CENTER FOR OCEAN-ATMOSPHERIC PREDICTION STUDIES
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REGIONAL ANALYSIS OF CANADIAN, ALASKAN, AND MEXICAN PRECIPITATION AND TEMPERATURE FOR ENSO IMPACT

By
Phaedra M. Green

Technical Report
96 - 6
November 1996

COVER BY CARLOS J. MIRANDA V.

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Table of Contents

Page

Foreword iii

Abstract v

1. Introduction 1

2. Data 7

3. Methodology 11

4. Results Overview 17

4.1 Canada and Alaska Results 18

4.1.1 Geography 18

4.1.2 Temperature Means 24

4.1.3 Precipitation Means 34

4.1.4 Probability Density Functions 40

4.2 Mexico Results 50

4.2.1 Geography 50

4.2.2 Temperature Means 53

4.2.3 Precipitation Means 59

4.2.4 Probability Density Functions 63

5. Conclusions 74

Acknowledgment 81

References 82

Appendix 88

FOREWORD

This is a Master's Thesis prepared by Ms. Phaedra Green. A previous student, Mr. Matthew Sittel had analyzed over 600 stations in the Continental United States for shifts in precipitation and temperature for El Niño and El Viejo, or the warm and cold phases of ENSO. This work extends the analysis to Canada, Alaska and Mexico. It is unfortunate that only limited data are available from the other North American countries.

There are numerous applications for information on climate variability such as agriculture, fishing, forestry, energy, health, etc. Our main intent in these works is to identify regions and seasons where consistent ENSO impacts are seen in past data.

Again I will observe that the cold phase of ENSO is much more important for North America. It is still a wonder that most of the scientific community and the press ignores El Viejo. During the cold phase of ENSO, there are more tornadoes, hurricanes, droughts, floods, forest fires, and more disruption of fisheries, etc.

These data and the Continental United States data have been organized into 8 cartoons for North America and are available, by request, and can be accessed on www.coaps.fsu.edu under the title "The North American Climate Patterns Associated With El Niño-Southern Oscillation."

James J. O'Brien
Professor and Director
COAPS, Florida State University

ABSTRACT

The changes in seasonal average monthly temperature and precipitation associated with El Niño Southern Oscillation (ENSO) phases are assessed at 125 stations in Canada, Alaska, and Mexico. Forty years of monthly data are classified as occurring during either a warm phase (El Niño), cold phase (El Viejo or La Niña) or neutral phase of ENSO using sea surface temperature (SST) data from the equatorial Pacific Ocean.

Monthly mean temperature and monthly total precipitation are resampled to estimate population distributions for ten seasons in an ENSO year for each phase of ENSO. The differences in seasonal climate means are calculated between the cold (warm) phase and the neutral phase. An ENSO year is defined as the October after onset of the ENSO event through the following September.

The results for temperature indicate that Canada and Alaska tend to be cooler in the cold phase, and southern Canada tends to be warm during the warm phase. Mexico tends to be cooler in the warm phase and warmer in the cold phase.

The precipitation regime during these phases is complex and is dependent on region as well as season of the ENSO year. Eastern Canada generally has the warm phase wetter than the cold phase. Western Canada and Alaska are generally wetter in the cold phase. The coastal regions have a more complex regime. Mexico generally has a wetter warm phase year.

1. INTRODUCTION

Variations in climate and weather can significantly impact our daily lives in subtle and not so subtle ways. From the heating bills from an extremely cold winter, to rising food prices due to crop failure from drought, to emergency conditions such as flooding, heat waves, and forest fires, we are irrevocably linked to our ecosystem. Many of our valuable resources are wasted due to lack of preparation and repairing damage is often more expensive than early prevention. Effective planning requires study of regional analysis of climatic variability, such as the effects associated with El Niño Southern Oscillation (ENSO).

The phenomenon known as El Niño has been observed since at least the 1600's off the coast of Peru. At varying intervals, anomalously warm waters off the Peruvian coast appeared around Christmas and were dubbed El Niño, for the Christ child. The development of the El Niño phenomenon has its origins in the western tropical Pacific Ocean. Easterly trade winds relax and a westerly wind anomaly develops, exciting eastward propagating Kelvin waves along the equator. These waves suppress the thermocline, deepening the surface mixed layer. Warm sea surface temperature (SST) anomalies develop as a result, and spread eastward to the South American coast. Teleconnections, links

Oscillation (SO), the interannual pressure fluctuations between the Indian Ocean and the eastern tropical Pacific. Bjerknes (1966) first noticed that coherent sea surface temperature anomalies (such as the El Niño phenomena) accompanied SO extremes. Since then, parts of every continent, (Ropelewski and Halpert 1987, Kiladis and Diaz 1989), including Antarctica (Simmons and Jacka 1995), have been studied for connections to ENSO .

Early studies focused on El Niño, the warm phase of ENSO. However, recent studies (e.g. Ropelewski and Halpert 1996, Kiladis and Diaz 1989, Philander 1990) included investigation of the opposite phase of ENSO, i.e. the cold phase. Recent findings showed that the temperature and precipitation anomalies associated with the cold phase can be as or more significant than those associated with the warm phase (Sittel 1994).

Past investigations of North American temperature and precipitation anomalies associated with ENSO include the following studies. Shabbar and Khandelar (1996) investigated temperature anomalies associated with ENSO over Canada and found significant cold temperature anomalies in western Canada, consistent with the reverse PNA pattern. However, their studies spanned over a large grid, ignoring local variability due to topography, and ignoring Alaska. Yarnal and Diaz (1989) studied southeastern Alaska and coastal British Columbia in terms of temperature and precipitation. They found that precipitation anomalies could not be explained by the PNA and reverse PNA patterns as well as the temperature anomalies. Ropelewski and Halpert (1986) and Smith et al. (1996)

anomaly pattern extending throughout North America for both temperature and precipitation.

A developed set of historical monthly data (section 2) is utilized to estimate seasonal means associated with ENSO extremes. A description of the methodology appears in section 3. Results of anomalous temperature and precipitation are examined in section 4 and are finally synthesized and interpreted in section 5.

2. DATA

Monthly mean temperature and monthly precipitation totals for 84 Canadian, 14 Alaskan, and 27 Mexican stations (Figure 1, Table 1) are chosen from the Global Historical Climatology Network dataset (GHCN) (Vose et al. 1992). Data were subject to quality control and flagged by the GHCN for suspicious, revised, or largely discontinuous data.

The selected stations are poorly spaced due to the lack of development in the Canadian and Alaskan Arctic, and in the Mexican deserts and tropical lowlands (Figure 1). Most Canadian stations lie within 500 km of the United States. The most sparse regions in terms of station density are the Northwest Territories, Northern Quebec, and Labrador, due to continuous permafrost.

The time periods chosen are 1947-1986 for Canada/Alaska, and 1944-1983 for Mexico. These years are chosen in order to maximize the number of stations included in this study. For inclusion, each Canadian and Alaskan station must have less than 10% missing data. Of the 98 stations selected, 40 Canadian and Alaskan stations have no missing precipitation and temperature values and 48 have less than 5% missing. Mexican stations are selected if they have less than 15% missing precipitation and temperature records. The increase of missing data for Mexican

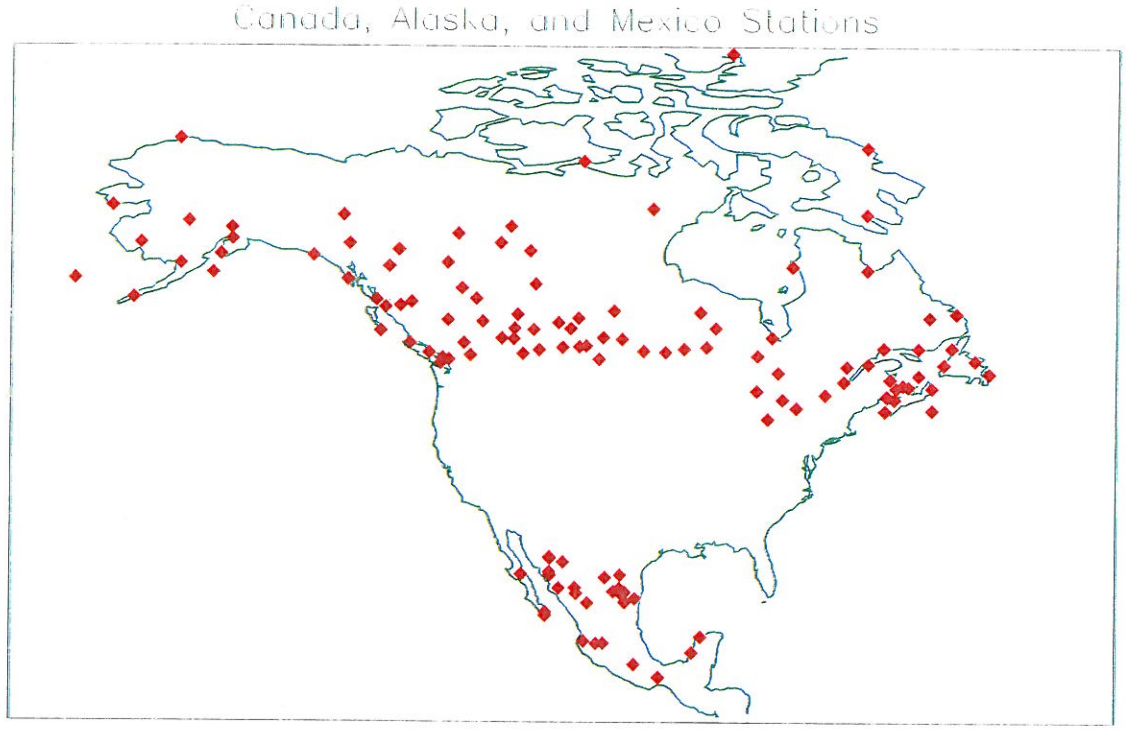


Figure 1: Station Density. Distribution of stations used in this study

Table 1: Latitude and longitude of stations used in this study (in appendix).

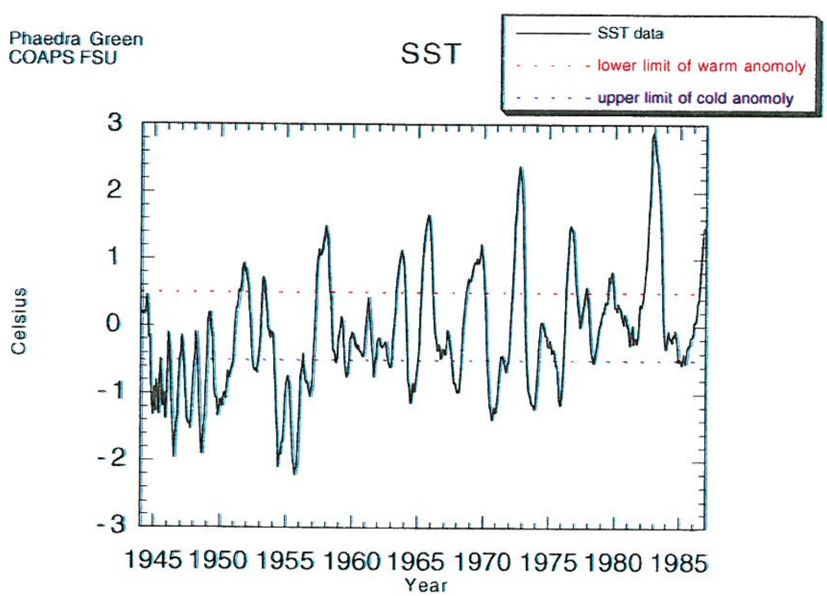


Figure 2: Mean monthly SST anomalies for the region 4°N to 4°S and 150°W to 90°W, these values are used in defining the JMA SST index. The threshold for extreme events is ±0.5°C.

The GHCN Canadian, Alaskan, and Mexican data are classified as occurring during one of the three phases of ENSO, the warm phase of ENSO (El Niño), the cold phase of ENSO (El Viejo or La Niña), or neither, the neutral phase, depending on the JMA index. A warm (cold) phase classification is defined as an ENSO year in which the five month running means of the JMA monthly SST anomalies are +0.5°C or warmer (-0.5° or colder) for at least six consecutive months, starting before the first month (October) of the ENSO year, and including October, November, and December. October, November and December are the months that typically correspond with the maximum amplitude in the SST anomalies. The classification for the cold phase was selected to be symmetric to the warm phase for simplicity since there is no agreed upon definition of the cold phase at this time. (Sittel 1994). The resulting warm phase years generally agree with other studies. The number of cold phase years is slightly larger than in other studies (e.g., Diaz and Kiladis 1992) which classify 1971, 1967, 1956, 1955, 1954, 1948 and 1947 as neutral years. In this study these years are cold phase years (Table 3).

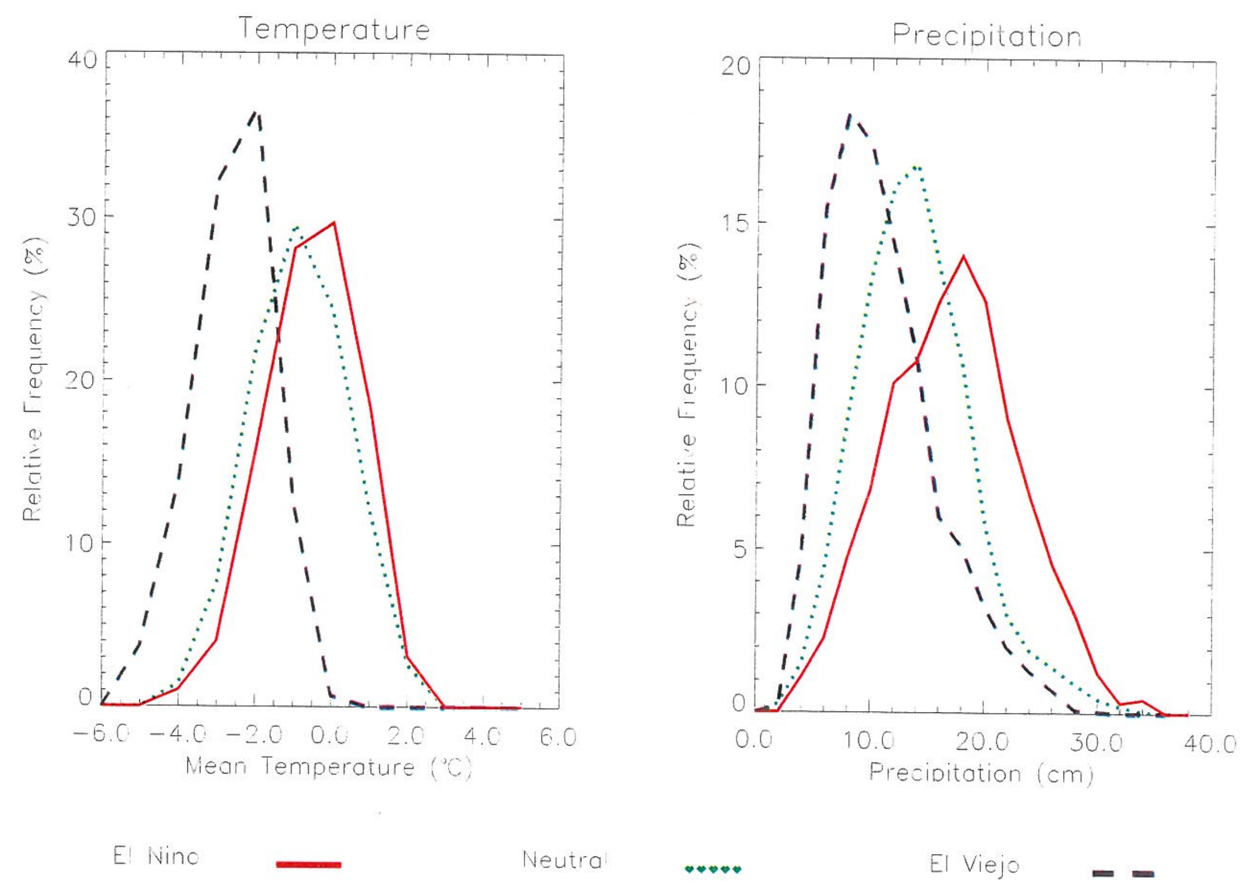
3. METHODOLOGY

The forty years of GHCN temperature and precipitation data are classified into appropriate ENSO categories: cold, neutral or warm phases, according to the JMA SST index. In each ENSO category, an average of all the Januaries is taken for a mean January value for that particular ENSO phase, as are the rest of the months. A three month running average is applied to the twelve averaged months to smooth out high frequency noise. The result is ten ENSO seasons as opposed to twelve, because of the overlap of the months. The ENSO year starts in October-November-December (OND) and ends in July-August-September (JAS)(Table 2) for the three ENSO categories. Deviations of the warm and cold phases from the neutral phase values indicate spatially variable results. Animations of these results, plus results from a similar study on the United States (Sittel 1994), are composed to show a comprehensive view of the deviations associated with the cold and warm phases for the entire North American continent.

Classification of the temperature and precipitation data into each ENSO category results in insufficient data to determine the underlying statistical distribution. For example, there are only nine climate values for each month in the warm phase category (Table 3). One problem that arises when inferences are made on such a small sample is that a Gaussian assumption cannot be made with respect to the central limit theorem. Therefore the resampling technique applied by Sittel (1994) and based on the Bootstrap method (Diaconis and Efron 1983) is implemented for generating a larger representation of the data set for robust statistical distributions. This method was successfully applied in previous studies (Sittel 1994, Richards and O'Brien 1994). In the Bootstrap method, each value of the climate data for each month is considered independent (Sittel 1994). Precipitation data are independent and temperature data are semi-independent, therefore the technique is accurate for precipitation data and only approximate for temperature (Sittel 1994).

