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Climate and Climate Variability in the Arenal River Basin of Costa Rica

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ABSTRACT

This work examines some of the effects of climate and climate variability in the Arenal River basin of Costa Rica, the site of the largest hydropower complex in the country. The Arenal system, which drains part of the north-central portion of Costa Rica covers a total area of approximately 493 km^2; it is mainly managed for electric power generation and produces nearly a quarter of the total annual electricity in Costa Rica. Monthly, pentad (5-day means), and daily precipitation data are used to study signals associated with climate and shorter-term atmospheric disruptions in the basin. Although the study area is relatively small, strong spatial and temporal contrasts of precipitation patterns are found. A clear distinction in the seasonal distribution of precipitation is observed over short distances (~30–40 km), between the northwestern (NW) low lands of the basin compared to the southeastern (SE) sector. The former region exhibits a bimodal precipitation distribution, with maxima in June and September–October, and relative minima in July and December–April. The July minimum suggests a weak mid-summer drought or "veranillo" signal. The latter region has practically no dry season with the highest precipitation values occurring during the second part of the calendar year. As determined by principal component analysis of anomalies of monthly precipitation data, the main disruption of the normal pattern of precipitation appears to be related to the ENSO signal in the NW region, whereas the SE sector shows a positive correlation with Caribbean low-level wind changes. Some of the latter changes are associated with warm or cold ENSO episodes that seem to modulate wind intensities of the low-level jet over the Caribbean. Precipitation effects in the basin for selected extreme cases, such as that of hurricane Mitch, and other so-called "temporales" are also analyzed. The importance of these systems as fundamental components of the basin's hydrological cycle is well

established. ENSO related variability of the regional summer circulation (such as that of the low-level jet in the western Caribbean), and the appearance of cases of extreme strong trade winds during the winter circulation are also important forcing mechanisms for precipitation variability in the basin. In these cases, the interaction between the basin complex topography, and changes in the flow pattern and intensity seem to be of fundamental importance for precipitation variance. Some socioeconomic impacts of precipitation variability, as well as a discussion about the potential use of climate variability information for water management in the basin are presented.

INTRODUCTION

Costa Rica's economy has relied in the past mainly on agriculture. During the last decade, however, some high technology industries have been established increasing the demand of qualified professionals, and stimulating the adaptation and improvement of higher education and training programs at universities and technological institutes. Tourism has become an important source of national income, therefore, building and access to facilities in natural and ecologically rich environments have expanded substantially. Also, public health services, and telecommunications are widely spread throughout the country and its more than three million inhabitants. As expected from this socio-economic situation, there has been an urgent requirement for providing various forms of energy to users, especially electricity. Lately, the demand for this type of energy has increased dramatically in Costa Rica, where, electricity generation is mainly provided by hydropower (75%). Thermal, geothermal, and wind energy generation (18%, 5%, and 2%, respectively) are the others sources of energy used to supply electricity to industry and residential users.

Climate variability on various time scales, from inter-annual to seasonal, and shorter-term meteorological phenomena have affected Costa Rica's economy and jeopardized social conditions in many different ways during the past. After the severe impacts of El Niño and La Niña during the last decade, specially those associated with the 1997–98 El Niño event, and perhaps after the impact of hurricane Mitch in 1998, the general public realized the relevance and importance of timely meteorological and climate information in the planning, management and utilization of water resources in the country. A relatively small country, Costa Rica also possesses a very complex topography (Fig. 1), with distinct annual rainfall distributions, even on small spatial scales. Large mean annual precipitation totals and suitable sloping terrain conditions have made hydropower one of the most important natural resources of the country. The Costa Rica Institute of Electricity (Instituto Costarricense de Electricidad, ICE), a technical body of the Costa Rica Government created in 1949, has been given the responsibility of building the infrastructure, and the planning and managing of the water resources for hydroelectric production. Costa Rica, as has been shown in the last few years, is very sensitive to water management policies and to changes in water availability. Climate variability, and in some cases related extreme events, can represent significant challenges to the long-term well-being of a country that is seeking to develop both economically and socially. Agriculture is still, of course, a major activity in many rural areas of the country and a major provider of national income, however, major industries (i.e., electronic industry), and large commercial factories that also contribute important percentages to the national income, are located in urban areas and depend on a reliable supply of electricity.

The present contribution deals with the climate setting and with major climate disruptions affecting the largest hydroelectric system in the country, the Arenal-Corobicí-

Sandillal (ARCOSA) complex in the Arenal River basin of Costa Rica. The study is intended to focus on some regional climate systems affecting the Arenal basin's own mesoescale climate, and on how changes in these physical mechanisms are related to disruptions in precipitation patterns that may have significant effects on the reservoir inflows and water level, and on electricity production. Despite the importance of the basin for hydropower generation, relatively few studies have been published regarding meteorological and climatic conditions in the reservoir and their relationship with regional or global scale phenomena. Fernández *et al*. (1986) discussed some of the mesoscale characteristics of the region, and focused on the reservoir effects on several meteorological parameters around the basin, such as an increase of locally measured wind velocities. More recently, Amador *et al*. (2000a,b) made an extensive study of the disruptions in precipitation patterns due to some selected El Niño/Southern Oscillation (ENSO), and extreme meteorological events that affected the basin, especially during the last decade. Some of the major findings of these works will be discussed below.

There has been general agreement that the skill in ENSO prediction has improved considerably in the last few years (Hoerling and Kumar, 2000). There is a need, therefore, to identify and understand major deviations in regional precipitation patterns in order to improve the application of prediction schemes associated with ENSO events. It is known that El Niño has an important impact on Costa Rica's climate, especially along the Pacific slope (Fernández and Ramírez, 1991; Waylen *et al*., 1996a). Here, we study precipitation variations in the Arenal basin for both the 1997–1998 El Niño and the 1998–2000 La Niña events, in the context of regional and global scale phenomena. The study of any form of variability related to ENSO or non-ENSO signals requires, however, an adequate description of the "normal" climate conditions of the basin. Therefore, the approach taken here would allow decision makers to take advantage of any additional information about the above-mentioned phenomena when planning and operating power generation facilities. In this context, the seasonal precipitation cycle is examined through analysis of the relative contribution of different precipitation systems during the course of the year, and the associated rainfall variability in the basin. The main characteristics of both summer (June-July-August) and winter (December-January-February) circulations are analyzed and related to relevant features of the temporal and spatial distribution of sea surface temperature in the adjacent oceans. In the latter context, the mid-summer drought (Magaña *et al.*, 1999), and the low-level jet over the Caribbean during the boreal summer (Amador 1998; Amador and Magaña, 1999; Amador *et al.*, 2000c), constitute two important physical mechanisms associated with the seasonal cycle leading to some unique characteristics in the distribution of mean monthly precipitation within the Arenal basin. Finally, in order to show the wide range of climatic variability that can modulate the spatial and temporal precipitation distribution in the basin, the anomalous contributions to precipitation of some case studies during the 1997–1998 El Niño and the 1998–2000 La Niña events are presented. A goal of this study is to contribute to a better understanding of climate and its variability in this important region for hydropower generation in Costa Rica, with the goal of providing governmental and private institutions with improved climate information for decision making. By improving the understanding of the elements that control regional climate and its variability, in relation to both ENSO and non-ENSO signals, more accurate and tailored climate predictions could be developed to fulfill some of the needs of this particular socioeconomic sector.

In the following, we first present information about the more important hydroelectric projects in Costa Rica; we then follow with an analysis of general regional climate patterns and those that pertain specifically to Costa Rica. We then consider the hydroclimatology of the Arenal River Basin and the large-scale teleconnection patterns that affect the general climate of the region. The chapter concludes with a summary and discussion.

THE ARENAL BASIN PROJECT

Brief historical account

The Arenal dam and reservoir are located at the southern tip of the Guanacaste Mountains, in the Guanacaste Province (Fig. 1), some 190 km northwest of San Jose, the capital city of Costa Rica. The Arenal system is located in a northwest-southeast trending chain of volcanic cones that is part of Middle America range of active volcanoes. The bedrock at the dam site, referred to as the "Aguacate formation," is characterized by a complex of lava flow rock, tuff, agglomerate, and volcanic breccia, with occasional thin interbeds of sandstone and shale. Lava flows are known to have blocked the most important local river, the Arenal River, in the geologic past. The lava flows resulted in deposits, up to 40 meters in thickness, of fluvio-lacustrine river channel and old flood plain sediments overlying the local bedrock at all but the highest elevations at the dam site. In recent geological times, most of the dam site has been covered by a mantle of unconsolidated pyroclastic deposits varying up to 15 meters in thickness, and consisting of alternating, and often discontinuous layers of volcanic ejecta, which probably originated from the nearby Arenal Volcano (Wahler and Associates, 1975).

The basin covers an area of approximately 493 km^2, about one quarter of the Arenal Conservation Area. The reservoir is about 17% (84 km^2) of the basin's area, and the current water surface area is about three times that of the original lake. The Arenal River used to drain the lake towards the Caribbean, as a tributary of the San Carlos and San Juan Rivers, the latter being part of the border between Costa Rica and Nicaragua. Since the first field studies a few decades ago, the region showed extraordinary potential for electricity generation, consequently, the ICE initiated the Arenal project back in 1967. In contrast to the original Arenal River draining course towards the Caribbean Sea, once the project was completed, the reservoir was left draining water towards the Gulf of Nicoya in the Pacific Ocean. Other projected hydroelectric plants, such as Corobicí and Sandillal, were planned to make use of the water resource in a sort of cascade system. Planning of water use and reservoir system management included from the beginning, not only the generation of hydropower, but also the use of water for irrigation projects in the Guanacaste Province, one of the driest regions in Costa Rica. This area receives tremendous socio-economical benefits from the Arenal-Tempisque irrigation project, especially, those sectors related to crop activities. The amount of irrigated land dedicated to agriculture in 1995 was of the order of 16,000 hectares. Positive changes in productivity after irrigation have been very important for social well being and farming, since rice and sugar yields have increased from 3 to 8 metric tons per hectare, and from 8 to 14 metric tons per hectare, respectively.

The Arenal-Corobicí-Sandillal Hydroelectrical Complex

The ARCOSA complex consists of three power generating plants located at different elevations, namely Arenal, Corobicí and Sandillal, which have a total installed generating capacity of 362 MW of power. Fig. 2 shows the relative location of the Arenal, Corobicí, and Sandillal plants with respect to the reservoir. Corobicí alone contributes 174 MW to the system. This capacity has recently been surpassed by the plant at Angostura (177 MW) located in the Reventazón River on the Caribbean slope of Costa Rica, inaugurated in December 2000. Arenal plant has a generating capacity of 157 MW. Altogether, the ARCOSA plants contribute about one quarter of the total annual electrical energy that is consumed in the country, hence their great importance in the National Electrical System. The Arenal reservoir has a storage capacity of 2400 million m^3 at its maximum operation level of 546 meters above sea level (masl), and has the potential to support electricity demands of 1700 GWh.

