On the Rainfall Distribution with Altitude over Costa Rica

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Resumen

Se estudia la distribución de la precipitación vertical en Costa Rica, a lo largo de un perfil topográfico que cruza el país del Pacífico hasta la costa del mar Caribe. El perfil en montaña, cuyo pico más alto llega a los 3000 m.s.n.m., está orientado en dirección paralela a la de los predominantes vientos alisios del noreste, a gran escala. El análisis de las precipitaciones anuales y de las variaciones estacionales y diurnas, en base a registros en catorce estaciones pluviométricas ubicadas sobre o cerca del perfil topográfico, muestra que existe considerable variación con altura sobre el nivel del mar y que los máximos a uno y otro lado de la principal cordillera ocurren a alturas intermedias y no en la cima de las montañas. A barlovento se oberva la precipitación máxima media de 7735 mm, y a sotavento 6692 mm, a alturas de 2000 m y 800 m respectivamente. Una característica interesante en la distribución de la precipitación a barlovento es la ocurrencia de un mínimo a una altura de 1000 m. Se describen también los patrones de precipitación a ambos lados del perfil topográfico.

Se sugieren causas físicas para la distribución de la precipitación vertical, estas dependen de la interacción a mesoescala de la circulación térmicamente impulsada y el flujo a gran escala.

Abstract

The vertical rainfall distribution in Costa Rica along a topographic profile which crosses the country from the Pacific to the Caribbean coast is studied. The mountain profile, whose highest peak is at about 3000 m, is oriented parallel to the prevailing large-scale northeasterly trade winds. Analysis of the yearly rainfall amounts and of

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the seasonal and diurnal variations using records at fourteen rain-gauge stations located on or very close to the topographic profile shows that there is a considerable variation with altitude and that the maxima on both the windward (Caribbean) and leeward (Pacific) sides of the main mountain range occur at intermediate altitudes rather than on the mountain tops. Average yearly maxima of 7735 mm on the windward side and 6692 mm on the leeward side at about 2000 m and 800 m respectively are observed. An interesting feature of the rainfall distribution on the windward side is the occurrence of a minimum at about 1000 m. Rainfall patterns occurring on both sides of the mountain profile are also described.

Physical causes for the observed vertical rainfall distributions are suggested; these depend on the interaction of thermally driven mesoscale circulations and the large-scale flow.

Introduction

Several studies of the vertical distribution of precipitation in midlatitudes have shown that precipitation increases with altitude in areas with small (0 to 100 m) as well as those with high (0 to 2000 m) terrain elevations (Bergeron 1968, 1970 and Rydén 1972). Similar studies in the tropics have indicated that precipitation maxima occur at intermediate altitudes rather than on the mountain tops (Flohn 1971; Mendizabal 1973; Chacón and Fernández 1985; Davies *et al.* 1985). A clear example of this is the vertical yearly rainfall distribution on Kilimanjaro (Africa) with a maximum at about 1500 m and sharply decreasing amounts at higher and lower levels (Flohn 1971). A comparison of this example with the vertical yearly rainfall distribution on both the eastern and western slopes of the main island of Hawaii revealed that the location of the maxima in the Hawaiian case was close to 1000 m (Riehl 1979, figure 6.23). In the case of rainfall distribution on the Caribbean side of Costa Rica, the maxima occurred at about 2000 m (Mendizabal 1973; Chacón and Fernández 1985).

A detailed study of the vertical rainfall distribution on the Pacific and Caribbean slopes of the Costa Rican mountains is presented here.

Area of study and data

The Pacific and Caribbean sides of Costa Rica are divided by a series of mountain ranges (Figure 1). For an analysis of the vertical rainfall distribution, fourteen rain-gauge stations located at or very close to a topographic profile across Costa Rica from the Pacific to the Caribbean coast are chosen (Table 1, Figures 1 and 2). The mountain profile chosen, whose highest peak is at about 3000 m, is oriented parallel to the prevailing large-scale northeasterly trade winds. The rainfall data used are for periods from 18 to 73 years (average 24.5 years), except for stations