The resampling technique was implemented as follows. Each climatic data value is sorted by month and ENSO category with respect to the JMA index. One seasonal composite sample is created by replacing each of the three months in a season by one value selected at random from a set of all values in that particular month for any year of a particular ENSO category. The mean of the three selected months are averaged, producing a seasonal average. For example, a seasonal composite for MAM in the cold phase could consist of March 1946, April 1976, and May 1971 climate values. Temperature and precipitation data for each station, ENSO month, and ENSO category are randomly sampled in this way 10,000 times for each season in the ENSO phase. Ten thousand samples were found to be a sufficient amount in earlier studies (Sittel 1994). The resulting 10,000 composites represent the distribution for that

Figure 3a. and 3b. Kodiak Alaska Histograms of bootstrapped data for the ENSO month of DJF



4. RESULTS

Due to the large number of stations analyzed, the results are discussed by country, region, and then sub-regions for each climate variable. Canada and Alaska are discussed together in section 4.1 and Mexico in section 4.2. Alaska and Canada are broken into ten subregions and Mexico, five subregions, to assess the effect of ENSO on the diverse climatic areas in these regions. The stations within each sub-region have results comparable to the selected stations chosen to represent the sub-region in the following discussion and graphics. Significant deviations of other stations' results from the selected stations' results are noted.

In the following sections, discussion of the cold (warm) phase refers to the deviation of the cold (warm) phase means from the neutral phase means. Probability density functions are presented at the end of each section to illustrate the separation of phases.

is aligned southwest to northeast, the maritime influence is "experienced" up to one thousand kilometers inland. The climate is typically dry, with a wetter climate to the south in the Aleutian Islands and Alaska Peninsula. The Kilbuck, Kuskokwim, and Kaiyuh Mountain ranges bisect the Bering Coastal region into north and south sections. The north region has more of a continental influence in the winter with the encroachment of sea ice.

The Alaskan-Yukon Interior stations range from the south coast of Alaska to the Brooks Range in the north to the Richardson mountains in Yukon and west to the 160°W longitude. The stations generally have a larger range of temperature than the Bering Coastal stations. The Alaska Range bisects the region, leaving the greater part of the Alaskan-Yukon Interior cut off from maritime influence. North and northeast of the Alaska Range the climate regime is continental; drier with a larger range of temperature. The climate south of the Alaska Range is milder and moister due to its proximity to the Gulf of Alaska. The precipitation on the southern Alaskan coast is not as abundant as that of the Pacific Northwestern region.

The Pacific Northwestern region ranges from the contiguous US border north to the Wrangel-St. Elias Mountains in the northern Alaskan panhandle and is confined by the Coastal Mountains to the east and the Pacific Ocean to the west. This narrow region is one of the wettest regions in the world: rainfall can exceed 200 cm per year. Temperature range is relatively small due to the region's proximity to the ocean.

Table 4 (cont.): Canada and Alaska stations by region

ALASKA-YUKON INTERIOR
Talkeetna, AK *
Anchorage, AK
Homer, AK
Kodiak, AK
Mayo, YT
Whitehorse, YT
Watson Lake, YT

BERING COAST
Nome, AK *
McGrath, AK
Bethel, AK
St. Paul, AK
Cold Bay, AK
King Salmon, AK

PACIFIC NORTHWEST
Annette Island, AK
Yakutat, AK
Sitka Magnetic Laboratory ,AK
Port Hardy, BC *
Cape St James, BC
Abbotsford, BC
Comox, BC
Victoria, BC
Vancouver, BC
Prince Rupert, BC

* indicates representative station for each region

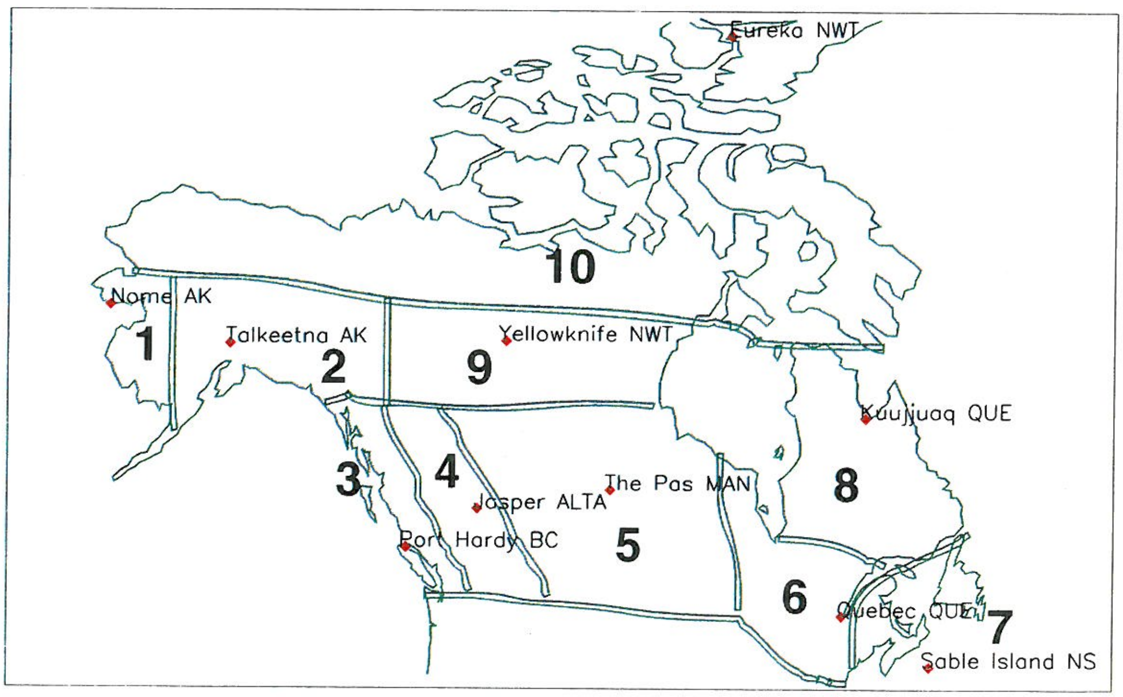


Figure 4: Representative stations for Canada and Alaska in their respective regions: 1 Bering Coastal, 2 Alaska-Yukon Interior, 3 Pacific Northwest , 4 Western Cordillera, 5 Interior, 6 Eastern Interior,7 Eastern Maritime, 8 Eastern Arctic, 9 Western Arctic, and 10 High Arctic.

The Western Cordillera region extends from the Coastal Mountains, encompassing the Selkiak Mountains, to the foothills of the eastern extent of the Rocky Mountains in Alberta. Stations are drier with distance east due to the orographic effect of the multiple mountain ranges on the Pacific maritime airmass traversing the Western Cordillera region. Precipitation increases with altitude on both the leeward and windward sides of the mountains in the Western Cordillera. Temperatures are generally cooler and the annual range smaller than that of the interior stations.

The Interior region encompasses western Alberta to central Ontario, from the US border to the NWT. This region is flat and dry, with a large range in annual temperature that is typical of interior continental climates. The region is comprised of two major areas of topographic significance. The high plains area in the western portion of the interior, which is often called the breadbasket of Canada, has rich soil suitable for farming. In the eastern area of the interior, the soil is poorly drained due to the highly resistant properties of the underlying rock.

The Eastern Interior region extends from central Ontario to Labrador and the St. Lawrence River and from the Great Lakes to central Quebec. The climate in this region is milder and less continental in nature than that of the Interior region. The annual precipitation is greater for eastern interior stations due to contributions from the Great Lakes, St. Lawrence River and Hudson Bay (in summer).

(in terms of station density) in my study. The stations in the High Arctic are grouped together for brevity; there are slight climatic differences between Barrow, AK and Iqualuit, NWT. Common to all stations are desert-like precipitation conditions in the winter months. The climatic regime is continental for most of the year due to sea ice extent. The region has a plethora of different topographic features, and permafrost is continuous, hampering plant growth.

4.1.2 Temperature anomalies

Canadian and Alaskan stations have cool anomalies in the cold phase, and have warm anomalies in the warm phase. Exceptions do occur. The time and location of the significant anomalies varies.

4.1.2a. Alaska-Yukon interior and Bering Coastal regions

All stations in the Alaska-Yukon region have a significantly cooler winter associated with the cold phase (Figure 5). During the peak seasons in Nome (JFM) and Talkeetna (DJF) winters are on average 3.1°C colder. All stations experience the coldest extreme in DJF except for the Bering coastal stations of Nome and Cold Bay (JFM), and St. Paul (FMA). The T-test results indicate all anomalies in these regions are significant for DJF, with the coastal stations' anomalies significant over six months out of the ENSO year in the cold phase (Figure 6a).

The anomalies during the warm phase in Alaska and the Yukon are significant less often than those of the cold phase. The Alaskan and Yukon interior stations have a slightly warmer than normal fall

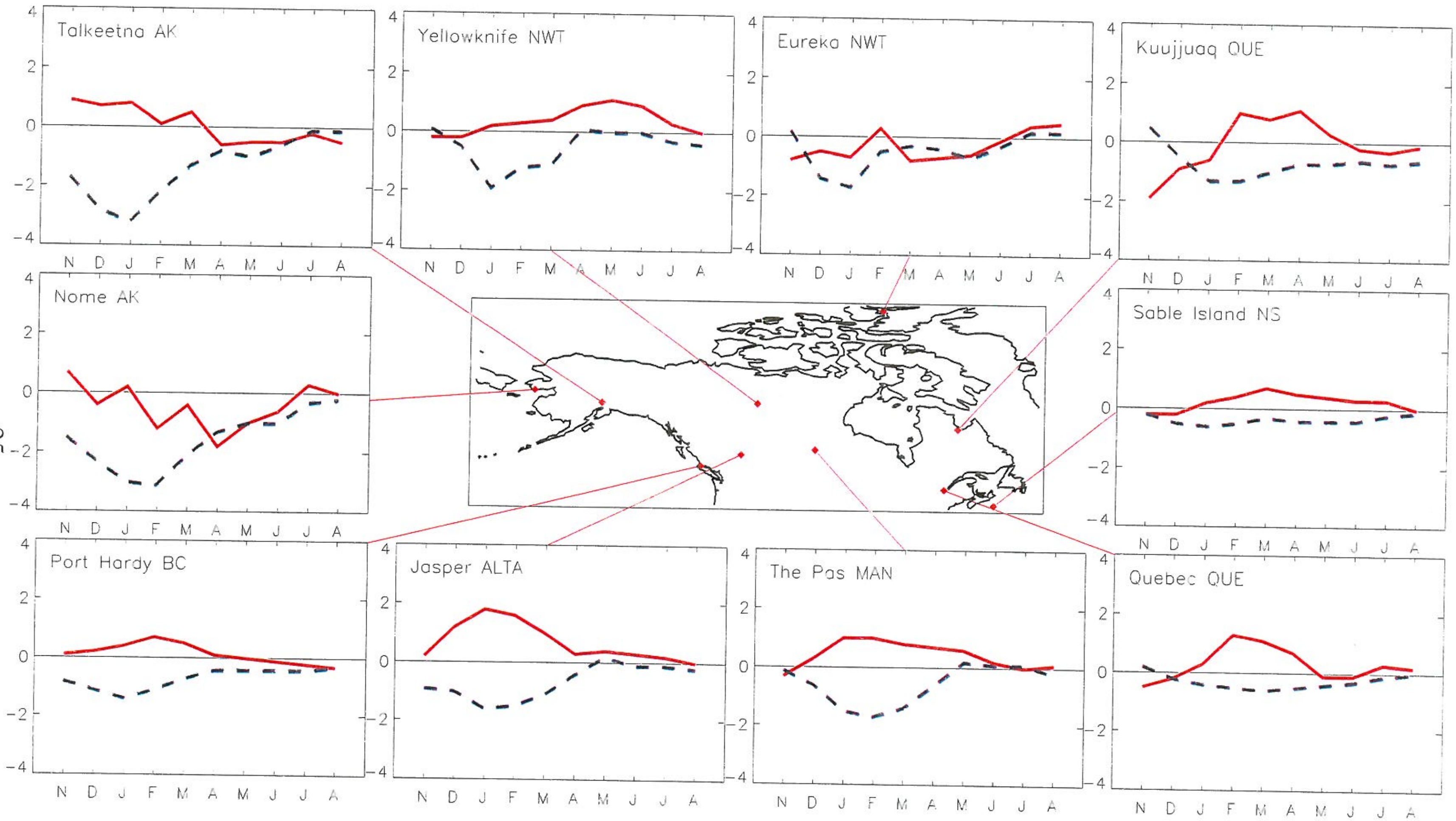


Figure 5: Departure from Neutral Mean in Degrees Celsius for Seasonal Mean Monthly Temperature at Canadian and Alaskan Stations.

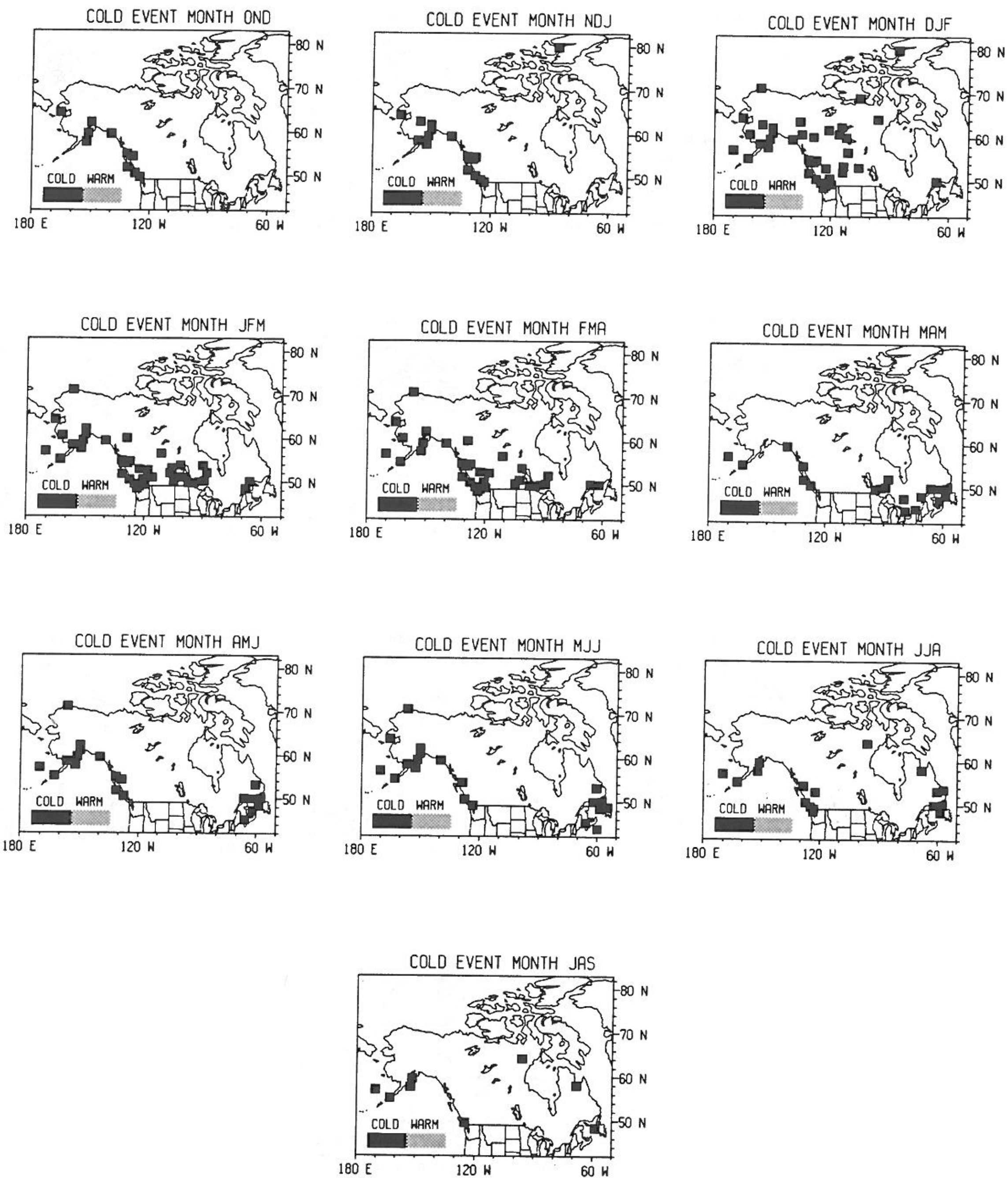


Figure 6.a: T-test results for Canada and Alaska during the cold phase.

and winter. The Bering coastal stations are slightly warmer in fall; however, they become colder than neutral until the following summer. Nome (Figure 5) has no significant temperature deviations. Talkeetna has a slight, but statistically insignificant, warming of 0.9°C during the warm phase winter. The results from the T-test find no significant warming during the warm phase in the Alaska-Yukon region; however, significantly cooler than normal temperatures are experienced in select coastal Gulf of Alaska and Bering Coastal stations in spring and summer (Figure 6b).

4.1.2b. Pacific northwest and Western Cordillera regions

British Columbia, the Alaskan Panhandle and western Alberta can be broken up into two regions: Pacific Northwest (windward of the Western Cordillera) and the Western Cordillera. The Pacific Northwestern coastal stations have a damped, i.e. lower amplitude, ENSO-related response when compared to the continental stations. The continental stations are dominated by dry, warm subsidence from downslope flow. Results from Port Hardy and Jasper (Figure 5) demonstrate this observation. All stations in these western regions are colder than normal winter during the cold phase, with the maximum impact in DJF. Jasper has a winter as cold as -1.7°C below neutral in DJF, and Port Hardy BC, as cold as -1.4°C below the neutral case in DJF. The T-test (Figure 6a) results show all the Pacific Northwest stations and Western Cordillera stations on the windward side of the continental divide to be significantly colder during the cold phase from fall (OND) to spring (MAM). The highlands

During the warm phase, the winters are anomalously cool; but not as cold as during a cold phase. The warm phase temperatures approach neutral values in spring for the southernmost stations and summer for the northernmost stations (e.g., Eureka; Figure 5). T-test results show no significant warming in warm phases in the High Arctic (Figure 6b), except for the interior High Arctic stations in late summer (JAS). Barrow is significantly cold from late winter (JFM) to summer (MJJ). Only Iqaluit is significantly colder in the fall (OND).

