Rainfall Distribution and Regime in Costa Rica and its Response to the El Niño-Southern Oscillation

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ABSTRACT
The precipitation climatology of Costa Rica is complex both seasonally and spatially, reflecting the influence of hemispheric and local controls. Larger scale factors include the North Atlantic anticyclone and northeast trades, the Intertropical Convergence Zone of the eastern equatorial Pacific and cross-equatorial westerlies, and the positions of the northern subbtropical and polar jet streams controlling the timing and origin of cold air outbursts from North America during the boreal winter. Locally, location, east or west of the major cordilleras, controls the relative dominance of each precipitation-generating mechanism, while at the smallest scale local variability appears to depend on aspect and topographic setting. Analyses of annual and seasonal rainfall indicate considerable interannual variability, particularly in association with the EI Niño-Southern Oscillation phenomenon. Precipitation related to each of the larger scale factors varies in both the nature of its response to ENSO (both floods and droughts may be expected in differing portions of the country), and its season of occurrence. The nature of these observed responses to ENSO is identified and a comprehensive set of causal physical mechanisms, which are consistent with other regional and hemispheric observations of interannual variability, is proposed.

INTRODUCTION
Several determining influences, tied to features of the global circulation, converge in Costa Rica. These influences can be considered the main climatic controls in Central America and are subject to parrticular interannual variabilities. Among these important controls are: (1) the seasonal shifts of the Inter-Tropical Convergence Zone (ITCZ) on the Pacific coast; (2) the northeast Trades originating from the Bermuda High; (3) the southward penetration of cold air masses ('northers') and fronts developed over continental North America; and (4) the perturbing influences of hurricanes and tropical cyclones. The variable effect of these controls merits a detailed study of the rainfall-generating processes which operate to varying degrees in Central America, using Costa Rica as an example due to its location at this "climatological crossroads' and its excellent nettwork of long-term meteorological stations (Figure 1).

The complex pattern of rainfall regimes apparent in the country reflects influences at a variety of geographic scales, from global pressure belts to local valley winds and sea breezes, each originating from disparate geographic provenances. Knowledge of the spatial and temporal variability of this natural **[end p. 75]** resource is of great national economic significance for activities such as national power generation (60% of the country's power is derived from hydro-electricity), agriculture (60% of all Costa Ricans are employed in occupations directly related to agriculture), and tourism, but it also has important implications for public health and housing conditions. Moreover, information gained on precipitation regimes and their variabilities in Costa Rica can serve as indicators of, and provide insights into, the variability of precipitation in other countries of the region, which may be less well-equipped with meteorological stations and more poorly monitored.