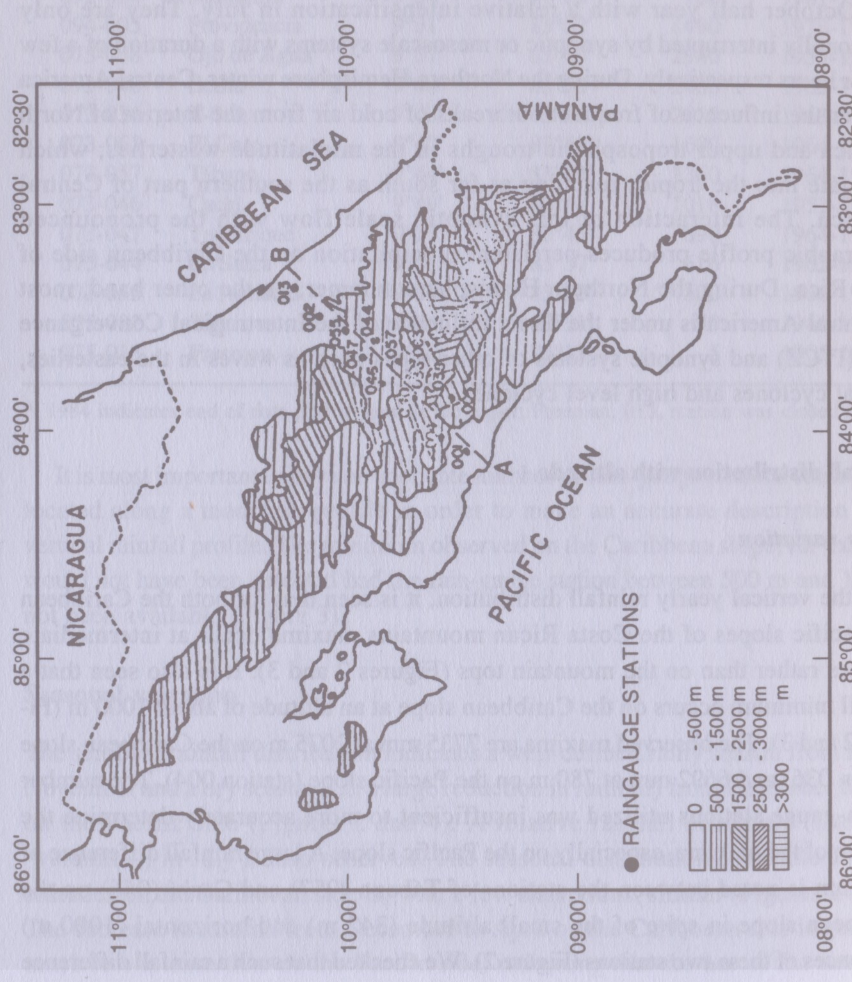

Figure 1. Relief map of Costa Rica, where A-B indicates the location used for the topographic profile (shown in Figure 2).

001 and 004 on the Pacific side which had only four and seven years of data, respectively. The reliability of short rainfall series is a problem that Davies *et al.* (1985) faced and discussed in their study of rainfall in West-Central Kenya. As they pointed out, short records are not ideal because trends may exist. For our purposes, however, this should not affect the results substantially.

The northeasterly trades are stronger in the November-April period than in the May-October half year with a relative intensification in July. They are only occasionally interrupted by synoptic or mesoscale systems with a duration of a few days or hours respectively. During the Northern Hemisphere winter, Central America is under the influence of frequent outbreaks of cold air from the interior of North America and upper tropospheric troughs in the midlatitude westerlies, which propagate into the tropics reaching as far south as the southern part of Central America. The interaction of this synoptic scale flow with the pronounced topographic profile produces persistent precipitation on the Caribbean side of Costa Rica. During the Northern Hemisphere summer, on the other hand, most of Central America is under the direct influence of the Intertropical Convergence Zone (ITCZ) and synoptic systems of other types such as waves in the easterlies, tropical cyclones and high level cyclones.

Rainfall distribution with altitude

Yearly variation

From the vertical yearly rainfall distribution, it is seen that for both the Caribbean and Pacific slopes of the Costa Rican mountains maxima occur at intermediate altitudes rather than on the mountain tops (Figures 2 and 3). It is also seen that a rainfall minimum occurs on the Caribbean slope at an altitude of about 1000 m (Figures 2 and 3). The observed maxima are 7735 mm at 2075 m on the Caribbean slope (station 036) and 6692 mm at 780 m on the Pacific slope (station 004). The number of rain-gauge stations utilized was insufficient to more accurately determine the location of the maxima, especially on the Pacific slope. A large rainfall difference of 4562 mm is noted between the stations of Tábano (057) and Cachí (046) on the Caribbean slope in spite of the small altitude (342 m) and horizontal (1000 m) differences of these two stations (Figure 2). We checked that such a rainfall difference is not due to gauging error.

The annual rainfall on the Caribbean slope shows little change below 500 m and a minimum at about 1000 m (Figure 3). This finding is somewhat unexpected and is to be contrasted with the vertical distributions at Kilimanjaro and Hawaii, which show a smooth increase up to about 1500 and 1000 m, respectively, and a smooth decrease from there on (Riehl 1979, Figure 6.23).