4.1.2d. Western Arctic region

The typical western Arctic pattern during the cold phase is large anomalies in the earlier months of the ENSO year: the coolest temperature anomaly in DJF for Yellowknife (Figure 5) is -1.9°C. The T-test results confirm the entire region is significantly colder in winter (DJF) (Figure 6a).

The warm phase temperature anomalies peak later in the year (AMJ) at 1°C. Summers are slightly warmer than usual during a warm phase. The warm phase temperature anomaly pattern shows a "sawtoothed" ENSO-related response similar to that of the northern Western Cordillera and Alaska-Yukon Interior regions' pattern. The T-tests (Figure 6b) show that only the interior stations of Hay River and Fort Simpson are significantly warm in early summer (MJJ).

cooler in early spring (MAM). Natashquan and Sept Iles, the northeastern-sector on the St. Lawrence River, are significantly cooler from winter through summer (Figure 6a).

In all Eastern Interior stations, the warm phase is anomalously cold in the fall (OND) of the ENSO year, and has peak warm anomalies at JFM. Quebec (Figure 5) shows the typical pattern of this region, with maximum temperature anomaly of 1.3°C. T-test results show a significant warm winter (JFM and FMA) only for Gore Bay and Quebec stations near the St. Lawrence River (Figure 6b).

4.1.2g. Eastern Maritime region

The Eastern Maritime region consists of the island portion of Newfoundland, Nova Scotia, New Brunswick, and Prince Edward Island. The cold phase's effects are damped and less significant throughout this area. The anomaly for Sable Island (Figure 5) is largest in DJF and MJJ; however, according to the T-test, only the cold anomaly in early summer is significant. The T-test results also show significantly colder spring and summer seasons for the west coast of Newfoundland and Iles de la Madeleine. In summer, southern Nova Scotia is significantly colder (Figure 6a).

The warm phase has a slightly warmer (but significant) winter. The peak anomalies occur in JFM for western stations, and they occur in FMA in the eastern stations. In northeastern Labrador, the ENSO effects are greater in terms of amplitude than for the southern maritime stations. Sable Island (Figure 5) has the smallest warm phase anomaly of 0.8°C in FMA. The T-test shows warm phase

4.1.3 Precipitation anomalies

Precipitation regimes during both phases of ENSO vary with region and season in Canada and Alaska. Generally the most pronounced changes in precipitation during ENSO phases are in the coastal regions.

4.1.3a. Alaska-Yukon Interior and Bering Coastal regions.

The warm phase in Alaska and Yukon has a slightly drier winter, a wet spring, and a dry summer. During the warm phase, Nome (Figure 7) and Bethel (north Bering coastal stations) have smaller precipitation anomalies in the winter and spring than the rest of the region. In the summer, warm phases are associated with a deficit of 15mm in Talkeetna (Figure 7), an Alaska-Yukon Interior station. The cold phase is associated with wetter winters and drier summers. Most of the Alaska-Yukon and Bering Coast stations resemble this pattern. The exceptions in the Alaska-Yukon Interior are the coastal stations of Homer and Kodiak, for which the precipitation pattern resembles that of the northern portion of the Pacific Northwest region (Figure 7a). The anomalies are wetter during winter in the warm phase and drier during winter in the cold phase.

4.1.3b. Pacific Northwest region

The Pacific Northwest region shows a gradual shift in anomalous precipitation winter regime from the north to the south. The northern coastal stations of British Columbia and the Alaskan panhandle, such as Annette Island (Figure 7a), show the warm phase

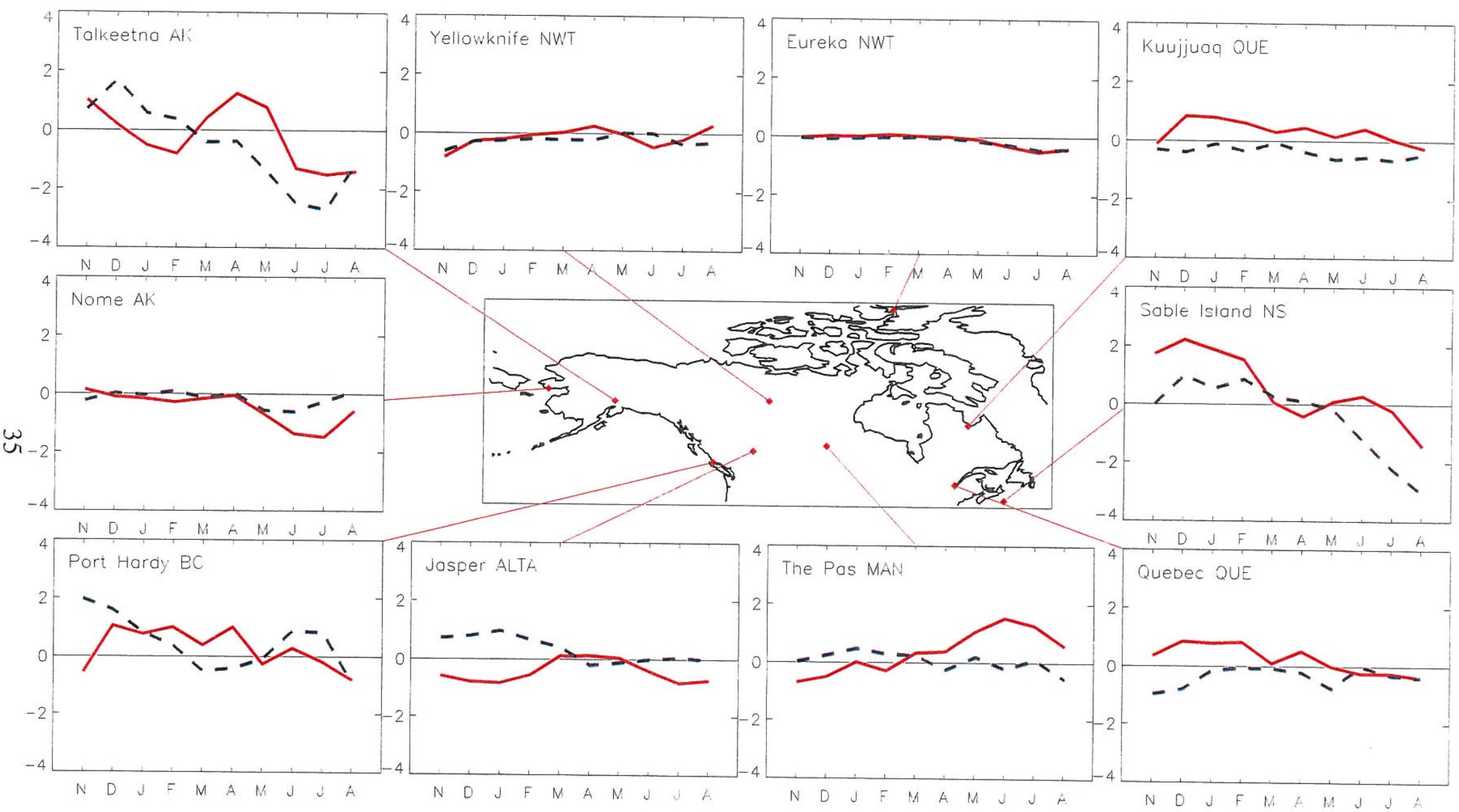


Figure 7: Departure from Neutral Mean in Centimeters for Seasonal Mean Monthly Precipitation at Canadian and Alaskan Stations.

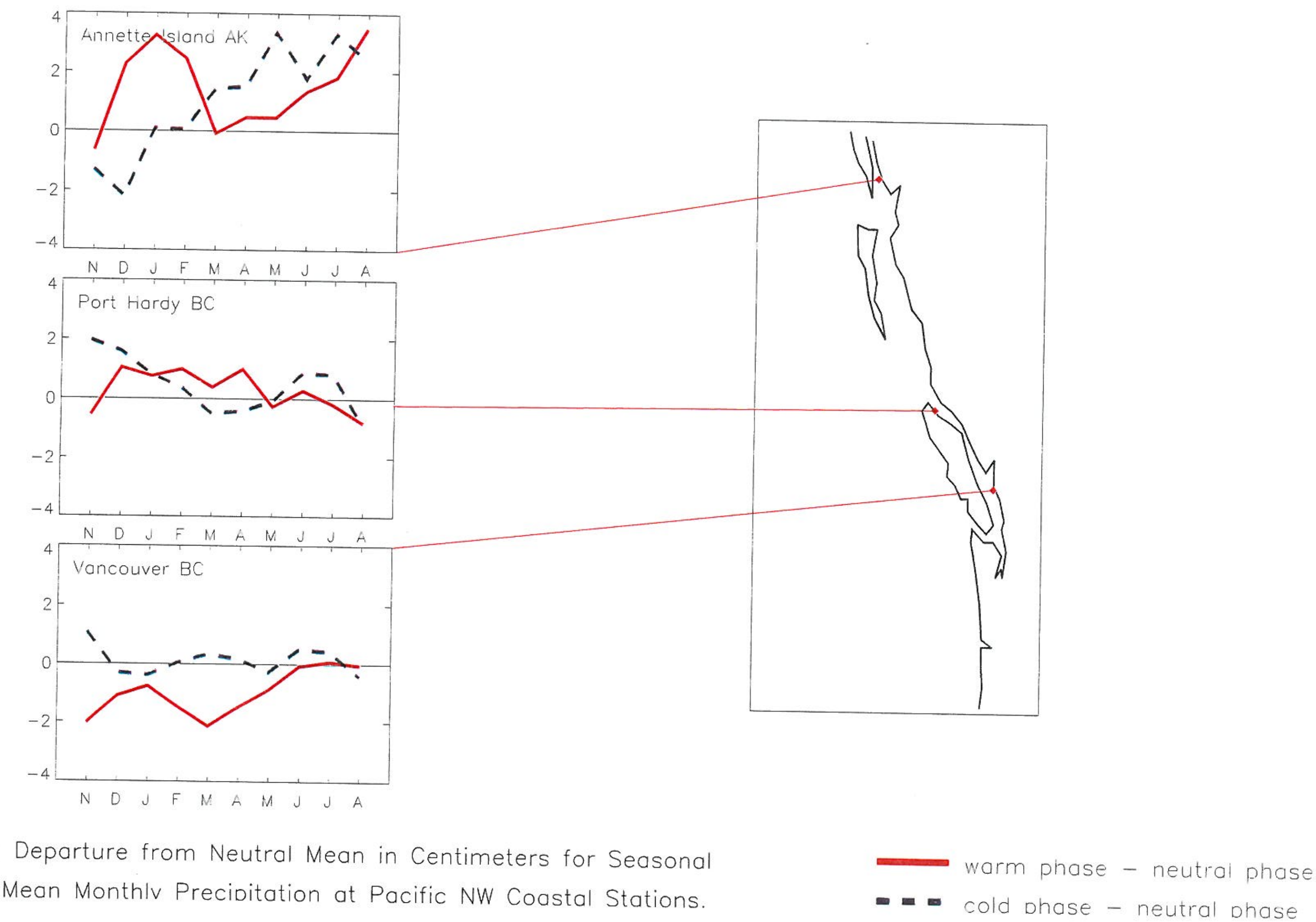


Figure 7a: Departure from Neutral Mean in Centimeters for Seasonal Mean Monthly Precipitation at Pacific NW Coastal Stations.

winters are anomalously wet and cold phase winters are slightly drier. Southern coastal stations of British Columbia, such as Vancouver (Figure 7a), have a similar pattern as the northwestern United States stations: anomalously wet winters in the cold phase, and anomalously dry winters in the warm phase.

Cold phases have a wet regime from fall to spring, and warm phases have a dry regime from fall to spring. Port Hardy (Figure 7a) is a transitional station between the northern and southern sections in this region, i.e. both warm and cold phases have a wet fall, the cold phase is slightly drier in the late winter. Both phases have smaller amplitudes at Port Hardy.

4.1.3c. Western Cordillera

The Western Cordillera region has slight differences between each phase in winter. In cold phase winters most stations are roughly 5mm per month wetter in winter except for four mountain stations which are 10-15mm per month wetter in winter: Banff, Jasper (Figure 7), Quesnel, and Smithers. Cold phase summers are slightly wetter or have little deviation from neutral phases. Only three stations are drier during the cold phase summer: Banff, Dease Lake, and Calgary (all mountain stations).

The precipitation regime during warm phases is slightly drier in winter, with anomalies within the range of 5mm per month below conditions in the neutral phases. Jasper and Banff range up to 10mm per month drier than neutral. Terrace, an inland valley station, is the

4.1.3f. Eastern Interior region

In the Eastern Interior region, the cold phase is associated with a wetter late winter and a slightly dry summer. The two exceptions are on the St. Lawrence River: Quebec (Figure 7) and Mont Joli, which have a drier winter as well as a drier summer in the cold phase. The cold phase appears to be more significant than the warm phase in terms of magnitude. The warm phase is associated with a drier winter in an area near the Great Lakes, and with a slightly wetter winter in the northern section of the East Interior region.

4.1.3g. Eastern Maritime region

The maritime region has characteristic dry summers during the ENSO cold phase and wet winters for the southern maritime stations. In the north the cold phase winter signal is neutral; becoming slightly drier than normal during the winter with increasing latitude.

Most interior Eastern Maritime stations experience dry summers during the warm phase. In contrast, it is wetter than normal in summers on the outer islands and Atlantic coast. Sable Island behaves as an interior Eastern Maritime station; it is dry in late summer. During warm phases only the coastal stations have a wetter winter (e.g., Sable Island at 10mm in NDJ, Figure 7).

4.1.3h. Eastern Arctic region

The Eastern Arctic stations have a damped (i.e. low amplitude) version of the ENSO pattern from the Eastern Interior. The warm

In winter (DJF), the cold phase has a cooler winter in most of Canada. The exceptions are the Eastern Maritime and Eastern Interior regions. The warm phases are significantly warmer only in southern Canada (Figure 8b).

In winter (DJF), eastern Canada is more likely to be slightly drier during the cold phase and slightly wetter during the warm phase. In the interior west, the cold phase is likely to be wetter, and warm phases are usually drier. Alaska, the High Arctic, and coastal Canada shows little difference between the phases (Figure 9b).

The spring (MAM) probability density functions show little change in the High Arctic and significant cold anomalies in the western and eastern continental Canada during the cold phase. The southern Arctic and eastern Canada are warmer during the warm phase and Alaska is cooler during the warm phase (Figure 8c).

During cold phase spring (MAM) it is more likely to be drier in interior Alaska, the Eastern Arctic, and the Western Cordillera (Figure 9c). In these same regions, the warm phase spring is wetter.

By summer (JJA) only the maritime region shows a significant difference in temperature between the warm and neutral phase. The cold phase signal has little significance (Figure 8d). Summer (JJA) precipitation histograms show a drier regime in the maritime, Eastern Arctic, High Arctic and Alaskan interior during the cold phase. Alaska and western Canada are dry during the warm phase (Figure 9d).

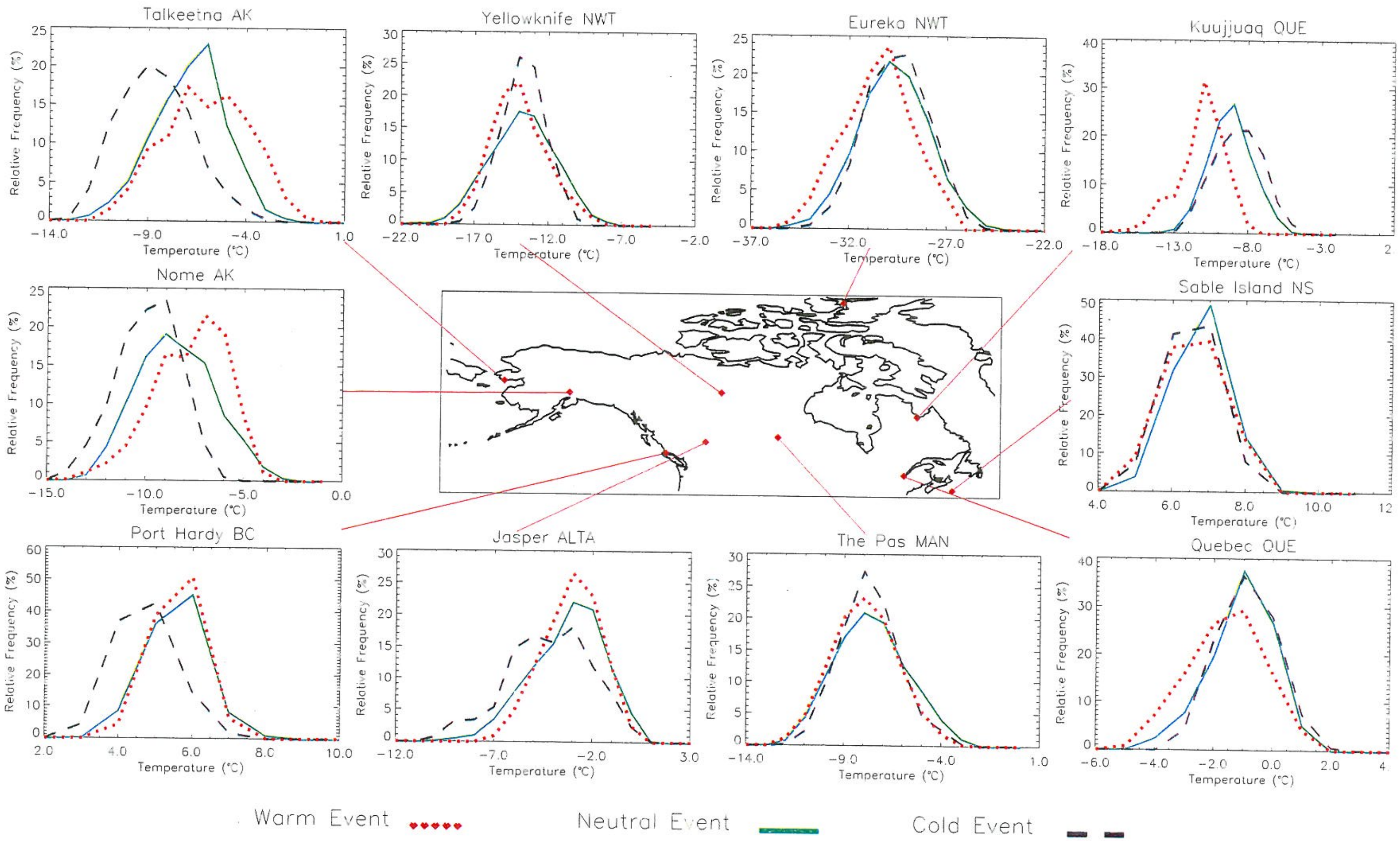


Figure 8a. Canada and Alaska Temperature Probability Density Functions for ENSO month OND