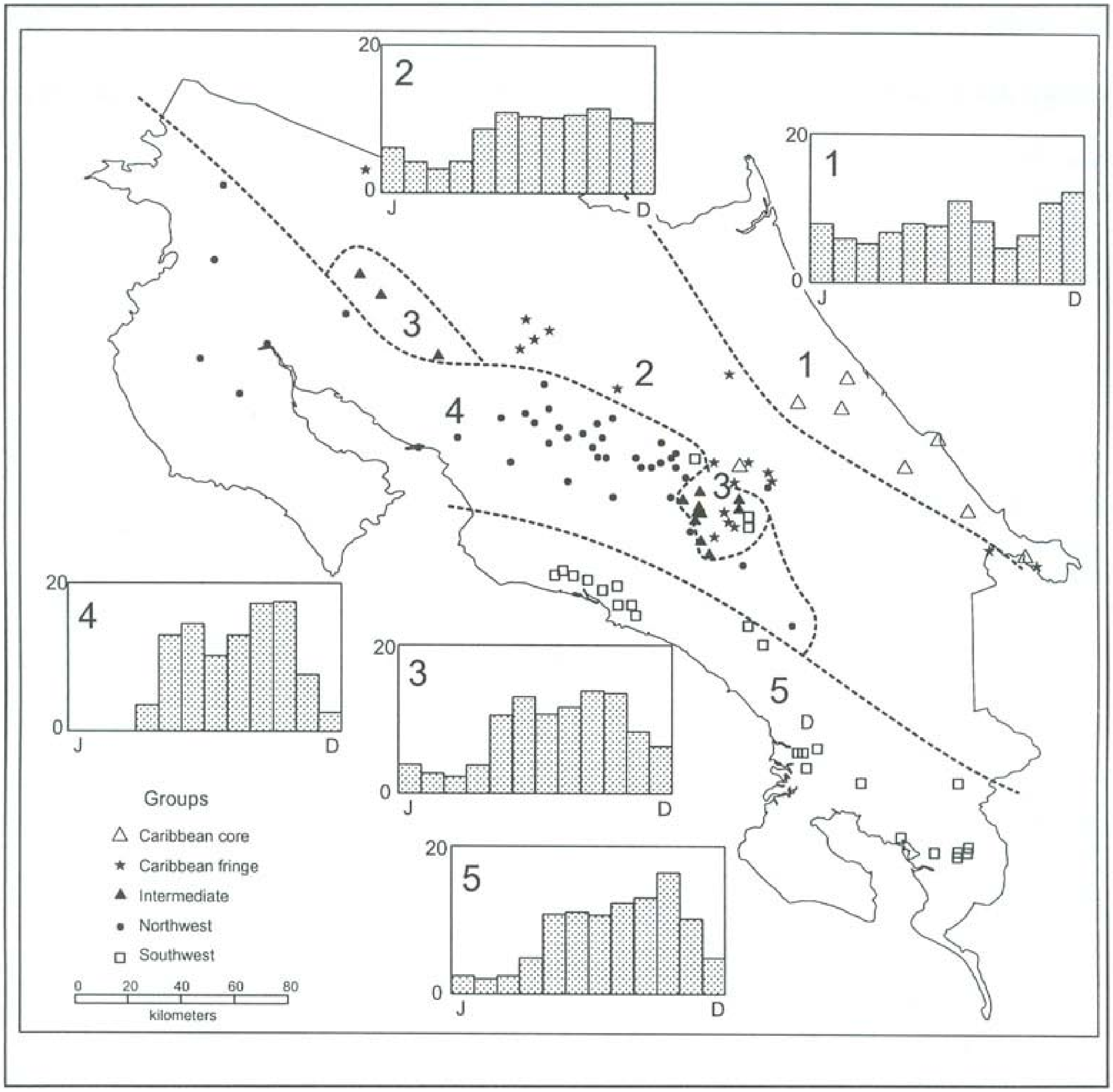

Figure 1. The Geographic Disposition of Long-Term (>20 years) Monthly Rainfall Recording Stations and the Regionalization of Their Regimes in Costa Rica.

This paper reviews the main controls governing the precipitation climatology of the country, incorporating global factors and peculiar responses due to the regional setting, in order to offer a coherent and internally consistent picture of the physical mechanisms in operation. In so doing, this paper draws on a body of newly published information and on previous**[end p. 76]** research conducted by the authors on the hydro-meteorology of Costa Rica (Poveda and Mesa 1997; Waylen et al. 1994, 1996a, b).

RAINFALL REGIMES OF COSTA RICA

A regionalization of rainfall regimes, derived through the application of clustering analyses (Waylen et al. 1996b), is illustrated in Figure 1 and is based on mean monthly rainfall from over 100 meteorological stations possessing at least 20 complete years of monthly records (Ministerio 1988). Figure 1 also displays graphs of 'regional regime' expressed as the average percentage of annual rainfall falling in each month based on individual rainfall records of all stations within the region. These regional divisions are similar to those described elsewhere (see Coen 1970; Hastenrath 1967; Portig 1965). The established regions run parallel to the coastlines in a northwest to southeast direction that follows the orientation of the trending *cordilleras*, reflecting in many places the separation that elevation imposes between Pacific and Caribbean sources of moisture, but also revealing the important role played by elevation in controlling local precipitation. Only the Pacific regions (northwest and southwest) are arranged latitudinally as they respond to controls dictated by the seasonal shifts of the ITCZ.

The country lies within the tropical belt dominated by the northeast Trades, or *alisios*, albeit at the western margin of influence of the North Atlantic anti-cyclone. Areas on the Pacific side of the cordilleras remain at the rainshadow of Atlantic winds for much of the year, while those on the Caribbean experience orographic lifting as the air is forced over divides which may exceed 3,000m. At low levels, the Trades tend to jet through local cols and passes in the Central American cordillera (Legeckis 1988; MccCreary et al. 1989); one of the major wind gaps is along the line of the San Juan river, which constitutes the Nicaragua-Costa Rica border, and Lake Nicaragua. When the Trades reach the Pacific, offshore winds over the Gulf of Papagayo deflect to the right producing an upwelling of cool water in the Gulf known as the Costa Rica Dome (Umatani and Yamagata 1991). This feature enhances atmospheric stability and causes reduced precipitation over the northwestern part of the country, particularly in the Guanacaste peninsula.

During the northern summer, the dominant dryness on the Pacific slope is interrupted by the seasonal northward migration of the Inter-Tropical Convergence Zone in the eastern equatorial Pacific.