Table 1
List of rain-gauge stations

Index number basin-station	*Station name*	*Latitude (North)*	*Longitude (West)*	*Altitude (m)*	*Period of data**
092-001	Bartolo	9°26'	84°06'	10	1941-1984
092-004	Naranjillo	9°34'	84°02'	780	1981-1984
094-005	Providencia	9°31'	83°52'	1490	1978-1984
073-038	Ojo de Agua	9°37'	83°49'	2960	1959-1984
073-040	Berna	9°40'	83°50'	2480	1962-1984
073-036	T-Seis	9°43'	83°46'	2075	1963-1984
073-063	El Gato	9°42'	83°42'	1600	1964-1984
073-057	Tábano	9°44'	83°42'	1360	1964-1984
073-046	Cachí	9°49'	83°48'	1018	1952-1984
073-047	Tucurrique	9°51'	83°45'	890	1964-1984
073-044	La Suiza	9°51'	83°37'	616	1962-1984
073-055	La Amistad	9°59'	83°35'	500	1966-1984
075-002	Siguirres	10°06'	83°31'	70	1966-1984
075-013	Freeman	10°12'	83°22'	5	1905-1978

* 1984 indicates end of data period used in the paper; Freeman, 013, station was closed in 1978.

It is most important to have an adequate number of rain-gauge stations strategically located along a mountain profile in order to make an accurate description of the vertical rainfall profile. The minimum observed on the Caribbean slope, for example, would not have been detected had the rain-gauge station between 500 m and 1000 m not been available (Figure 3).

Seasonal variation

The seasonal rainfall distribution indicates a well-defined rainy season from May to November and a dry season (i.e. a large reduction in rainfall) from December to April on the Pacific side (Figures 2 and 4). A relative rainfall minimum (known as "veranillo") in July is also observed. The seasonal distribution at middle and high altitudes on the Caribbean side is, with a few exceptions, similar (Figures 2 and 4). The decrease in rainfall from December to April on the Caribbean side is generally much less intense than on the Pacific side, indicating that the use of the term "dry season" may be misleading in this area. This also holds true for Naranjillo (004) station, where the monthly rainfall from December to April is greater than 150 mm (Figure 4).

There are some marked differences in the rainfall patterns at low altitudes (below 600 m) between the Caribbean and the Pacific sides and between middle and high altitudes on the Caribbean side (Figures 2 and 4). At low altitudes on the Caribbean