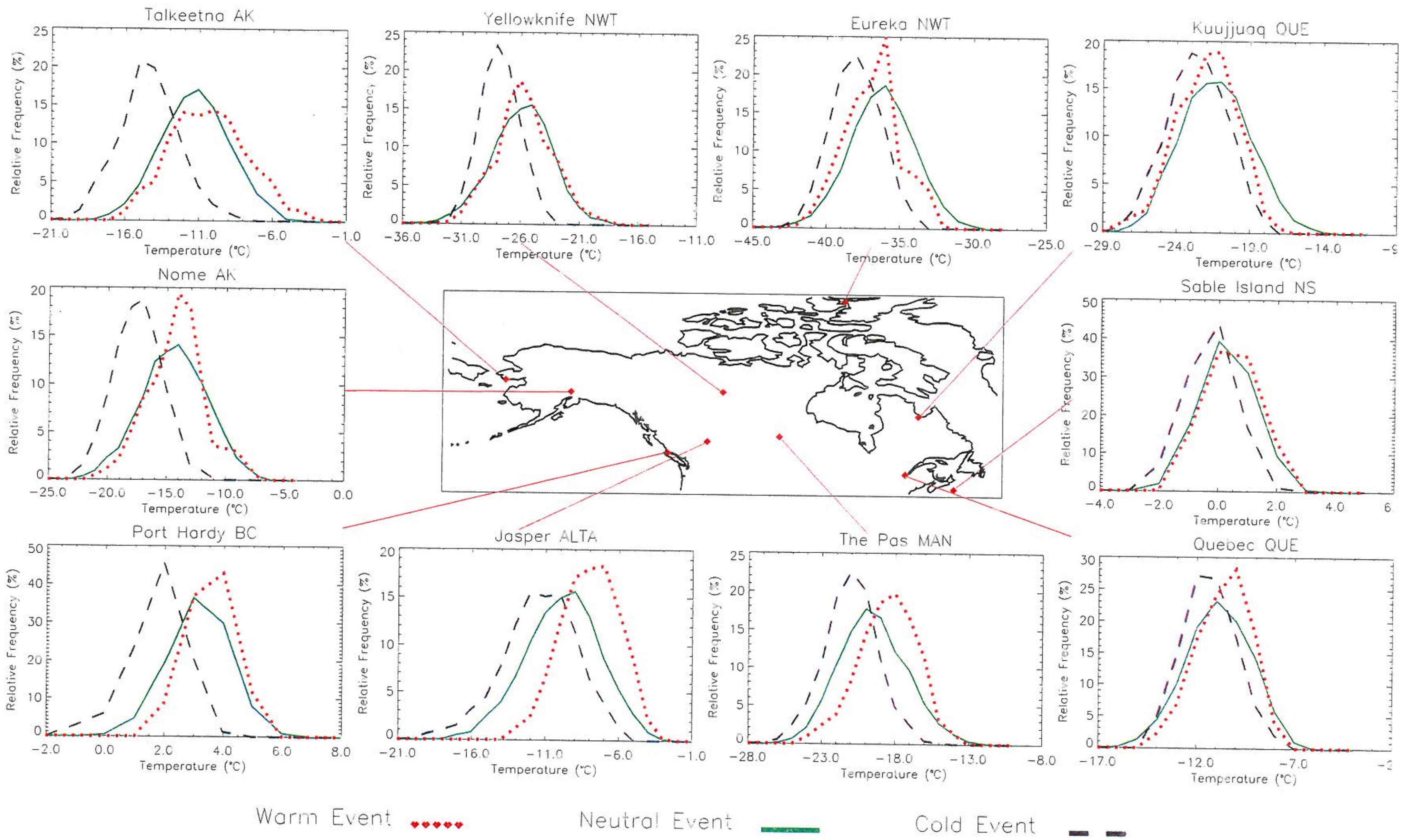


Figure 8b. Canada and Alaska Temperature Probability Density Functions for ENSO month DJF

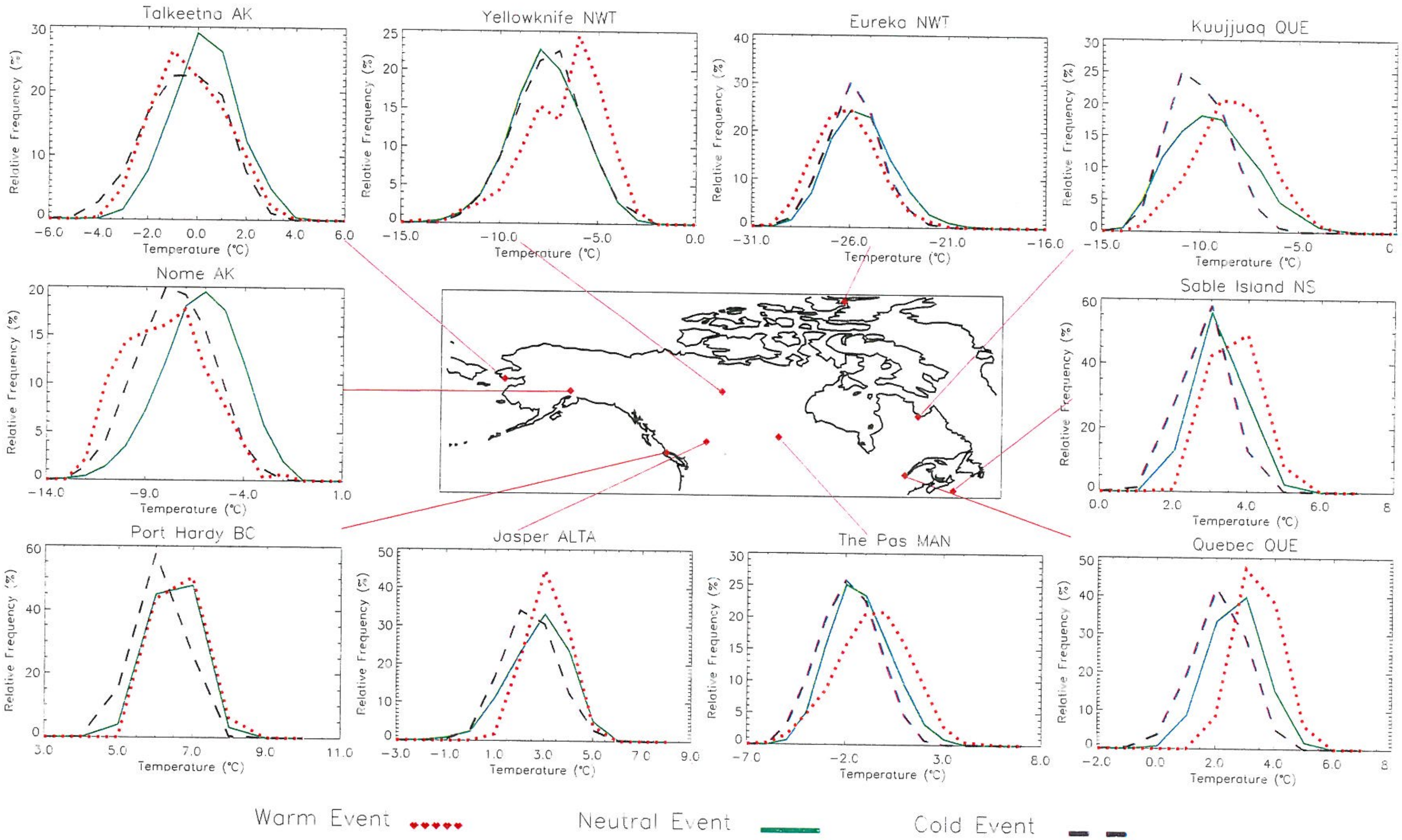


Figure 8c. Canada and Alaska Temperature Probability Density Functions for ENSO month MAM

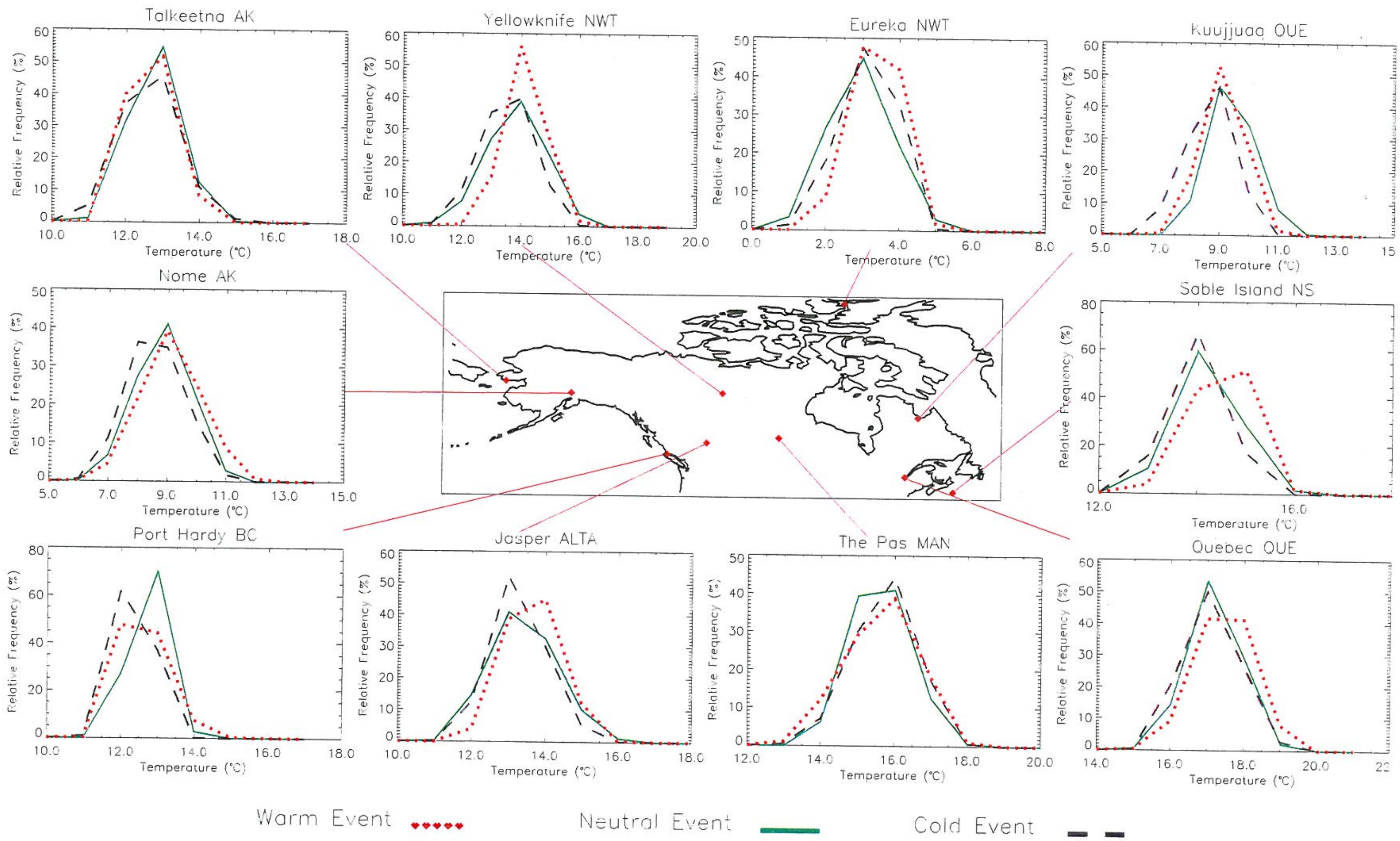


Figure 8d. Canada and Alaska Temperature Probability Density Functions for ENSO month JJA

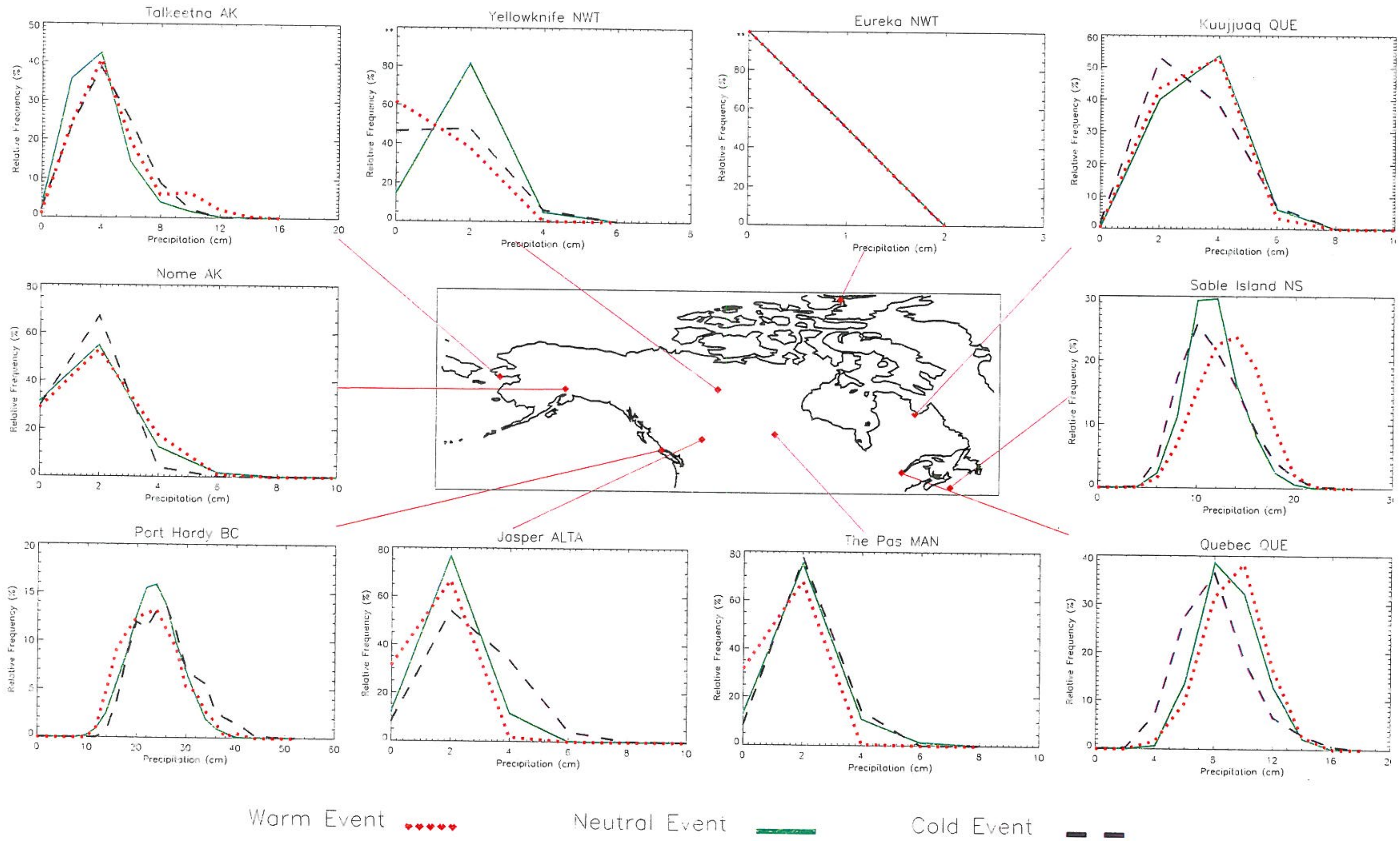


Figure 9a. Canada and Alaska Precipitation Probability Density Functions for ENSO Month OND

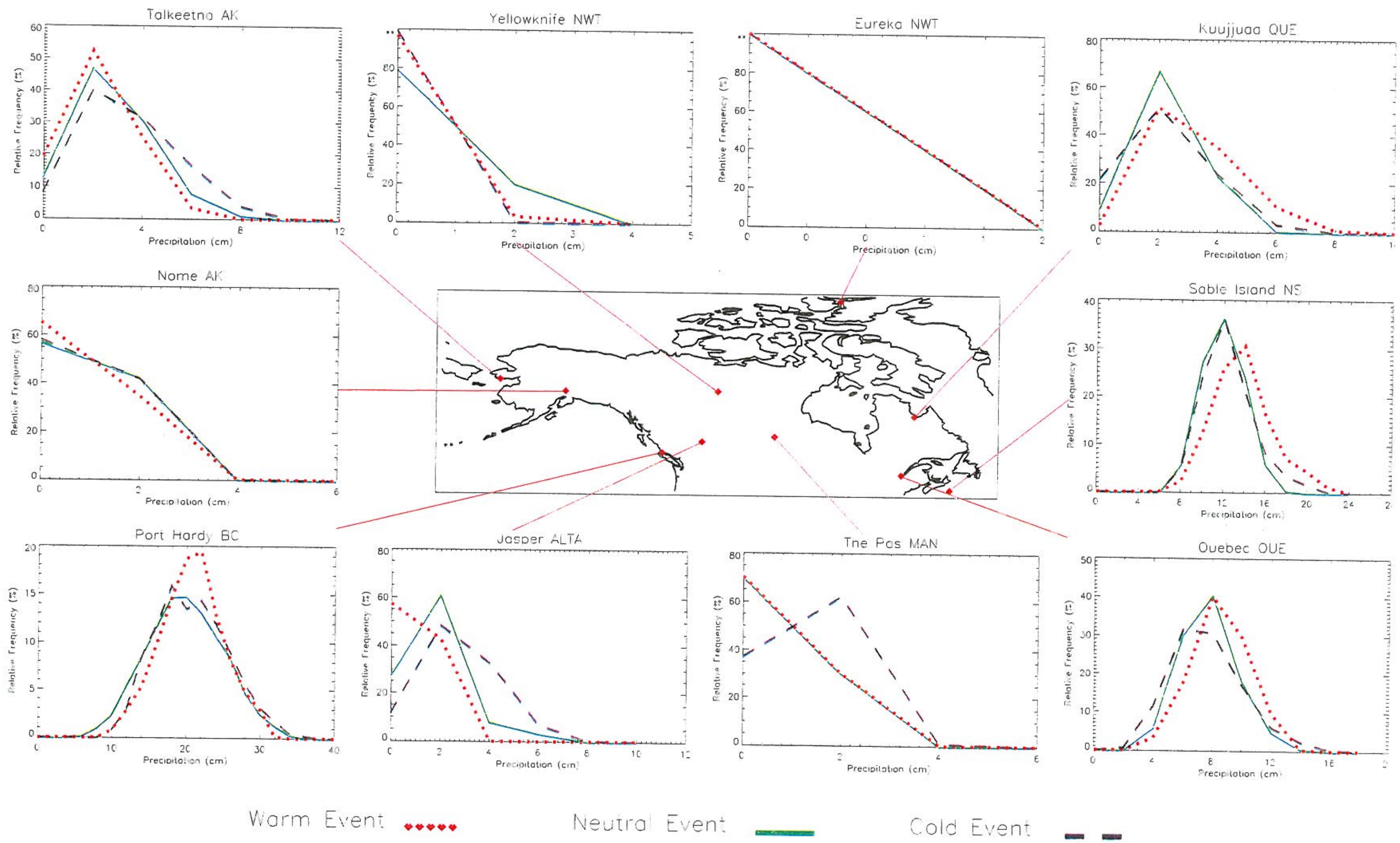


Figure 9b. Canada and Alaska Precipitation Probability Density Functions for ENSO Month DJF

