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VARIABILITY OF INTRASEASONAL PRECIPITATION EXTREMES ASSOCIATED WITH ENSO IN PANAMA

By

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I would like to dedicate this work to my family, specially my mom and dad who have always been supportive of my decisions. May God bless you all.

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ABSTRACT

Extensive analysis has been conducted over past decades showing the impacts of El Niño-Southern Oscillation (ENSO) on various regions throughout the world. However, these studies have not analyzed data from many stations in Panama, or they have not analyzed long periods of observations. For these reasons, they often miss climatological differences within the region induced by topography, or they do not possess enough observations to adequately study its climatology. Accordingly, the current study focuses on ENSO impacts on precipitation specific to the Isthmus of Panama. Results will be useful for agricultural and water resources planning and Panama Canal operations.

Monthly total precipitation data were provided by Empresa de Transmisión Eléctrica S.A., which includes 32 stations with records from 1960 to 2004. The year is split into three seasons: two wet seasons (Early and Late Wet), one dry season (Dry). The country is also divided into regions according to similarities in the stations' climatology and geographic locations. Upper and lower precipitation extremes are associated with one of the three ENSO phases (warm, cold or neutral) to estimate their percentages of occurrences. The differences between each ENSO phases' seasonal precipitation distributions are statistically examined.

Statistical analyses show effects of ENSO phases that vary by season and geographical region. Cold and warm ENSO years affect the southwestern half of the country considerably during the Late Wet season. Cold ENSO phases tend to increase rainfall, and the warm phase tends to decrease it. The opposite is true for the Caribbean coast. The Dry season experiences drier conditions in warm ENSO years, and the Early Wet season does not show any statistically significant difference between ENSO years' rainfall distributions.

INTRODUCTION

In this paper, we analyze precipitation climatology and variability in Panama. We define precipitation climatology for the different seasons and geographical regions. We also study precipitation variability, and any possible association with El Niño-Southern Oscillation (ENSO) phases.

Different socioeconomic and scientific areas are greatly affected by variations in Panama's intraseasonal rainfall patterns, and ENSO events have been previously pointed out as the main influence. In previous years, droughts have affected agricultural resources, the normal transit of ships through the Panama Canal, and reduced the availability of potable water (Donoso and Bakkum 1998, Rosales 1998). The severe droughts of 1983 and 1998 forced the local government to implement water usage restrictions, and prompted the Canal administration to increase the storage capacity of artificial lakes (PCC 1998). Local authorities started to be vigilant of predictions of ENSO after noticing the occurrences of droughts during El Niño, or warm ENSO phases, in particular during strong events. Other minor ecological events show the tendency of the local scientific community to speculate about climate change, El Niño, and effects on the local flora and fauna. Wright et al. (1999) provide one example of associations between El Niño and its effects on the ecology when they hypothesized fruit production in the tropical forest of Barro Colorado Island was stimulated by El Niño's sunny and dry conditions. The cases described above showcase the importance of studying impacts of both ENSO and other major phenomena on intraseasonal precipitation variability in Panama. The author's intention is to provide the general public and other scientific communities with a detailed analysis of precipitation climatology and variability in Panama.

This study uses monthly precipitation data provided by Empresa de Transmisión Eléctrica (ETESA). Stations are spread throughout the country, covering areas close to the coast and in the mountainous region (Fig. 1). There are fewer stations on the eastern half of the country where jungle predominates. Most stations have collected data since 1960, some starting even as early as 1955.

The Isthmus of Panama is located in Central America between latitudes 9.5° N and 7° N and longitudes 77.28° W and 83° W. It is marked by a chain of mountains in the west, moderate hills in the interior, and a low range on the east coast (Fig. 1). There are extensive forests in the fertile Caribbean area. The climate is mostly tropical maritime with two distinct seasons: one prolonged rainy season (April through November) and a short dry season (December through March). The climatological characteristics of these two seasons differ slightly in different parts of the country due to the interaction between patterns of regional circulation and Panama's topographic features.

Previous Studies

Panama's climatology has been studied within the context of previous Central American analysis of annual regimes of precipitation (Portig 1965; Hastenrath 1967; Zárate 1978; Chacón and Fernández 1985). There is also research related to impacts of ENSO in the Central American and Caribbean region. They indicate that drought in boreal summer (July through October) precedes a major low phase ENSO event (Hastenrath 1976, 1988; Rogers 1988; Ropelewski and Halpert 1987; Aceituno 1988, Waylen et al. 1996). However, the reduction for the period from July to October (5 %) is considered rather subtle and the weakest of those observed by Ropelewski and Halpert (1996). A detailed research of climate and ENSO in Costa Rica by Waylen et al. (1996) finds there is no ENSO signal along the Caribbean slope of Costa Rica. On the other hand, heavier precipitation is experienced on the Pacific slope during the year following a drought (Waylen et al. 1996; Hastenrath 1976), and this condition may persist a further year in the extreme southwest of Costa Rica (Waylen et al. 1996).

Research has found a series of ENSO effects on the mechanisms that drive the weather in Central America and the Caribbean. One example shows both Intertropical Convergence Zones (ITCZ), eastern equatorial Pacific and tropical Atlantic, experiencing a northward shift during the months of July and August of the positive phase of the Southern Oscillation Index (Wolter 1987). In addition, Zolman et al. (2000) have found that the number of mesoscale convective systems in the tropics associated with the ITCZ tends to be larger during cold ENSO phases than during warm ENSO phases during the Dry season. Furthermore, Giannini et al. (2000) links warm ENSO events with warmer sea surface temperatures (SST) in the Caribbean Sea following the mature phase of a warm ENSO event. The Trade winds are also affected by ENSO, weakening in the eastern Pacific during the positive SOI phase and strengthening in the Atlantic, although only during the winter hemisphere for the latter (Wolter 1987). The warm ENSO phase also affects the atmosphere over the Caribbean basin diverging it towards the eastern Pacific (west) and towards the tropical North Atlantic (east) (Giannini et al. 2000).

Even though ENSO has a great impact on different weather driving mechanisms, it is not the only factor to consider when discussing precipitation variability over Central America and Panama. According to Giannini et al. (2000), the controls of weather in Central America and the Caribbean regions are affected by a constant competition between the North Atlantic subtropical high (NAH) sea level pressure and the eastern Pacific ITCZ. The competition from both atmospheric conditions can have either a positive or negative interference pattern. For example, increased pressure in the NAH during a warm ENSO phase can cancel warming effects of SSTs in the Caribbean region. In addition, Enfield (1996) finds rainfall's strongest response occurs when the tropical Atlantic sea surface temperature anomalies (SSTA) are in a meridional dipole (antisymmetric across the ITCZ), i.e., the eastern tropical Pacific's SSTAs are of opposite sign to the North Atlantic's.

Previous studies of ENSO impacts on precipitation over Central America and the Caribbean region suggest a drying effect in Panama during the mature stage of a warm ENSO phase. The opposite result, more precipitation, is suggested during the mature stage of a cold ENSO event. In addition, research in Costa Rica shows that not all regions within the country are affected similarly, but that some regions (i.e. Caribbean coast) do not even show a statistically significant impact from ENSO. Furthermore, previous studies suggest ENSO alone cannot explain precipitation variability in the Central American and Caribbean region, and that other atmospheric conditions need to be considered. For example, Panama's rainfall pattern will vary (more rain or drier conditions) depending on the type of meridional dipole for that season. On the other hand, rainfall variability is less predictable when the meridional dipole does not exist.

Patterns of Regional Circulation

Weather in Panama is mainly driven by the ITCZ, especially in the eastern Pacific, which affects the region most of the year (Hastenrath 1988). Next in importance are the Trade winds and the subsidence inversion associated with them (Hastenrath 1988). The indirect effect of tropical cyclones in the Caribbean and the passage of easterly tropical waves also need to be considered (Peña and Douglas 2002). Topography is another important factor affecting Panama's precipitation climatology (Hastenrath 1988, Peña and Douglas 2002). It can enhance or diminish the rain-producing effects of the ITCZ, Trade winds and the other atmospheric factors. It can also induce contrasting rainfall conditions within the country climatology (Hastenrath 1988, Peña and Douglas 2002).

The Trade winds are a permanent feature in the Caribbean coast where they vary seasonally in intensity and direction (Hastenrath 1966, 1976; Hastenrath and Lamb 1977; Chacón and Fernández 1985). The Trade winds in the Caribbean coast are mainly northeasterly, being the most intense in boreal winter, with a greater meridional component (Fig. 2a - 2c). They extend over the Pacific coast as weaker northeasterly winds during the Dry season. Trade winds produce precipitation along the Caribbean slope and rainshadow effects on the western half of the Pacific slope (Waylen et al. 1996). Strong subsidence on the synoptic scale, thus inhibited convective activity, is responsible for the drier conditions in boreal winter (Riehl 1979). The Trades relative strengthening in July and weakening in August is part of a dynamic response of the low-level atmosphere to the magnitude and location of the convective forcing in the ITCZ (Magaña and Medina 1999). The Trades strengthening and the orographic forcing of the mountains in July result in maximum precipitation along the Caribbean coast and minimum precipitation along the Pacific coast of Central America known as midsummer drought (MSD).

Surface heating in the Tropics results in heat transfer to the air, mean upward motion and convergence of moist, low-level air into the ITCZ (Magaña and Medina 1999). Deep atmospheric convective activity associated with the ITCZ is generally confined between 3ºN and 10ºN north of the eastern Pacific equatorial cold tongue or front (Alpert 1945; Hastenrath and Lamb 1977) and it is supported by the eastern Pacific warm pool (Fig. 2). The confinement of the ITCZ to this region results from air-sea interaction triggered by latitudinal asymmetries in continental geometry (Hastenrath 1966). Its northward migration initiates the summer rainy season in May-April along Panama’s Pacific coast, and is coincident with convection inland (Chacón and Fernández 1985; Cavazos and Hastenrath 1990), and possibly, periods of heavy precipitation, or “Temporales” (Hastenrath 1988). The presence of the ITCZ over Panama is characterized by northeasterly Trade winds in the Caribbean coast and low-level flow from the southwest on the Pacific coast (Fig. 2b-2c). It is the convergence of moist air, in particular from the Pacific that is associated with the “Temporales” (Peña and Douglas 2002). They can last a few days up to a week and prevail during the months of June, September and October when the southwesterly flow is strongest. Topography in the western half of the country where the mountain range is located enhances convection in the ITCZ located over Panama. The ITCZ begins retreating southward in November, caused by the decrease of surface heating by the Sun in the northern tropical region.

Panama is located well south of most tropical storm tracks, so their effects on precipitation are mostly indirect. The passage of these tropical disturbances on the Caribbean usually disrupts the northeasterly airflow, causing the reversal of the pressure gradients across the isthmus and a corresponding enhancement of precipitation along the Pacific coast (Peña and Douglas 2002).

Although previous studies have begun the explanation of ENSO’s impacts on Panama, they overlook regional and seasonal precipitation climatology and variability particular to the country. There are studies that consider regional and seasonal precipitation differences (Peña and Douglas 2002, Zolman et al. 2000) but they are focused on ENSO’s short-term impacts on precipitation. This paper seeks to explore further Panama’s precipitation climatology, ENSO’s impact on different regions within the country, and how it affects precipitation in the different seasons.

DATA

ETESA’s department of Hydrometeorology provided monthly precipitation totals for 32 stations. The instruments used to collect data consist mainly of digital and tipping bucket raingauges. The 30-year period with the least amount of missing and incomplete monthly data spans from 1970 to 2000. Only the stations with 30 consecutive years of data within the 1970-2000 period of time are selected. Eighteen stations met the 30-year criteria and another two stations were accepted with 28 and 27 years of observations. The two stations with less than 30 years are accepted because they are the only ones with a long period of record located in the sparse and rather unpopulated eastern half of the country. Therefore, they are the only ones that can provide some information on the climatology of that region.