Regional Climate Systems

As has been discussed recently by Magaña *et al*. (1999), the annual distribution of rainfall contrasts dramatically in the Caribbean side of Central America to that in the Pacific side. The latter slope exhibits a bimodal distribution, with maxima in June and in September-October, and a relative minimum during July-August. This reduction in the precipitation is the so-called mid-summer drought, known locally as the "veranillo" or "canícula". The existence of such reduction in the annual distribution of rainfall has been shown to be part of the seasonal cycle of precipitation over much of Central America (Magaña *et al*. 1999). According to these authors, the "veranillo" is related to changes in the intensity of convective activity over the northeastern Pacific "warm pool". During the mid-summer drought period, the trade winds over the Caribbean strengthen, due in part to the dynamical response of the low-level atmosphere to the magnitude of the convective forcing in the Intertropical Convergence Zone (ITCZ), which is in turn, associated with the sea surface temperature (SST) distribution. The starting date, intensity, and duration of the mid-summer drought varies from year to year, and it constitutes an important climate disruption for different sectors of the economy regarding water availability along much of the Pacific side of Central America. From December to March, the Pacific slope of Central America enjoys warm and mostly dry conditions.

The most interesting dynamical feature over the Caribbean Sea during summer is the low-level jet that develops during June, reaches a maximum in July and weakens in September (Amador, 1998; Amador and Magaña, 1999). This intense easterly current over the Caribbean is part of the summer trade wind regime, and constitutes the most important factor in determining regional climate during this season. The long-term mean (1968–1996) of the vector wind at 925 hPa (approximately 800 m height) for July, using data from the NCEP/NCAR Reanalysis Project (Kalnay *et al.*, 1996), is shown in Fig. 3. As can be seen from the wind field, values in excess of 14 m/s dominate the central Caribbean Sea near 14°N, 75°W. The origin of this strong jet has not been fully established, however, its barotropically unstable nature (Molinari *et al.*, 1997; Amador, 1998; Amador and Magaña, 1999) suggests that it is through the interaction with transients, such as the easterly waves, that the jet may obtain part of its kinetic energy. Another possibility may be that this strong flow feeds energy to the easterly waves, which amplify, increasing their meridional amplitude to the north of its mean position. Also, from early summer to November, easterly waves and tropical cyclones constitute major elements among the tropical systems that produce rain over the region. Portig (1976), and Hastenrath (1991), among others, have documented in some detail the role of these systems in the annual distribution of precipitation in Central America.

In the Caribbean region, precipitation during the winter months is closely related to mid-latitude air intrusions (Schultz *et al*. 1997; 1998) and to low-level cloud systems traveling from the east (Velásquez, 2000). Generally speaking, the winter months along the Caribbean slope of Central America are wetter and more humid, than conditions prevailing along the Pacific side, during the same season.

Regarding the beginning and ending of rainy spells, several studies have shown that fluctuations of the sea surface temperature of the tropical Atlantic and Pacific Oceans are related to variations in the duration and timing of the rainy season in Central America (e.g., Enfield and Alfaro, 1999). Tropical North Atlantic SSTs, for which Alfaro (2000) defined warm and cold episodes, show the largest influence over the region when compared with that of other indices, having a positive correlation with rainfall in Central America (Alfaro and Cid, 1999). In contrast, the Niño3 region, was found to have a lower negative correlation with the precipitation of the region, influencing only the Pacific slope of Central America.

The Climate of Costa Rica

When dealing with the elements that control climate in Costa Rica, several factors should be considered. One of these elements, as it could be inferred from the previous section, is the large influence of the two adjacent oceanic masses on mean precipitation distribution through the seasonal variation of sea surface temperature and associated circulation patterns and convective activity. During northern winter, SSTs over adjacent areas of the Caribbean and the Pacific are relatively uniform, with values usually below 28°C. As a consequence of this, and the presence of strong vertical trade wind shear, no major convective activity takes place. Furthermore, the ITCZ is at its southernmost position during the winter months (Srinivasan and Smith, 1996). Throughout the course of winter, trade winds intensify and relatively cold air intrusions frequently reach latitudes south of 10°N (Schultz et al., 1997;

1998). During summer, the presence of two warm pools dominate the SST distribution, one over the Caribbean and Gulf of Mexico and the other over the northeastern Pacific, just off the southern coast of Mexico and west of Central America (Magaña, 1999). In the latter, organized convective activity is barely observed due mainly to strong subsidence associated with regional scale circulations, such as those associated with the low-level jet noted earlier. Other factors, such as the meridional migration of the ITCZ, affects seasonal rainfall characteristics, especially in southern and central Costa Rica. On the other hand, trade winds, over the Caribbean side, and south-westerlies on the Pacific side, are important mechanisms for moisture convergence and rainfall production. The interaction between the main flow and topographic barriers constitutes a predominant process that contributes to precipitation all year round.

In countries such as Costa Rica, with very irregular topography, precipitation exhibits very high temporal and spatial variability. Fig. 4 shows the mean annual distribution of precipitation over Costa Rica (main map), and the seasonal precipitation patterns at some selected stations (inserted figures) for different periods. The average annual isohyetal contours were hand drawn by using 347 stations with precipitation data for the 1970–89 period. Over some mountain basins, such as those of central Costa Rica where precipitation data is scarce, isohyets were depicted utilizing vertical precipitation profiles from neighbor basins with enough information that are known to have similar general topographic and climatic characteristics. Precipitation values estimated by means of this method were constrained in such a way that they did not exceed the mean runoff of any particular basin. From the map in Fig. 4, it can be seen that precipitation in the Pacific side varies from about 1400 mm in the northwestern region in the Guanacaste Province, to over 7000 mm in some isolated high elevation areas of Costa Rica. In the Caribbean side, precipitation ranges from about 1600 mm in the eastern region of the Central Valley and Cartago (to the east of San José), to 9000 mm in the central Caribbean slope of the northwest-southeast trending cordillera (see also Fig. 1). Note the relative rainfall maximum (>5000 mm) in the Caribbean side, near the border between Costa Rica and Nicaragua. This maximum, in fact, extends well along the Nicaragua coast to the north reaching southeastern Honduras (Amador and Magaña, 1999). At first sight, it seems that this maximum may be due to orographic forcing of the trade wind flow, however, as can be observed from Fig. 1, the terrain over that area is almost flat. The physical processes responsible for this rainfall maximum have yet to be fully explained; however, as suggested by Amador (1998), at least, a major factor in summer rainfall could be due to the low-level convergence associated with the jet exit over the western Caribbean (Fig. 3).

To show that this trade wind current forms part of the basin's fundamental climate features, Fig. 5 is presented. Using data from the Pan American Climate Studies Sounding Network (PACS-SONET) pilot balloon project at Liberia, located some 50 km west of the reservoir. Fig. 5 shows, for July 1997, the vertical structure of the jet downstream of the basin's region. This intense current attains its maximum values of about 10 m/s, just at the level of the basin's main topographical features (1500 to 2000 m).

Average precipitation value for Costa Rica is 3300 mm using data for the period 1970–89. Fig. 4 also shows, as inserted diagrams, the distribution of mean monthly precipitation for some selected regions of Costa Rica. Different types of annual rainfall distributions can be observed. In the north Pacific region (Bagaces), a pronounced dry period extending from December to April dominates the Northern Hemisphere (NH) winter season, with a well defined rainy spell from May to November. A secondary minimum associated with the “veranillo”, can be seen clearly during July-August. In the south Pacific region (Potrero Grande), the dry period from December to March is less marked than that in the North Pacific sector. The wet period, on the contrary, is more pronounced in southern Costa Rica, but the “veranillo” signal can still be observed.

The contrast between Pacific and Caribbean rainfall distributions is noteworthy. At the eastern Caribbean region (Bataán), rainfall shows two minima, one in March and the other one in September–October. The maximum rainfall occurs in July, probably associated with the Caribbean low-level jet that develops during this period. It may appear that orography plays an important role in the occurrence of this maximum, however, Bataán is located in an almost flat terrain, some 50 km to the east of the mountain range. A secondary maximum is observed in December as a result of the intensification of the trade winds, and the southward displacement of air masses, during the Northern Hemisphere winter. These relatively cold northerly winds that appear especially during December–February are often referred locally, as “los nortes” (Portig, 1976). Finally, the northern region of Costa Rica (Ciudad Quesada) shows a distribution with a minimum in March – April. The maximum rainfall tends to occur in July, although, during most of the wet season precipitation is relatively large.

HYDROCLIMATE OF THE ARENAL RIVER BASIN

The average rainfall pattern over the Arenal basin is presented in Fig. 6. The distribution was estimated using 25 gauging stations (6 conventional, 19 automatic) located within the basin and adjacent regions for the 1970–1999 period. To ensure a proper rainfall analysis, the station precipitation records were verified by means of the double accumulation curve method, and those sites containing errors of a systematic type were corrected. From Fig. 6, it can be seen that annual rainfall varies from a maximum of 5000 mm in the southeastern (SE) region to 2000 mm in the northwestern (NW) lower side of the basin. A secondary maximum of 4000 mm is located in the higher lands of the northwestern region. The above mentioned rainfall maxima are due partly to the interaction of the trade wind regime with the mountain ranges having a southeast to northwest orientation. Rainfall tends to diminish towards the western basin sectors, comprising the driest region of Costa Rica in the Guanacaste Province with just over 1400 mm per year (see Fig. 4).

Although the study area is relatively small, strong spatial and temporal contrasts of precipitation patterns are found (Fig. 7). A clear distinction in the seasonal distribution of precipitation is observed over short distances (~30–40 km), between the NW lower part of the basin (represented by Naranjos Agrios rainfall data, hereafter NA) as compared to the SE part (represented by Caño Negro data, hereafter CN). As observed in Fig. 7a, using pentad data, the NW region exhibits a bimodal precipitation distribution with maxima around May and September-October, and a relative minimum in late June to late July. This minimum suggests a weak mid-summer drought or "veranillo" signal. The SE region, presented in Fig. 7b, has only a relatively short dry season with the highest precipitation occurring during the second part of the calendar year. In this distribution, a rainfall peak is noticeable during the summer months, which indicates the importance of the interaction of the trade winds, associated with the Caribbean low-level jet, with the basin topographic features. The analysis also suggests that changes in the intensity of the low-level jet could be an important mechanism for precipitation variability during the summer months, which in turn, may affect inflows to the reservoir.

Additional hidroclimatological information for the Arenal Basin is presented in Fig. 8. In Fig. 8a, monthly values of extreme air temperatures for two transects are shown. Nueva Tronadora (NT) is located in the NW lower lands, and Presa Sangregado (PS) is situated in the SE part of the basin. As discussed earlier based on Fig. 7, the above two regions show the largest contrast in monthly precipitation distribution within the basin. As was expected, changes in radiation and cloudiness are responsible for extreme surface temperature behavior. Note that absolute maximum temperature (Tmax) corresponds well with reduced periods of precipitation, from March to April approximately, in both regions of the basin (see Fig. 7). As rainfall increases during April–May, as a consequence of the onset of the rainy season and the ITCZ northward migration, maximum temperature drops in both sites to a relative minimum in July, suggesting a weak or masked "veranillo" signal. Since the presence of the mid-summer drought (Fig. 7a) implies a relative reduction of precipitation and cloudiness, Tmax should show a relative maximum during the mid-summer drought, as opposed to what is observed in the NW sector of the basin. A plausible explanation for above-noted behavior of Tmax could be the presence of strong winds associated with the low- level jet during the summer season which may act to lower temperature somewhat. Minimum temperatures (Tmin) are consistent with the development of the dry and wet seasons, but they do not show any significant changes that could be associated with the "veranillo", as was the case shown by Magaña *et al*. (1999). During July–August an increase in Tmin is indicated for station PS that could be related to greater atmospheric moisture content associated with an increase in cloudiness and rainfall, due to the interaction of the strong summer winds with topography in the SE sector of the basin.