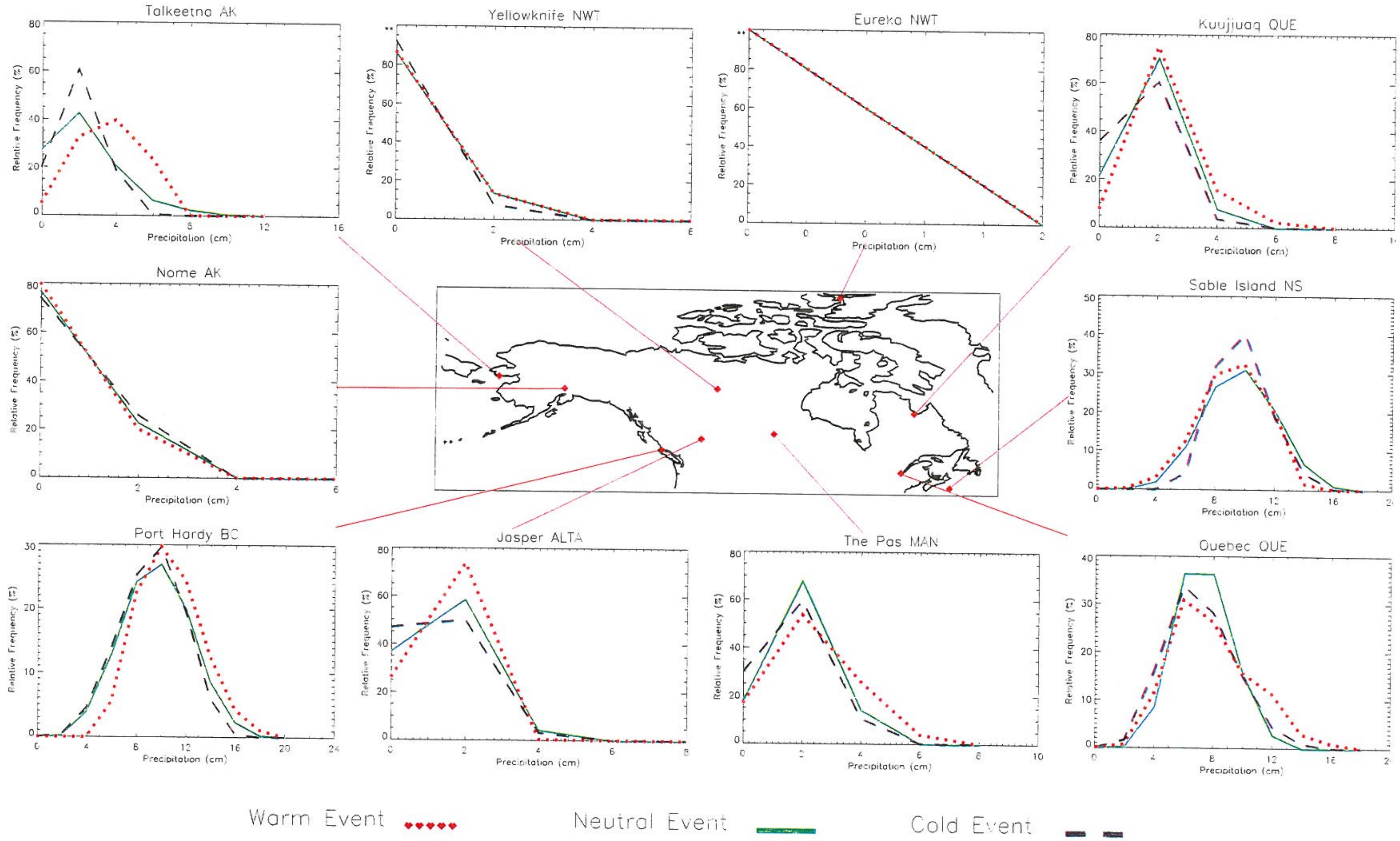
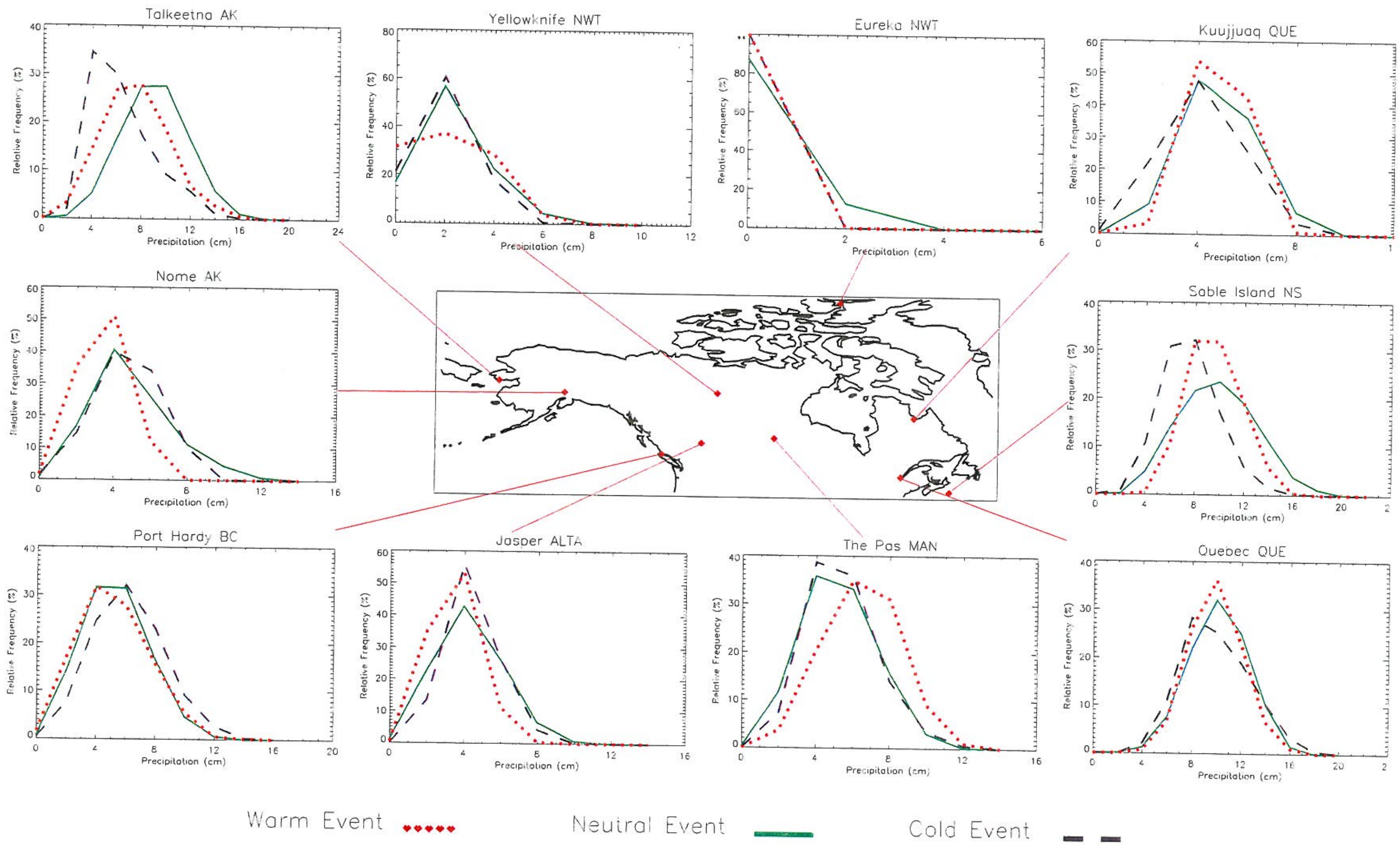


Figure 9c. Canada and Alaska Precipitation Probability Density Functions for ENSO Month MAM



Fiaure 9d. Canada and Alaska Precipitation Probability Density Functions for ENSO Month JJA

4.2 Mexican Results

Five stations were chosen from the 27 Mexican stations to illustrate the differing effect of ENSO on the diverse regions of Mexico (Table 5, Figure 10). The stations chosen are Quiriego, Sonora, to represent Northwestern Mexico; Monterrey, Nuevo Leon to represent Northeastern Mexico; Champoton, Campeche, to represent the Yucatan and Tropical Lowlands; Yurecuaro, Michoacan, to represent the Tropical Highlands; and Santiago, Baja California to represent Baja California.

4.2.1 Mexican geography

Mexico has many and diverse types of climates; according to Trewartha and Horn (1980), there are at least six. Baja California has two, most of the peninsula has a coastal desert climate and in the far northwestern part is a subtropical dry summer type climate. The coastal desert climate in Baja California is among the driest in the world in terms of monthly and annual precipitation, yet due to its proximity to the ocean, the atmosphere is moist. The region is dominated by subsiding air, preventing convection.

Northern Mexico (excluding Baja California) is broken into two regions, Northwestern Mexico and Northeastern Mexico. Each of the two regions has a mountain range, The Sierra Madre Occidental runs

Table 5: Mexican stations by region, station name and state

NORTHEASTERN MEXICO
Cuartro Cienegas, COAHUILA
Ramos Arizpe, COAHUILA
Villagran, TAMAULIPAS
San Fernando, TAMAULIPAS
Granja Experimental, NUEVO LEON
Monterrey, NUEVO LEON *
Las Enramadas, NUEVO LEON
Montemorelos, NUEVO LEON

YUCATAN-TROPICAL LOWLANDS
Merida, YUCATAN
Champoton, CAMPECHE *
Matias Romero, OAXACA

BAJA CALIFORNIA
Santiago, B. CALIFORNIA *
San Felipe, B.CALIFORNIA
San Ignacio, B. CALIFORNIA

NORTHWESTERN MEXICO
Arivechi, SONORA
Sahuaripa, SONORA
Ciudad Guerrero, CHIHUAHUA
Tres Hermanos, SONORA
Quiriego, SONORA *
Jaina, SINOLA
Tepehuanes, DURANGO
Guanacevi, DURANGO
Francisco I. Madero, DURANGO

TROPICAL HIGHLANDS
Piaxtla, PUEBLA
Yurecuaro, MICHOACAN *
Macsota, JALISCO
Chapala, JALISCO

* indicates representative station for each region

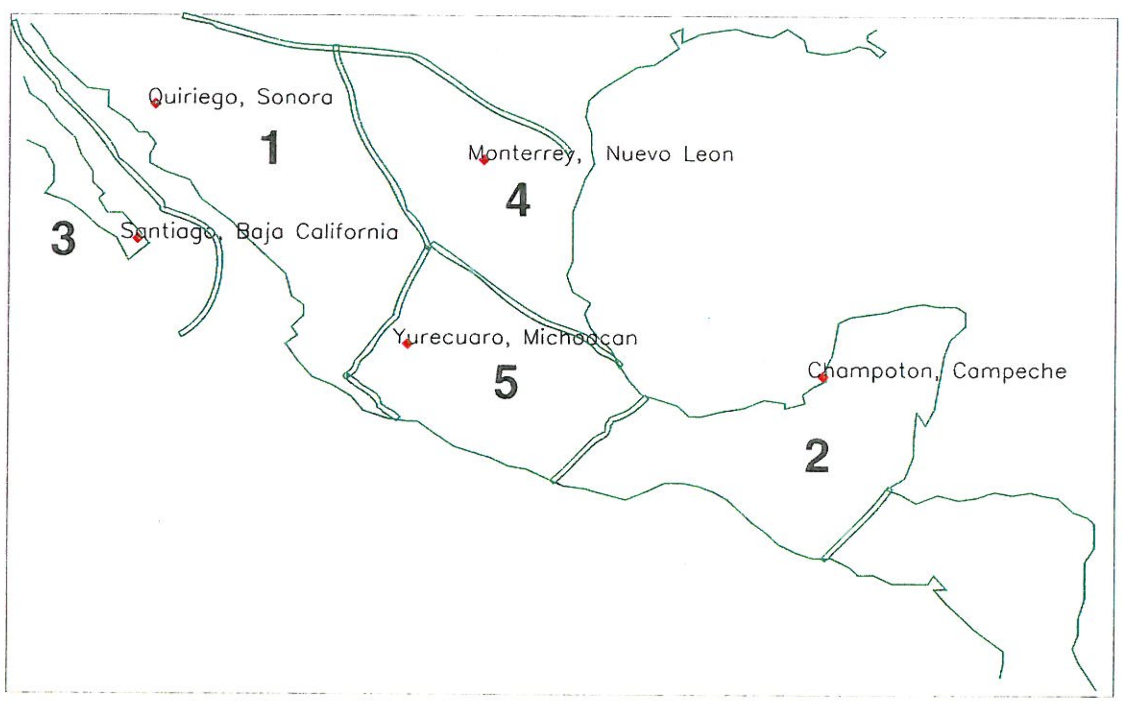


Figure 10: Representative Mexican stations in their respective regions: 1 Baja California, 2 Yucatan and Tropical Lowlands, 3 Northwest Mexico, 4 Northeast Mexico, and 5 Tropical Highlands

4.2.2. Temperature anomalies

In general, Mexican regions are colder (warmer) than the neutral phase during the warm (cold) phase in the first half of the ENSO year.

4.2.2a. Northeastern region

The Northeastern region shows moderate temperature effects associated with ENSO. During the cold phase, Monterrey, Nuevo Leon (Figure 11) has a warmer winter and fall, with a temperature anomaly maximum of 1.1°C in NDJ. Cold phase summers are cooler; Monterrey has a cold minimum of -0.5°C in summer (JJA). The T-test (Figure 12a) shows that all stations in this region, except for the westernmost stations in Coahuila, are significantly warmer in fall and winter. All stations in this region, except for the coastal stations, are significantly cooler in summer (Figure 12a).

During the warm phase, northeastern Mexico is consistently cooler throughout the year. Monterrey (Figure 11c) has a cold anomaly of -0.9°C in winter (JFM). The T-test shows significant cold anomalies for most stations from winter to summer (JFM to JJA). In early winter, the western stations in this region are significantly cooler (NDJ to DJF). In late summer (JAS) and in the fall (OND) there are no significant cold anomalies in this region (Figure 12b).

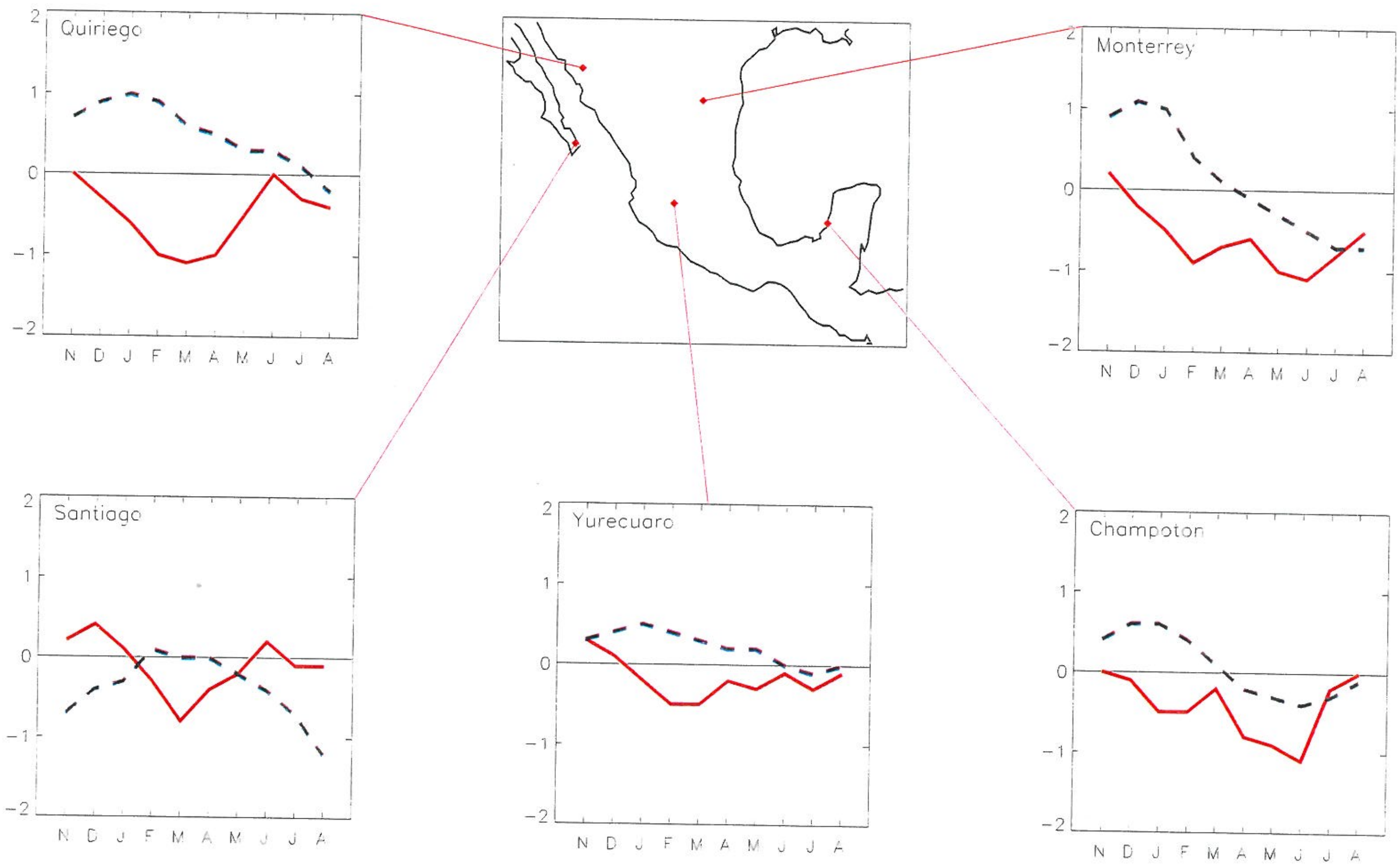


Figure 11: Departure from Neutral Mean in Degrees Celsius for Seasonal Mean Monthly Temperature at Mexican Stations.