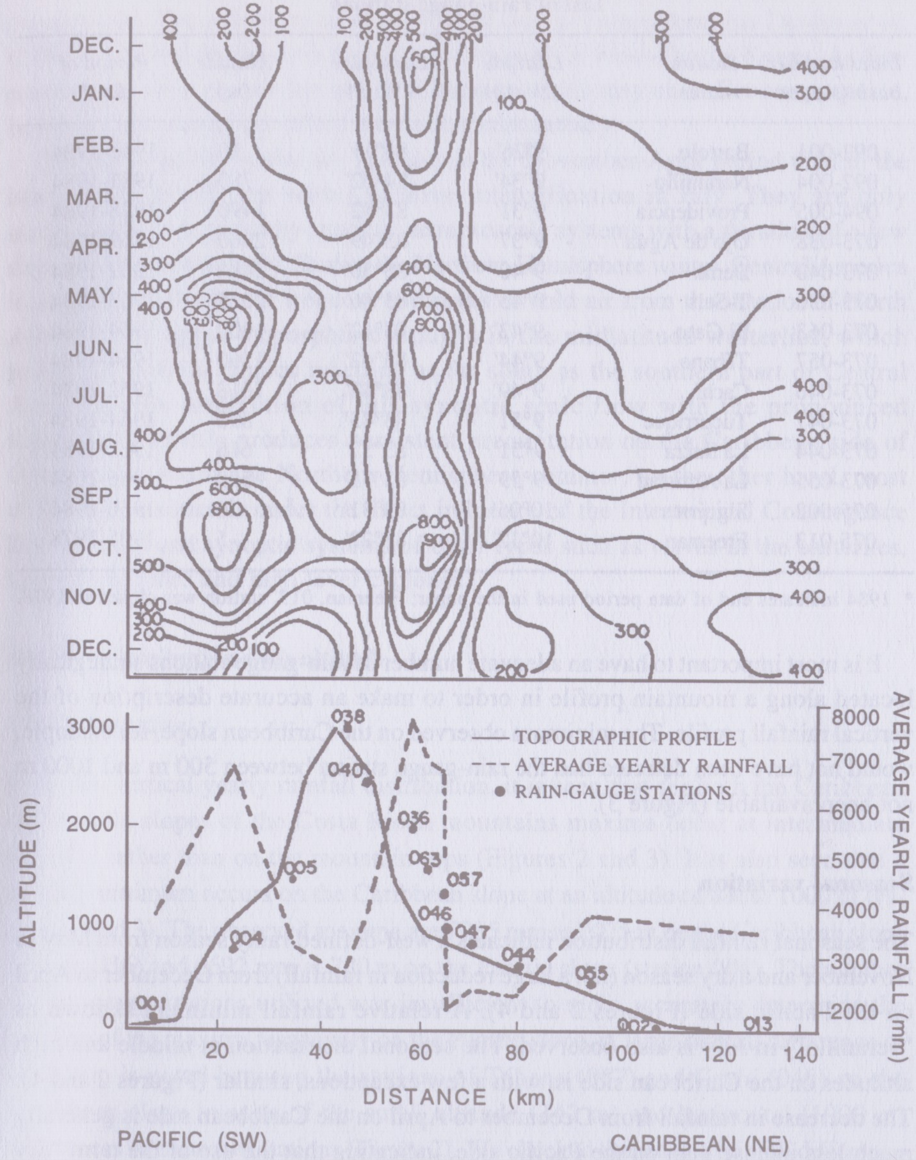

Figure 2. Top diagram: annual variation of rainfall along the topographic profile. Isohyets are in millimeters and the period of analysis is 1981-1984, except at Freeman Station (013, 1905-1978). Bottom diagram: distribution of the yearly rainfall along the topographic profile. The locations of the rain-gauges (and their station numbers) are also shown and the period of analysis is given in Table 1. The topographic profile is smoothed and the gauge heights are spot heights.

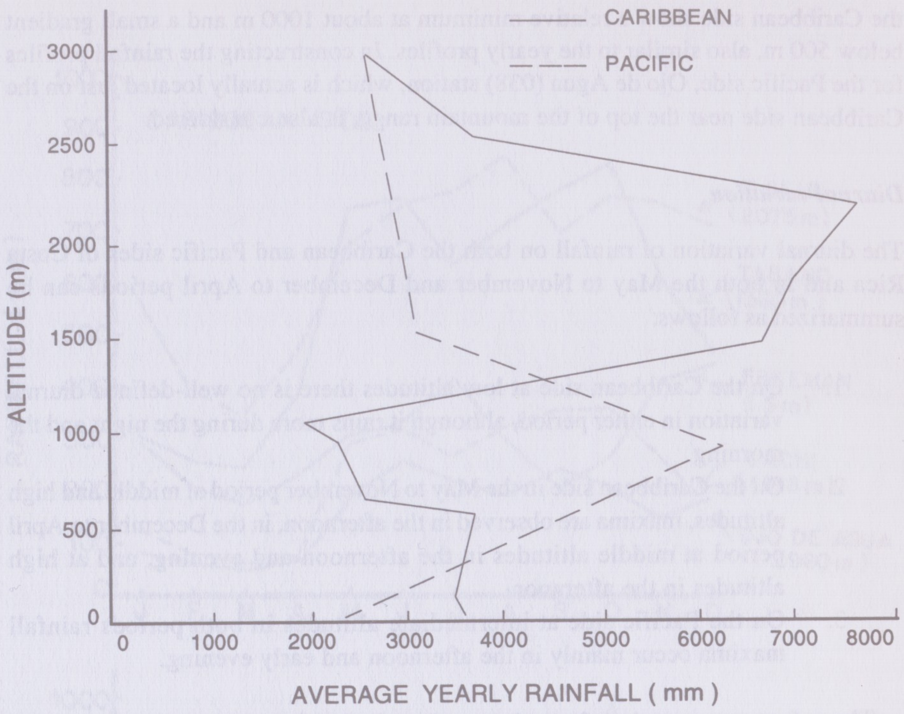

Figure 3. Distribution of average yearly rainfall with altitude on the Caribbean and Pacific sides of the topographic profile. The periods of analysis are 1966-1984 and 1981-1984 for the Caribbean and the Pacific sides, respectively.

side (Freeman 013 station), maxima in December and July are observed; the one in July usually coincides with the relative minimum ("veranillo") on the Pacific side and the relative minimum at middle and high altitudes on the Caribbean side. On the Pacific side, and at middle and high altitudes on the Caribbean side, rainfall profiles show that a maximum generally occurs from September to October (excepting T-Seis 036 station), coinciding with the relative minimum at low altitudes on the Caribbean side.

In a separate investigation of rainfall amounts in Costa Rica, using a different cross-section from the Pacific to the Caribbean coast, similar patterns were found (Portig 1976, Figure 9), except that in the cross-section used in the present study, the "veranillo" is not as well defined as in the previous one (Figure 2). For example, the observations at Bartolo (001) station at an altitude of 10 m near the Pacific coast does not show a case of "veranillo" (Figure 4).

Rainfall maxima for each month of the year and on both sides of the topographic profile occur at intermediate altitudes rather than on the mountain tops, following the pattern of the yearly distribution (Figure 5). Furthermore, the rainfall profiles for the Caribbean side show a relative minimum at about 1000 m and a small gradient below 500 m, also similar to the yearly profiles. In constructing the rainfall profiles for the Pacific side, Ojo de Agua (038) station, which is actually located just on the Caribbean side near the top of the mountain range, is also considered.

Diurnal variation

The diurnal variation of rainfall on both the Caribbean and Pacific sides of Costa Rica and in both the May to November and December to April periods can be summarized as follows:

1. On the Caribbean side at low altitudes there is no well-defined diurnal variation in either period, although it rains more during the night and the morning.
2. On the Caribbean side in the May to November period at middle and high altitudes, maxima are observed in the afternoon, in the December to April period at middle altitudes in the afternoon and evening, and at high altitudes in the afternoon.
3. On the Pacific side at intermediate altitudes in both periods rainfall maxima occur mainly in the afternoon and early evening.