When it reaches its northernmost position at about 100 N from June through to September (Alpert 1945), the ITCZ brings with it a broad band of unstable air and frequent heavy storms. The resultant rainy season is of longer duration in the southern part of the country than in the north (Figure 1), and is partially interrupted by a temporary strengthening of the trade winds over the Caribbean, generally in July. This pause in precipitation is known locally as the *Veranillos de San Juan*, and is associated with both a temporary abatement of rainfall along the Pacific and a related slight retreat or standstill in the northward progression of the ITCZ. Stations along the Caribbean slope generally experience increased rainnfall at the same time.

The remaining portions of the rainy season along the Pacific coast, following the Veranillos are generally wetter than those preceding it. Seasonal cross-equatorial westerlies which flow onshore in southern areas of the Pacific coast, are greatly enhanced along the entire coast when tropical cyclones enter the Caribbean basin, disrupting the consistency of the trade winds and reversing the normal pressure gradient across the isthmus. The post-veranillos peak in precipitation corresponds closely to the season of maximum tropical storm activity in the tropical North Atlantic (Neumann et al. 1988; Vargas and Trejos 1994).

During the boreal winter (November-March) high meridional pressure gradients may be established across the Gulf of Mexico and the Caribbean when high pressure cells move southwards over the central United States (Klaus 1973; Reding 1992; Schultz et al. 1997, 1998). Cool air moving down the gradient towards Central America warms and acquires moisture from the intervening water bodies (Cavazos and Hastenrath 1990; García et al. 1978). In northeastern Costa Rica and neighbouring Nicaragua, the outline of the Caribbean coast is ideal for the generation of stress differential-induced convergence and locally heavy precipitation caused by these northerly winds, or *nortes* (Bryson and Khun 1961), resulting in large quantities of rain throughout this season. Schultz et al. (1998) analyzed occurrrences of fronts which reached Costa Rican latitudes and constructed composite hemispheric synoptic conditions for these times. They recognize two separate types of fronts: the first fronts occur with greater frequency earlier in the year (November-December), when high pressures settle over the central United States after crossing the Rockies from the North Pacific, causing fairly small declines in temperature; the second are much colder and occur in **[end p. 77]** February-April, when cold air masses descend southward from the Canadian prairies. Although these fronts are less frequent, they have been responsible for the most intense rainfalls observed in the country

EFFECTS OF ENSO ON SEASONAL PRECIPITATION

Considered a major control on tropical weather development, the El Niño-Southern Oscillation (ENSO) has decisive consequences for the fluctuations of monthly and interannual precipitation in Costa Rica. A regional association of drought with warm phases of EN SO (El Niño) has been established in the Caribbean and Central American region (Hastenrath 1988; Rogers 1988; Ropelewski and Halpert 1987). However, analyses at finer temporal and spatial scales have revealed more complex patterns of associations within the region (Estoque et al. 1985; Fernández and Ramírez 1991; Waylen et al. 1996a, b), and a potentially complex feedback between the atmosphere-ocean systems in the equatorial Pacific and North Atlantic as revealed by the hydrological regimes of southern Central America and northern South America (Hastenrath 1990; Poveda and Mesa 1997).

Figure 2 depicts the observed patterns of association between annual rainfall in the different regions of Costa Rica and the Southern Oscillation Index (SOl) for both simultaneous correlations and the two years following the SOl (Waylen et al. 1996a). The Southern Oscillation Index, which is widely available from a variety of sources including NOAA's *Climatic Diagnostics Bulletin* (Kousky 1997), is defined as the standardized differences in atmospheric pressures between Tahiti and Darwin, Australia. These two locations serve as representative of the poles of atmospheric pressure (high and low respectively), which are indicative of the general state of atmosphere-ocean conditions in the southern equatorial Pacific. Negative values of the SOl generally are associated with El Niño occurrences (warmer water in the eastern equatorial Pacific) and positive values with anti-El Niño or *La Niña* conditions (colder water in the eastern Pacific). Every historic El Niño event is unique in its pattern of development but, in general, changes in atmospheric pressures and sea surface temperatures in the equatorial Pacific are first monitored during the boreal summer, the wettest season in almost all of Costa Rica. This paper, therefore, follows the convention of assigning the label 'Year 0' to the calendar year in which the SOl changes markedly (Philander 1989), years preceding it are assigned positive values, and succeeding years negative ones (Figures 2 and 3)

Figure 3 illustrates the regionally-averaged, standard deviates of monthly precipitation from their long-term means, experienced during a series of warm events, or El Niños (Waylen et al. 1996b). On the basis of these generalizations the spatially varying, seasonal responses in rainfall to ENSO can be inferred.