The locations of the stations extend throughout most of the country (Fig. 1). There are four stations northward of the Tabasara mountain range facing the Caribbean Sea (regions E and F, Fig. 1). Two of these stations have over 30 years worth of data, while the other two have over 40 years. No reliable data was available for most of the eastern half of the country, except for two stations on the Pacific coast (region D, Fig. 1). The Azuero Peninsula (region C, Fig. 1), on the Pacific Ocean side, is the flatter region away from the Tabasara mountain range and it has four stations available for study. The southwestern regions, which are close to or partly in the mountainous region, have a total of ten stations (region A and B, Fig. 1). The westernmost stations all have above 40 years worth of data. Two important areas are not represented by the distribution of the stations: the eastern half of the Caribbean coast and the regions including the Panama Canal Zone and Panama City. Since there was no data for these areas, they were not included in the study.

There are several indexes that can be used to study ENSO effects on climate. Niño 3 and Niño 3.4 have a good ability to pick up both cold and warm ENSO events, but they are substantially less sensitive to one of them (Hanley et al. 2003). The Japan Meteorological Agency (JMA) index is the preference since it has similar quality to Niño 3.4 without being less sensitive to one of the events. The index is a 5 month running mean of spatially averaged SSTAs over the tropical Pacific Ocean: 4°S-4°N, 150°W-90°W. The running mean removes some of the noise, which is necessary in order to have certain degree of confidence in any conclusions. The SST is monthly mean sea surface temperature averaged over the predefined box on the tropical

Pacific Ocean. Observed SST data are used for the period from 1949 to present. If index values are 0.5°C or greater for 6 consecutive months (including October, November and December), the ENSO year of October through the following September is categorized as the warm phase, cold if index values are -0.5°C or less, and neutral for all other values (Hanley et al. 2003). Stations with only 30 years of records have 7 cold, 7 warm and 16 neutral ENSO phases. Stations with the longest periods of record have 11, 12 and 25 cold, warm and neutral ENSO phases, respectively (Table 1).

A new objectively-derived time series of in situ-based monthly surface winds, known as the FSU2 winds, are used in this study. The objective analysis method (Bourassa et al. 2005) was designed to overcome gridding problems related to observational coverage and observational errors. For the Pacific Ocean and Caribbean Sea near Panama, the FSU2 monthly fields are available 1978 through the present month. The product used is analyzed on a 2˚ latitude by 2˚ longitude grid. The analysis region around Panama ranged from 20˚N-5˚S and from 130-70˚W.

Although in situ ship and buoy observations are recorded as wind speed and direction, pseudostress fields are produced for the FSU2 since these products are intended for ocean modeling (e.g., the FSU fields were first used to study equatorial Kelvin waves and as forcing for model studies during TOGA COARE). The zonal (Ψ_x) and meridional (Ψ_y) components of the pseudostress are defined as

$$\Psi_x = uw \qquad \Psi_y = vw$$

where w is the scalar mean wind speed, and u and v are the mean zonal and meridional components of the wind vector respectively. The ocean responds to the wind stress; however, the wind stress includes a drag coefficient whose value over the ocean is still not well known. Pseudostress values remove the controversy and allow the user to derive their desired stress values by multiplying the pseudostress components by their desired drag coefficient and the density of the air.

For monthly temporal resolution, the FSU2 winds have been shown to be more accurate than GCM generated fields (Bourassa et al. 2005). They also offer more years of observations than satellite wind fields.

A monthly one-degree global SST climatology was constructed using Reynolds' SST analyses by the Climate Prediction Center (CPC/NOAA). This climatology was derived from monthly Optimum Interpolation (OIv2) SST analyses with an adjusted base period of 1984-2004. Climatological monthly Reynolds' SST plots (Fig. 3) from the Climate Diagnostic Center show how temperature gradients ranging from the eastern equatorial Pacific Ocean to the lower Caribbean Sea vary for the months of February, June and October.

METHODOLOGY

Monthly means of precipitation were calculated for each of the 20 stations. Three different seasons were created based on the characteristics of the annual rainfall cycle. The Dry season months are December, January, February and March (DJFM), and they denote the months of continuous minimum average monthly precipitation totals throughout the country. The Early Wet season months are April, May, June and July (AMJJ) and the first month of the season has the first increase in average monthly precipitation after the Dry season months. Ending of the Early Wet season is marked by the decrease in rainfall totals in July associated with the MSD. The Late Wet Season encompasses the rainiest months after the MSD and before the beginning of the next dry season: August, September, October and November (ASON). Subregions were also created in order to group stations with similar climatology and geographic location. There are a total of 6 regions: South West, Central, South Central, South East, and Caribbean (North West and North East) (Fig. 1).

Monthly means were used to create a precipitation anomaly time series for each station by seasons. A precipitation anomaly time series is estimated using all the years of observed data for a particular station. Some of the stations have longer time series than others based on the number of recorded years. Percentages of occurrences of extreme precipitation events during ENSO phases are calculated for all seasons. The top (bottom) ten percent of the wettest (driest) years of each season are determined for each station. For example, the top (bottom) ten percent would be the three wettest (driest) events for that season in a station with 30 years of recorded data. The wettest (driest) events for a region are categorized by ENSO phase and then are divided by the total number of wet (dry) events. Table 2 summarizes the percentage of occurrence values for all seasons and regions. The percentages of occurrences are then normalized in order to facilitate histogram interpretation. Each percentage is divided by the ratio of cold, warm or neutral years to the total number of years so that departures from the unit number indicate abnormal occurrences of extreme events for a particular phase.

The Kolmogorov-Smirnov (K-S) test was used to ascertain whether the distributions of seasonal precipitation anomalies for the different ENSO phases are significantly different from each other. The K-S test is a distribution-free test for general differences in two populations and tests the difference of the entire distribution (Hollander and Wolfe 1999). The test does not reveal significant differences at any particular percentile. The null hypothesis is true if the distribution of seasonal precipitation anomalies of an ENSO phase is equal to one of another ENSO phase for that same season. Rejection of the null hypothesis occurs when ENSO phases' distributions of seasonal precipitation anomalies are significantly different from each other at a 5% confidence level.

The location of the ITCZ for a month was determined by finding the area of maximum monthly convergence at a level of ten meters. FSU2 winds' monthly divergence values and pseudostress vectors climatology serve to find areas of convergence and divergence subjectively. The period of the climatology is from 1978 to 2004.

RESULTS

Annual Precipitation Climatology

The analysis of each station's monthly precipitation climatology shows a marked annual seasonality between the dry and rainy months (Fig. 4a– 4e). The rainiest season, or Late Wet season (ASON), accounts for up to 60 % of the total annual precipitation, whereas the Dry season (DJFM) only accounts for 10 % to 15%. The Caribbean Coast region (North East and North West) (Fig. 4e) does not exhibit as strong an annual cycle as is seen in the Pacific coast. In the Caribbean coast region, the entire rainy season accounts for up to 70 % of the annual total rainfall and is almost evenly distributed between the Early and Late Wet seasons. Annual rainfall totals on the Pacific coast vary between 900 mm and 4000 mm. On the other hand, annual precipitation variability on the Caribbean coast is usually not as large as on the Pacific coast ranging between 3000 mm to 4000 mm.

Three distinctive regions characterize the Pacific coast: The South West, Central and South Central regions. The South West region (Fig. 1, Fig. 4a) is located near the highest section of the Tabasara range, and it is the rainiest region on the Pacific coast of Panama. Annual rainfall totals are around 4000 mm for most of its stations, and it has the wettest Late Wet season. The Central region (Fig. 1, Fig. 4b) is embedded between the end of the Tabasara range, the South West region and the flatter South Central region. It averages around 4000 mm annual rainfall, but its Late Wet season is usually second wettest to that of the South West region. The South Central region (Fig. 1; Fig. 4c) is the least rainy of all with annual rainfalls averaging less than 2000 mm, and a dry season registering the lowest average seasonal precipitation.

The eastern half of the Caribbean coast (Fig. 1, Fig. 4e) has annual rainfall totals averaging around 3500 mm of rain. Its dry season ranks as the wettest for the entire country, averaging around 800 mm of rain on that season. The average seasonal precipitation during the Early and Late Wet seasons is around 1500 mm.

Extreme events and ENSO distribution differences

The seasonal precipitation anomaly time series shows constant variability in the climatological pattern from year to year (Fig. 5 – 9). Warm ENSO phases appear to register below normal precipitation, whereas cold ENSO phases register above normal during the Late Wet season for stations in the South West, Central and South Central regions (Fig. 5a – 6a). The 1976-77, 1982-83 and 1997-98 warm ENSO phases standout as years with large negative anomalies on the Late Wet season for stations in the South West region. The cold phases of 1973, 1988 and 1999 also have large anomalies, positive in this case, for stations in the South West and South Central region during the Late Wet season (Fig. 5a, 7a). The ENSO effect is reversed for the Caribbean side where the ENSO events mentioned above tend to have negative anomalies for the cold phases and positive anomalies for the warm phase (Fig. 9a). The single exception is the 1973 cold phase registering positive anomaly precipitation. No tropical cyclones were reported near Panama in that period. Some other type of climatic factor must have influenced the 1973 cold ENSO phase. All regions tend to experience negative anomalies during warm ENSO phases of the Dry season (Fig. 5c – 9c). The Early Wet season does not show any particular association with ENSO phases (Fig. 5b – 9b). Neutral years appear to have great variability and their anomalies can be as large as those seen during the other two ENSO phases no matter what region or season of the year.

Wet extreme events in the Caribbean coast regions during the Late Wet season can be related to warm ENSO phases (Fig. 10a). Warm phase years are dominant in the percentage of occurrences of the wettest events, and cold and neutral phase years follow, almost equally splitting the remainder percentage of occurrences (Table 2). Dry extreme events seem to be slightly more likely to happen during cold and neutral ENSO phases (Fig. 10b) than during the warm phase. On the other hand, wet extreme events are more likely to happen during a cold phase year on all three regions in the southwestern half of the Pacific coast (Fig. 10a). A dry extreme event is more likely to happen in a warm phase year, followed by a neutral year. The Pacific coast regions least affected by the warm ENSO phase–dry extreme event association are the South Central and South East, where a dry extreme event occurrence is more likely during the neutral phase followed by the warm phase (Table 2).

The Early Wet season shows an arrangement of percentages of occurrences values of extreme events during ENSO phases different from those seen during the Late Wet season (Fig. 11). The Caribbean region's extreme events, wet and dry, are not influenced very much from any particular ENSO phase (Table 2). On the western Pacific coast, the influence from an ENSO phase varies depending on the region. The South West and Central regions are the only ones to have high percentages of occurrences of wet extreme events during the warm ENSO phase compared to those seen in the neutral and cold ENSO phases (Table 2). There is little association of dry extreme events with any particular ENSO phase for the southwestern half of the country except for a slight hint of cold ENSO phase influence over the South West region in this season (Fig. 11b). The South East region's percentages of occurrence values resemble the Caribbean region ones.

The Caribbean region's dry extreme events seem to be influenced by the warm ENSO phase during the Dry season (Fig. 12b). Wet extreme events on the other hand are more likely to occur during cold and neutral ENSO phases (Fig. 12a). Warm ENSO phases also dominate dry extreme events in the Pacific side regions, whereas the cold phase is the least likely to host them (Table 2). Wet extreme events are more likely to occur during cold ENSO phase years with warm phase years being the least likely for most of the entire country (Fig. 12a). The South East region is the only region where the cold phase is not dominant for the wet extreme events.

