinean Patagonia, just across the Andes. On the coasts of Argentina and southern Brazil, which are affected by frequent frontal passages and associated depressions (LAUER and BREUER, 1976), the precipitation correlates well with that in central Chile and all of the Venezuelan-Colombian Llanos. In the case of the latter, however, rain develops for a different reason: the MJJ triad is the high-sun period and the time of the year when the Llanos receive the action of humid advective winds from the Amazon basin (SNOW, 1976). During May, June, and July, precipitation in central Chile correlates negatively with that of stations in the Pampa, the Altiplano, the southern Llanos, and the highlands of Ecuador, regions which are experiencing their driest season as a result of anticyclonic dominance and low sun elevation.

In mid-winter in the southern hemisphere (JJA) two belts of maximum precipitation can be defined clearly: one along the coast of Peru and north-central Chile; the other from the cordilleras of Venezuela to the Caribbean coast of Panama. The timely correspondence of precipitation highs is underlined by significant correlations between stations on the west coast of South America, such as Coquimbo and Lima, and Cristobal (Panama) during the months of June and July. Caracas, on the other hand, correlates well during this time of year with stations in central and southern Chile, such as Talcahuano and Valdivia, where the frontal winter rains attain their maximum (LAUER, 1961).

In contrast with the regions that exhibit rainfall peaks during JJA are the central lowlands of South America, the Brazilian highlands, northeastern Brazil, the Altiplano, and the Andes – from Colombia down to northwest Argentina – which undergo their annual precipitation minima. From a regional perspective, while the west coast of South America receives winter precipitation as the result of frontal activity and the northern extreme of the continent records rainfall maxima for convective-advective reasons, the rest of the continent, under the influence of a lower sun and winter cooling, experiences its lowest levels of precipitation of the year. When the sun returns south from the Tropic of Cancer, convection in northern South America and frontal activity in the temperate regions of the continent slacken and, thus, during the JAS and ASO triads, there occurs that general lull in precipitation that characterizes South America during the late northern summer and the late southern winter.

The peculiarities of the circulation over South America and linkages with the general circulation

A review of the annual march of precipitation over South America provides illuminating clues about the synchronic occurrence of precipitation in different regions of the continent and about connections with particular patterns of the atmospheric circulation. On the basis of this evidence some long-standing assumptions can be dispelled and new avenues of explanation can be explored.

According to the isochrones of rainfall peaks, the march of precipitation throughout the year follows a parallel pattern only in the equatorial and tropical lowlands (e. g. the Amazon basin, the Venezuelan-Colombian Llanos, and the southern Llanos), an indication that much of the rainfall is dominated largely by sun position. But, where there is a rise in the relief, as in the Brazilian highlands, the Pampean Sierras, or the highlands of the Guianas, the parallel pattern is upset and island-like areas of seasonal precipitation develop. From this it can be concluded that topographic controls affect not only amounts, but also seasonal variations of precipitation because relief features alter the airflow near the earth's surface. It cannot be taken for granted, then, that highlands that are contiguous to tropical or subtropical plains share similar precipitation regimes, even though the seasonal position of the sun is the same.

Maritime influence on seasonal precipitation is also emphasized by the analysis of harmonics. Rainfall regimes of the Guianas, of the northern and central coast of Brazil, and along the Venezuelan coast indicate that precipitation in these regions is affected by weather systems that develop on the adjacent seas, and, therefore, diverge from the rain-causing processes of their continental interiors. In most of the above-mentioned regions, precipitation is generated by cyclonic activity, orographic influence over maritime air masses, or frontal displacement whose effects are restricted to coastal areas, while in the hinterland thermal-convective rains prevail.