During the *veranillos* (notably July) when sea surface temperatures (SST) in the central and eastern equatorial Pacific rise (Year 0), Fernández and Ramírez (1991) and Waylen et al. (1996b) have noted increased precipitation, especially in years of a warm eastern Pacific (El Niño). Marked increases in stream-flow and flooding occur along the Caribbean coast (George et al., in press). This strengthening of the Trades enhances the rainshadow effect along the Pacific and induces a drier and more sustained veranillo. In the northwestern Guanacaste region, the drought is further exacerbated by strong jetting over the Gulf of Papagayo and increased upwelling of the Costa Rica Dome (Barberan et al. 1984). These associations tend to persist through September and October, perhaps in keeping with the observed tendency for fewer tropical cyclones in the North Atlantic during years of a warm Pacific (Caviedes 1991, Gray 1984). Generally there is a corresponding decline in the intensity of the trade winds and the amount of summer rainfall along the Caribbean in the following years (Years +1 and +2). By contrast, rainfall increases along the Pacific coast and high levels of precipitation can persist for a second year, particularly in the south of the country. The apparent disparity in terms of rainfall amount in the years following a warm ENSO event arises from the fact that Figure 2 considers all years, while Figure 3 only encompasses El Niño years.

Schultz et al. (1998), in re-analyzing the data of Klaus (1973), found that in the boreal winter (Year 0-Year + 1) following a warm Pacific event, the number of cold fronts or nortes increased (14.6 per year), while the number following cold Pacific events declined (7.5 per year). However, the pattern of winter rainfall variability along the Caribbean coast (Figure 3) appears to be more complex than this, denoting a clear decline during November and December (Year 0) and increases in the remaining month, through to March (Year 1) This is in correspondence with the two different periods of *norte* generation as formulated by Schultz et al. **[end p. 78]** (1998). These opposing tendencies, compounded by the overriding rainshadow effects of the trade winds in the summer on the populated Pacific slope, have tended to obscure regional effects in previous studies on rainfall in the whole area carried out at annual or trimester time scales (for example, Hastenrath 1988; Rogers 1988; Ropelewski and Halpert 1987).