The previous analysis shows there are regions and seasons where there could be some ENSO impact on precipitation. The K–S test is used to statistically determine whether the populations for the different ENSO phases' seasonal precipitation anomalies all come from the same distribution at the 95 % significance level. Tables 3-4 summarize the results obtained from the test. The K–S test shows strong differences between cold and warm ENSO years' distribution of seasonal precipitation anomalies for the Central and South Central regions during the Late Wet season, and more than half of the stations in the South West region also have statistically different distributions (Table 3). Most stations in the South East and Caribbean regions do not show a statistically significant difference between ENSO phases' distributions of seasonal precipitation anomalies during the Late Wet season. The Dry season in the North East Caribbean and South East regions shows significant difference between neutral and warm ENSO phases' seasonal precipitation distributions for all their stations (Table 4). There is also ENSO influence during the Dry season in the South West and South Central regions where at least half of the stations show a significant difference between neutral and warm ENSO phases' distribution of seasonal precipitation anomalies. The Central region only shows one station with a statistically significant difference between ENSO phases' anomalies. There is no statistically significant difference between any of the ENSO phases' distributions during the Early Wet season.

DISCUSSION

Precipitation Climatology

The precipitation climatology of Panama is mainly marked by two distinctive seasons: the Dry season and the Rainy season. Both seasonal stages are closely linked to the passage of the ITCZ as it oscillates north and south on its annual cycle, northeasterly Trade winds blowing against the Caribbean coast, and formation and passage of tropical disturbances in the Caribbean sea.

The location of the ITCZ south of Panama (Fig. 2a) and the reigning subsidence inversion, also known as the trade-wind inversion, during most of the Dry season (Robinson and Henderson 1999), are the main factors preventing convective activity during these months. The Caribbean region experiences a Dry season rainier than the rest of the country (Fig. 4e) because of the presence of northeasterly Trade winds blowing almost perpendicularly to the coast and against the mountain ranges (Fig. 2a). This allows for orographic uplifting of the moist air brought in from the Caribbean, and thus helping counteract the drying effects of the reigning subsidence inversion. Trade winds on the Pacific side are considerably weaker than on the Caribbean. The combined drying effect of the subsidence inversion and rainshadow effects inhibits rain-producing convection on the Pacific coast.

The onset of the Early Wet Season coincides with the change in low level flow direction on the Pacific coast from weak northeasterly winds to southwesterly winds (Fig. 2a - 2b). This is a sign of the northward migration of the ITCZ, together with the arrival of intense deep convection and a subtropical lower-troposphere cyclonic circulation anomaly over the subtropics associated with intense convective heating off the equator (Gill 1980). The end of the Early Wet season is marked by the decrease in rainfall experienced during the MSD or “veranillo”. The minimum in precipitation experienced on the Pacific coast in July and August has been associated with an intensification of the trade winds and the formation of an anticyclonic circulation over the western coast of Mexico (Magaña and Medina 1999). It has also been associated with a decrease in SSTs over the warm pool in the eastern Pacific (Magaña and Medina 1999). The opposite is true for the Caribbean coast where enhanced easterly winds tend to increase precipitation.

The beginning of the Late Wet Season is marked by the increase in precipitation during MSD. There is a weakening of the Trade winds in relation to the appearance of cyclonic circulation straddling the southern-central part of Mexico and increased SSTs in the eastern Pacific warm pool (Magaña and Medina 1999). Increased deep convective activity related to the ITCZ and moist air brought in from the Pacific coast by the strengthened southerly flow become the propitiate environment to produce the heavy rainfall characteristic of the later months of the rainy season. It is during these months, in particular October, when the southwesterly flow is strongest and the Trades on the Caribbean coast are the most zonal (Fig. 2c). The meridional SST gradient at the cold tongue at the eastern equatorial Pacific Ocean up to the Panamanian Pacific coast is the greatest during this period too (Fig. 3c). The deviation of the Pacific coast winds from the more traditional southeasterly flow can be directly related to the SST gradient discussed above and the High-pressure system that produces the equatorial cold tongue. It is also at this time when Caribbean SSTs are the warmest and tropical disturbances tend to pass closer to Panama.

Precipitation, Low-Level Circulation and ENSO

Time series of precipitation anomalies and the analysis of extreme precipitation events show an impact of ENSO events on rainfall in Panama. The Late Wet season is the one that shows the greatest impact from both cold and warm ENSO phases. Rainfall deficits during the Late Wet season are the norm during warm phase years, and the opposite is true for most cold phase years. Cold phase years do not show much of an impact during the Dry season compared to warm phase years, which continues to bring drier conditions. The only exception to the rule is found in the Late Wet season on the eastern Caribbean coast where warm ENSO phases tend to bring more rain.

The Dry season, as discussed previously, is characterized by northeasterly winds and dry conditions induced by the subsidence inversion associated with them. A stronger subsidence inversion during warm ENSO phases is hypothesized since conditions are drier than normal throughout the country. A warm ENSO year is on its mature stage during the Dry season, which is accompanied by an anomalous low that brings rain to the equatorial Pacific South American coast. It is suggested that a strong anomalous subsidence will exist north of the anomalous low, and over the Caribbean. Warm ENSO phases' low-level winds during the Dry season do not show any particular pattern. On the other hand, the divergent atmosphere over the Caribbean basin during warm ENSO phases discussed by Giannini et al. (2000) seems to support the idea of a drier environment because of an intensified subsidence inversion.

There is not much evidence that the cold phase events have any particular effect on rainfall during the Dry season. Low-level winds do not show any particular pattern during cold ENSO phases of Dry seasons. The absence of a signal from low-level winds during cold ENSO phases could be attributed to the idea that other atmospheric conditions, mostly related to the state of the Caribbean Sea's SSTs, the NHA or the Atlantic ITCZ, overshadow its effects. Other authors in the Previous Studies section have repeatedly pointed out the idea of a struggle between ENSO events and the Atlantic's atmospheric and ocean conditions (Giannini et al. 2000, Enfield and Mayer 1997).

The Early Wet season shows hints of a reversal of the effects of ENSO phases on Panama's precipitation during the Dry season. The reversal in the ENSO-related precipitation pattern would agree with previous study's (Enfield and Alfaro 1999) findings about rainfall over the Caribbean basin being enhanced by persistent warm SSTA over the Caribbean Sea after the mature stage of warm ENSO phases. However, the difference in the distribution of ENSO phases' rainfall in this season is not statistically significant. An explanation could be that eastern equatorial Pacific SSTAs and ENSO induced climatic shifts have declined at this point. The above suggests that ENSO does not have a significant impact on rainfall at this stage.

Late Wet season's precipitation is the most affected by both ENSO phases. For the strongest warm ENSO events, there is an evident northeasterly low-level anomaly flow over the country as is shown by the pseudostress anomaly vectors in figure 13a for the 1997-98 warm ENSO phase. The presence of this anomalous low-level flow brings into light the idea of less favorable conditions for a wet or normal rainy season nearby and on Panama. Yet, warm ENSO events still bring drier conditions regardless of any evident anomalous northeasterly low-level flow. It could be inferred that low-level flow anomalies are not the most important signal, but a manifestation of what might be going on aloft. Therefore, shifting of the ITCZ position away from Panama during a warm ENSO phase could be one of the reasons for drier conditions. An underdeveloped ITCZ over the Central American region, migrating southward earlier than normal and contributing to the anomalous, rain-producing low in the eastern equatorial Pacific during boreal winter could also be a cause. On the other hand, the anomalous northeasterly low-level flow can be an explanation for the reversal of the ENSO signal in precipitation on the Caribbean coast. Stronger northeasterly winds induce orographic uplifting, which enhances convective activity for the Caribbean region.

Cold ENSO phase tends to bring more rain to the country during the Late Wet season, in particular the Pacific coast, and dwindle it in the Caribbean coast. Although low-level FSU2 pseudostress vectors only capture three cold ENSO events (1989,1998,1999), they still serve to show a marked southwesterly low-level flow anomaly. The anomalous flow pictured in figure 13b for the 1988 cold ENSO month of October could be an explanation for the wetter conditions experienced during cold ENSO events. The southwesterly flow anomaly is a reflection of a strengthened South Pacific High and cold SSTAs during cold ENSO phases. This stronger southwesterly flow would in turn act as an enhancer of convective activity on the Pacific coast, especially in the areas next to the mountains, and reinforce rainshadow effects on the Caribbean coast.

The inhomogeneity of the station's record lengths was of special concern in this study. Some calculations were performed twice in order to address questions about possible effects of varying record lengths on the results. The percentage of occurrences of extreme precipitation events during ENSO phases was performed twice for the South West region. The second calculation cut the length of records of all stations to the same period, from year 1970 to 2000. The K-S test was also performed again on all the stations of the South West region for the same period, years 1970 to 2000. Although the percentages had small changes, the results still showed the same conclusions. The second K-S test did not have different results from those obtained before fixing the length of records.

CONCLUSION

The previous results show that ENSO is an important player for Panama’s rainfall patterns. It significantly affects the rainiest months of the year, jeopardizing the country’s ability to collect and store water needed for economical and human purposes. At the same time, it has been shown that in a few cases ENSO affects precipitation in an unexpected way. For example, although a minority, some extreme precipitation events have occurred during an ENSO phase that is unlikely to host that type of event or have even occurred during neutral years. So not only ENSO is the main player in the overall picture; other atmospheric conditions can also have the ability to impose and override ENSO’s effects on rainfall. Previous studies point towards atmospheric and oceanic conditions in the Atlantic as the other key players, in particular the North Atlantic SSTs and NAH (Giannini et al. 2000, Enfield and Alfaro 1999, Enfield and Mayer 1997, Kane 1997).

Precipitation information from the Panama Canal Zone would help study precipitation variability for important areas that were not included in this paper. Longer periods of observations from these stations would allow a more comprehensive study of climate in Panama. Studying data from stations with better time-scale resolution would also help understand ENSO impacts that might go unnoticed using monthly data. For example, they would be useful to study ENSO effects on Early or Late Wet seasons' start dates. Future work would also include the study of upper-air data for long and short periods of records. Integrating observations from different sources would help understand how other atmospheric conditions affect precipitation over Panama, and how they interact with each other.

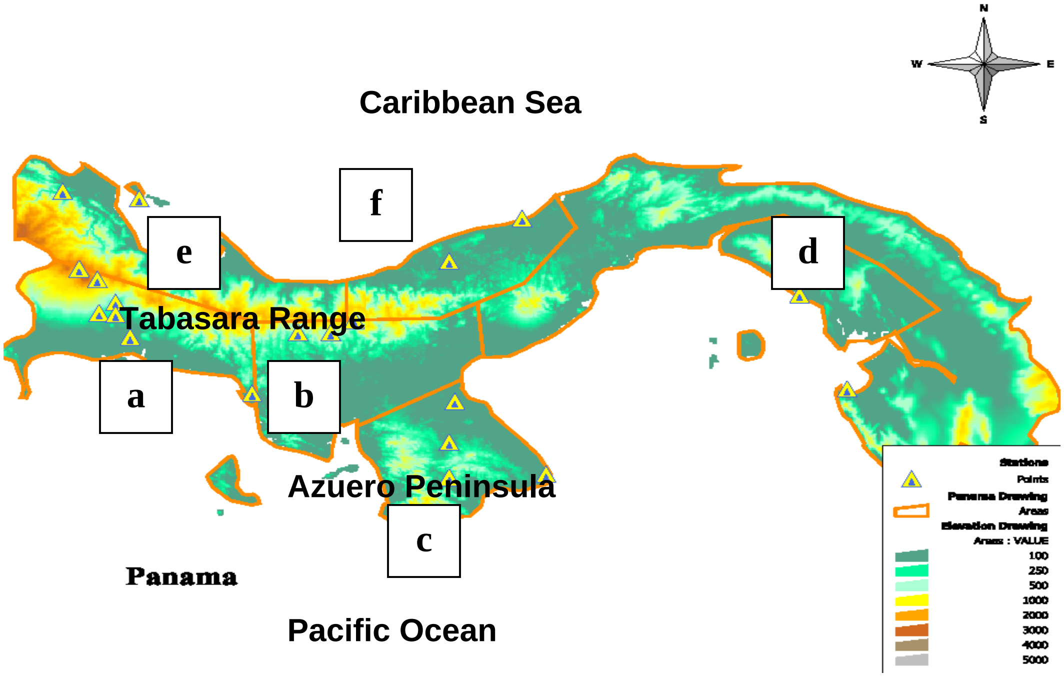


Fig. 1. Physical map of Panama and regional divisions: a) South West, b) Central, c) South Central, d) South East, e) North West (Caribbean) and f) North East (Caribbean).