In general terms, the observation of WEISCHET (1965) that in the lower levels of the troposphere (up to 2800 or 3000 meters) in tropical areas it is the convective processes that are responsible for precipitation, while the main factor affecting precipitation in subtropical regions is advective humidity transport, fits well the seasonal patterns of precipitation of many continental regions of tropical South America. In fact, most of the rain regimes of the lowlands south of the Amazon basin experience their rainfall peaks during the period of maximum continental heating of mid and late summer. But there is no denying the importance of the advection of humidity also inside the tropics, in many cases in addition to convective activity. It has been advanced in this paper that a strong correlation and synchronism exist between the rain peaks of the Altiplano and the southern Llanos. Although the copious summer rains in the Llanos lowlands can be explained by strong convection, that same argument cannot be used for the elevated Altiplano. Accordingly, GUTMAN and SCHWERDTFEGER (1965) have stressed that precipitation over the Altiplano in summer is fed by advective warm-humid air from the continental lowlands in the east rather than by autochtonous convection. Moreover, it has also been pointed out here that in the Guianas and in the Venezuelan Llanos the main annual peak of precipitation coincides with the highest sun elevation and occurs, strikingly, not under low pressure conditions as one would expect when considering the seasonal location of the equatorial trough (SNOW, 1976). This implies that for these regions the convective rains of the warmest season of the year are overwhelmed and masked by advective air transport from the Atlantic.

Such a statement poses the question of strong advection under conditions of increased insolation that resemble, in their coarse lines, a monsoon-like circulation. A. VULQUIN (1971) holds that there exist synoptic situations where air flows inland from the Guianas into the Amazon basin and other situations where that flow is reversed, i. e. from the Amazon basin towards the coast of central Brazil. Situations like these generally occur at about the time of the spring equinox in March. The close correlation of precipitation and pressures at Paramaribo with those of the Amazon basin during the rainy season (AMJ triad) and to a much lesser extent with precipitation and pressures in the Venezuelan-Colombian Llanos substantiate this thesis. More evidence on flows of compensation has been uncovered by SNOW (1976), who affirms that during the rainy season in the Amazon basin the Venezuelan Llanos have their minimum yearly precipitation and that the air flow is directed constantly from the Llanos into the Amazon basin. Conversely, during the wet season in the Llanos (MJJ triad) the Amazon basin experiences low precipitation and air flow is directed from this basin into the Llanos. SNOW concludes: "In this Llanos-Amazon monsoon the roles of 'continent' and 'ocean' change. 'Ocean' is played by the low-sun basin" (SNOW, 1976, p. 337).

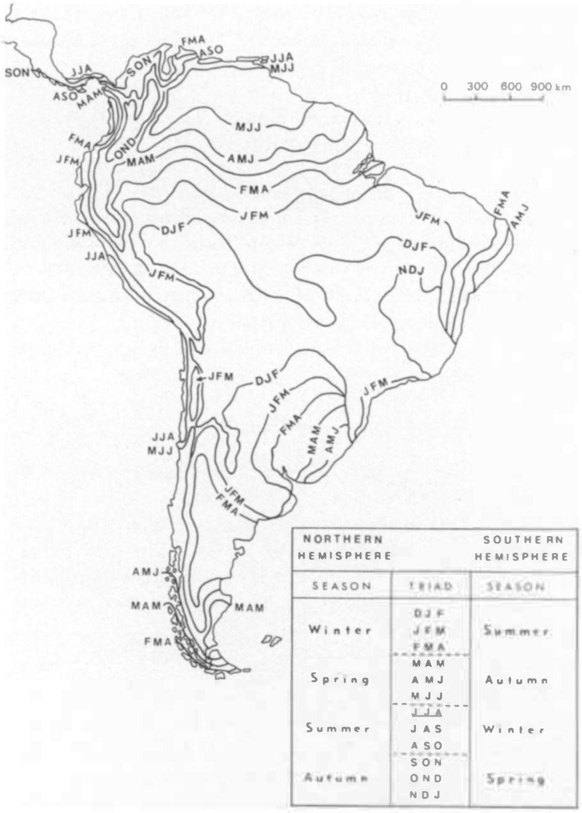
Even more intriguing are the relationships of certain precipitation patterns in South America with the zonal circulation of the nearby subpolar belt. For instance, seasonal precipitation records for the southern tip of the continent, which is under the influence of the westerlies, show rain maxima around the time of the equinoxes, as revealed by the annual and semiannual harmonics. The existence of biannual variations for the zonal wind in the southern subpolar latitudes has been pointed out by SCHWERDTFEGER and MARTIN (1967). This suggests that circulation and rain mechanisms which are stimulated in the equatorial belt during equinoctial sun positions have their counterpart in these latitudes. Such findings carry the implication that precipitation in the high latitudes of South America is more intense in autumn and spring, when the zonal flow in the subpolar belt is accelerated (SCHWERDTFEGER, 1976), than in winter, as one would expect in those pronounced oceanic latitudes. As WEISCHET (1968) states, it is also the high index circulation and the maritime character of southernmost South America that explain why this region is governed by extra-regional rather than by local (autochtonous) weather conditionants.