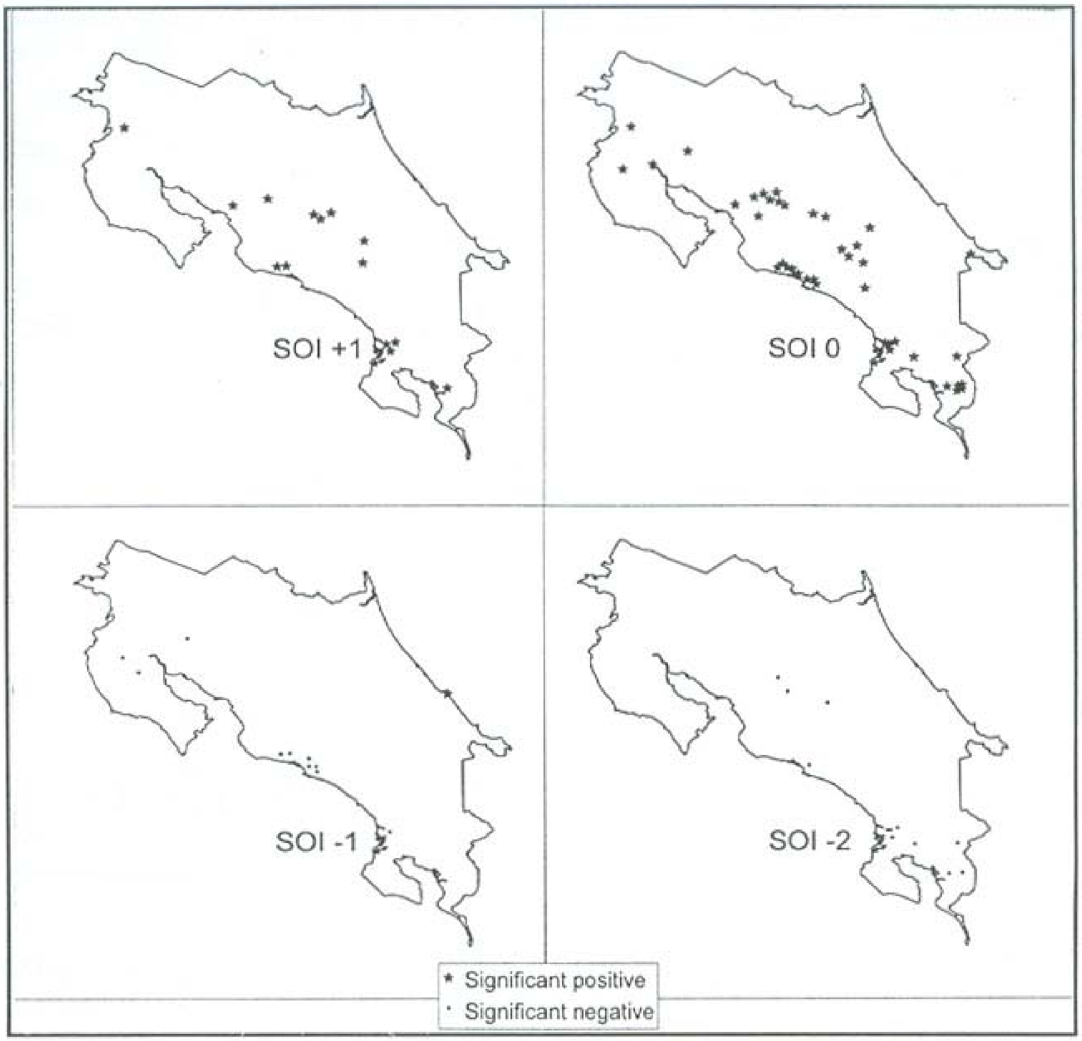

Figure 2. Stations Reporting Statistically Significant Associations Between Annual Rainfall Totals and the SOI (clockwise from top left) during the Year Before the SOI, Synchronous Periods, One Year after the SOI, and Two Years Afterwards.

The reconstruction of hemispheric synoptic conditions (Schultz et al. 1998), during which "cool" and "cold" nortes reach as far south as 10^{O}N, provides some potential insight into this mixed response to the ENSO. The "cool" (earlier) nortes typically occur when both the sub-polar and sub-tropical jets assume very zonal patterns over North America. A low pressure moves across the Great Plains and the northeastern United States, while a high crosses the Rockies from the North Pacific, moves down towards the Gulf of Mexico, and then bends up over the eastern U.S. By contrast, "cold" (later) nortes are associated with a pronounced meridional pattern in the sub-polar jet, sweeping southwards over the Rockies and converging with the sub-tropical jet flowing from the southwest, over the southeastern United States. The high pressure cell originates over the Canadian Prairies, moving directly southwards, while the low forms over the Gulf of Mexico and progresses northeast along the line of the sub-tropical jet as exemplified by the "super-storm" or "storm of the century" in March 1993. The synoptic pattern favoring the "cold" nortes is typical of the conditions found over the southeastern United states in the winters (Year 0- Year + 1) following a warm event (see Douglas and Englehardt 1981). Thus, in these winters, conditions discourage the formation of early "cool" nortes (decreased rainfall in November and December, Year 0), but encourage later "cold" nortes (increased rainfall in February and March, Year + 1). **[end p. 79]**