Table 1. ENSO phases (1955-2003) based on the JMA SST index for the period of study. Each year indicates the beginning of the ENSO year (e.g. 1982 indicates a warm phase from Oct 1982 to Sep 1983)

Warm phase	Neutral phase	Cold phase
1957, 1963, 1965, 1969, 1972, 1976, 1982, 1986, 1987, 1991, 1997, 2002	1958-1962, 1966, 1968, 1977-1981, 1983, 1984, 1985, 1989, 1990, 1992-1996, 2000, 2001, 2003	1955, 1956, 1964, 1967, 1970, 1971, 1973, 1974, 1975, 1988, 1998, 1999

Table 2. Percentage of occurrences during the Late Wet (ASON), Early Wet (AMJJ) and Dry (DJFM) season where the 10 % driest (wettest) events are simultaneous with warm, cold, or neutral ENSO phases for all regions.

		South West		Central		South Central	
		driest	wettest	driest	wettest	driest	Wettest
ASON	warm	54	17	75	19	36	7
	cold	8	58	6	69	0	64
	neutral	38	25	19	13	64	29
AMJJ	warm	21	42	31	44	23	15
	cold	42	25	25	13	31	23
	neutral	38	33	44	44	46	62
DJFM	warm	46	4	56	13	54	0
	cold	21	46	19	69	8	69
	neutral	33	50	25	19	38	31

		South East		North East*		North West*	
		driest	wettest	Driest	wettest	driest	Wettest
ASON	warm	33	0	14	43	0	67
	cold	0	17	29	14	50	17
	neutral	67	83	57	43	50	17
AMJJ	warm	25	25	0	14	17	17
	cold	25	0	29	14	0	0
	neutral	50	75	71	71	83	83
DJFM	warm	83	0	71	0	50	0
	cold	0	17	0	43	0	33
	neutral	17	83	29	57	50	67

*** Caribbean region**

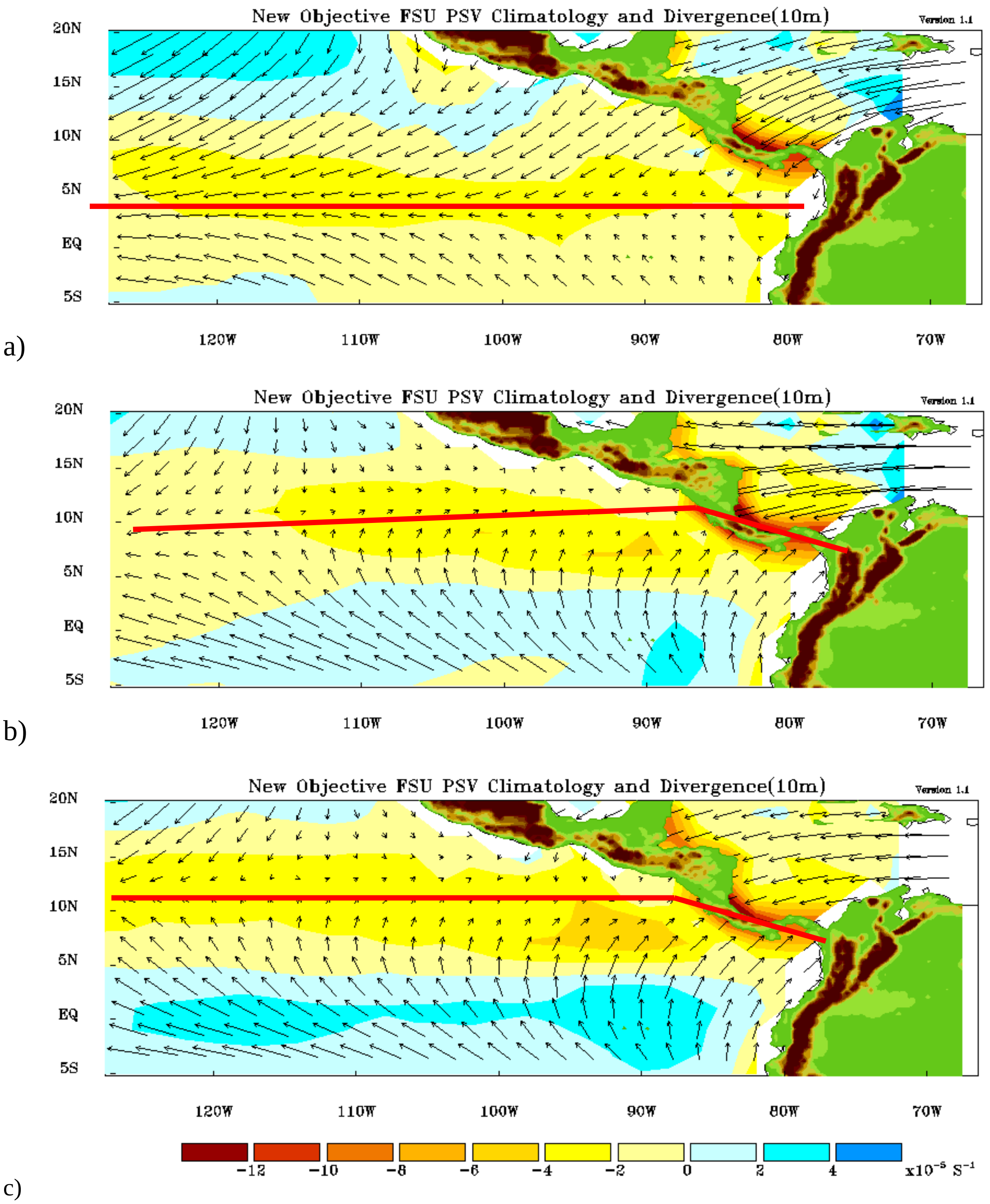


Fig. 2. New Objective FSU2 pseudostress and divergence (color contour) climatology for a) February, b) June and c) October. Red line represents average location of the ITCZ as determined by monthly mean 10 m wind convergence for the yearly range 1978 to 2004.

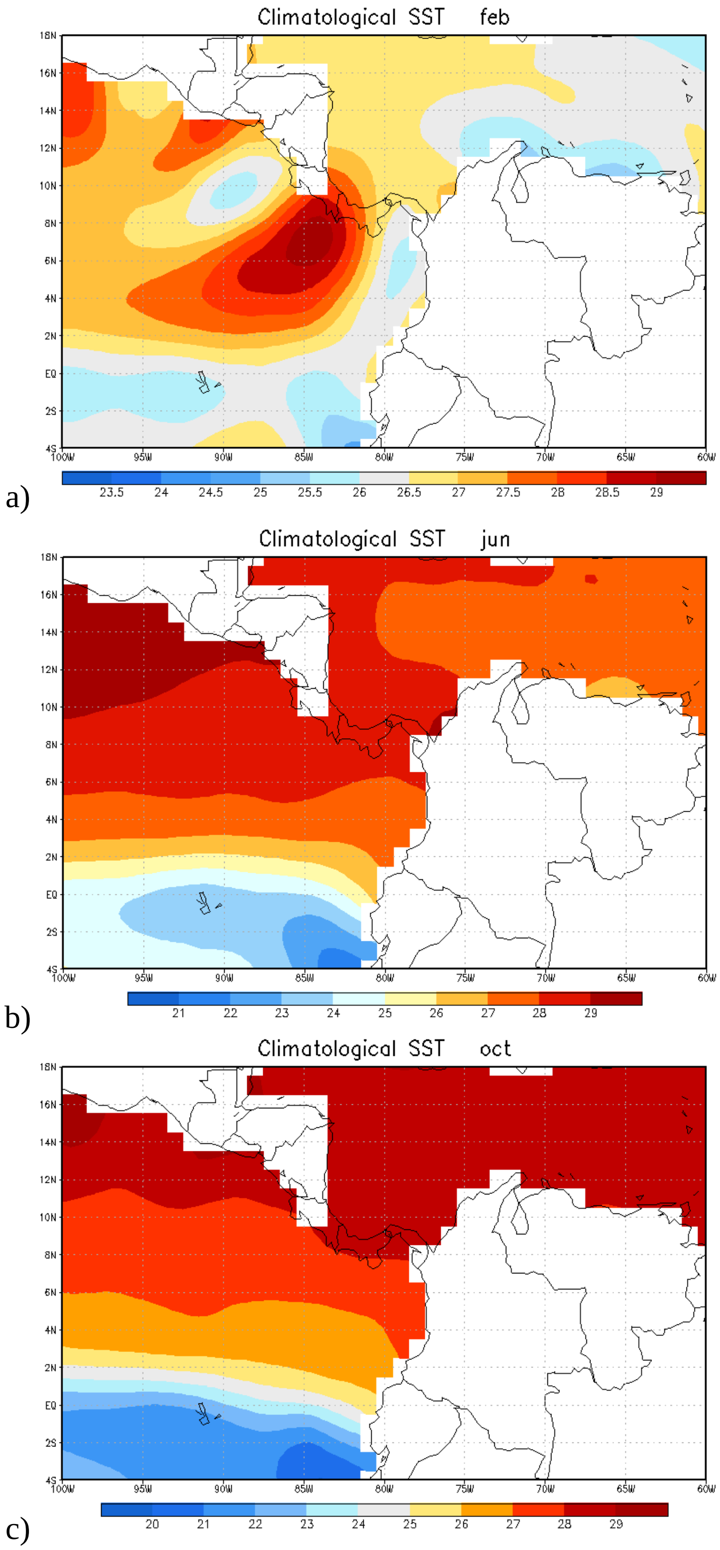
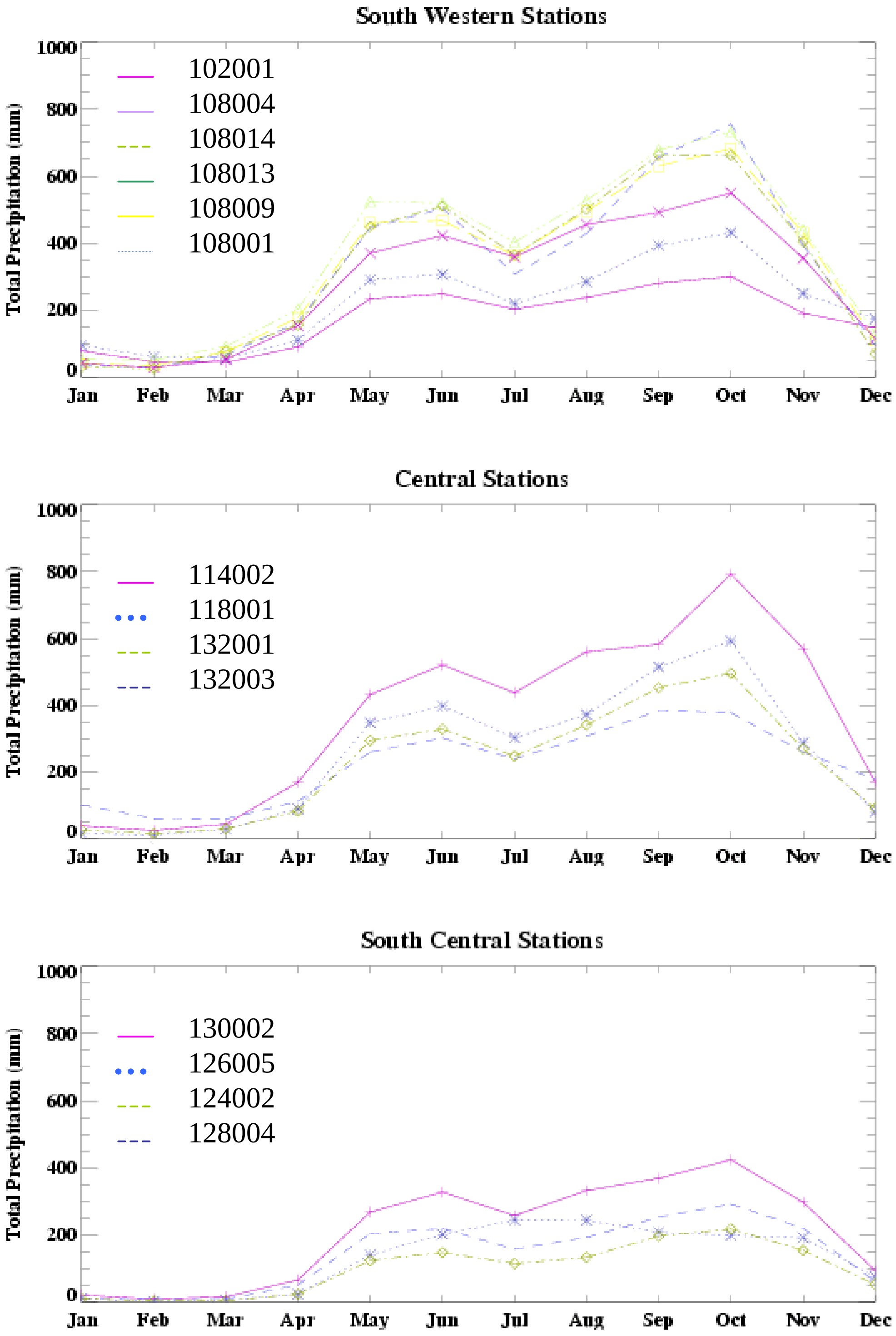