These features are taken from the results of other investigators, using either monthly-hourly cross sections at individual rain-gauge stations (Alfaro 1981 and Zárate 1977) or in the case of Chacón and Fernández (1985), from three stations on the Caribbean side of Costa Rica. They can be compared with results reported for another tropical region, the Cauca Rift of Colombia, where time-height cross-sections of diurnal rainfall show that nocturnal precipitation occurs at low levels (below 500 m) at about 01:30 hours (LST), afternoon showers at higher levels (above 1300 m) at about 14:30 hours (LST) and rainfall minima at all heights during the morning (Trojer 1959; Flohn 1969, Figure 13).

Discussion of the results

Rainfall patterns

In Central America in flat areas and in the lee of the mountains, rainfall patterns characterized by a rainy season and a relatively dry season during the Northern Hemisphere midsummer and midwinter, respectively, are commonly observed. The rain results mainly from convective activity associated with diurnal heating and also from such disturbances as tropical waves and hurricanes.

On the windward side at middle and high altitudes, the rainfall patterns are similar except for the less intense decrease towards low altitudes. In a separate

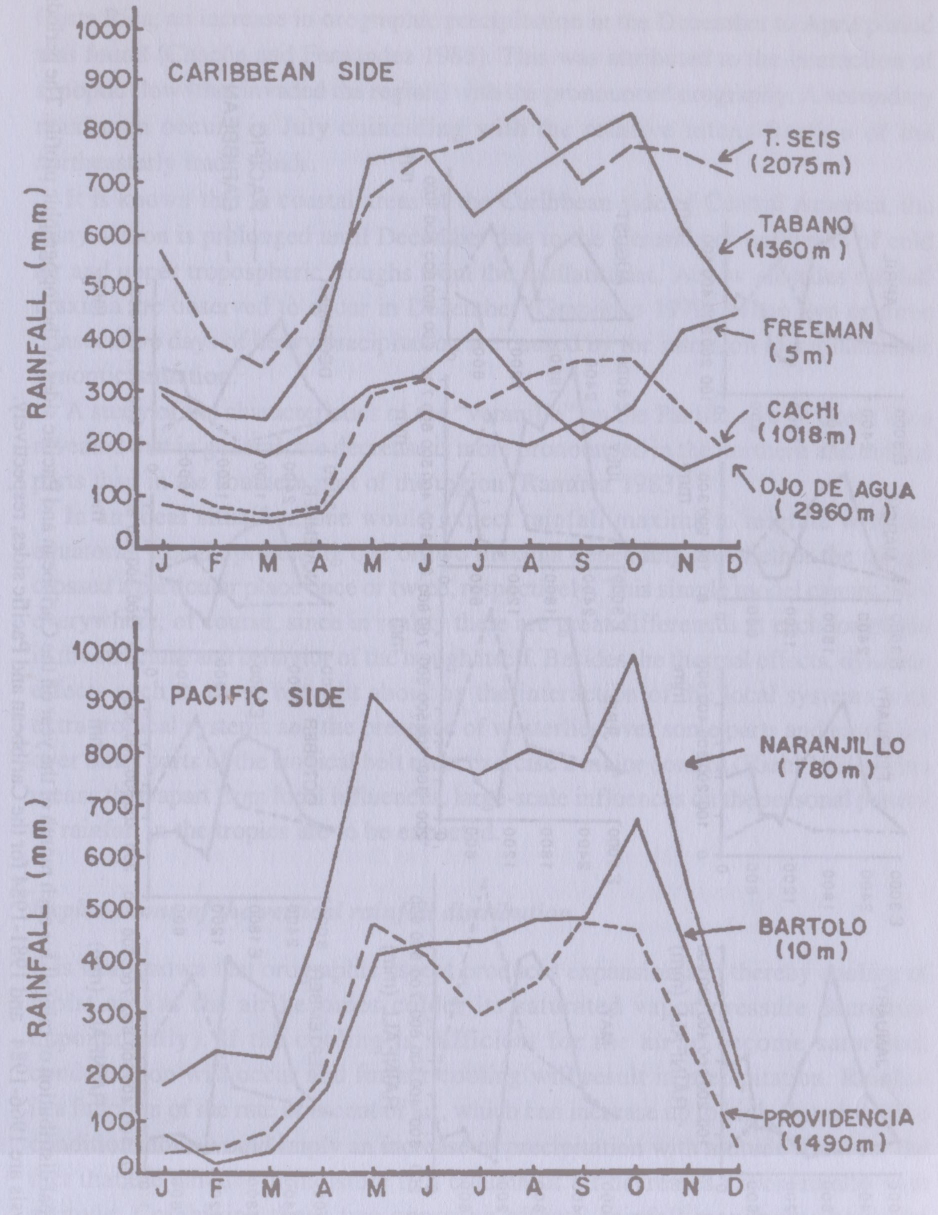

Figure 4. Monthly rainfall distributions at several stations located on the Caribbean side (top diagram) and the Pacific side (bottom diagram) of the topographic profile. The altitudes of the rain-gauge stations are below their station names and the period of analysis is in Table 1.