Another area where rain and rain anomalies are caused by extra-regional factors is northeastern Brazil. Dry winter months are dominated by air masses linked to the South Atlantic high, whereas late-summer and autumn rains come from humid equatorial air that moves into northeastern Brazil from the north (Markham, 1972). Since most of the air masses affecting the area circulate over sea surfaces, it is common that oceanic anomalies upset summer precipitation during abnormal years in the equatorial Atlantic (Markham and McLain, 1977). But since these oceanic anomalies depend on atmospheric influences of wide-areal extension (Doberitz, 1969), the causes of these major climatic oscillations are often found far from the equatorial Atlantic. Thus, Namias (1972) advanced the proposition that rain increases in Brazil's northeast are induced by abnormally strong anticyclones and blocking situations in the North Atlantic during the northern winter (DJB) and spring (MAM). Dry years, however, are dominated by strong anticyclonic development in the South Atlantic, by weak trades, and a weakened North Atlantic anticyclone. One way or another, the seasonal occurrence of rainfall in northeastern Brazil depends on the atmospheric conditions over the Atlantic on both sides of the equator. This principle was confirmed by Hastenrath (1978), who has found negative correlations between the rainfall in northeastern Brazil and the Caribbean basin, and positive correlations between the Caribbean basin and both the Venezuelan Llanos and the highlands of Ecuador. This coincides with our correlations for those regions, with the remark that the best correlations apply to the rainy season of central Venezuela (JJA), and not to the dry season (JFM), which occurs under the strong dominance of the northern trades. In disagreement with Hastenrath, month-by-month correlations for this paper show rather negative correlations of precipitation between the northern coast of Peru (Talara, as the typical station) and northeastern Brazil. The negative correlations are stronger in February and March (two wet months in both areas) than in the drier winter months, June through September, emphasizing the diversity of the circulation and rain-causing processes on both sides of equatorial South America.

This climatic split between the equatorial coasts of the Pacific and the Atlantic parallels the split of precipitation regimes in the tropical Andes at both sides of the Ecuadorian highlands. The timely correspondence and correlation of precipitation and pressures between the highlands of Ecuador and the upper Amazon basin (but not with other Andean areas north or south of the equator) are indications of a powerful circulation along the equator, and it is this circulation which accounts for the climatic correspondence between these two physiographically different landscapes. Very significant also is the fact that pressures in the Ecuadorian Andes correlate negatively with those at coastal stations of Ecuador and Peru all the year through and that precipitation shows only weak positive correlations and even that only during late summer. On this basis the Andean highlands relate much better to the interior Amazon basin than to the neighboring Pacific coastal lowlands. One can, in fact, state that there is no relationship in rain mechanism and rain level between the Ecuadorian Andes and the Ecuadorian-Peruvian coastal lowlands (Schütte, 1968).

If one considers this finding alongside with two previous observations, namely, the timely correlations of rainfall and pressure between the Ecuadorian highlands and the upper Amazon basin, and the divergences between the upper and lower Amazon basins, which become patent at about 60° and 65°W, one arrives at the fascinating preliminary conclusion that these patterns, although incoherent in appearance, fit well with one of the typical zonal circulation features of the equatorial belt – the Walker circulation. In 1971 H. Flohn proposed a model of cellular circulation along the equator which implied, for the South American continent, a center of thermal rise of air in the interior of the Amazon basin and subsidence in West Africa, where the stabilizing effects of the Benguela Current are felt (Flohn, 1971). By analogy, over the equatorial Pacific the ascending branch of the Walker equatorial circuit lies over the Caroline Islands and the descending branch off the coast of Peru-Ecuador, where the Peru Current leaves the South American continent. With the aid of this model it is easier to understand the good correlations of rainfall and pressure between the Ecuadorian Andes and the upper Amazon basin: both regions partake of the effects of the ascending branch of the Walker circulation. On the other hand, the Pacific coast differs from the Ecuadorean highlands because it is under the action of the descending and drying branch of the Pacific equatorial Walker circulation (see Flohn, 1975, figure 2). The seasonal variations of precipitation and pressures between the upper and the lower Amazon basin stem from the fact that the latter is under the influence of advectional flows from E to W which have been in contact with the cool upwelling waters of the equatorial Atlantic. In this context, it is easier to understand why the correlations of precipitation and pressures of the lower Amazon basin are better with the northeast coast of South America than with the upper Amazon basin, a condition which becomes even more pronounced toward the end of the southern winter, when the Atlantic and the South American continental margin fall under anticyclonic influence, while the upper Amazon basin resumes its seasonal warming. In this perspective one can understand the deep penetration of the northeast trades into the Llanos, and even into the Amazon basin, as well as the "monsoon-like circulation," because these lateral flows serve to stimulate the Walker zonal circulation (Bjerkness, 1974). A similar kind of stimulation from the southeast trades is inhibited, however, by the barrier imposed by the Brazilian Serras. Observe that the eastern façade of the Serras exhibit completely different rain regimes from those of the Amazon basin and northeastern Brazil (Figure 4).