Fig. 3. Climatological Reynold's sea surface temperature from CDC (1984-2004) for a) February, b) June and c) October (Courtesy of NWS). Sea surface temperature gradient from the equator to Panama's Pacific coast is greatest during the month of October, which coincides with the strongest southwesterly winds of the year (Fig. 2c).

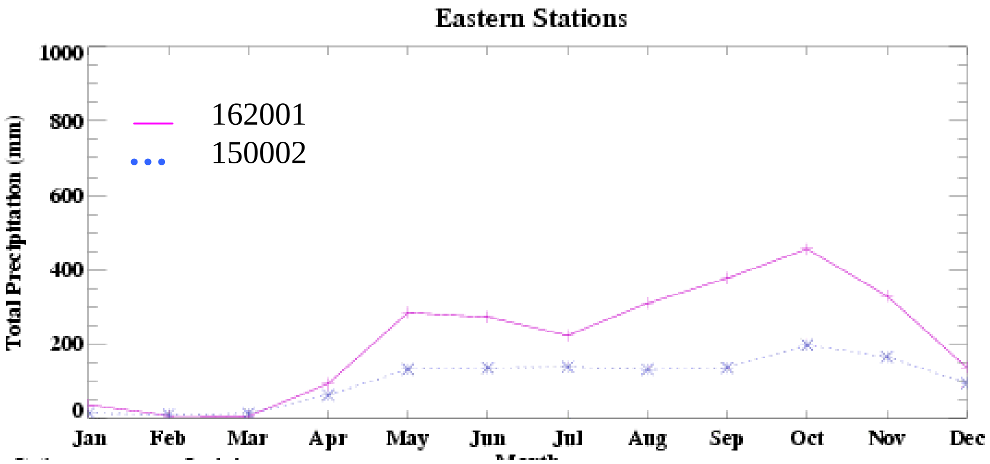


South Western Stations

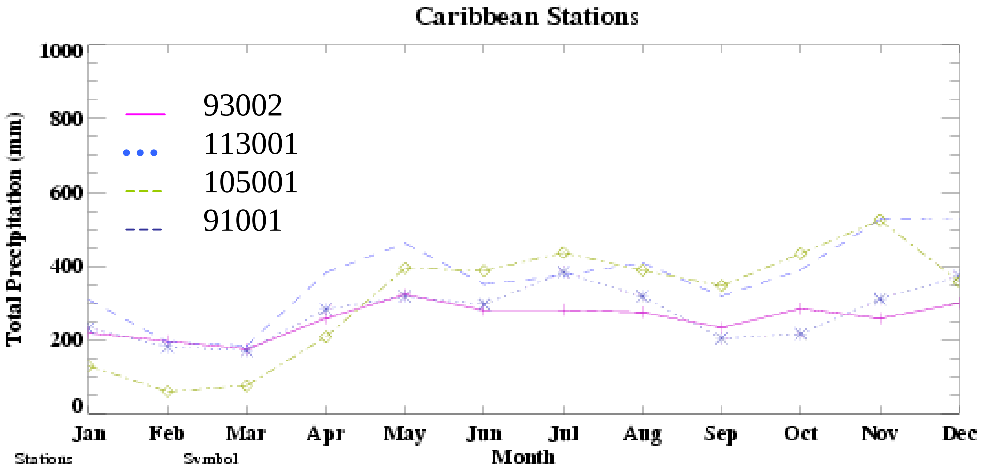
Central Stations

South Central Stations

Fig. 4. Monthly mean precipitation for stations in the: a) South West, b) Central, c) South Central.



d)



e)

Fig. 4. Continued, d) South East and e) Caribbean (North East and North West) regions.

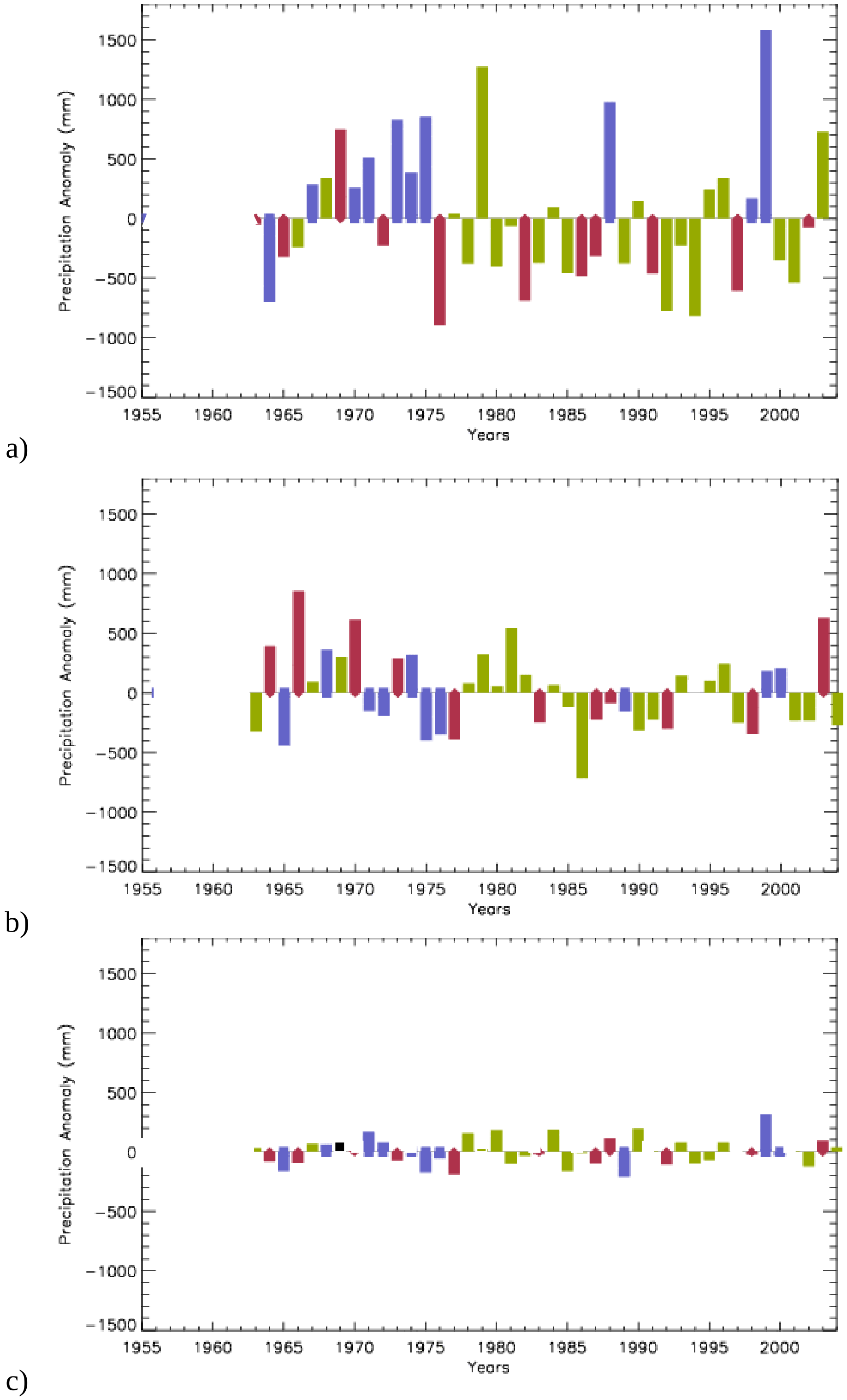


Fig. 5. Precipitation anomaly time series for the South West region: a) Late Wet (ASON), b) Early Wet (AMJJ) and c) Dry (DJFM) seasons. Blue squares represent cold ENSO years and red diamonds represent warm ENSO years in the time series. Anomalies' bars are color coded: blue-cold ENSO year, red-warm ENSO year and green-neutral ENSO year.