As discussed earlier, the increase in mean precipitation during the summer months over the eastern part of the basin appears to be associated with the development of the low-level jet in the Caribbean by means of the interaction of the mean wind and the eastern most topographical features of the basin. In Fig. 8b, mean streamflow for two stations (El Cairo, EC, for 1975–2000), and Nueva Arenal, AN for 1978–2000) is presented. The presence of a maximum in this parameter during July–August, corresponding to the period of maximum wind speed associated with the low-level jet over the Caribbean can be seen clearly in Fig. 8b. Two minima are found in this parameter at both stations, one in April and the other one in September, the former corresponding to the dry spell along the Pacific slope of Costa Rica and the latter occurring just after the drop of the trade wind intensity in September (Amador, 1998). After June-July, the intense interaction of the strong low-level trade winds associated with the low-level easterly jet with topography, produces an important contribution to mean precipitation in the SE sector of the basin, and as a consequence of that, there is a substantial seasonal increase in the reservoir water level. Both, the decrease in the streamflow, and the reduction in the intensity of the low-level jet, suggest that an index associated with this intense low-level flow over the Caribbean should be included in any prediction scheme of precipitation variability in the basin.

PHYSICAL MECHANISMS OF CLIMATE VARIABILITY IN THE ARENAL RIVER BASIN

Empirical orthogonal function (EOF) analysis of monthly rainfall anomalies was performed for two different subsets of station data in the basin. The subsets of stations were subjectively chosen following the two main seasonal precipitation distributions observed in the basin (see Fig. 7). In the NW lower terrain and relatively drier region, Naranjos Agrios (10° 32'N, 84° 59'W), Nueva Tronadora (10° 30'N, 84° 55'W), Toma de Arenal (10° 30'N, 84° 59'W), La Tejona (10° 31'N, 84° 59'W, Dos Bocas (10° 33'N, 84° 55'W), and Aguacate (10° 33'N, 84° 57'W) were used for the EOF analysis during the period 1979–1998. In the SE, Presa Sangregado (10° 29'N, 84° 46'W), Pueblo Nuevo (10° 26’N, 84° 47’W), Pastor (10° 25’N, 84° 45’W), Pajuila (10° 30’N, 84° 47’W), Jilguero (10° 27'N, 84° 43'W), and Caño Negro (10° 24'N, 84° 46'W) were utilized also during the above mentioned period (use Fig. 6 to approximately locate the stations used). The first principal component of precipitation anomalies for NW and SW regions explains 72% and 83% of this variable, respectively. Cross-correlation analysis of the dominant mode for both regions was carried out with corresponding anomalies from several global and regional indices, such as, the SST index for the Niño3-4 region, North Atlantic Oscillation (NAO), Southern Oscillation Index (SOI), and 925 and 700 hPa mean wind speeds. The latter parameter was averaged over the area 10°–20°N, 60°–80°W, as a simple index of the mean intensity of the low-level trade wind regime. Broadly speaking, the correlations are relatively small for both regions, indicating the presence of other dominant mechanisms for rainfall variability. The following aspects can, however, be identified from EOF analysis. From the estimates of the correlations for lags up to six months that are significant at a 99% confidence level, rainfall changes in the NW drier region have a maximum correlation coefficient of –0.23 for a lag of two months with El Niño3-4 index. In other words, changes in SST over the central Pacific associated with warm (cold) ENSO events lead for nearly two months to abnormally dry (wet) conditions in the Pacific side of the basin. Regarding the SE region of the basin (Caribbean side), precipitation anomalies do not seem to be significantly correlated to SOI or SST’s in the Pacific. Waylen *et* *al*. (1996b) in their study of time and space variability of annual precipitation in Costa Rica in relation to SOI, noted that there is a marked difference in response in those areas draining towards the Pacific and those towards the Caribbean, which in a broad sense, agrees well with the results of this study. George *et al*. (1998) also found that annual discharge for rivers within the Pacific watershed were positively associated with SOI values, whereas in the Caribbean, discharges showed less clear and coherent patterns of associations. They also suggested that this difference in response could be related to the elevation of the river basins. The complexity of the response in relation to topography has been pointed out by Waylen *et al*. (1996b), in reference to the differences in dominant precipitation generating mechanisms within the basins. For the SE region, however, 925 hPa wind speed changes averaged over the area 10°–20°N, 60°–80°W, are positively correlated (0.24) at a 99% confidence level, with disruptions of rainfall from the normal pattern at zero lag. Stronger (weaker) than normal winds appear to be responsible for wetter (dryer) than average conditions over the Caribbean side of the basin. In order to gain some insight into the nature of the prevailing precipitation originating mechanisms, the seasonality of the above results is analyzed below using a finer temporal precipitation resolution for the phases of El Niño 1997–98 (approximately, from March 1997 to June 1998) and La Niña 1998–2000 (from July 1998 to July 2000).

Fig. 9a,and Fig. 9b, present the normalized pentad precipitation anomalies for NA and CN, respectively, for El Niño 1997–1998, and Fig. 9c, and Fig. 9d for NA and CN, respectively, for La Niña 98–2000. Pentad precipitation anomalies were estimated as departures from the mean values for the period of analysis and normalized by the corresponding standard deviation. For both stations, during El Niño 1997–98, relatively long sub-periods of negative anomalies can be clearly identified. From the annual perspective, the impact of this event was to produce weak below average conditions as a whole, implying a deficit on water availability for electricity generation. These results are consistent with those of Amador *et al*. (2000a) for El Niño events of 1992–93 and 1994–95, although the physical mechanisms responsible for this kind of response have yet to be proposed. Previous results from principal component analysis discussed earlier suggest the importance of identifying the dominant regional climate variability modes to explain changes in precipitation within the basin.

We have noted that precipitation anomalies are associated with changes in trade wind intensity and in the low-level jet, which are also associated with ENSO episodes. Figure 10 shows the composite anomaly of the 925 hPa wind vector associated with the low-level jet over the Caribbean during several El Niño, (Fig. 10a), and La Niña, (Fig. 10b) events, for the summer months (June to August). Composite anomalies of the wind vector were estimated using at least 9 episodes for each of the two ENSO phases. El Niño and La Niña events were defined following Kiladis and Diaz (1989), and using a procedure similar to that proposed by Trenberth (1997). El Niño (La Niña) summers are characterized by stronger (weaker) than normal winds over the central Caribbean associated with the low-level jet core region. From Fig. 9b, a marked period of positive precipitation anomalies is observed, at CN during July-August 1997, which is consistent with the idea discussed earlier, that changes in wind intensities are associated with variations in the low-level jet, that in turn are related to precipitation anomalies over the basin through a wind–topography interaction mechanism. Note that in NA (Fig. 9a), July–August 1997 exhibit mainly negative precipitation anomalies, as expected from a strong descending wind flow over the NW sector of the basin. El Niño event during summer implies a stronger low-level jet, that are reflected in positive precipitation anomalies in the Arenal Basin, especially in the SE sector, which dominates the contribution of precipitation to the reservoir water level this time of year. Kiladis and Diaz (1989) detected a relatively weak trend toward drier than average conditions in the Caribbean basin from July to October of a canonical warm ENSO phase. Their result is consistent with the one found here, at least for the western Caribbean, since conditions are unfavorable for convection due to the strengthening of the trades during El Niño summer months, to increased vertical wind shears (Amador *et al.* 2000c), and to related negative SST anomalies due in part to enhanced evaporation. Once the trade winds weaken in September-October, the SSTs start to recover slowly towards the end of the rainy season, favoring again convective activity before the start of the winter months. Negative anomalies during El Niño winter of 1998 are discussed below in conjunction with results shown in Fig. 11.

Positive anomalies for other periods at NA and CN during the 1997–1998 El Niño correspond to the so-called "temporales" and mid-latitude air intrusions. Some of these cases are discussed later, in more detail, on this chapter. Fig. 9c and 9d, show for the NA and CN regions, respectively, the pentad precipitation anomalies during the most recent La Niña event (1998–2000). Contrary to what is observed in Fig. 9a and 9b, the 1998–2000 cold phase of ENSO presents both positive and negative anomalies with no apparent relationship with global or regional scale systems. A more detailed analysis, however, reveals relatively dryer than normal conditions at NA and CN during the summer months (July–August 1998, and July–August 1999). Fig. 10b implies that the low-level jet during summer of a cold ENSO phase is associated with weaker than normal wind velocities, which is consistent with the negative summer anomalies found at both stations in Fig.9c and 9d, under the assumption of weaker flow-topography interactions. Also, one could argue that weaker (stronger) trades associated with the low-level jet entail decreased (increased) influx of atmospheric moisture content into Costa Rica coming from the Caribbean, and as a consequence into the Arenal Basin. Changes in the strength of the low-level jet lead to favorable (unfavorable) conditions for the generation of rainfall. A similar mechanism that partially explains hydrological anomalies in some areas of the Pacific slope of Colombia is also associated with a low-level westerly jet that penetrates inland, especially from August to November, with maximum winds of about 6 m/s in October (Poveda *et al*. 1998; Poveda and Mesa, 2000).

El Niño and La Niña composites for the 925 hPa vector wind anomalies, for NH winter are shown in Fig. 11a and 11b, respectively. The warm (cold) ENSO phase shows weaker (stronger) than normal wind velocities over the Caribbean region that is reflected in less (more) precipitation at both stations (Fig. 9a,b). The exception to the above statement is December 1998 to February 1999 for CN (Fig. 9d), which displayed near normal conditions. Noteworthy are the positive precipitation anomalies of the winter months of 1999–2000. A discussion of one of the extreme cases studied for the winter months of 1999–2000 follows.

Some case studies of short-term meteorological phenomena that hit the Arenal Basin are presented in Fig. 12. The aim is to show their relative importance to precipitation variability, and to identify these types of systems as fundamental components of the basin's hydrologic budget. Figure 12a shows the contribution to local precipitation of several extreme cases during the 1997–98 El Niño event, namely, the "temporales" of 1–6 August 1997, and of 9–13 March 1998. The name "temporales" is the term used locally for a period of weak to moderate nearly continuous rain covering several days affecting a relatively large region. Hastenrath (1991) provides a definition, of the "temporales" for the Pacific Region of Central America, close to the one used here, however, a condition that is included in his concept is that winds are weak, while in some cases, as it is shown below, winds could be intense and long lasting. The frequency of these events shows a great deal of inter-annual and intra-seasonal variability, and their relationship to ENSO or to other large-scale climatic signals is still unclear. As discussed by Velásquez (2000), these perturbations not only originate in the Pacific as disturbances associated with the ITCZ, also discussed in Hastenrath (1991), but are also related to westward traveling low-level cloud systems over the Caribbean, not always associated with mid-latitude air intrusions. That is the case of the August 1997 episode and the beginning of the January 2000 event (the latter shown in Fig. 12b). It can be noted in Fig. 12a that CN experiences a dramatic increase in rainfall that surpasses 300 mm in about 5 days for the August 1997 temporal. Other stations (not shown) also measured important amounts of precipitation related to this temporal. Note from Fig. 12a that NA in the NW low lands of the basin does not show an important response to this Caribbean temporal. Another case that confirms this difference in the response of the basin to Caribbean temporales is included in Fig. 12a for March 1998. The January 2000 case is initially characterized by a sudden wind intensification over the Caribbean from 5 to 9 January 2000, as illustrated in Fig. 13a. To show that this wind change is not initially related to cold air intrusions from mid-latitudes, Fig. 13b is shown. This case corresponds to the period 11–20 January 2000 that affected almost the whole basin (Fig. 12b). Due to the anomalous rainfall of late 1999 in the SE sector (see Fig. 9d), and to the temporal of January 2000, the reservoir level rose to an unprecedented level of nearly 548 m. A safe level of operation, according to ICE is 546 m, and therefore emergency measures had to be taken regarding the water use and management for electricity generation. The photograph presented in Fig. 14 illustrates the overall impact of the anomalous precipitation on the water level of the lake. Note that this temporal, contributed more than three times the precipitation attributed to Hurricane Mitch at CN during 26–30 October 1998 (Fig. 13b), which occurred during a cold ENSO event. After this extreme event hit Costa Rica's northern region in January 2000, overall bean crop losses due to flooding and severe meteorological conditions were reported to be of the order of US$3 million.