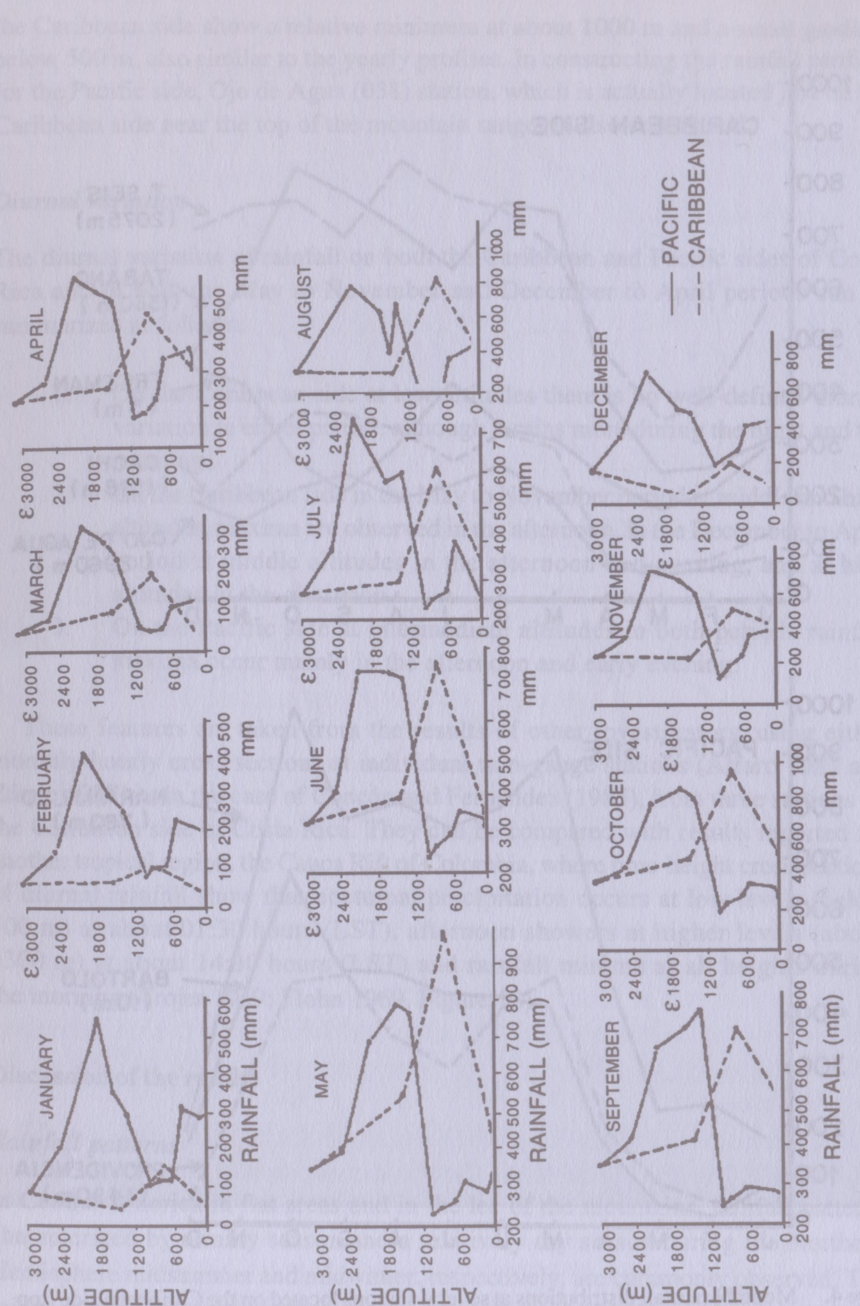

Figure 5. Vertical distribution of rainfall for each month of the year on the Caribbean and Pacific sides of the topographic profile. The periods of analysis are 1966-1984 and 1981-1984 for the Caribbean and Pacific sides, respectively.

investigation of orographic and convective precipitation on the Caribbean side of Costa Rica, an increase in orographic precipitation in the December to April period was found (Chacón and Fernández 1985). This was attributed to the interaction of synoptic flow (that invaded the region) with the pronounced orography. A secondary maximum occurs in July coinciding with the relative intensification of the northeasterly trade winds.

It is known that in coastal areas of the Caribbean side of Central America, the rainy season is prolonged until December due to the intrusion of outbreaks of cold air and upper tropospheric troughs from the midlatitudes. At low altitudes rainfall maxima are observed to occur in December (Grandoso 1979), when two or three consecutive days of heavy precipitation are caused by the intrusion of a midlatitude synoptic situation.