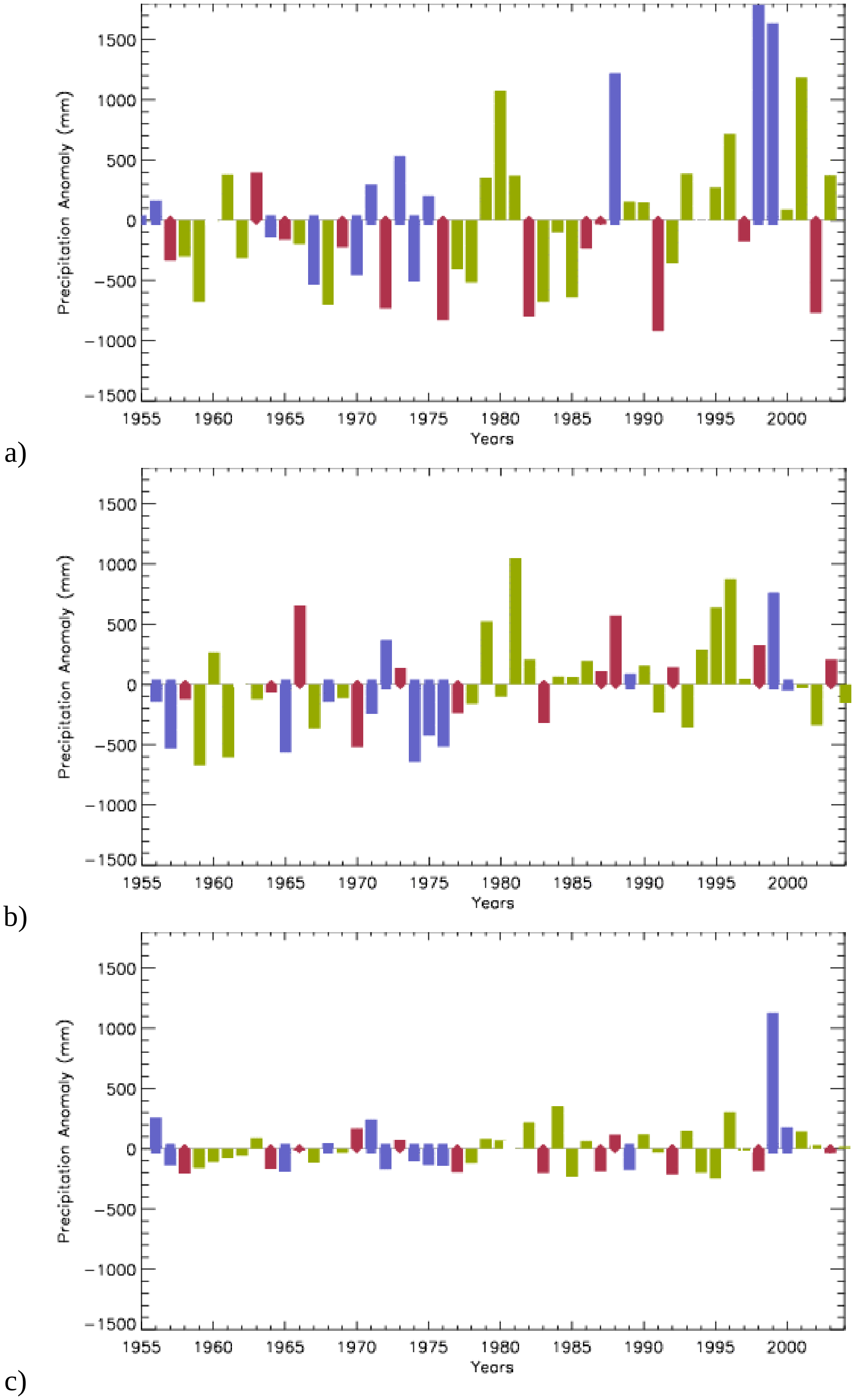


Fig. 6. Same as Fig. 5, but for the Central region: a) ASON, b) AMJJ and c) DJFM.

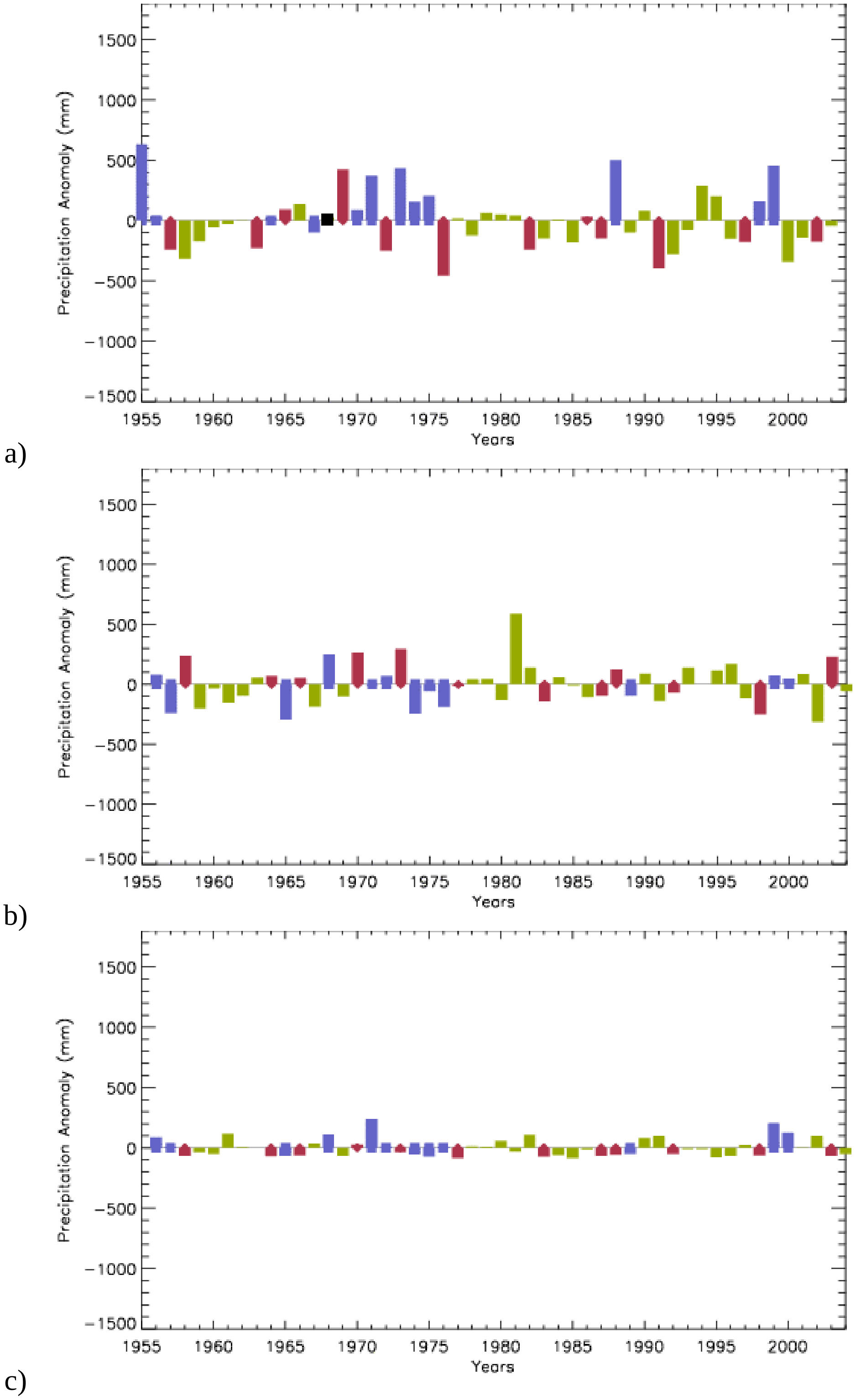


Fig. 7. Same as Fig. 5, but for the South Central region: a) ASON, b) AMJJ and c) DJFM.

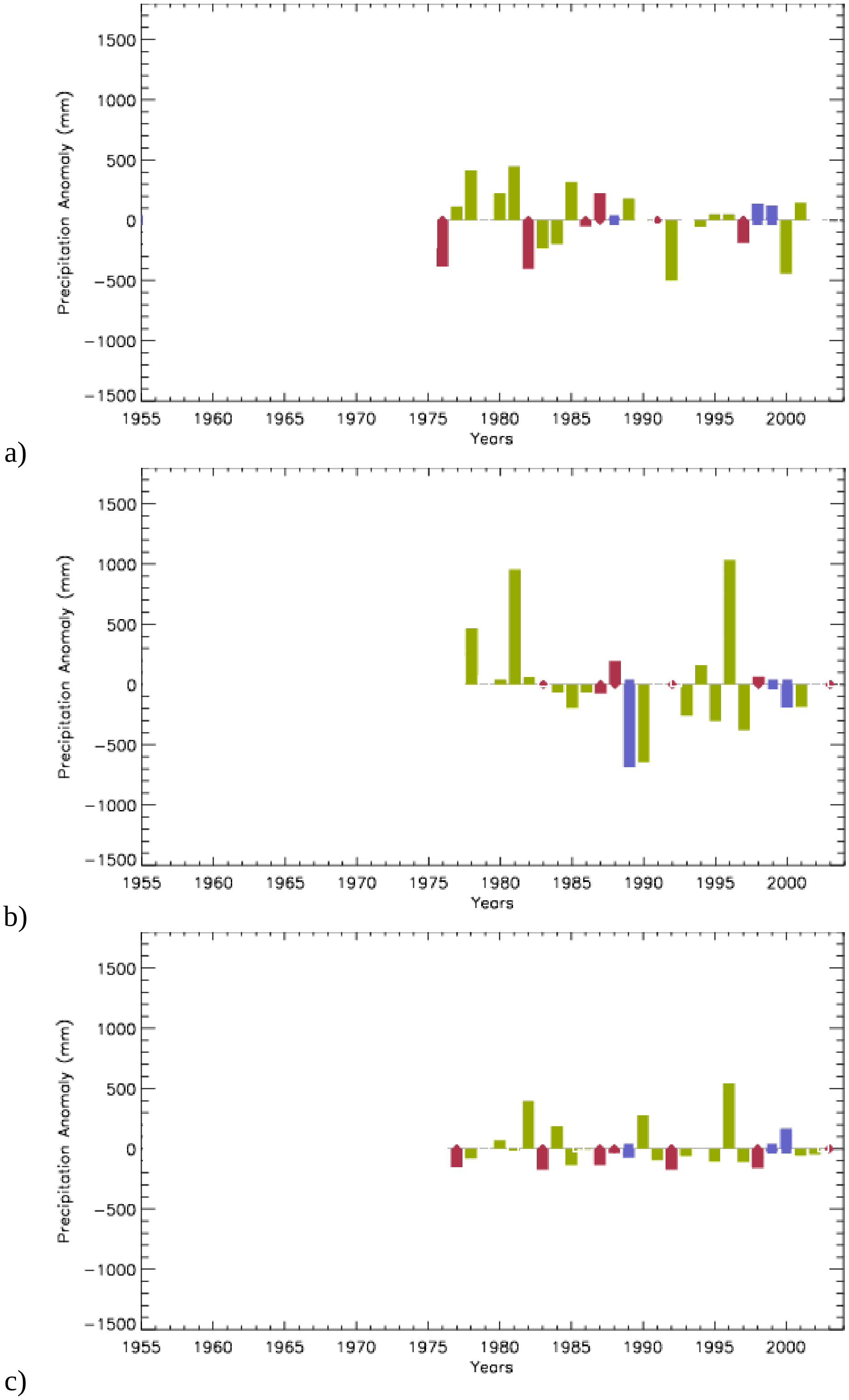


Fig. 8. Same as Fig. 5, but for the South East region: a) ASON, b) AMJJ and c) DJFM.