The cases presented before provide evidence that the topographical features of the basin play a crucial role as a forcing mechanism for generation of rainfall. Changes in low-level trade wind intensity are closely related to disruptions in precipitation by means of a flow-topography interaction process. The local dependence of precipitation amount upon elevation in areas of high relief in Costa Rica has been well established (Chacón and Fernández, 1985, Fernández *et al*. 1996), however, the relationship of wind intensity to precipitation amount still requires further investigation.

SUMMARY DISCUSSION

The use of pentad precipitation data and the availability of a relatively dense station network to update aspects of the climatology of the Arenal River Basin, clearly has helped to improve our understanding of the seasonal distribution of precipitation for water management purposes. It was also possible to identify the areas with strong spatial and temporal contrasts in precipitation patterns for water use purposes. A relative minimum in the annual cycle of precipitation, known as the mid-summer drought or "veranillo", weakly affects the most western portion of the reservoir during July-August. Intense trade winds, associated with the development of a low-level jet over the Caribbean during the summer months, have an opposite effect to that of the veranillo. Increases in the wind flow results in an increase of precipitation in the eastern most region of the reservoir, due mainly to the interaction of the wind flow with the basin's topography.

The 1997–98 El Niño and 1998–2000 La Niña episodes have been closely studied in relation to their influence on the basin precipitation distribution. Based on previous results by Amador *et al*. (2000a,b) and those of the present work, El Niño events are shown generally to be associated with a decrease in reservoir level, although some other factors also affect this parameter. La Niña events generally increase the precipitation in the basin, especially that of the northern and western parts, by means of disturbances originating in the Caribbean side, such as the so-called temporales and hurricanes.

The first order climate disruption from the normal precipitation pattern in the Arenal basin, as determined by principal component analysis of anomalies of monthly precipitation for two regions (NW and SE), appears to be weakly related to ENSO episodes and to a greater degree to low-level Caribbean wind anomalies, respectively. Although these low-level wind changes seem to be modulated partly by ENSO, results bring out the importance of other non-ENSO signals, such as variations in the low-level jet, for understanding climate disruptions in the region.

Another factor that contributes to inter-annual precipitation variability in the basin is one related to the frequency of cyclone formation in the Caribbean basin. It is generally accepted that during El Niño episodes, fewer tropical cyclones tend to form in the Caribbean region. Amador *et al*. (2000c) found, on the one hand, that the existence of anomalously warm SST's in the eastern Pacific results in an enhanced low-level jet, and therefore, in stronger than usual wind shear during summer. On the other hand, during La Niña years, the low-level jet weakens and the vertical wind shear decreases. Partly as a result of such changes in the wind shear environment, the number of hurricanes varies from one year to another. The fluctuations in the intensity of the low-level jet are also reflected in the SST anomaly field over the western Caribbean Sea, north of the Venezuelan coast. An intense (weak) jet results in negative (positive) SST anomalies over the western and central Caribbean, due to strong (weak) Ekman transport and upwelling. In this way, the low-level jet may also be playing a role relating the SST anomalies in the eastern Pacific during El Niño or La Niña events, to the SST anomalies over some regions of the Caribbean.

The importance of identifying precipitation variability on inter-annual time scales, other than ENSO, associated with regional climatic features, such as the “veranillo” and the low-level jet, has led us to identify basic steps in the development of practical rainfall forecasting schemes for the Arenal basin. The problem of climate variability in Costa Rica and other regions of Central America constitutes a challenge, since the region is surrounded by warm ocean pools in which convective activity is intense, sometimes as a result of the interaction of strong trade winds associated with regional climate systems in complex topography. Most forecasting schemes aimed at determining the spatial patterns of precipitation anomalies are based on statistical methods or on analogues, using the El Niño signal as primary input. As has been shown here, not all the anomalous climate patters exhibit the same spatial characteristics, or are related to the ENSO signal directly. Even more, differences in large-scale climatic patterns associated with different ENSO events sometimes makes the utilization of analogues or multiple regression models based only on tropical Pacific SST information of very limited use. Therefore, the use of more physically based prognostic tools, such as that provided by numerical models with a multi-parameter output, should in the future be incorporated as a more realistic alternative to the traditional predictions schemes.

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List of Abbreviations

AN: Arenal Nuevo Hydrometeorological Station
ARCOSA: Hydroelectric Complex Arenal-Corobici-Sandillal
CN: Caño Negro Hydrometeorological Station
EC: El Cairo Hydrometeorological Station
IAI: Inter-American Institute for Global Change Research

IGN: Instituto Geográfico Nacional (National Geographic Institute)
ICE: Instituto Costarricense de Electricidad (Costa Rica Institute of Electricity)
NA: Naranjos Agrios Hydrometeorological Station
NCEP: National Center for Environmental Prediction
NCAR: National Center for Atmospheric Research
NT: Nuevo Tronadora Hydrometeorological Station
PACS-SONET: Panamerican Climate Studies Sounding Network
PS: Presa Sangregado Hydrometeorological Station

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Figure Legends

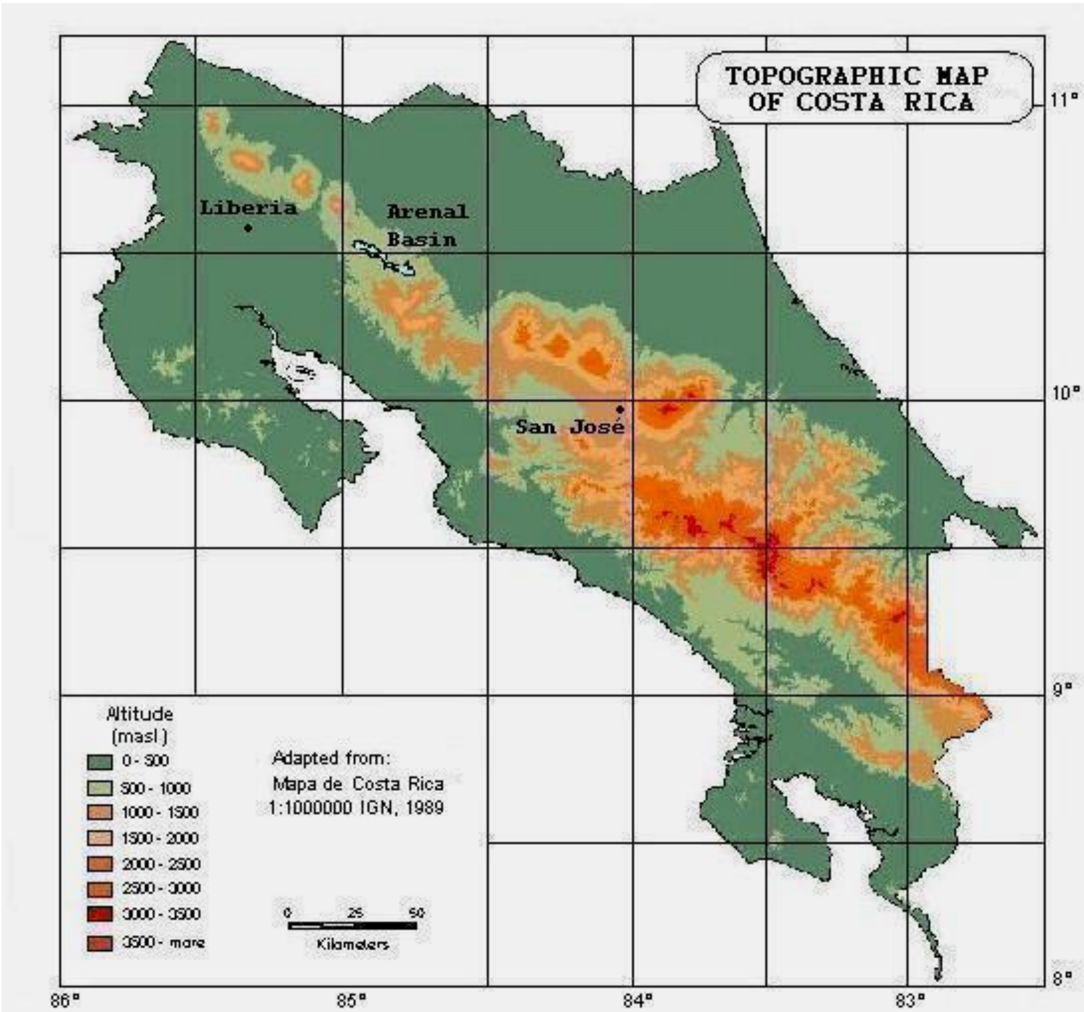


Fig.1. Topographic map of Costa Rica showing the approximate location of the Arenal Basin with respect to the town of Liberia in the Guanacaste Province, and San José, the capital city of the country. Altitude is given in meters above sea level (masl).