In conclusion, some of the peculiarities in South America that were unveiled by the study of the spatial patterns of seasonal precipitation and by means of spatial-correlations become coherent and understandable in the context of extensive patterns of atmospheric circulation within the tropics and the subpolar latitudes. The corollary one arrives at from all the exposed trends is that climatic oscillations within each of the zonal belts of South America find their explanation in connection with large-scale atmospheric anomalies. One of the most significant variations of the tropical circulation is the Southern Oscillation which, although rooted in the equatorial Pacific, has far-reaching effects for the



NORTHERN HEMISPHERE		SOUTHERN HEMISPHERE
SEASON	TRIAD	SEASON
Winter	DJF JFM FMA	Summer
Spring	MAM AMJ MJJ	Autumn
Summer	JJA JAS ASO	Winter
Autumn	SON OND NDJ	Spring

Figure 4: Triads of the annual peaks of rainfall

development of weather in South and North America, the North Atlantic, equatorial Africa, Australia, and the Indian Ocean (WRIGHT, 1977). Further, it is understandable that, under abnormal conditions of the general atmospheric circulation, the fluctuations of precipitation and pressure patterns in different regions of South America often appear related in space and time, but seldom under the same positive or negative sign. The El Niño phenomenon and the droughts of northeastern Brazil are perhaps the best examples of such situations, and have attracted, therefore, the attention of many geographers and meteorologists. However, the dynamic linkages of these phenomena with other major climatic anomalies of South America, such as the droughts in the Pampas, in central Chile, and the southern Llanos, the cold air outbreaks in southern Brazil, and the floods in the Colombian-Venezuelan Llanos still await investigation.

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DER EINZUGSBEREICH EINER FREMDENVERKEHRSGEMEINDE (BEISPIEL BOPPARD)

Erfassung mit Hilfe von Stichproben: Fehlerquellen und Kontrollmöglichkeiten

Mit 6 Karten (Beilage V + VI) und 7 Tabellen

HELMUT HAHN

Summary: The catchment area of a municipality engaged in tourism (the example of Boppard). An investigation based on sample surveys: sources of error and possibilities of control

The difficulty of locating the places of origin of tourists, especially of day visitors, but also of overnight guests, is the cause of the great difficulty of demarcating the catchment areas of municipalities engaged in tourism. It is for that reason that the opportunity has been taken for some time of noting down the registration numbers of parked vehicles as a means of locating the catchment area with relatively little effort. The example of such data collections in Boppard on the Middle Rhine serves to prove that isolated collections or a few counts on so-called "representative" or "normal" days do not provide a sufficient base for the definition of the catchment area because of fluctuations resulting from the most diverse external circumstances and behaviour patterns. Only numerous counts paying the best balanced attention possible to the rhythm of the week, as well as to that of the year, to local peculiarities and so on are able to minimise the sources of error. Since individual groups of visitors use cars as the means of arrival in differing proportions, and day visitors cover distances different from those of overnight guests the noting-down of registration numbers needs to be supplemented by separate questioning of each group of visitors. These will of course not only have to attain a sufficient volume of sample surveys but also to take into account the criteria mentioned above. In the case of Boppard there emerges a clearly definable, bipartite nucleus, the southern part of which is the catchment area of day visitors, while the northern part caters for day and overnight guests. It is surrounded by a marginal zone in which overnight guests again predominate in the north, and day visitors in the south. Only the marrying of the methods of investigation justifies hopes for a realistic result.