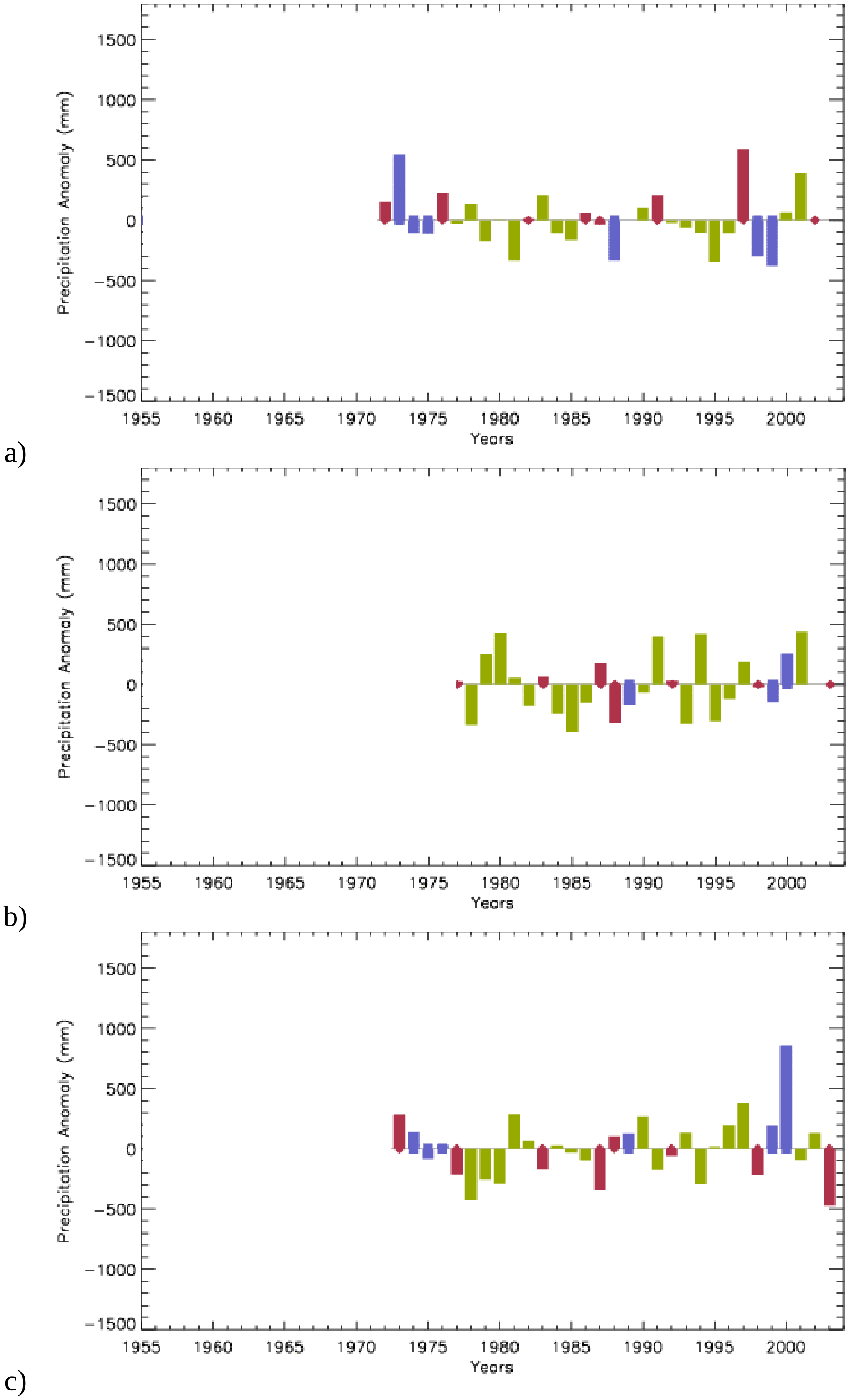


Fig. 9. Same as figure 5, but for the Caribbean region (North East and North West): a) ASON, b) AMJJ and c) DJFM.

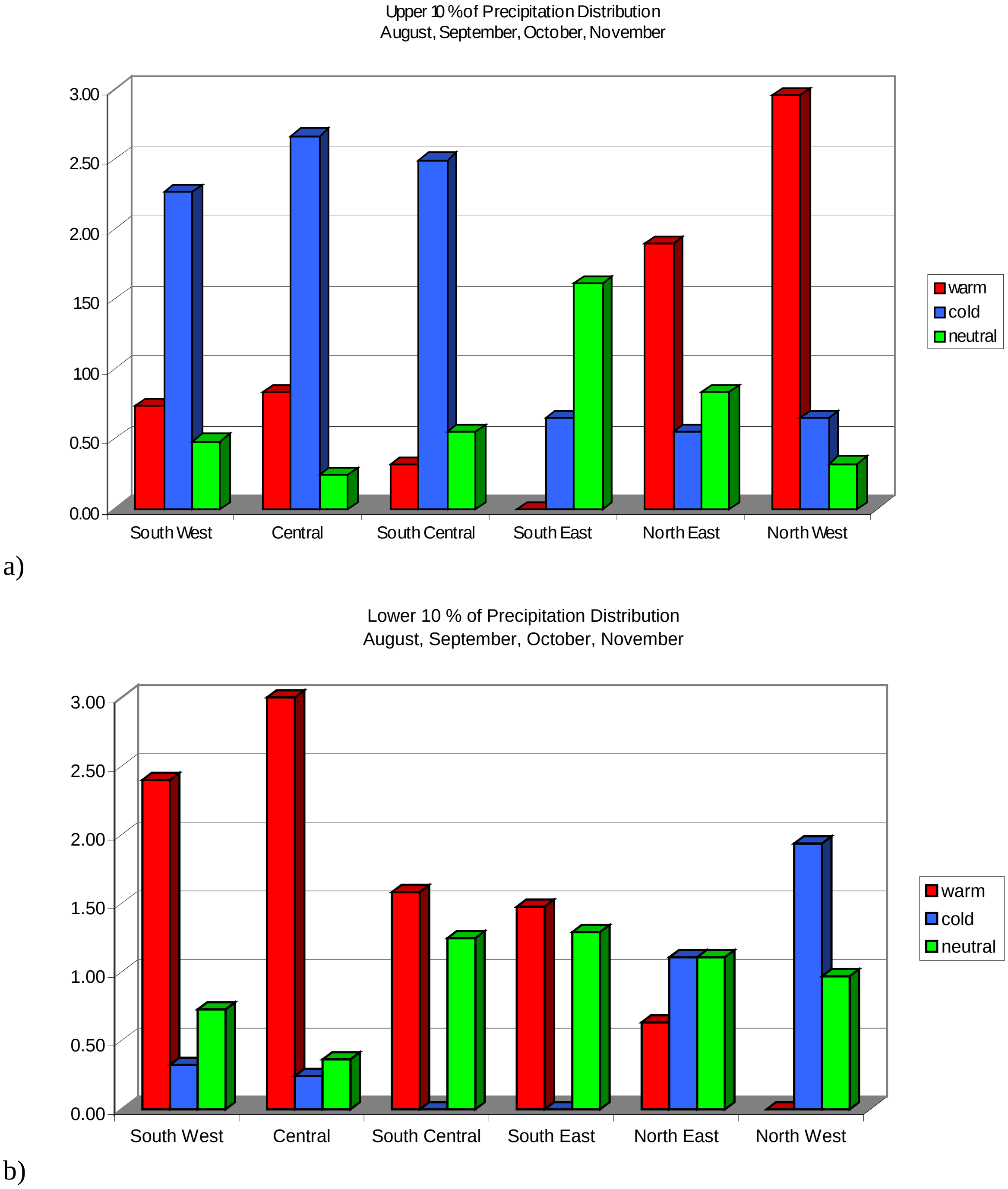
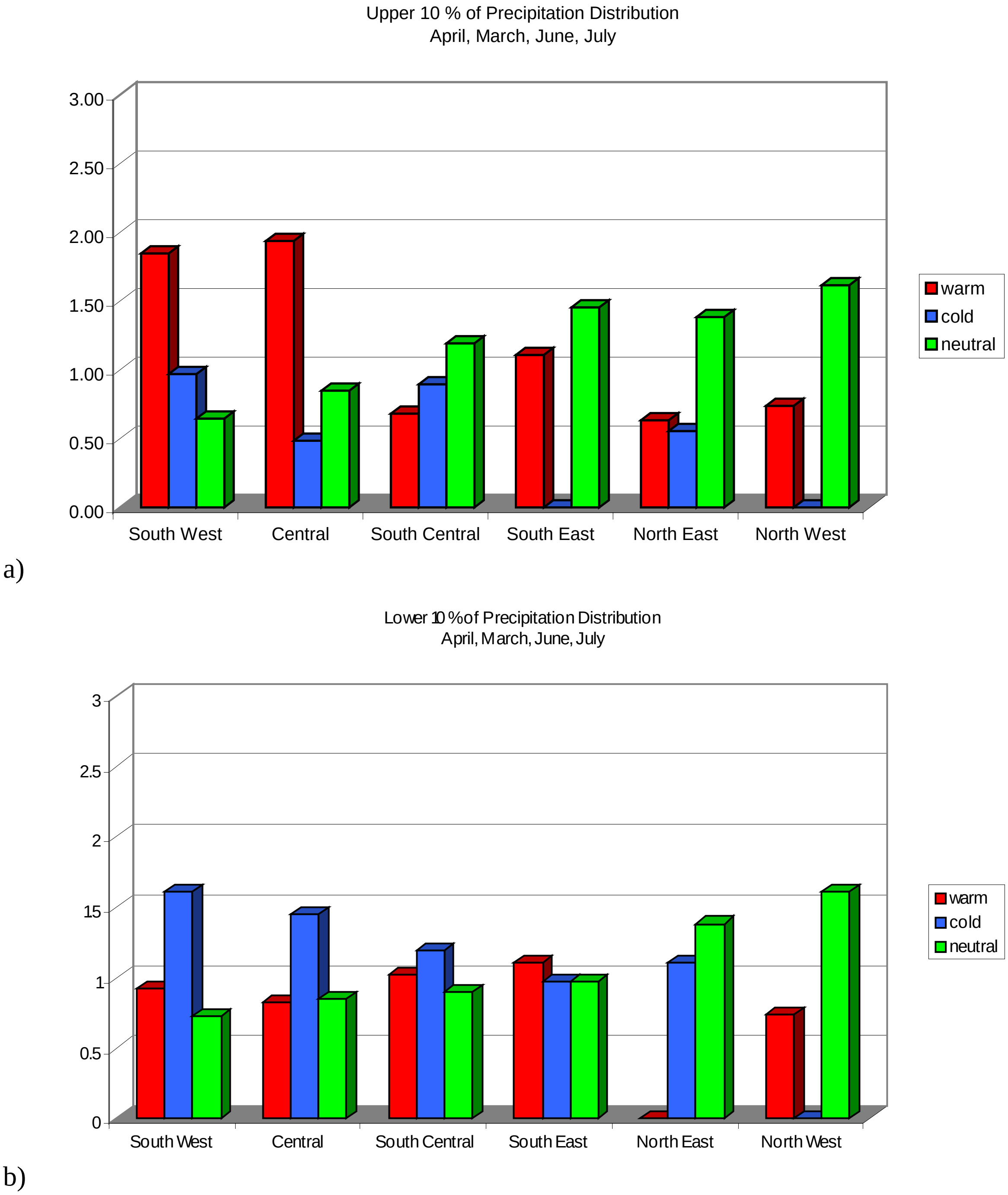


Fig. 10. Normalized Percentage of Occurrence histograms for the Late Wet Season (North West and North East represent the Caribbean region): a) Upper 10% of distribution and b) Lower 10 % of distribution. Values are the Percentage of Occurrence for a phase divided by the ENSO phase ratio of occurrences (cold 0.26, warm 0.22, and neutral 0.52).


Upper 10 % of Precipitation Distribution
April, March, June, July

Lower 10 % of Precipitation Distribution
April, March, June, July

Fig. 11. Same as Fig. 10, but for the Early Wet Season.