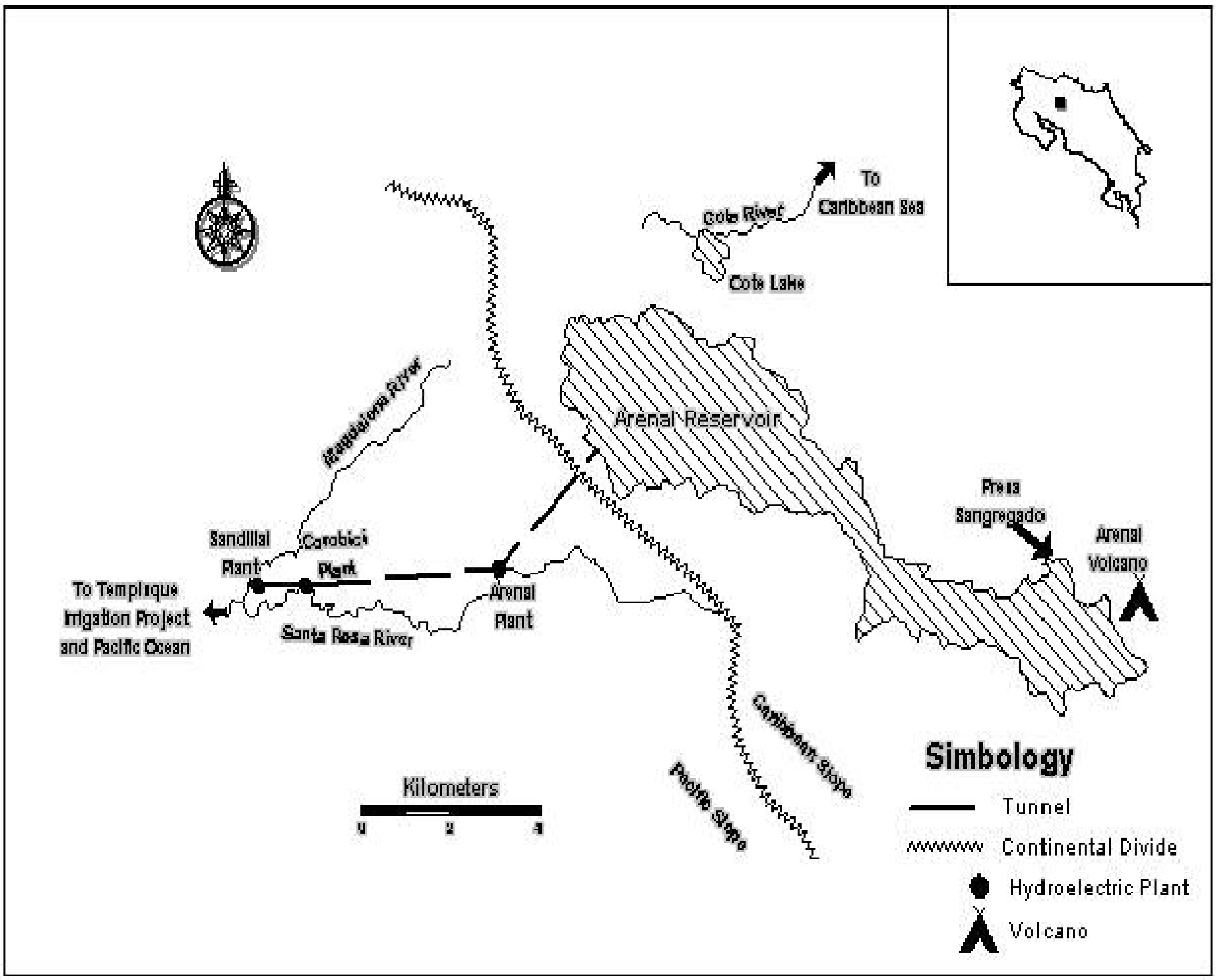


Fig. 2. Relative location of the Arenal, Corobici, and Sandillal hydroelectric plants with respect to the Arenal reservoir.

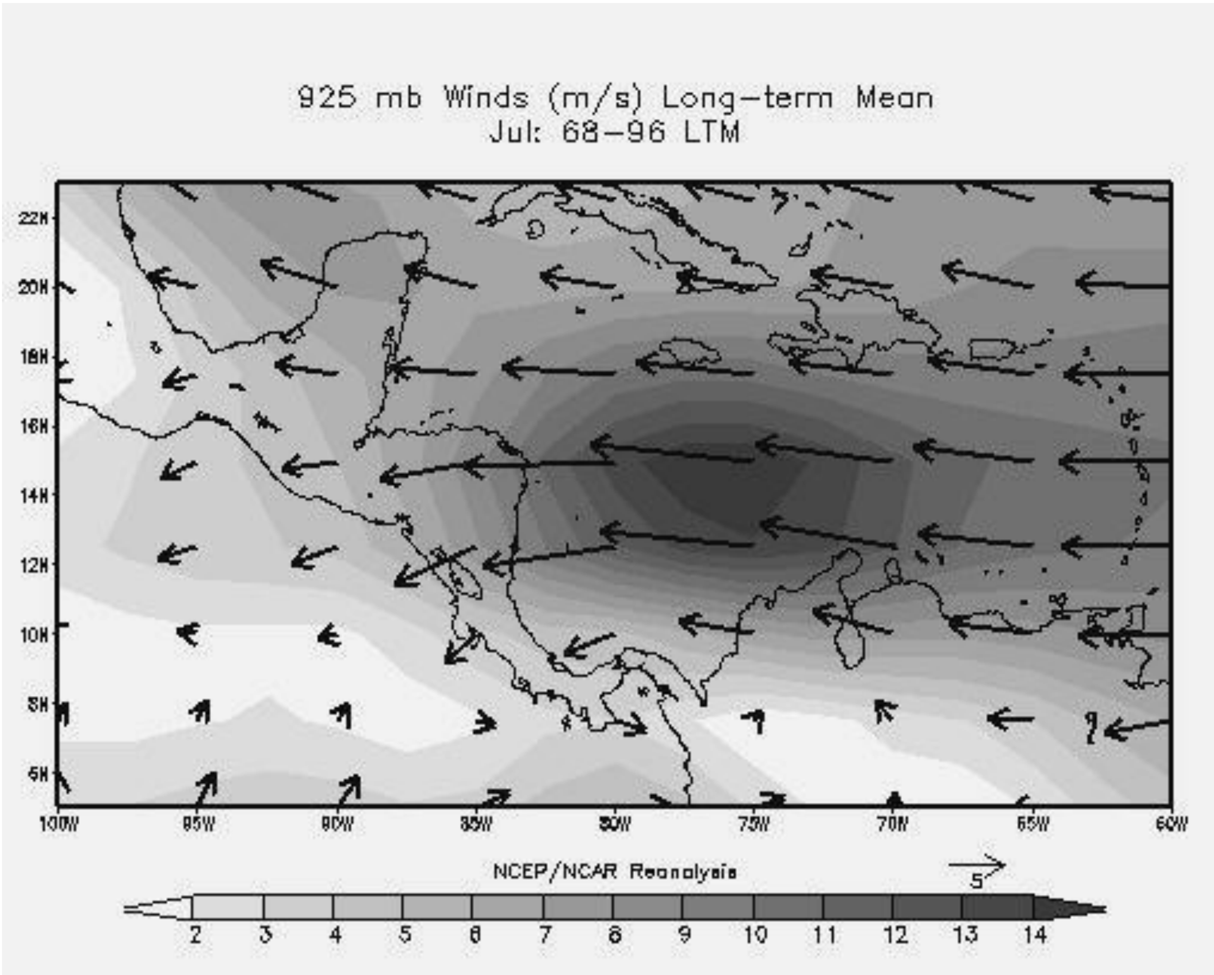


Fig. 3. Long term 925 hPa mean wind vector (m/s) showing the location of the low level jet over the Caribbean during July using NCEP/NCAR Reanalysis data for the period 1968-1996.

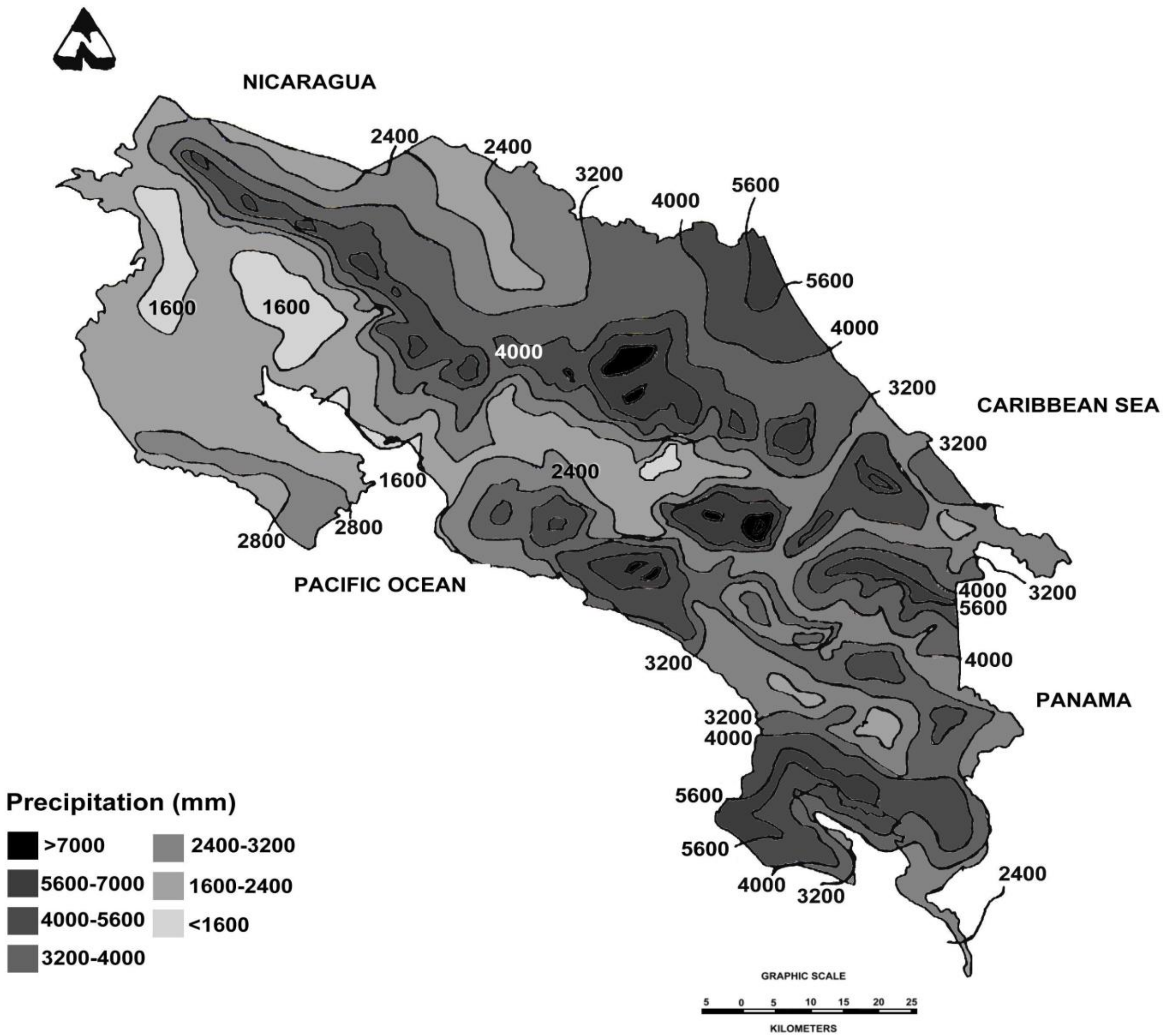


Fig. 4. Mean annual distribution of precipitation over Costa Rica (main map) for the period 1970-1989, and seasonal rainfall distribution at some selected stations (inserted figures) for shown periods. Precipitation contours are in mm per year and intervals are shown in gray scale.