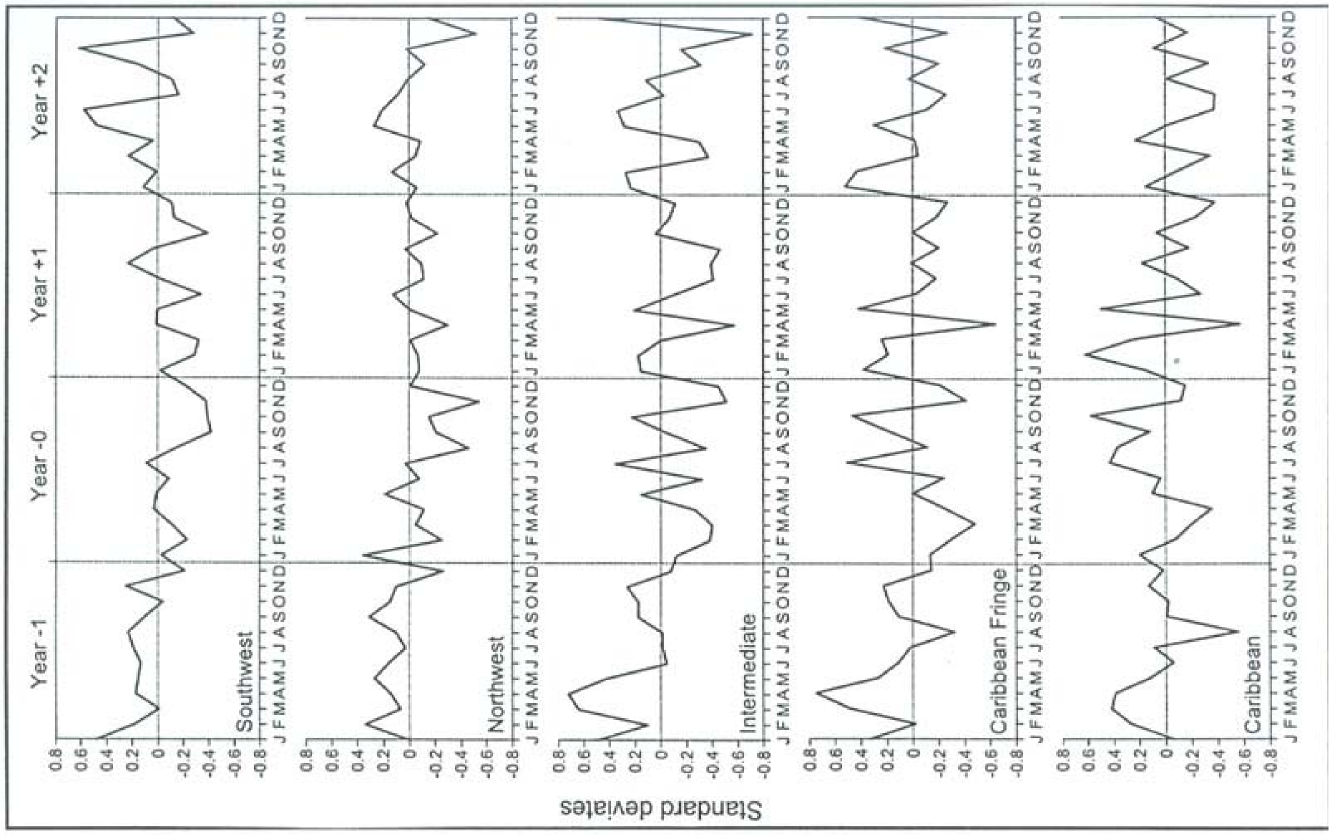

Figure 3. Standard Deviates from Monthly Rainfall Totals in Years Immediately Prior to (-1), During (0), and After (+1 and +2) Historic El Niño Events in the Five Regions Described in Figure 1.

THE REGIONAL MECHANISMS IN ACTION

To explain the linkages between the atmosphere-ocean interactions over the Pacific and Atlantic oceans using hydrological indicators from equatorial South America, Poveda and Mesa (1997) propose a sequence of events during and after a typical warm Pacific event. The proposed explanatory model can be combined with other physical evidence from North and Central America to provide a plausible set of explanatory mechanisms for the observed changes in rainfall regime in Costa Rica caused by ENSO warm events.

During the boreal summer, when warm water first appears in the central Pacific, the ITCZ in the eastern equatorial Pacific is displaced south and west of its mean seasonal position, pulled by the appearance of unusually warm waters in the central Pacific (Pulwarty and Diaz 1993). The northeast trades conntinue to blow strongly across the isthmus from the North Atlantic anticyclone towards the displaced ITCZ (Fernández and Ramírez 1991). This produces an unusual strengthening of the seasonal rainshadow over the Pacific, a prolonged veranillos, and an expansion of the Costa Rica Dome and its associated atmospheric stability (Barbenin et al. 1984; Umatani and Yamagata 1991). The intensified trade winds deter the formation of tropical cyclones over the tropical Atlantic (Gray 1984; Landsea et al. 1992), an effect which is further enhanced by the cooler sea surface temperatures in the Caribbean resulting from greater surface mixing (Hastenrath 1988). The reduced number of tropical cyclones (Figure 4) leads to limited westerly onshore winds along the Pacific littoral and prompts regional drought in September and October. Figure 4 also clearly indicates the extension of veranillos during warm events, when no floods have been observed in either July or August.

The southerly displaced ITCZ directs mesoscale convective cells, which generally penetrate to the basins of the Magdalena, Cauca, Amazon and Orinoco rivers (Velasco and Fritsch 1987), and to the south, into southern Ecuador and northern Peru, where they originate episodes of torrential rains (Gessler 1995; Horel and Cornejo-Garrido 1986; Waylen and Caviedes 1986). Seasonal flow **[end p. 80]** reductions and soil moisture depletion are experienced in these major equatorial basins (Hastenrath 1990; Quesada and Caviedes 1992; Riehl 1984; Vorosmarty et al. 1996), while the streams of coastal Ecuador and Peru swell to catastrophic levels.