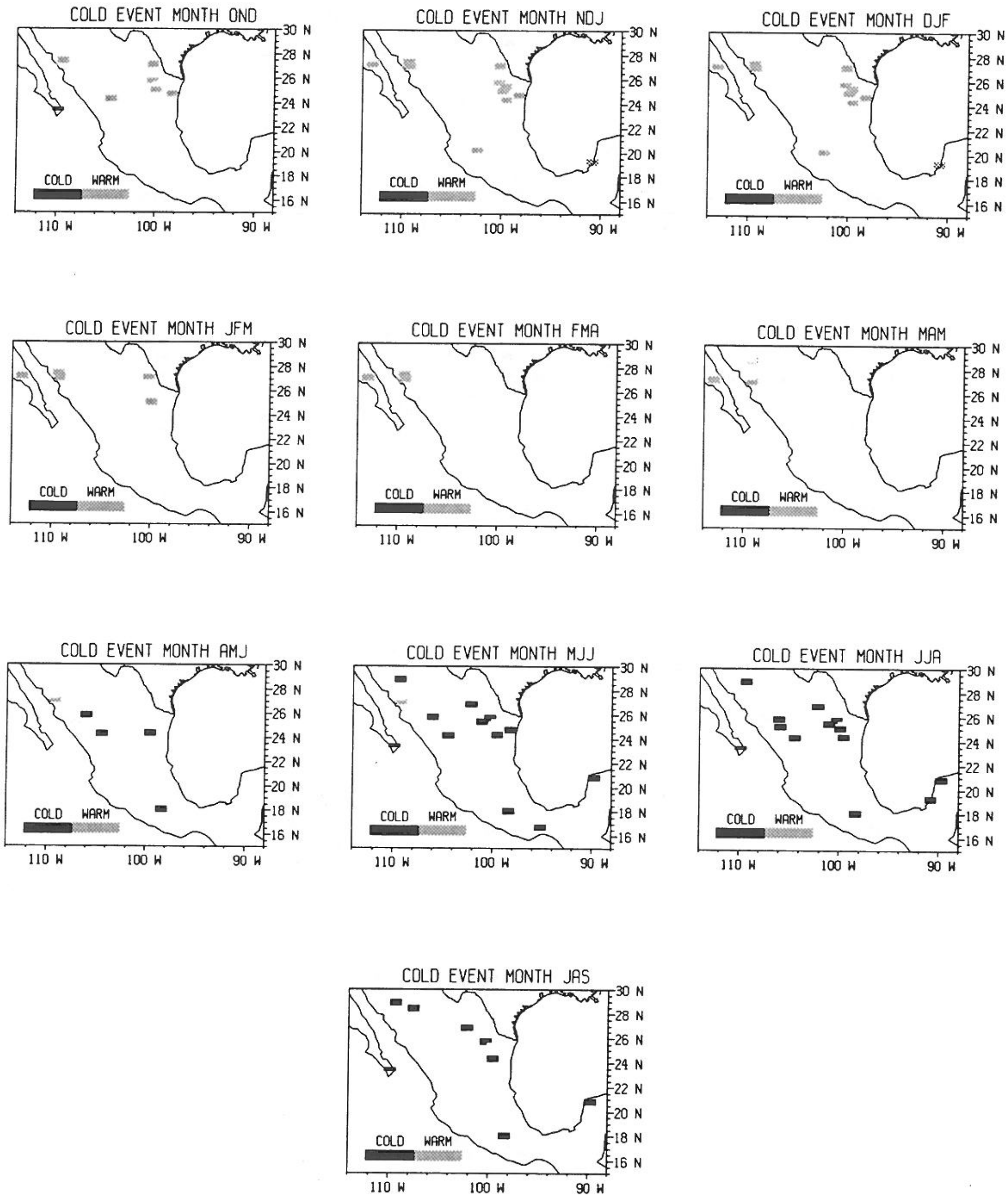


Figure 12.a: T-test results for Mexico during the cold phase.

4.2.2b. Tropical Highlands region

The tropical highlands region, represented by Yurecuaro (Figure 11), has the cold phase associated with a slightly warmer year, except in summer, which has cooler anomalies. The lack of large temperature variation is expected, due to the normal temperature regime in the tropics. Yurecuaro has a warm winter (DJF) anomaly of 0.5°C. T-test results (Figure 12a) show Yurecuaro is significantly warmer in the winter (NDJ-DJF) and only Piaxtla is significantly colder in summer.

The warm phase in the tropical highlands are associated with slightly colder years, except at onset (OND). Yurecuaro has cold winter anomalies of -0.5°C at JFM. Piaxtla shows an anomalous effect; the warm phase year is warmer than neutral for the entire year. T-test results (Figure 12b) show Jalisco significantly warmer in fall (OND) and Yurecuaro is significantly colder in late winter (FMA). Piaxtla is significantly warm from late fall to spring (Figure 11).

4.2.2c. Northwestern region

Northwestern Mexico shows moderate temperature effects associated with ENSO. The cold phase has warmer winters except Jaina, where there is little effect throughout the year. Quiriego, Sonora (Figure 11) reaches a warm maximum anomaly in winter (DJF) at 1°C. The T-tests (Figure 12a) show significantly warmer fall, winter, and spring in Tres Hermanos and Quiriego, which match winter (JFM to FMA). In addition, San Felipe is significantly colder through spring (Figure 12b).

4.2.2e. Yucatan and the Tropical Lowlands region

Yucatan and the Tropical Lowlands in southern Mexico have the cold phase warmer than normal during the winter and slightly colder in the summer months. Champoton (Figure 11) is significantly warmer in winter (NDJ-DJF) and all stations are significantly colder during summer (Figure 12a).

Warm phases are colder throughout the year, with the exception of early spring where there is little difference from neutral (spring is also the season where the cold phase switches from warmer to colder than normal). Champoton (Figure 11) has two cold seasons in the warm phase: winter and summer. Champoton is significantly colder during late spring and early summer; and only Matias Romero is significantly cold in winter (Figure 12b).

4.2.3. Precipitation anomalies

Mexican regions generally have a regime of wetter than normal conditions during warm phase winters. The exceptions are scattered in the western interior.

4.2.3a. Northwestern region

Northwestern Mexican stations have generally a wetter year during the warm phase. However, all stations show a slightly drier season during the warm phase in late spring to early summer (AMJ to

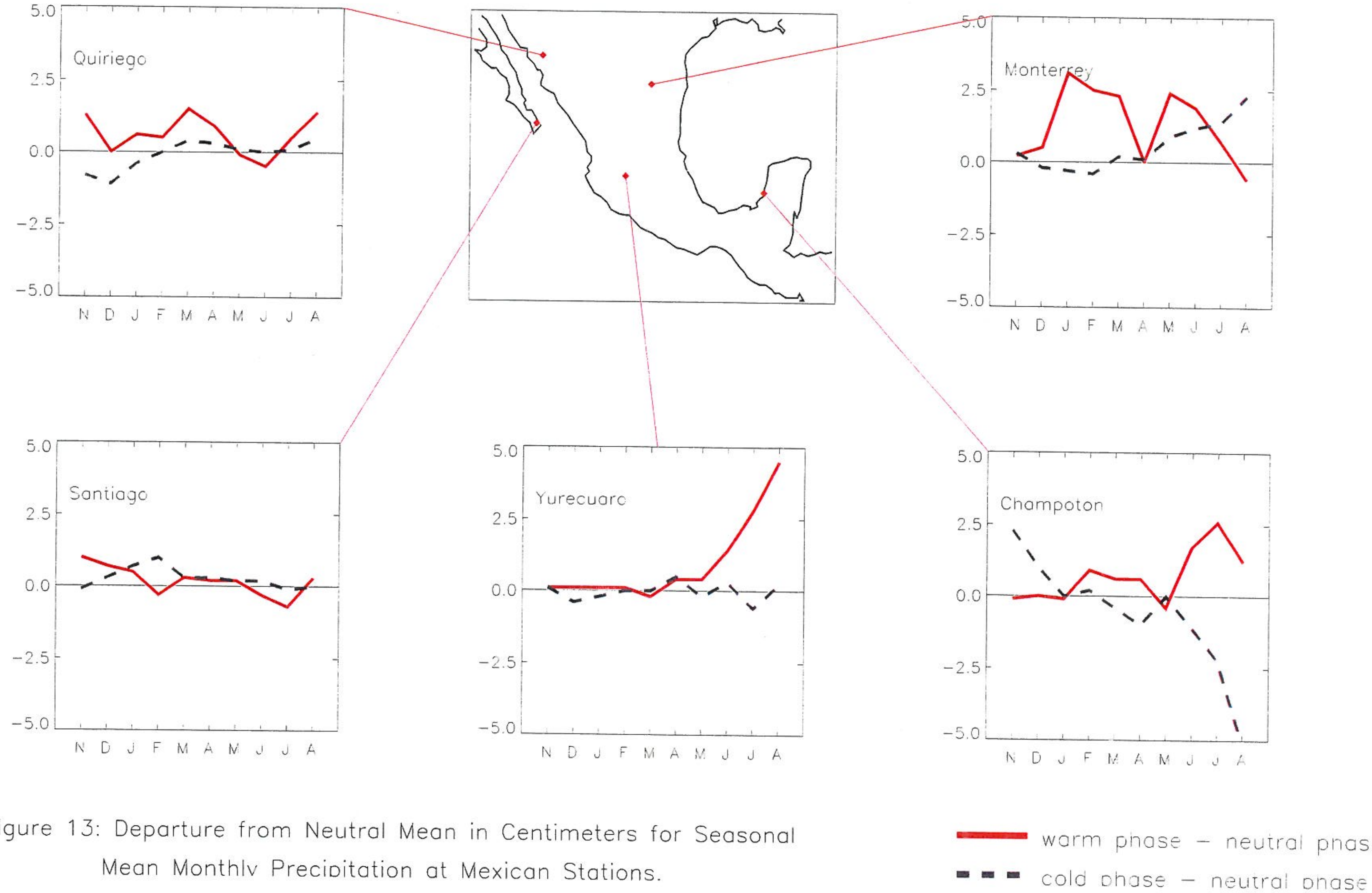


Figure 13: Departure from Neutral Mean in Centimeters for Seasonal Mean Monthly Precipitation at Mexican Stations.

4.2.3c. Baja California region

The Baja California stations in my study have the smallest ENSO precipitation signal of all the Mexican stations. The amplitudes are small because the climatic regime of the region is a desert, among the driest in the world in terms of monthly and annual precipitation, yet due to its proximity to the ocean, the atmosphere is moist. The region is dominated by subsiding air, preventing convection. Warm phases are slightly wetter in the fall, early spring and late summer (JAS); there are also dry periods in JFM and MJJ.

During the cold phase the effects vary from station to station; generally the winter and summer are slightly wetter. Santiago (Figure 13) is wetter in the winter, whereas San Felipe (at a higher elevation) is wetter in the summer.

4.2.3d. Tropical Highlands region

The warm phase in the tropical highlands region exhibit a slightly wetter fall and early winter with a peak wet anomaly in summer. In Yurecuaro (Figure 13), the JAS anomaly averages 4cm wetter. The warm phase has larger precipitation anomalies. Cold phases have variable effects in the tropical highlands, but all stations tend to be slightly drier than normal in winter and late summer.

4.2.3e. Yucatan and the Tropical Lowlands region

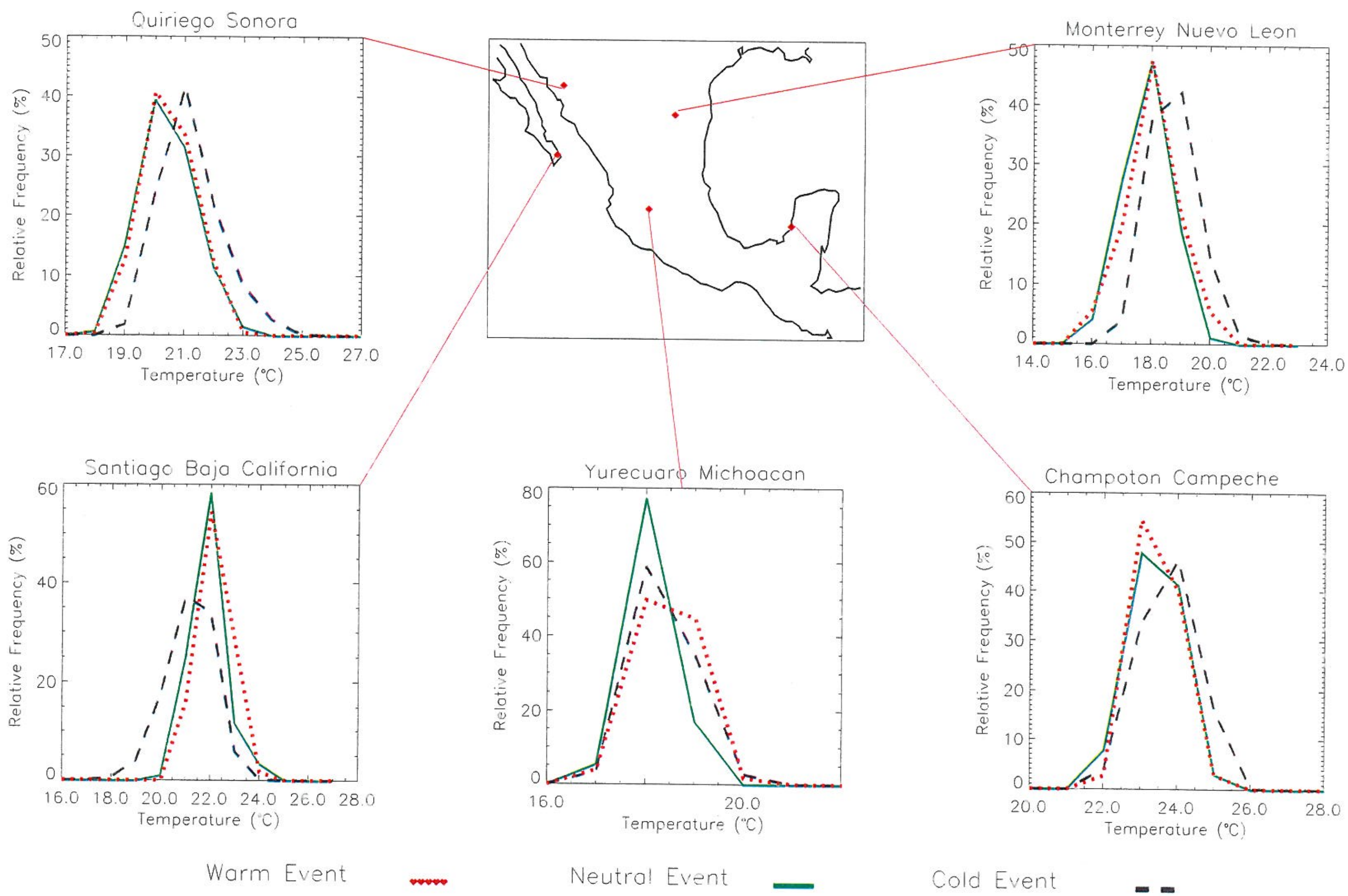
In the Yucatan and the Tropical Lowlands, the warm phase is wetter throughout the year except for a brief dry period in spring shows a tendency for the cold phase to have extreme wet periods, although the general distribution shows the warm phase to be slightly wetter than the cold phase (Figure 15a).

Temperature distributions for winter (DJF) show a warm winter during cold phases for all regions, except Baja California, which has a colder winter during the cold phase. Warm phase winters are significantly warmer in northern Mexico and the Yucatan (Figure 14b). Precipitation distributions for winter (DJF) indicate wetter warm phase winters in northern Mexico and the Highland region, and little difference between cold and neutral phases (Figure 15b) There is little discernible effect in Baja California in either phase.

Temperature distributions for spring (MAM) show little effect in the highlands for either phase. Warm phases are significantly cooler in the rest of the regions. The cold phase has significant impact in Northwest Mexico and Baja California: in Northwest Mexico it is warmer and in Baja it is colder (Figure 14c).

The spring (MAM) precipitation distributions show Sonora to be wetter during warm phases (Figure 15c). In the Yucatan region, there is a tendency for wetter warm phases and drier conditions during the cold phase. The highlands are wetter during the cold phase springs.