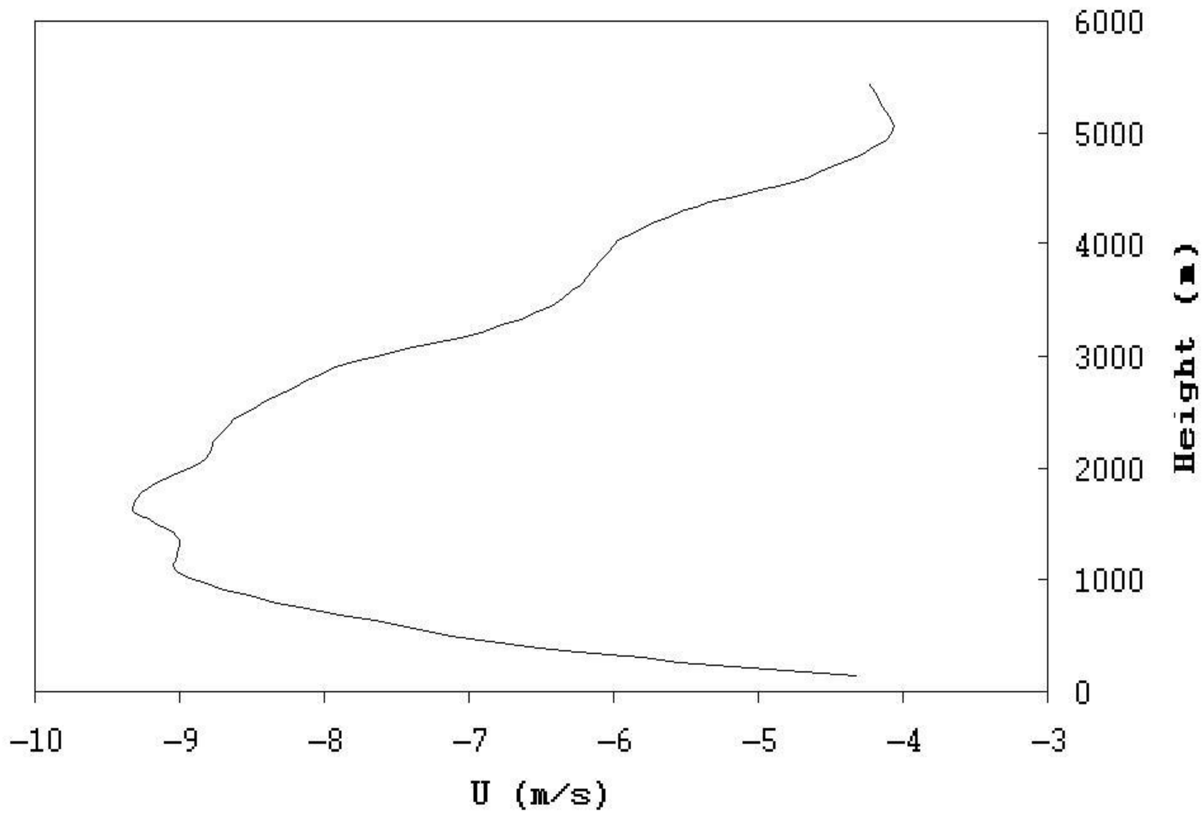


Fig. 5. Vertical structure of the mean zonal component (m/s) of the low level jet, using PACS-SONET pilot balloon data at Liberia, Costa Rica, for July 1997.

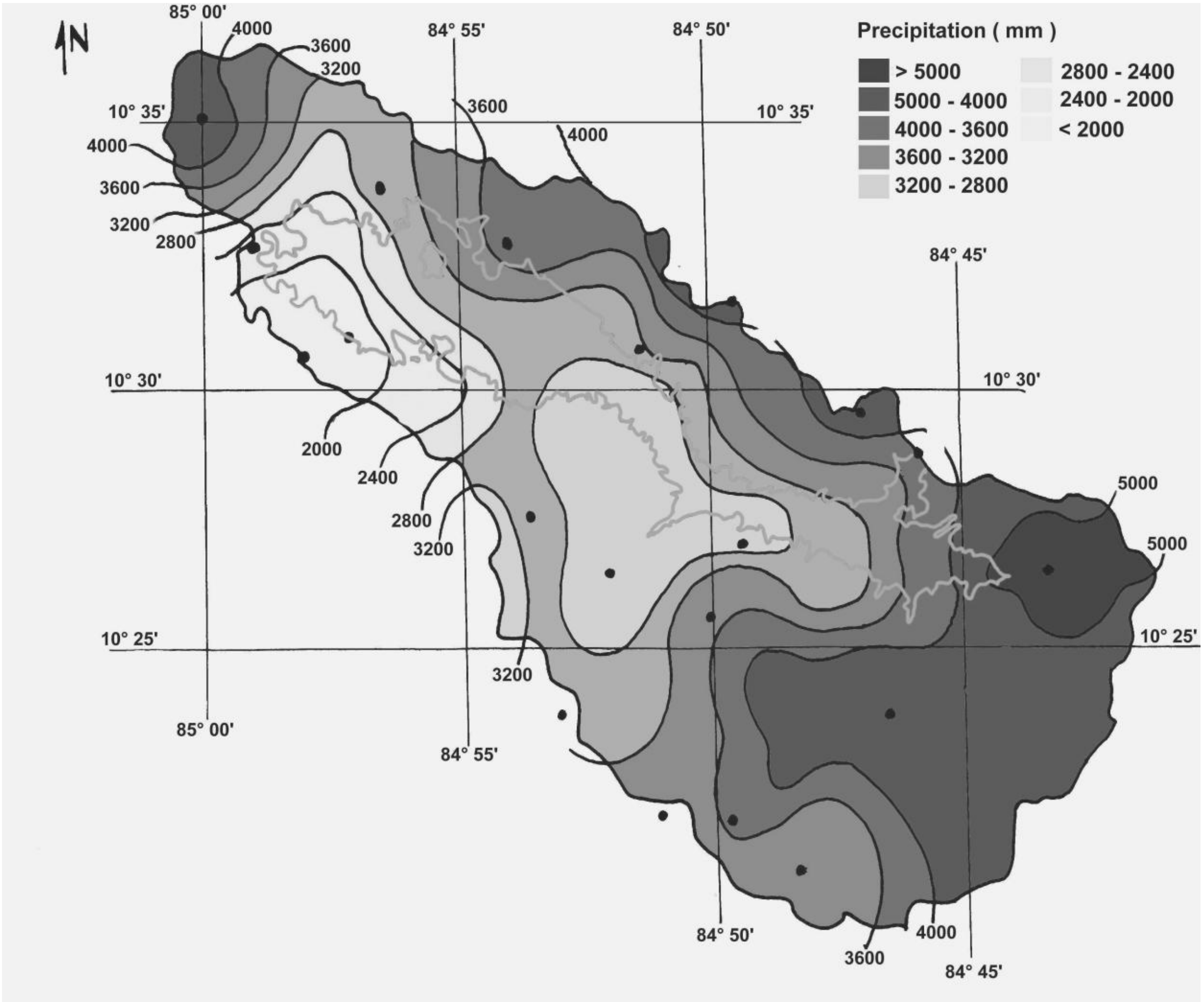
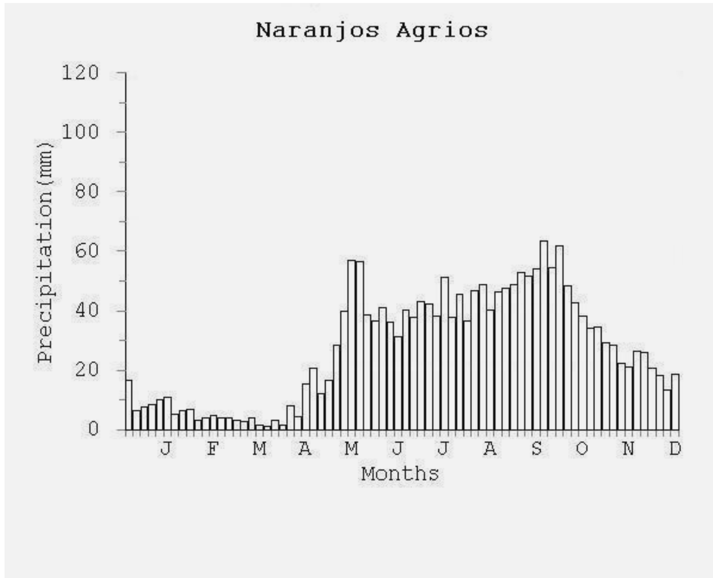


Fig. 6. Mean annual distribution of precipitation in the Arenal Basin for the period 1970-1999 showing, approximately, the hydrometeorological station network used in this study (black dots). The stations, for which data is explicitly discussed, are NA (Naranjos Agrios), NT (Nueva Tronadora), CN (Caño Negro), EC (El Cairo), PS (Presa Sangregado), and AN (Nuevo Arenal). Green solid line shows approximately the boundaries of the Arenal reservoir. Isohyets are contoured at 400 mm intervals from 2000 to 4000 mm, and at 1000 mm intervals above 4000 mm.



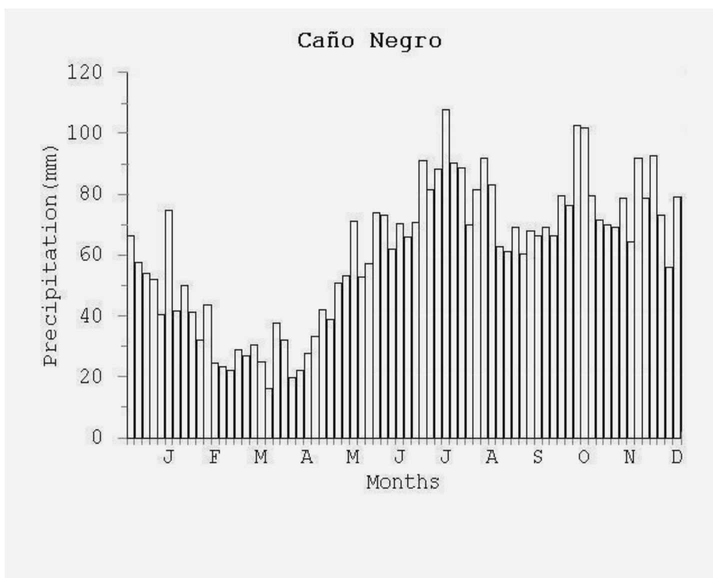
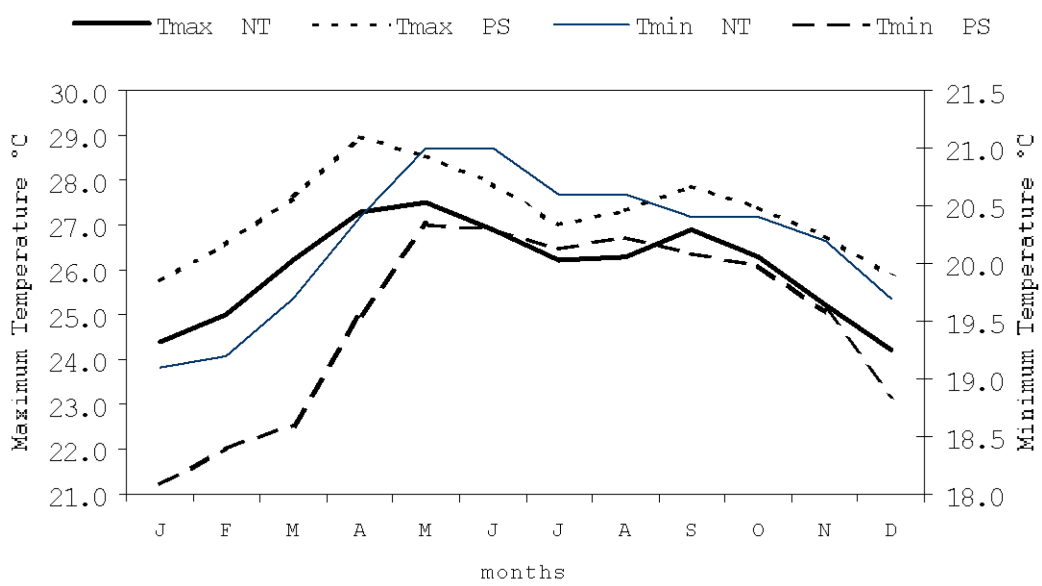


Fig. 7. Mean pentad precipitation distribution for a) Naranjos Agrios for the period 1974-2000, and b) Caño Negro for the period 1966-2000. Precipitation units are mm per pentad.