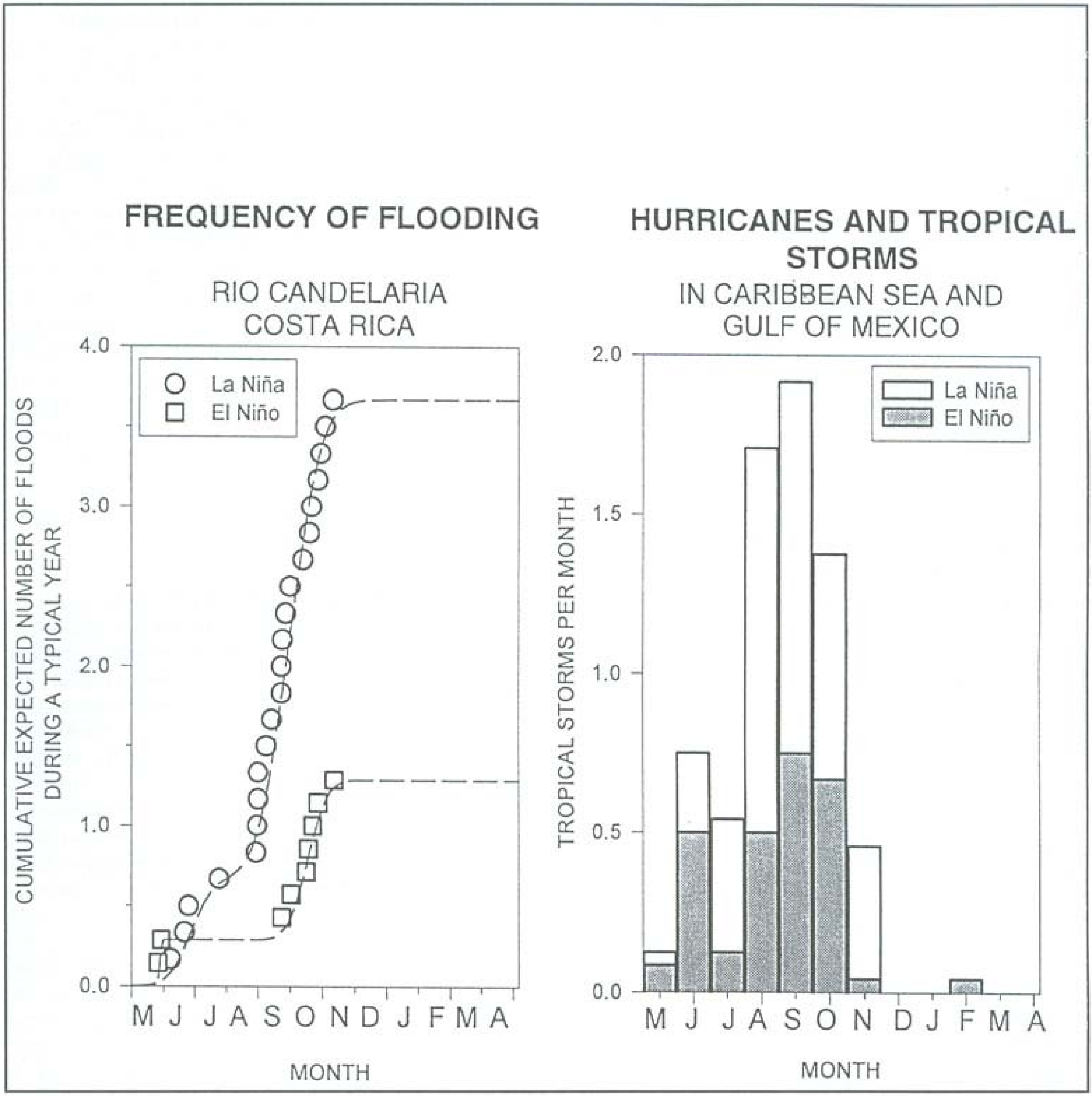

Figure 4. A Comparison of Historic Frequencies of Flood Events (flows about the 1.1 year return period level) in the Candelaria River on the Pacific Coast, and the Monthly Frequencies of Tropical Storms and Hurricanes in the Caribbean and Gulf of Mexico during El Niño (warm Pacific) and La Niña (cold Pacific) Events.

The warmer waters of the central Pacific promote the southwesterly flow of the sub-tropical jet across the southeastern United States during the winter and provoke a relative warming of the Gulf of Mexico, in comparison to the thoroughly mixed Caribbean (Cavazos and Hastenrath 1990; Douglas and Englehardt 1981). The resultant weakening of the meridional pressure gradient, combined with the meridional pattern of the jet streams over North **[end p. 81]** America, reduces frontal activity early in the winter season. As continental North America cools, this configuration of the jet streams facilitates the southward movement of cold Canadian air masses (Schultz et al. 1998) and produces copious rainfalls later in the winter season.