Summer (JJA) temperature distribution results show that the only affected regions are Baja California and Northeast Mexico: both phases bring about a colder summer (Figure 14d). Precipitation distributions for summer (JJA) show that warm phases have a slightly wetter regime in all regions, except Baja California which



Fiaure 14a. Mexico Temperature Probability Density Functions for ENSO Month OND

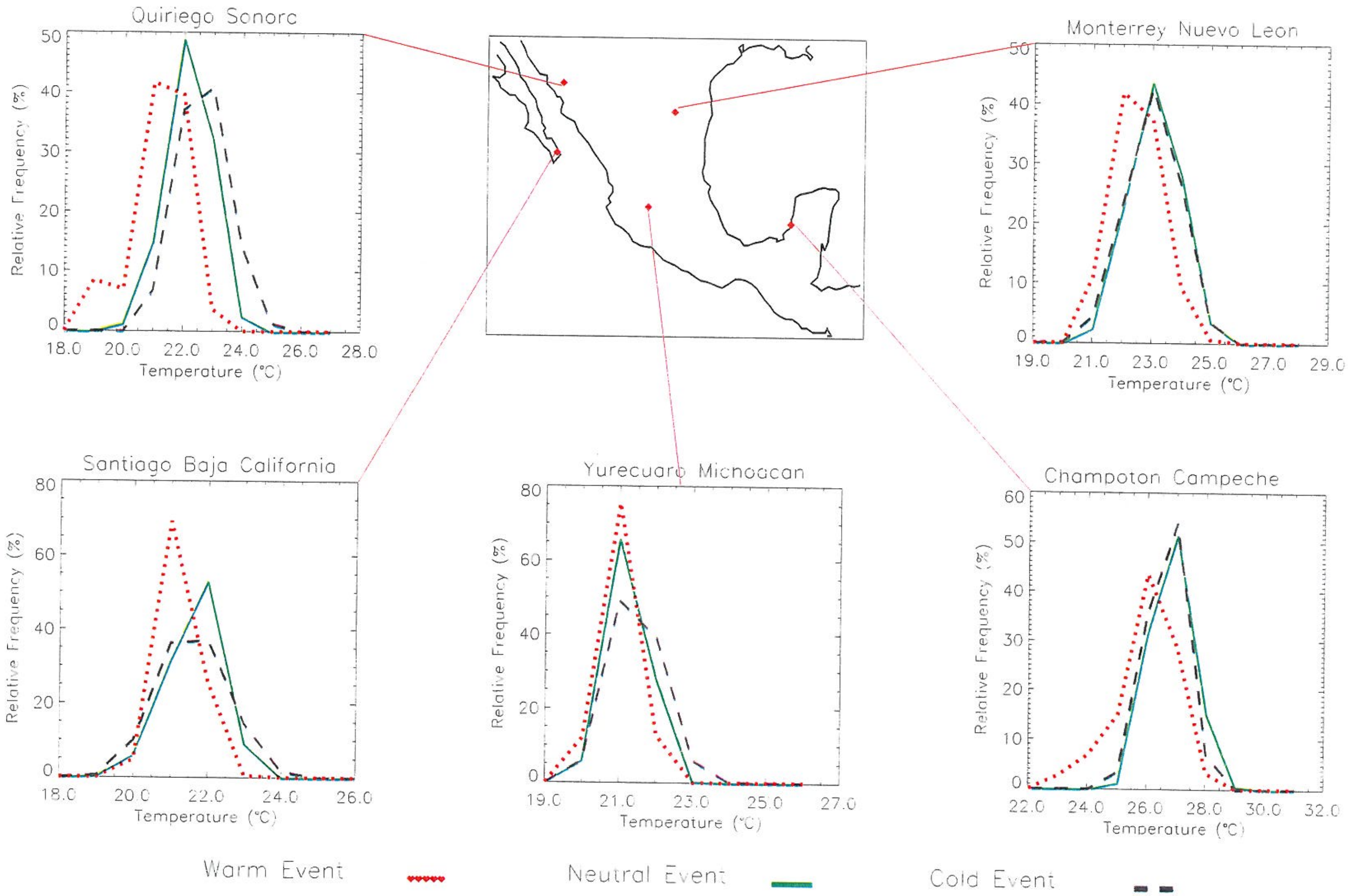
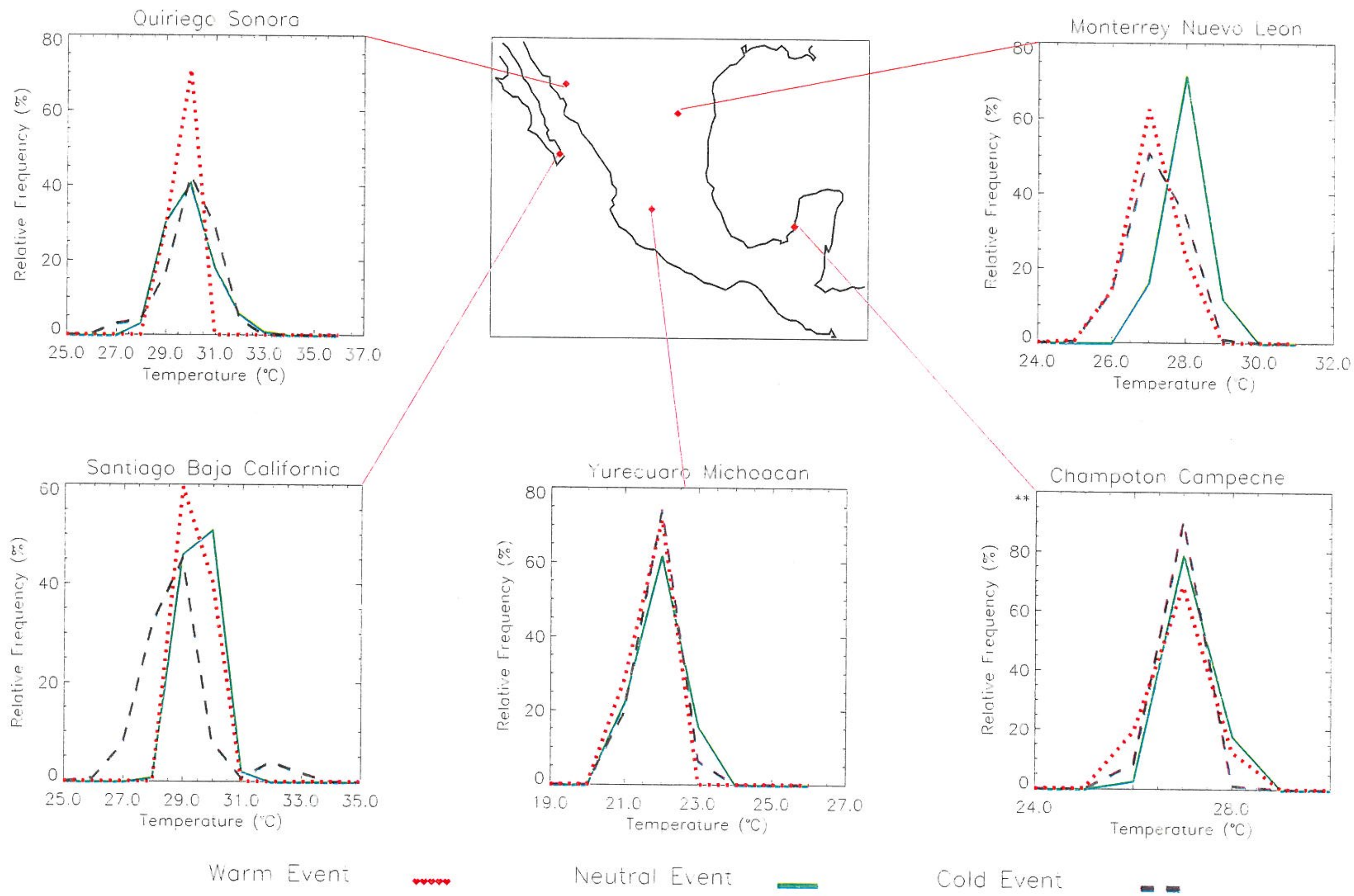


Figure 14c. Mexico Temperature Probability Density Functions for ENSO Month MAM



Fiaure 14d. Mexico Temoerature Probabilitv Densitv Functions for ENSO Month JJA

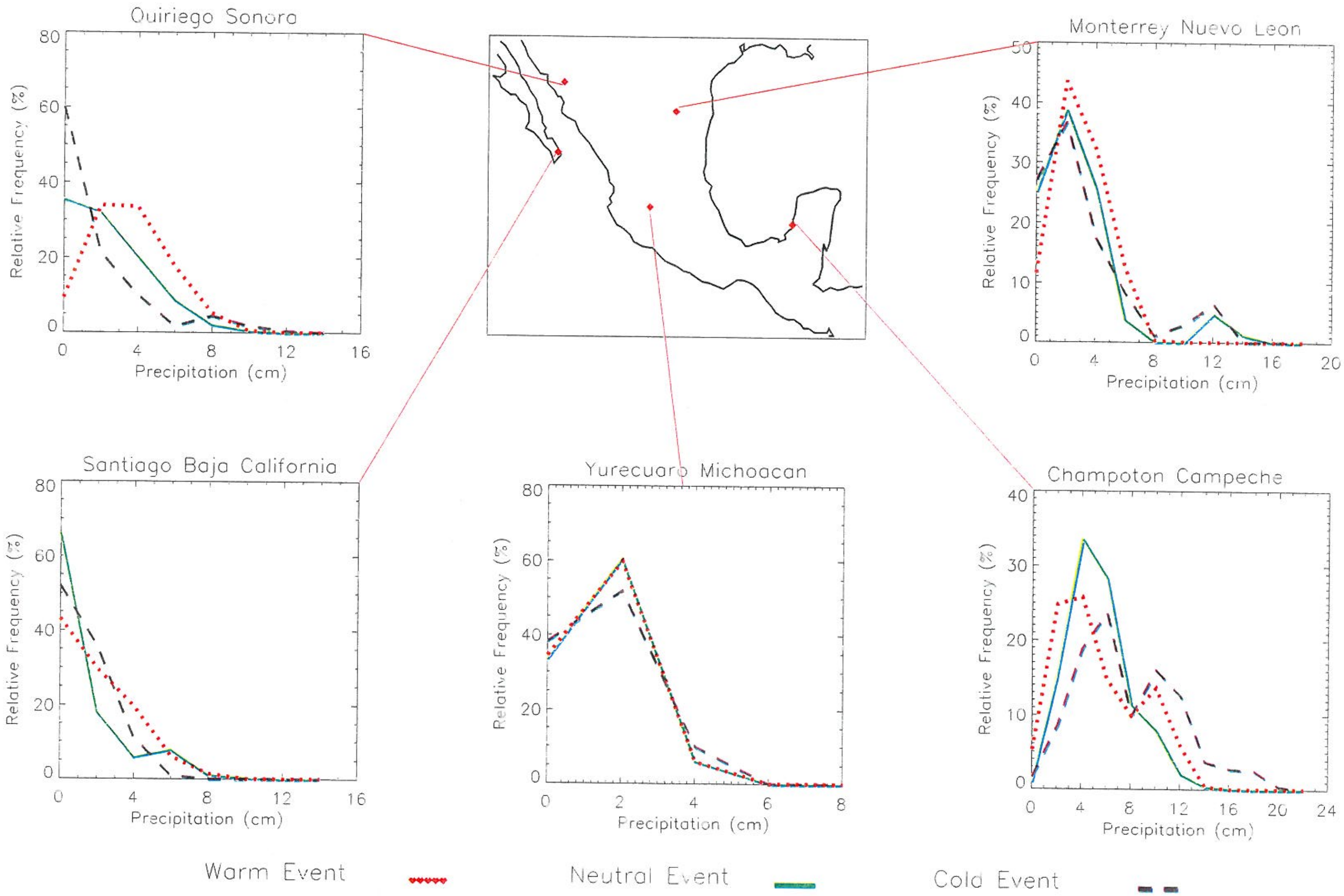
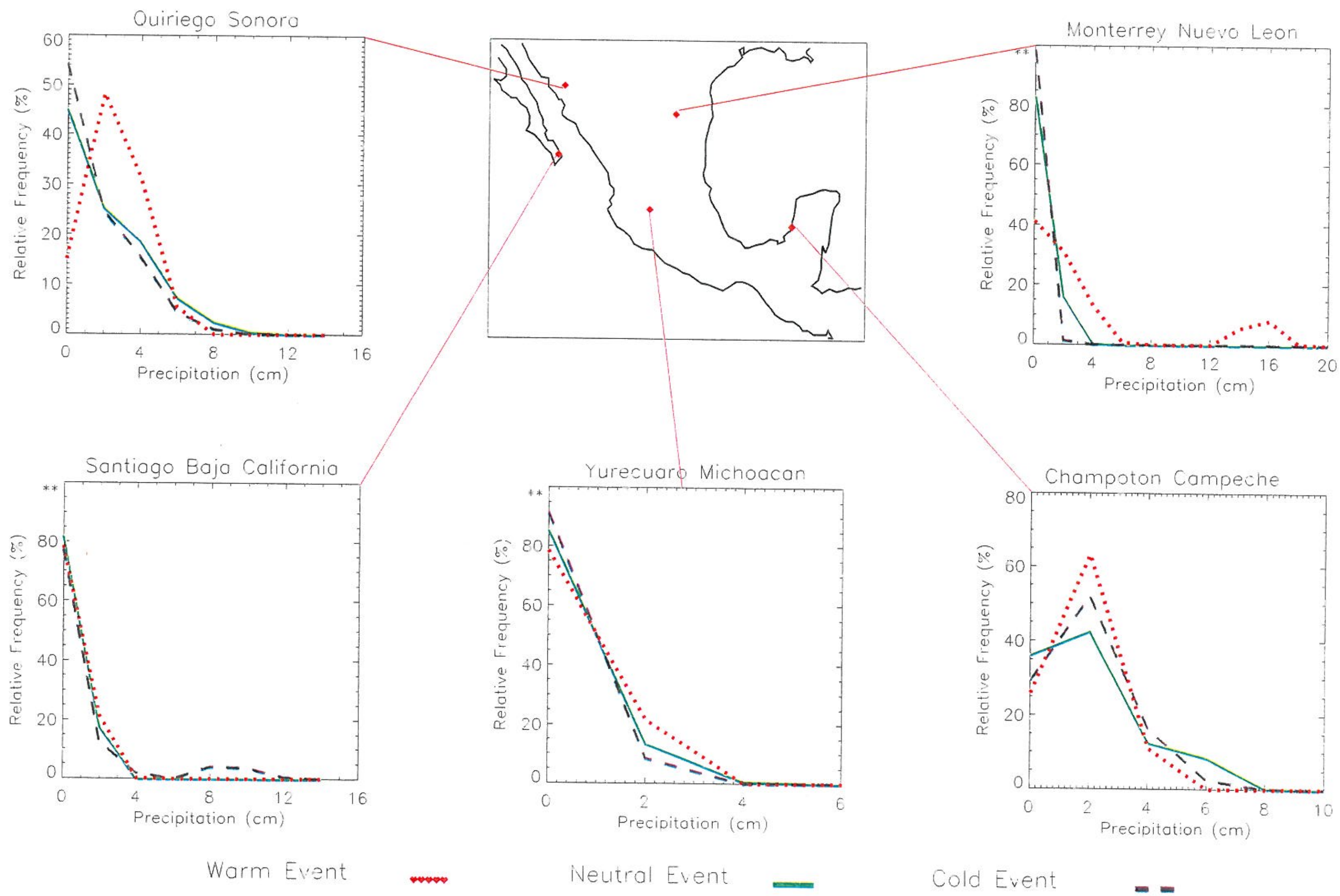


Figure 15a. Mexico Precipitation Probability Density Functions for ENSO month OND



Fiaure 15b. Mexico Precipitation Probability Density Functions for ENSO month DJF

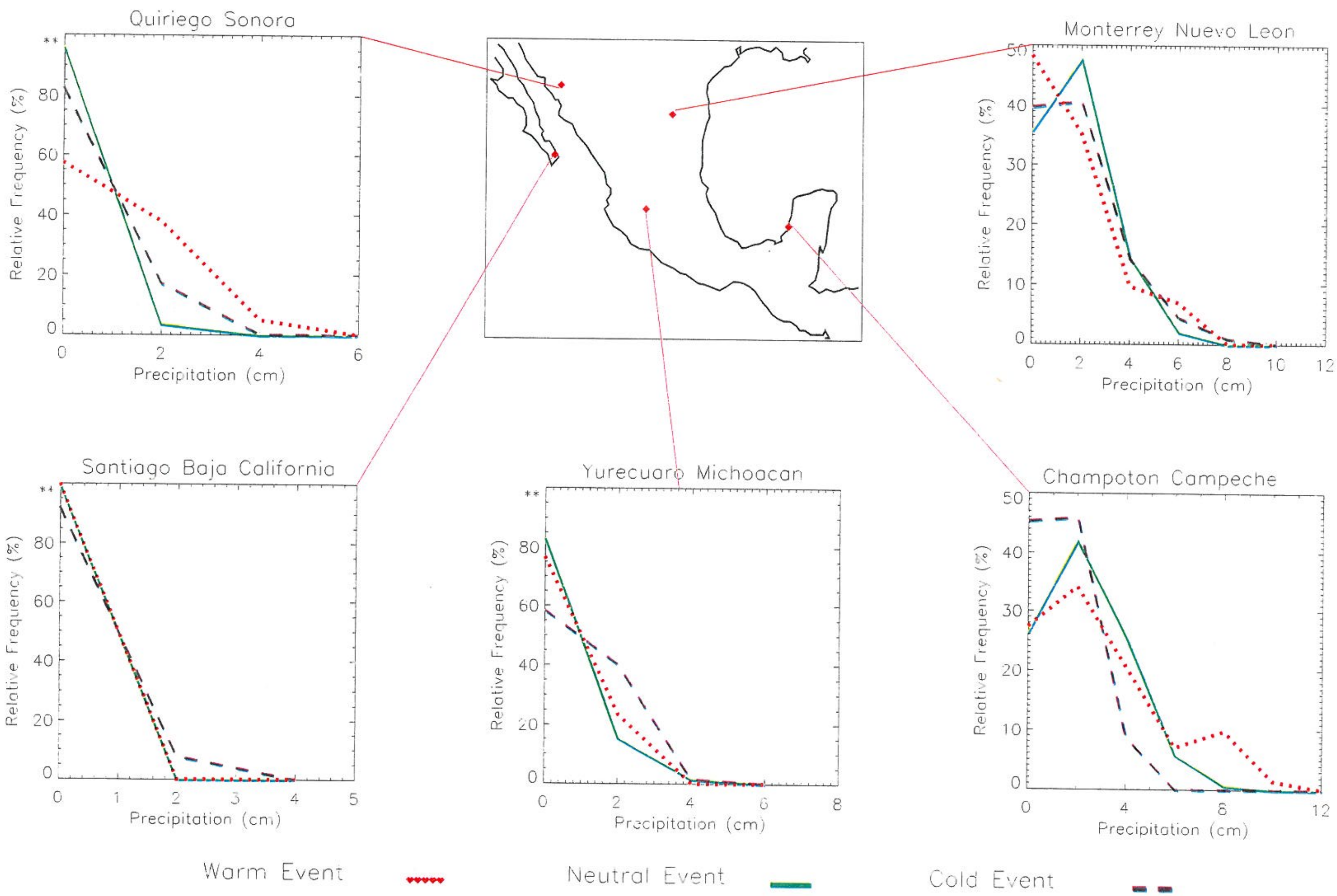


Figure 15c. Mexico Precipitation Probability Density Functions for ENSO month MAM