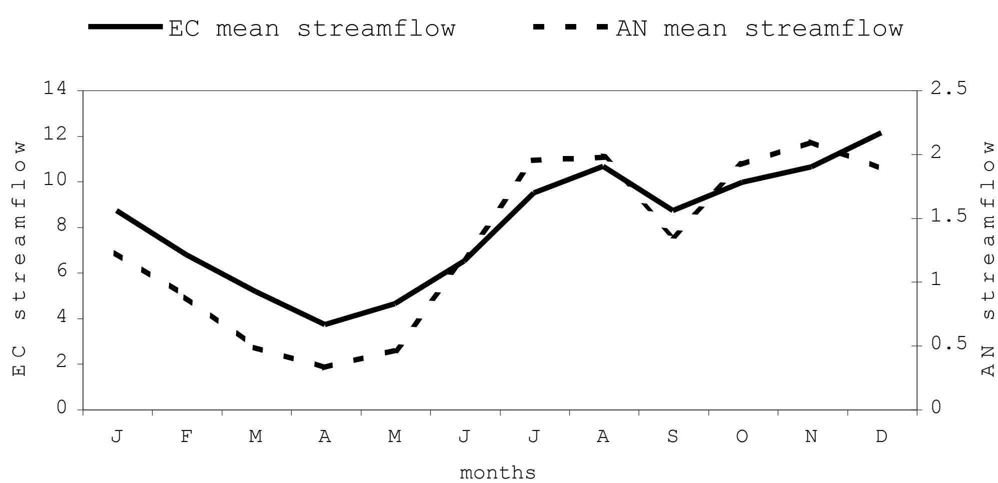


Fig. 8. Mean monthly distribution of a) maximum and minimum temperatures (Tmax and Tmin, respectively, both in °C) at Nueva Tronadora (NT) for 1978-1999, and Presa Sangregado (PS) for 1983-1999, and b) streamflow in m^3/s at El Cairo (EC) for 1975-2000, and Nuevo Arenal (NA) for 1978-2000.

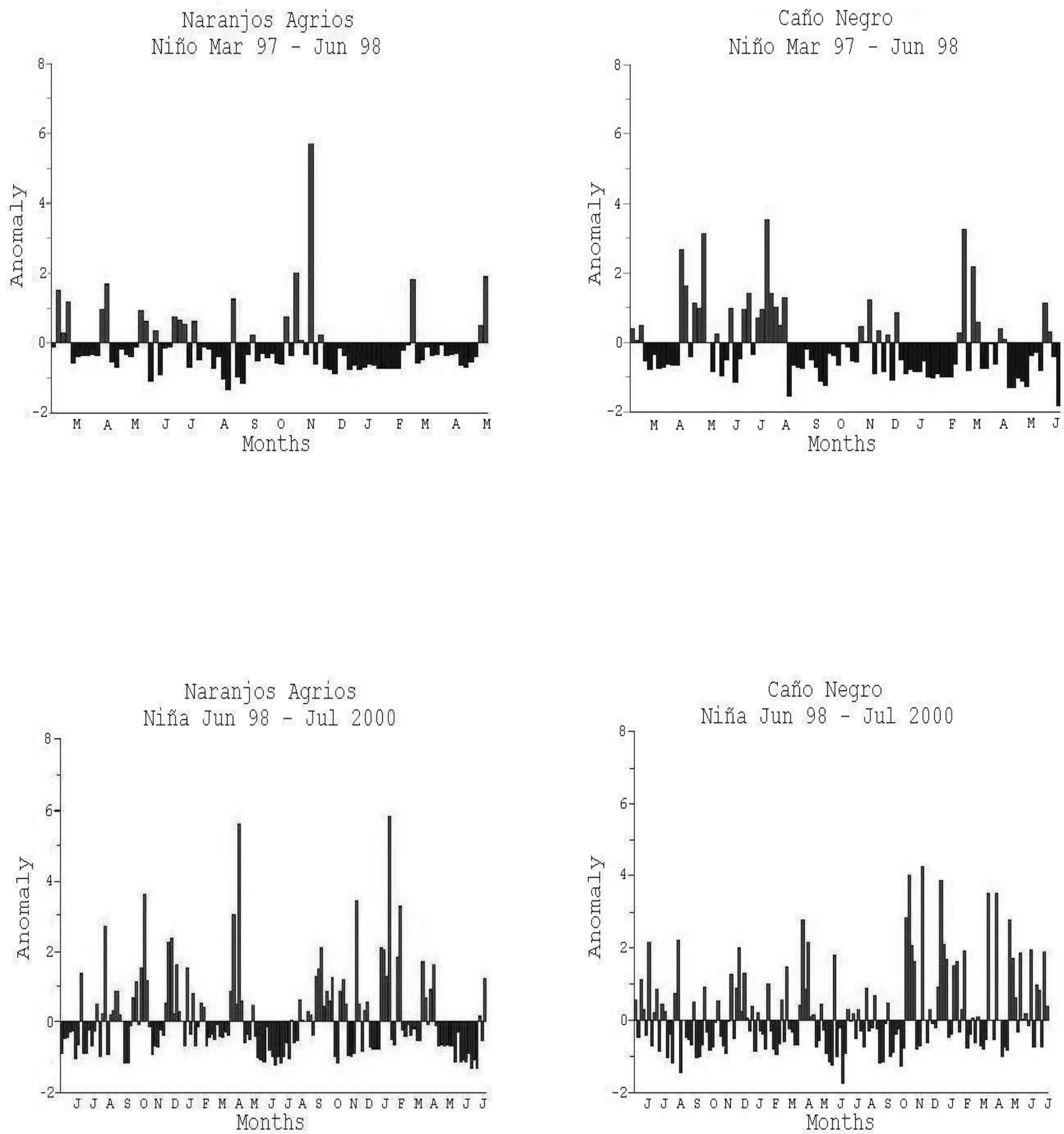
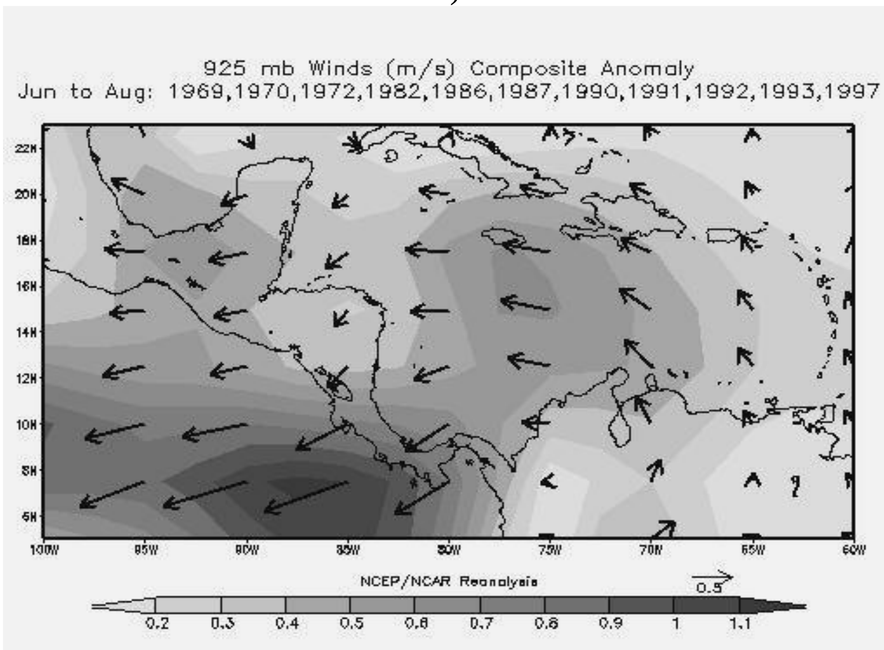


Fig. 9. Normalized precipitation anomalies (mm) by pentad for a) El Niño 1997-1998 at Naranjos Agrios, b) as in a) but for Caño Negro, c) La Niña 1998-2000 at Naranjos Agrios, and d) as in c) but for Caño Negro.

a)



b)

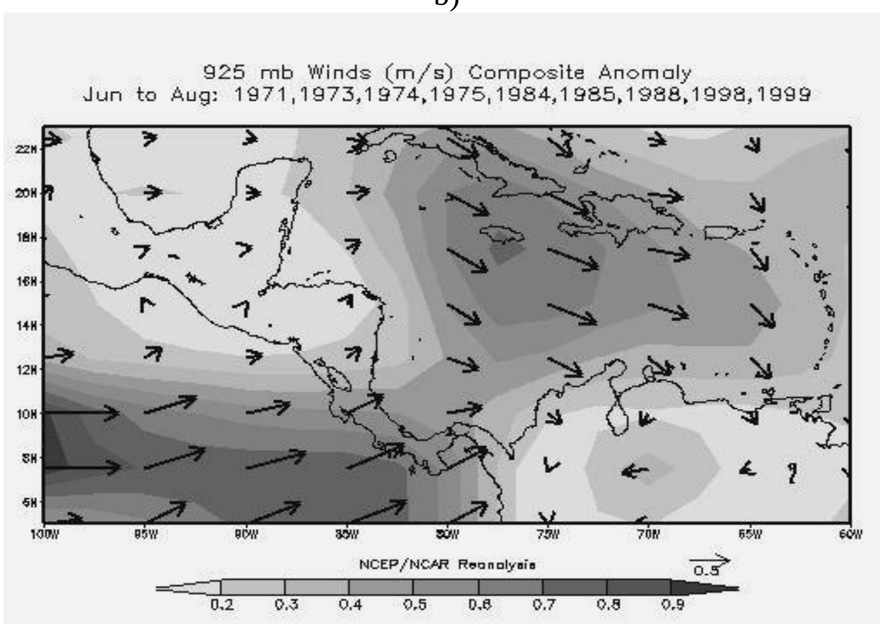
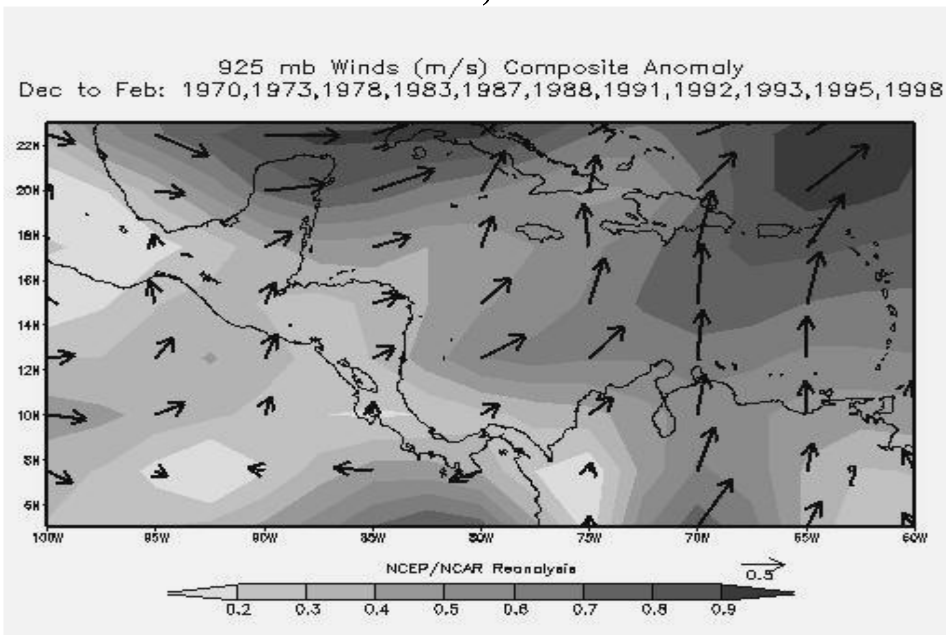