In December and January, the warmer waters arrive off the coast of equatorial western South America and expand northwards, through Kelvin waves, towards Central America. In the ensuing February to October period, evapotranspiration beneath the ITCZ over continental northern South America is greatly reduced because of the depletion of moisture during the thwarted previous rainy season (Poveda and Mesa 1997). Latent heat release into the atmosphere above the region is reduced correspondingly; the regional low pressure is therefore higher than normal so that the gradient with the North Atlantic anticyclone is diminished and the trade winds across the Caribbean basin weaken accordingly.

Along the Pacific coast of Costa Rica, the rainshadow effect is minimized, the *veranillos* becomes less marked, warm waters allow the early northward migration of the ITCZ, and the intensity of the Costa Rica Dome may subside, thereby reducing atmospheric stability. The weaker Trades over the Caribbbean favor the development of tropical cyclones, which are further enhanced by higher sea surface temperatures (Hastenrath 1976). Increased storm activity in the Caribbean basin induces frequent westerly winds along the Pacific coast, bringing warm unstable air and excessive rainfall which, when reinforced by regional topography, markedly increases the chances of excessive flooding in rivers draining the Pacific slopes of Costa Rica (see Figure 4).

The warming of the Caribbean causes low-level atmospheric pressures, which increase the meridional gradient with North America during the subsequent winter. The jet streams over North America resume their more zonal configurations and the number of early, "cool" nortes increase, while the later events diminish in frequency. In this manner, warm or cold phases of the ENSO have a determining influence over the rain-generating mechanisms operating on the two sides of the Central American land bridge.

CONCLUSIONS

The circulation around Central America typically has been considered a simplified one, with influences from the Caribbean Sea and the tropical Atlantic affecting the eastern slopes of the isthmus and the air masses of the Pacific determining the climate of the western slope (West and Augelli 1989). More recent studies of precipitation in the region have been based on these notions, but have failed to recognize the complexity of the local and regional signals imposed by the ENSO upon the southern isthmus. This diversity of signals arises partly because of the region's location between two large oceanic centers of action (one equatorial and the other sub-tropical) and two continental masses (one dominantly equatorial/tropical (South America) and the other mid- to high-latitude (North America)). Atmospheric, oceanic, and continental hydrologic systems all interact with varying degrees of feedback at hemispheric, regional, and local scales. Each system exhibits responses that vary in rate and phasing, leading to a variety of spatially and temporally diverse responses. At the smallest scale, this complexity is further compounded by the local topography. However, there is evidence for recurring and identifiable patterns of responses to the ENSO within the country.

Knowledge of the spatial and temporal sequencing of events may have tremendous practical applications in countries like Costa Rica, which experience devastating floods on a particular coast or region and droughts in opposing places in successive seasons or sequential years. The progression of events described above provides an explanation for the reversal of signs of correlation between the Southern Oscillation Index (SOl) and rainfall in years contemporary to (positive correlations), and in the two years following (negative correlations), a warm phase event (see Figure 2). The proposed explanation not only adequately represents the complex sequence of events experienced in the study area, but also complements and is an integral part of the known and postulated physical mechanisms and their responses to the ENSO throughout the Americas. Increased awareness of their importance imposes a necessity to monitor their development with greater accuracy and to attempt the preparation of paliative measures against flooding, erosion, droughts, and harvest failures. In this sense, the study of the influences of the ENSO over the precipitation and runoff of Central America is an ideal case for applied geography.

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RESUMEN

La climatología de las precipitaciones en Costa Rica es compleja, espacialmente y estacionalmente, reflejando la influencia de factores hemisféricos y locales. Factores de gran escala incluyen el anticiclon del Atlántico norte y sus vientos alisios del noreste, la convergencia inter-tropical del Pacífico este-ecuatorial, los vientos del oeste que cruzan la línea ecuatorial, y la posición de los corrientes de chorro subtropical y polar que controlan la temporalidad y el caracter de las ondas frías provenientes de Norte América durante el invierno boreal. La posición sea al este o al oeste de las cordilleras controla la manera cómo operan ciertos mecanismos generadores de precipitaciones, mientras que a la escala local mínima la variabilidad de las precipitaciones parece ser controlada por la ubicación topográfica. Los análisis de lluvia anual y estacional revelan gran variabilidad interanual, especialmente cuando tiene lugar el fenómeno El Niño/Oscilación del Sur (ENOS). La precipitación causada por cada uno de los factores mayores varia sea en cuanto a las respuestas a ENOS (inundaciones en ciertas regiones, y sequías en otros) y la estación en que ocurren estos fenómenos. En este trabajo se indentifica las distintas respuestas a ENOS y se propone una serie de mecanismos físicos que explican, y son concordantes, con las variaciones interanuales de pluviosidad que se ha observado hemisférica y

regionalmente. **[end p. 84]**