A study of the characteristics of the "veranillo" on the Pacific side of Costa Rica revealed that in general, the decrease is more pronounced in the northern and central parts than in the southern part of the region (Ramírez 1983).

In an ideal situation, one would expect rainfall maxima to migrate with the equatorial trough, producing one or two maxima depending on whether the trough crossed a particular place once or twice, respectively. This simple model cannot hold everywhere, of course, since in reality there are great differences at each longitude in the structure and behavior of the trough itself. Besides the thermal effects, dynamic effects such as those brought about by the interaction of the local systems with extra-tropical systems and the presence of westerlies over some parts and easterlies over other parts of the tropical belt must exercise a major control (Riehl 1979). This means that, apart from local influences, large-scale influences on the seasonal pattern of rainfall in the tropics are to be expected.

Explanations of the vertical rainfall distribution

It is well known that orographic ascent produces expansion and thereby cooling of moist air (as the air becomes colder its saturated vapor pressure decreases exponentially). If the cooling is sufficient for the air to become saturated, condensation will occur and further cooling will result in precipitation. Rainfall is a function of the rate of ascent of air, which can increase up to high altitudes. This condition alone would imply an increase of precipitation with altitude if not for the fact that the amount of moisture in a column of air decreases exponentially with altitude. Combining these two opposing effects, rainfall maximum should be observed at some intermediate level. Depending on the topographic and meteorological conditions of a region, this level may be different for different regions. Evaporation of precipitation below the cloud base may also contribute to the increase of precipitation with height.

Observations show that in general, rainfall increases up to the mountain tops (about 3000 m, approximately) in midlatitudes and to intermediate elevations (between 1000 and 2000 m, approximately) in the tropics. It has been suggested that this difference is partly due to the fact that midlatitude westerlies increase to the top of the mountains on the windward side, while in the tropic, relatively high wind speeds are found in the lower troposphere, below mountain tops (Flohn 1971). One exception to this general rule is the precipitation observed at Ruwenzori mountain (0°, 30°E), where the decrease of precipitation with height begins at 3000 m (Riehl 1979).

For the case dealt with in this paper, when the prevailing wind is forced to pass a mountain range, heavy precipitation associated with the ascending motion on the windward side will be produced. The ascending motion on the leeward side is probably associated with a combination of the following factors: (a) mechanical lifting produced by the mountains and smaller orographic features, (b) thermally driven circulations and (c) synoptic conditions affecting this side of the mountains. The descending air on the leeward side will be relatively warm and dry since most of the water vapor will have been condensed and precipitated on to the windward side (Scorer 1978); some spillover of rain takes place close to the mountain top on the leeward side. Two types of thermally driven circulation of importance are the well-known sea and land breezes over horizontal surfaces at coastal areas and the anabatic and katabatic winds on slopes (Gutman and Melgarejo 1981); additional discussions of these and other mesoscale phenomena can be found, for example in Atkinson (1981), Barry (1981) and Pielke (1984). A conceptual model for the explanation of the vertical rainfall profile presented here thus emerges (Figure 6):

1. On the Caribbean side, daytime sea breeze and upslope winds will strengthen the prevailing northeasterly trades, while land breeze and downslope winds will counteract this effect producing a zone of convergence. Thus, large rainfall amounts can be expected between middle and high altitudes, mainly in the afternoon when the ground is hottest. At nighttime, a large amount of rainfall will be found in coastal areas, where the zone of convergence of the northeasterly trade winds with the land and mountain breezes might be located. Downdrafts from convective clouds formed along this zone of convergence will interact with the existing northeasterly and southwesterly winds forming other zones of convergence where more convective clouds may also develop. Nocturnal thunderstorms observed over the sea may be the result of this triggering mechanism. Since during the day large rainfall amounts are expected to occur mainly between middle and high altitudes and at night at coastal areas, the existence of a rainfall minimum somewhere in between the two maxima is to be expected. Furthermore, since daytime rain-producing mechanisms are probably more efficient than those operating at nighttime, monthly and yearly rainfall maxima are expected to be found at intermediate rather than at lower altitudes.

2. On the Pacific side, the daytime sea breeze and upslope winds will interact with the descending branch of the northeasterly flow producing a zone of convergence, while the nighttime land breeze and the downslope winds will strengthen it. Thus large amounts of rainfall are expected at middle altitudes, where the zone of convergence may be located during the afternoon at the time of the strongest heating. At times, synoptic systems in the region will bring winds with a component from the west. When this happens, persistent and heavy rainfall (the "temporales") will occur (e.g. Zárate 1977). While these synoptic scale winds from the west will