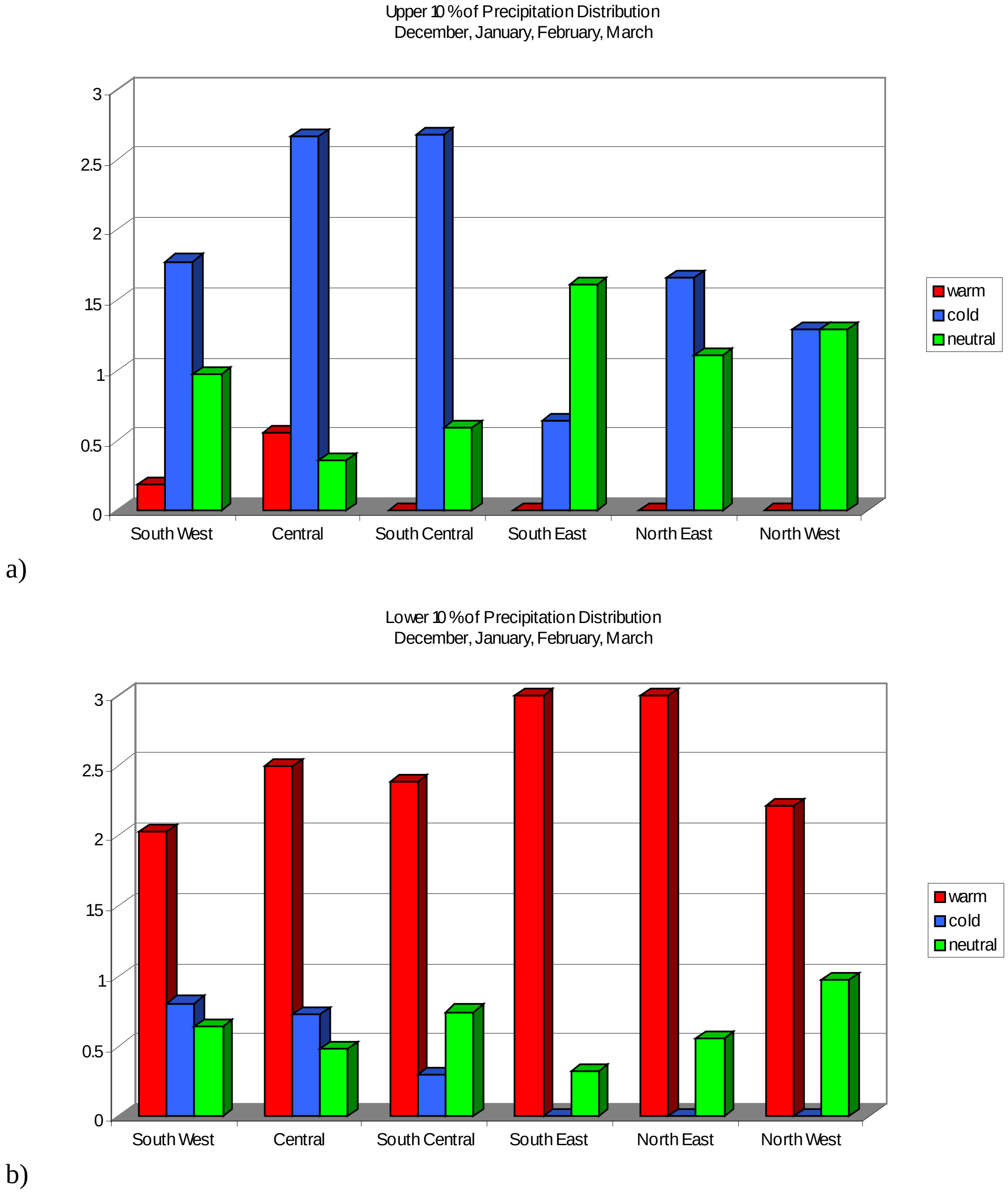


Fig. 12. Same as Fig. 10, but for the Dry Season.

Table 3. Kolmogorov-Smirnov test statistics results for the Late Wet season. D alpha represents the critical value. D statistic must be greater than D alpha in order to reject the null hypothesis. Cells painted in yellow have D values that reject the null hypothesis at 95% confidence level.

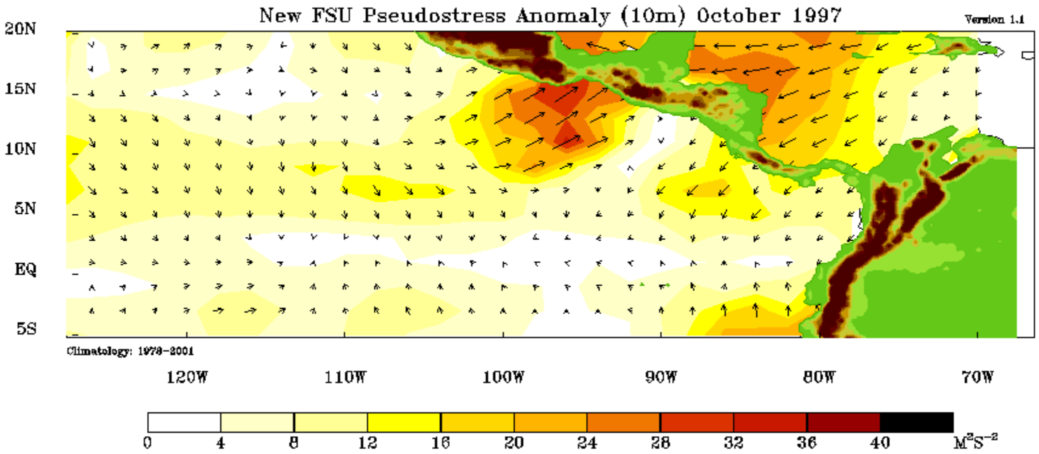
		Late Wet season					
		Cold - Warm		Neutral - Warm		Neutral - Cold	
		D alpha	D statistic	D alpha	D statistic	D alpha	D statistic
South West	108004	0.5455	0.8091	0.5105	0.3091	0.5267	0.6500
	102001	0.5455	0.5273	0.5105	0.2955	0.5267	0.4000
	108001	0.5455	0.6091	0.5105	0.1773	0.5267	0.5500
	108013	0.5455	0.8091	0.5153	0.4880	0.5313	0.4947
	108014	0.5455	0.5273	0.5105	0.3545	0.5267	0.4000
	108009	0.5455	0.7273	0.5105	0.5773	0.5267	0.5000
Central	114002	0.5455	0.5606	0.4808	0.4583	0.4952	0.2727
	118001	0.5455	0.6273	0.4921	0.4545	0.5089	0.5200
	132001	0.5455	0.5273	0.4921	0.3745	0.5089	0.4600
	132003	0.5455	0.6273	0.4921	0.4145	0.5089	0.5000
South Central	124002	0.6667	0.7778	0.5503	0.5731	0.5503	0.3099
	128004	0.6667	0.7500	0.4776	0.5067	0.4776	0.6300
	130002	0.6389	0.8750	0.5779	0.6528	0.5552	0.7778
	126005	0.6389	0.4028	0.5503	0.3567	0.5732	0.1908
South East	150002	1.0000	0.8000	0.7023	0.4667	0.8601	0.4000
	162001	n/a	0.5000	0.7023	0.3333	1.0238	0.6000
Caribbean*	113001	0.8333	0.6667	0.6511	0.3958	0.6511	0.3333
	105001	0.7000	0.3000	0.5151	0.2652	0.5151	0.2826
	93002	0.7143	0.8333	0.6163	0.5446	0.6511	0.4583
	91001	0.6389	0.3750	0.5552	0.3333	0.5779	0.3333

*** First two stations from North East region, others, North West**

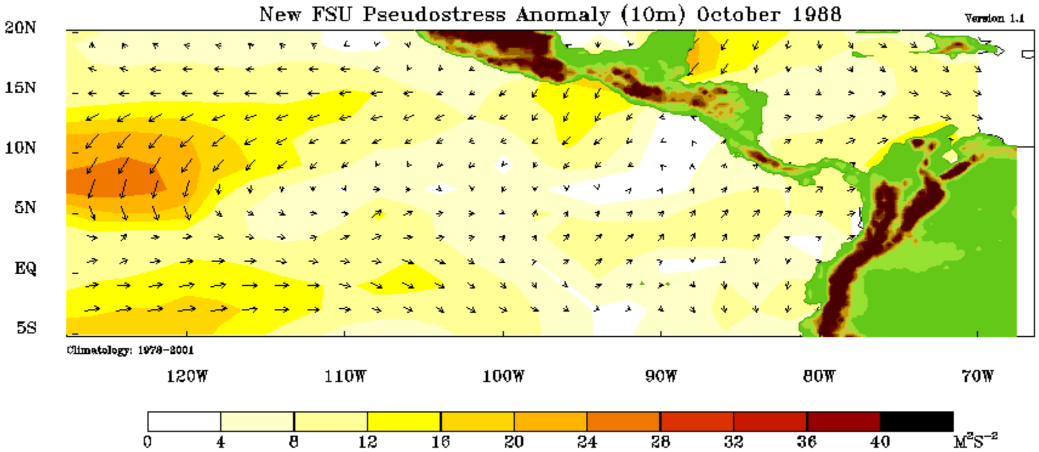
Table 4. Same as table 3, but for the Dry season.

		Dry Season					
		Cold – Warm		Neutral - Warm		Neutral - Cold	
		D alpha	D statistic	D alpha	D statistic	D alpha	D statistic
South West	108004	0.5455	0.2455	0.5062	0.4416	0.5225	0.2667
	102001	0.5455	0.6182	0.5062	0.6277	0.5225	0.3095
	108001	0.5455	0.5182	0.5105	0.5364	0.5267	0.2000
	108013	0.5455	0.3273	0.5105	0.3955	0.5267	0.2500
	108014	0.5455	0.4182	0.5105	0.5591	0.5267	0.2500
	108009	0.5455	0.4182	0.5105	0.5591	0.5267	0.2500
Central	114002	0.6667	0.3333	0.4776	0.4233	0.4776	0.3400
	118001	0.5455	0.2182	0.4921	0.2655	0.5089	0.3000
	132001	0.5455	0.6182	0.4921	0.4982	0.5089	0.2600
	132003	0.5455	0.3182	0.4921	0.3782	0.5089	0.3000
South Central	124002	0.6667	0.4444	0.5503	0.5731	0.5503	0.3392
	128004	0.6667	0.5833	0.4808	0.625	0.4808	0.25
	130002	0.6389	0.5417	0.5779	0.4861	0.5552	0.3333
	126005	0.6389	0.6670	0.5503	0.5614	0.5732	0.3158
South East	150002	1.0000	0.8333	0.6569	0.7667	0.8601	0.3333
	162001	n/a	1.0000	0.7603	0.9375	1.0200	0.5000
Caribbean	113001	0.8333	0.6667	0.6636	0.7619	0.6636	0.1429
	105001	0.5889	0.6778	0.5151	0.6391	0.5347	0.1787
	93002	0.7083	0.6250	0.5831	0.3382	0.6458	0.4118
	91001	0.6389	0.4444	0.5503	0.2339	0.5732	0.3816

*** 113001 and 105001 belong to North East region, other two, North West.**



a)



b)

Fig. 13. New FSU Pseudostress Anomaly (10m) for a) El Niño (warm ENSO) October 1997 and b) La Niña (cold ENSO) October 1988. Strong warm ENSO events show anomalous northeasterly flow and strong cold ENSO events show anomalous southwesterly flow during the Late Wet season.

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BIOGRAPHICAL SKETCH

Gloria Arrocha was born and raised in Panama City, Panama. She obtained her high school diploma from Colegio De La Salle, and then went on to obtain a B.S. in Meteorology from Florida State University. She hopes to use her education to improve public decision-making. Previous research looked at multiannual droughts in the Apalachicola-Flint-Chattahoochee river basin under the supervision of Dr. Paul Ruscher at FSU.