Fig. 10. Composite anomaly of the 925 hPa wind vector (m/s) for a) El Niño summers (June to August), and b) La Niña summers, using NCEP/NCAR Reanalysis data. El Niño and La Niña events follow basically the definition provided by Kiladis and Diaz (1989) and the procedure proposed by Trenberth (1997).

a)



b)

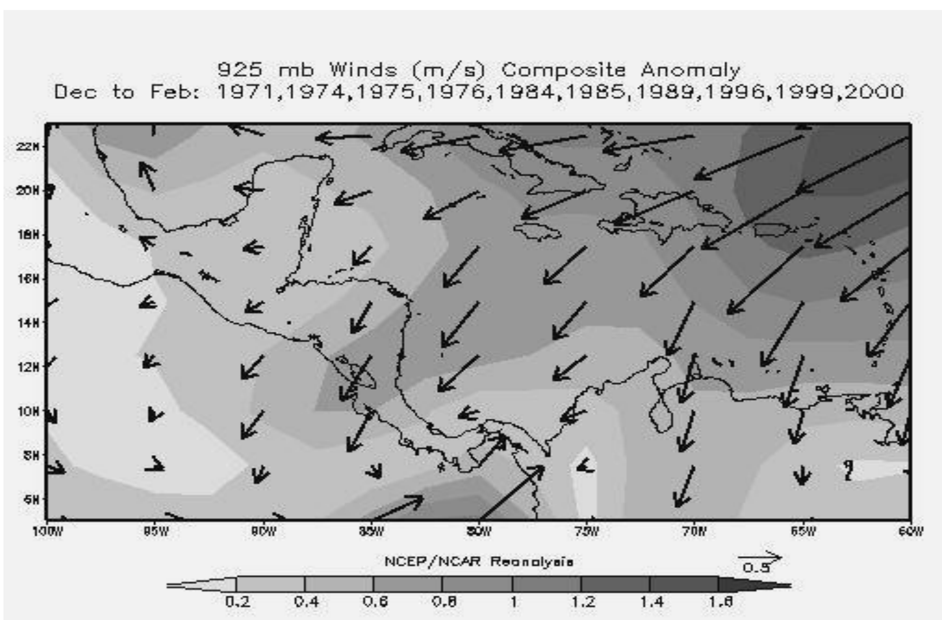
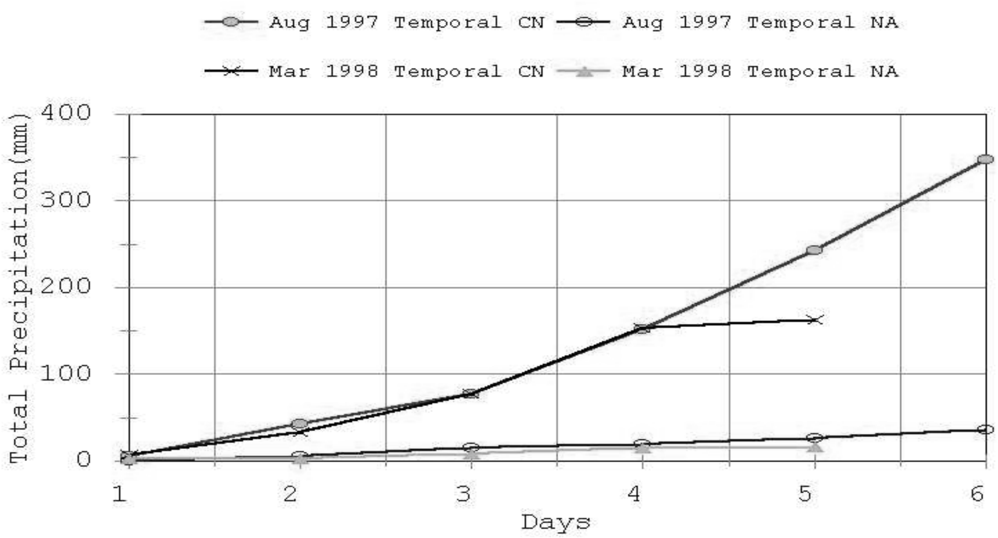


Fig. 11. As in Fig. 10 but for a) El Niño winters (December to February), and b) La Niña winters.



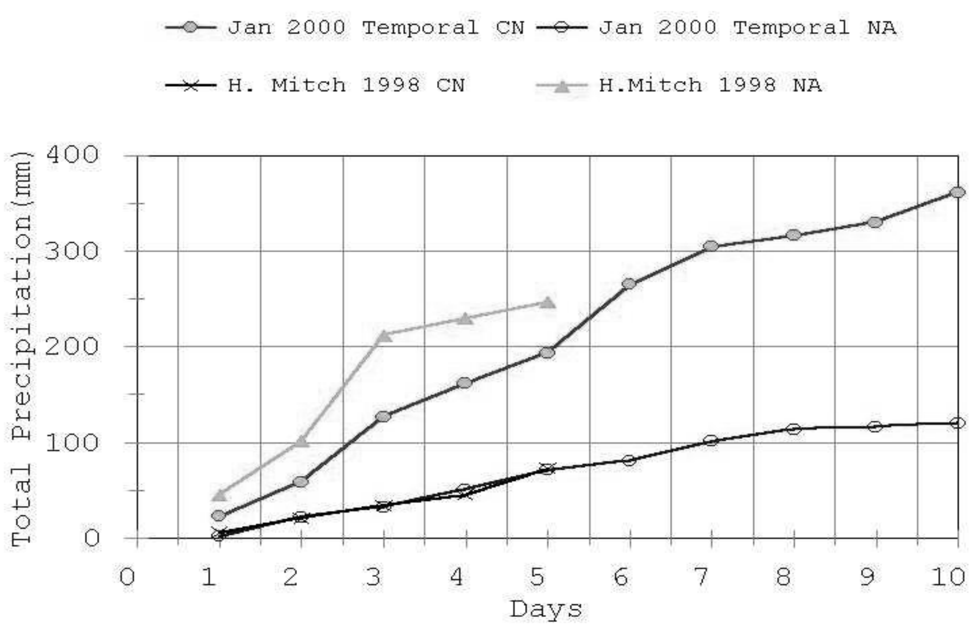
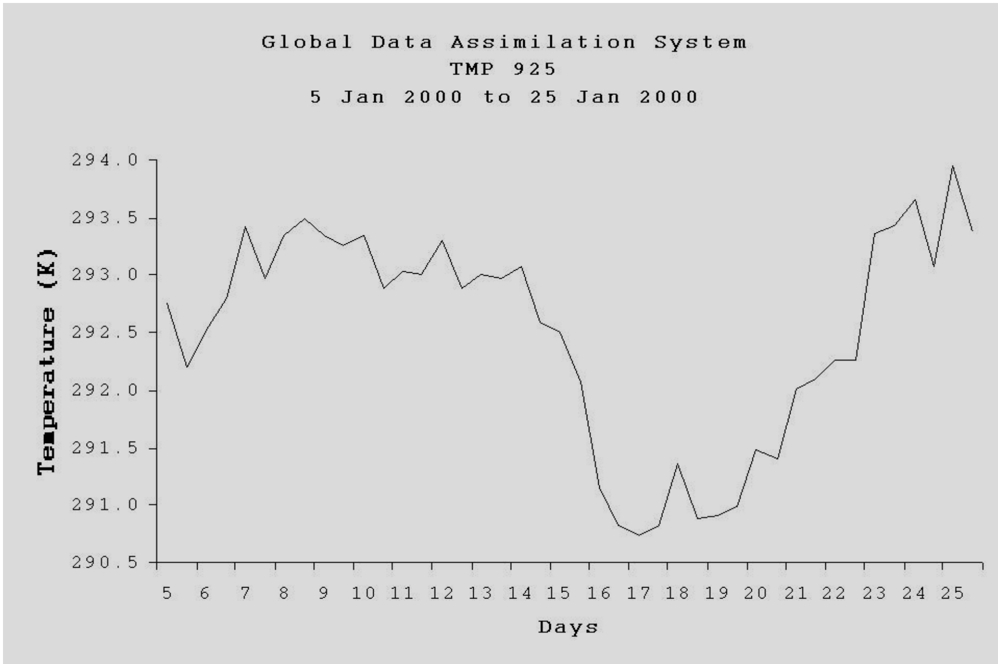


Fig. 12. Total precipitation contribution (mm) of selected "temporales" and extreme meteorological events at Caño Negro (CN) and Naranjos Agrios (NA) during a) El Niño 1997-1998, and b) La Niña 1998-2000.

a)



b)

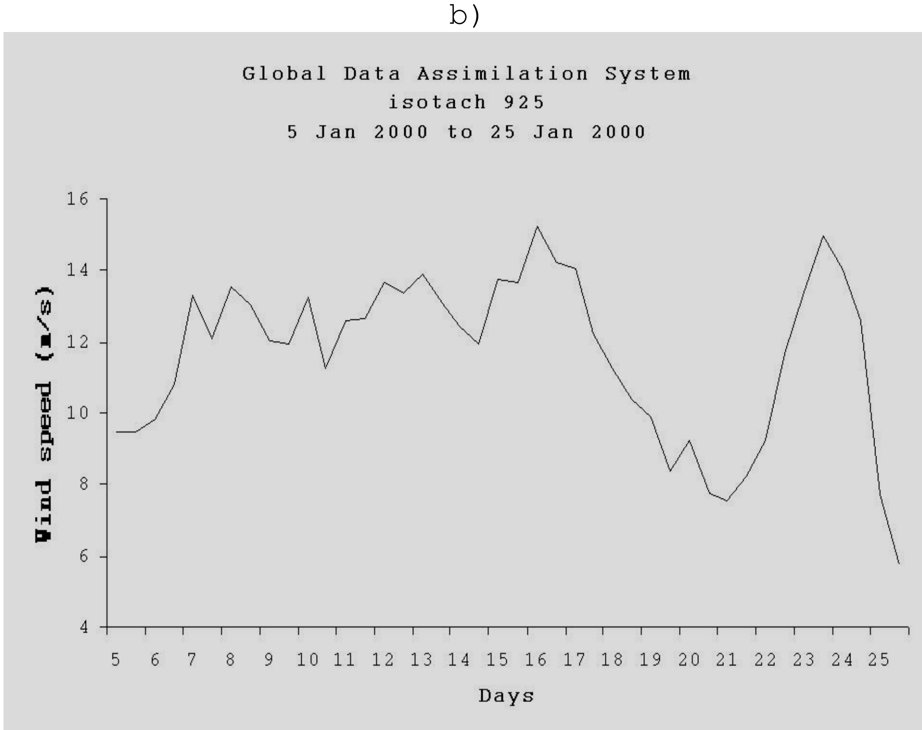


Fig. 13. Average values at 925 hPa over the area 10-15°N,75-80°W from 5-25 January 2000 for a) air temperature (°K), and b) wind speed (m/s).

Fig. 14. Photograph of the Arenal Lake during the “temporal” of 11-20 January 2000. Note the location of an approximately 6 m high tree seen in the lake, which used to be along the lakeshore before the unprecedented water level rise due to the temporal and La Niña rainfall anomalies of late 1999 and early 2000. Photo taken by J.A. Amador on January 15, 2000.