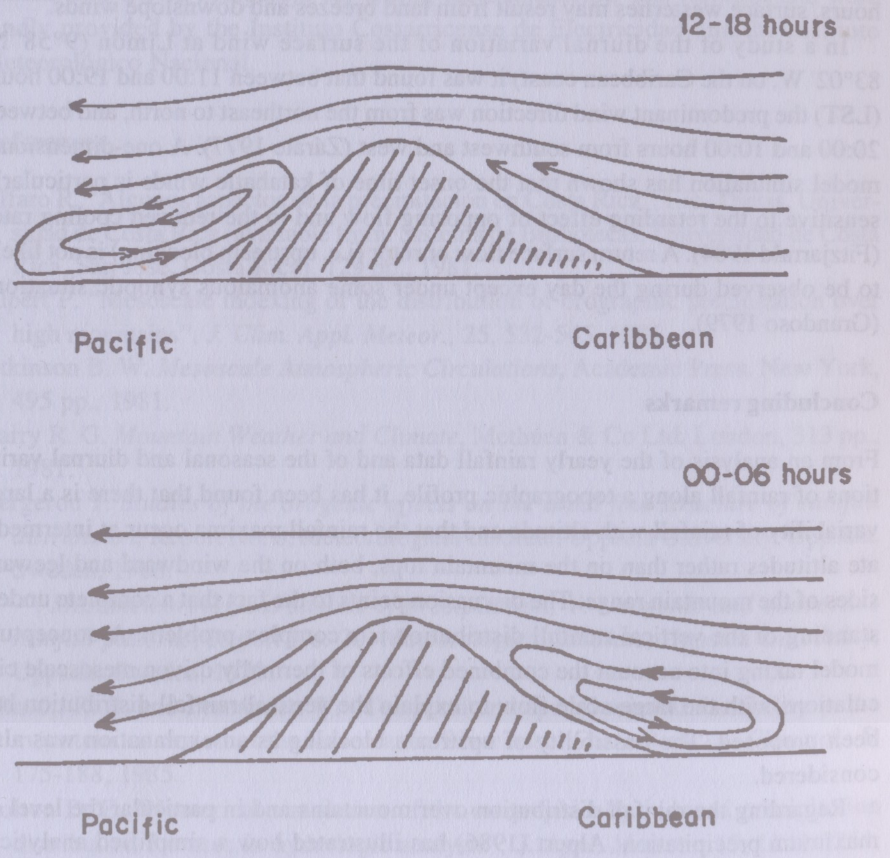

Figure 6. Schematic representation of the wind field patterns over the topographic profile during the day (top diagram) and night (bottom diagram) when the prevailing large-scale flow is from the northeast.

strengthen the sea breeze and the upslope winds during the day, they will interact with the land breeze and downslope winds at night producing a zone of convergence at coast areas or even over the sea, where convective clouds may develop. Actually, the occurrence of nocturnal thunderstorms over the Pacific relatively close to the coast is frequently observed.

The possibility of upstream blocking

Blocking may occur under some circumstances on the windward side of the topographic profile and appear as a stagnant zone separated from the upper flow by a large velocity shear or as a return stream close to the surface (rotor). In order to observe upstream blocking in the Caribbean coastal areas during the day it is necessary for westerly flow to occur at the surface. At night and in the early morning hours, surface westerlies may result from land breezes and downslope winds.

In a study of the diurnal variation of the surface wind at Limón (9°58' N, 83°02' W, on the Caribbean coast) it was found that between 11:00 and 19:00 hours (LST) the predominant wind direction was from the northeast to north, and between 20:00 and 10:00 hours from southwest and west (Zárate 1977). A one-dimensional model simulation has shown that the onset time of katabatic winds is particularly sensitive to the retarding effect of opposing flow and to the reduced cooling rates (Fitzjarrald 1984). A return surface flow or rotor (i.e. upstream blocking) is not likely to be observed during the day except under some anomalous synoptic situations (Grandoso 1979).

Concluding remarks

From an analysis of the yearly rainfall data and of the seasonal and diurnal variations of rainfall along a topographic profile, it has been found that there is a large variability of rainfall with altitude and that the rainfall maxima occur at intermediate altitudes rather than on the mountain tops, both on the windward and leeward sides of the mountain range. The discussion points to the fact that a complete understanding of the vertical rainfall distribution is a complex problem. A conceptual model taking into account the combined effects of thermally driven mesoscale circulations with the large-scale flow to explain the vertical rainfall distribution has been proposed. The possibility of upstream blocking as an explanation was also considered.

Regarding the rainfall distribution over mountains and in particular the level of maximum precipitation, Alpert (1986) has illustrated how a simplified analytical formula could be applied to get realistic distributions and positions of different maxima in various mountainous profiles. Since Alpert's formula assumes that the primary component for orographic ascent is the geometric-dynamical uplift and not differential heating, it is planned, in a further study, to run the calculations for the Costa Rica mountain profile in order to strengthen our argument which assumes that the differential heating, mainly on the leeward side, does play an important role in the distribution of orographic precipitation. Alpert's formula requires wind data and at present there is a lack of such data in the region. Numerical studies with a model of the mesoscale type are also planned, such as the one developed by Colton (1976) which includes a diabatic heating, in order to gain a better understanding of the vertical rainfall distribution over mountain slopes.

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