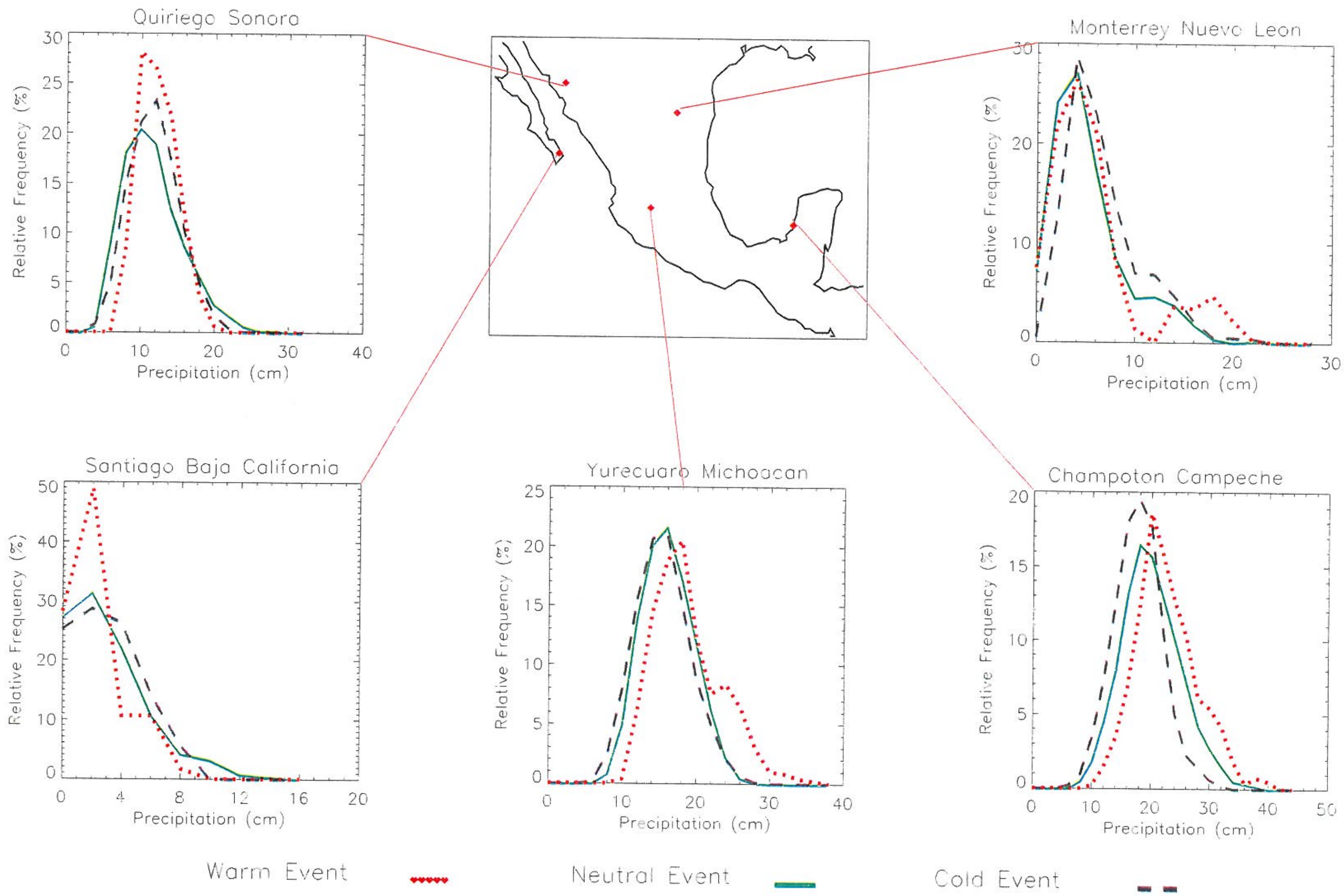


Figure 15d. Mexico Precipitation Probability Density Functions for ENSO month JJA

5. CONCLUSIONS

5.1. Summary of results

There are significant temperature and precipitation anomalies associated with ENSO phases in Mexico, Alaska, and Canada. The largest temperature anomalies occur during fall, winter, and spring of the ENSO year for both cold and warm phases. The magnitude of cold phase temperature anomalies are larger and more significant in Canada and Alaska. Mexican temperature anomalies and precipitation anomalies are both larger in magnitude during warm phases.

During cold phase fall and winter seasons, nearly all the Canadian and Alaskan stations experience cold temperature anomalies. These cold anomalies weaken in the late spring and summer. During warm phase winters, western and central Canada as well as southern Alaska encounter warm anomalies. In contrast, the Arctic north has cold anomalies. During warm phase springs, central and eastern Canada are warmer while Alaska and the high Arctic are colder than in neutral years.

During the cold phase, precipitation in most of eastern Canada is reduced, whereas most of western and interior Canada is wetter than normal. An interesting feature on the Alaskan and Canadian Pacific Coast is the spatial change in precipitation regime: wet in Vancouver, dry in Port Hardy, wet in Yakutat and dry in Kodiak.

interior Alaska has the coldest temperature anomalies. Alaska remains significantly colder in fall and winter.

Mexican temperature anomalies are not as large as Canadian and Alaskan temperature anomalies. The range of the temperature anomalies is from -1.5°C to 1.5°C in both phases. These anomalies are small; however, these low values are significant by T-test results.

For both cold and warm phases, the largest precipitation anomalies are found in the coastal regions of southern Alaska, eastern Canada, and western Canada during fall and winter of the ENSO year. The largest precipitation anomalies in Mexico are found in coastal regions; excepting the coastal desert region in Baja California.

5.2. Comparison with other studies

There is agreement generally with conclusions of other studies. These results are compared to others in terms of the peak ENSO season, winter (DJF), because it is the month most often associated with the peak of the ENSO related anomalies (Sittel 1994). The author found that Sittel's (1994) pattern of warm temperature anomalies in the northern interior US continues into Canada (figure 18b) and up to just south of the High Arctic region. The High Arctic region throughout the warm phase winter remains cold. The warm phase cold temperature anomaly pattern in the southwestern US (Sittel 1994) continues into northern Mexico and the Yucatan. During the cold phase, the cooler temperature anomaly

5.3. Physical connection

The physical mechanisms that bring about precipitation and temperature anomalies are identified in previous works (for example Philander 1990; Smith 1996). The north-south excursions of the polar jet in warm phases is 180 degrees out of phase with the polar jet in cold phases. These shifts in the jet-stream correspond to pressure anomaly patterns such as the Pacific-North American (PNA) Pattern and the reverse PNA pattern

The Pacific-North American (PNA) pattern has been associated with the climatic effects of warm ENSO phases over North America (Horace and Wallace 1981). The pattern is characterized by a strong Aleutian low displaced to the southeast, a Canadian Arctic high pressure system west of the Hudson Bay, a low pressure system over the southeast US and strong ridging over the Western Cordillera (Philander 1990). The ridge over the cordillera region brings warm anomalies to Canada through warm air advection on the windward side of the ridge. This pattern effectively "blocks" the maritime influence from the western US. Temperature data clearly show the pressure system patterns. The warm (cold) anomalies occur in the general vicinity of a high (low) pressure anomaly system in both the PNA and reverse PNA patterns.

The reverse PNA pattern is associated with the cold phase ENSO effects. Ridging occurs over the southeast, with a strong meridional flow towards the northeast. Troughing occurs in the western US (Smith 1996) and cold air advection results in cold anomalies in northern Mexico and the western US. Alaska has variety of fields connected with this study. For the Arctic coastal regions in Canada and Alaska, further study could include ENSO's effect on sea ice extent. Sea ice formation has a dramatic effect on the coastal environment. With its solidification in winter, the local climate regime can change from a maritime climate to that of a continental climate. Dangers of ice freeze include rapid encroachment of the ice, and cyclogenesis at the ice edge. These pose serious problems for fishing fleets and naval vessels. If ENSO has a significant effect on sea ice, then sea ice extent, freeze up, and break up may be predicted more effectively. Future work could also include relating temperature and precipitation anomalies to crop yields in interior Canada and Mexico. Some applications of this study could be used in preparation for ENSO related drought and forest fires. On the municipal scale, energy budgets for a city in the upcoming fiscal year could be made more effective with these ENSO effects in mind.

ACKNOWLEDGMENTS

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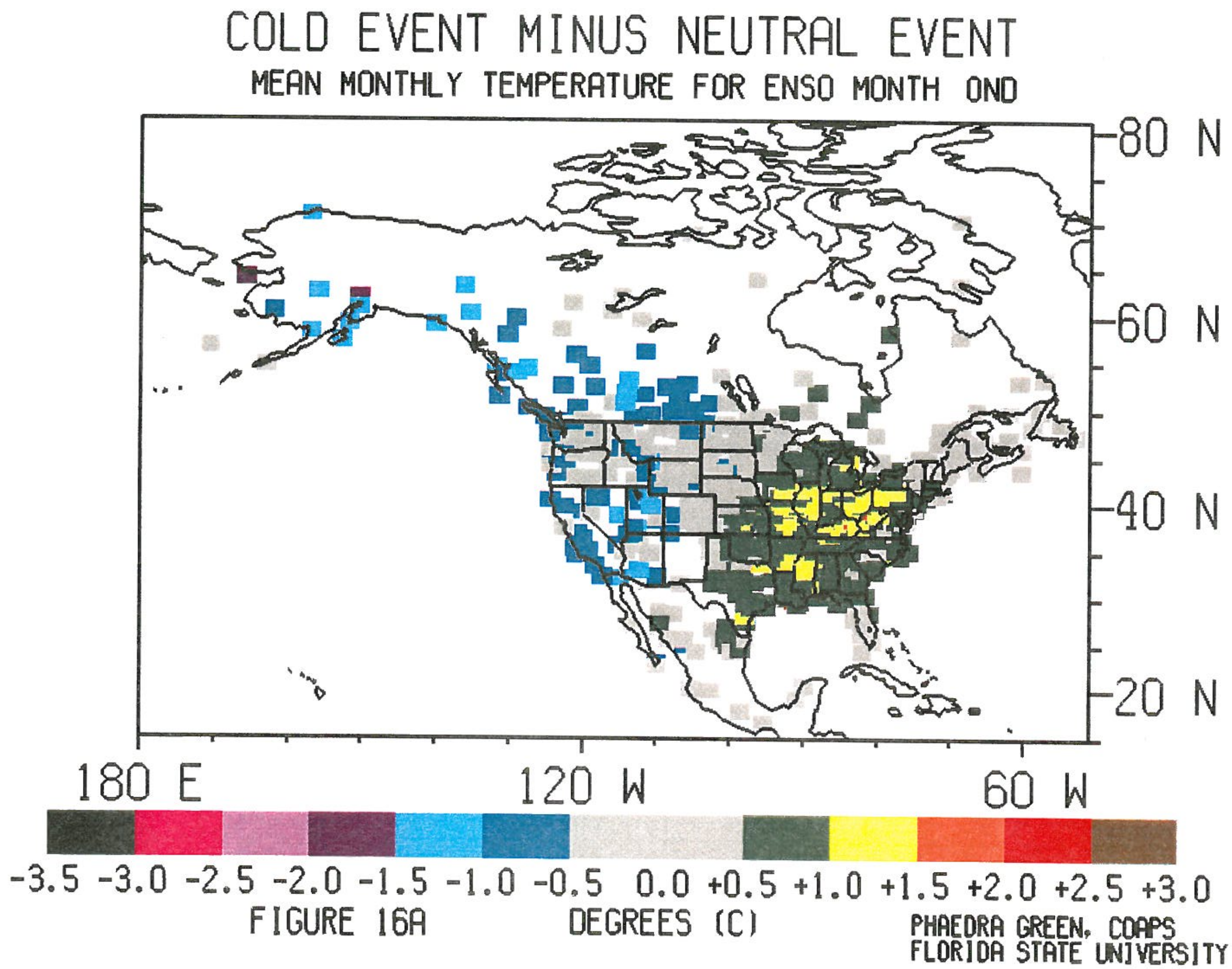
APPENDIX ONE


COLD EVENT MINUS NEUTRAL EVENT
MEAN MONTHLY TEMPERATURE FOR ENSO MONTH OND
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 +0.5 +1.0 +1.5 +2.0 +2.5 +3.0
DEGREES (C)
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY
FIGURE 16A

COLD EVENT MINUS NEUTRAL EVENT

MEAN MONTHLY TEMPERATURE FOR ENSO MONTH DJF

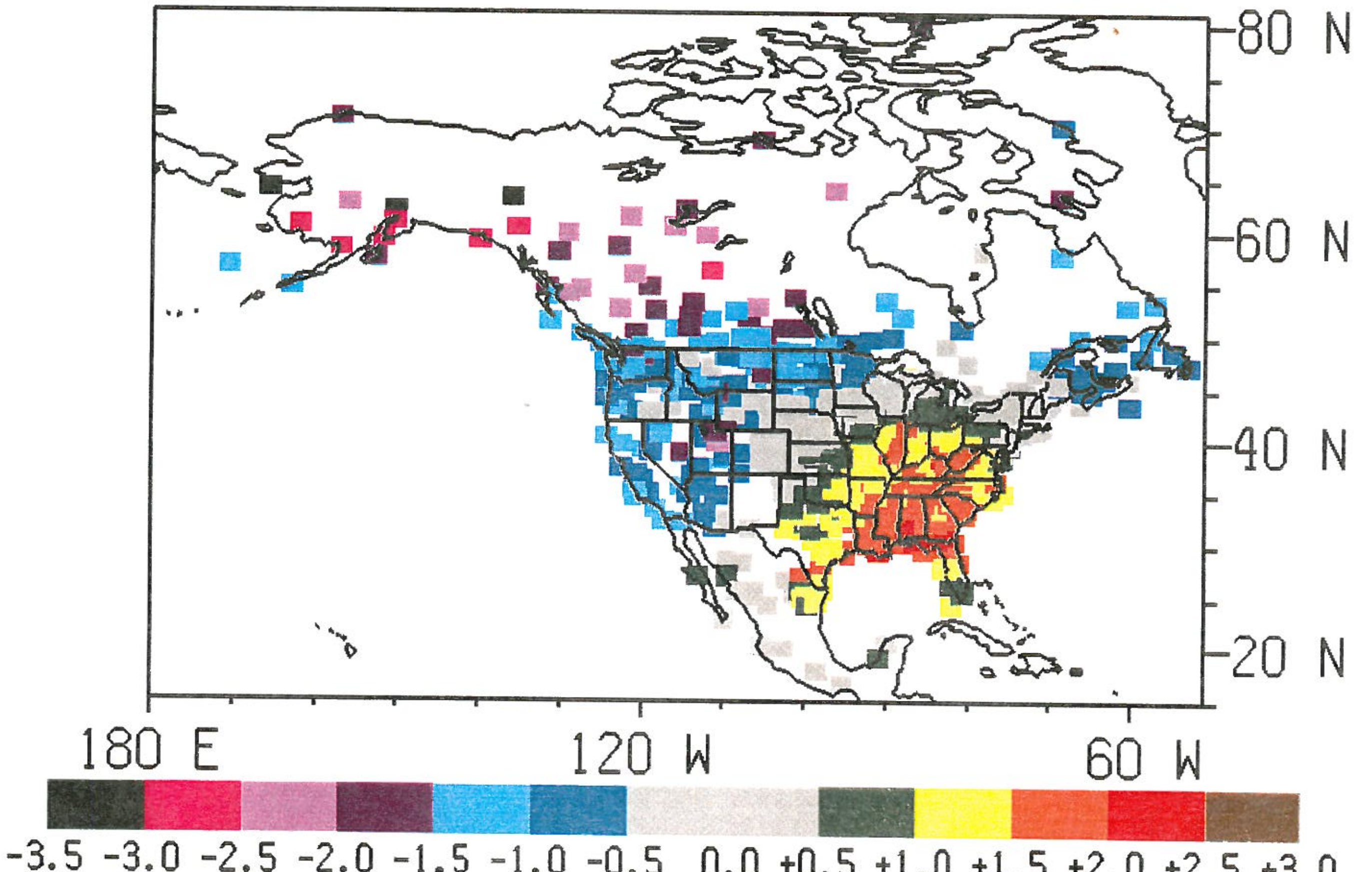


FIGURE 16B DEGREES (C)

PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY

COLD EVENT MINUS NEUTRAL EVENT

MEAN MONTHLY TEMPERATURE FOR ENSO MONTH MAM

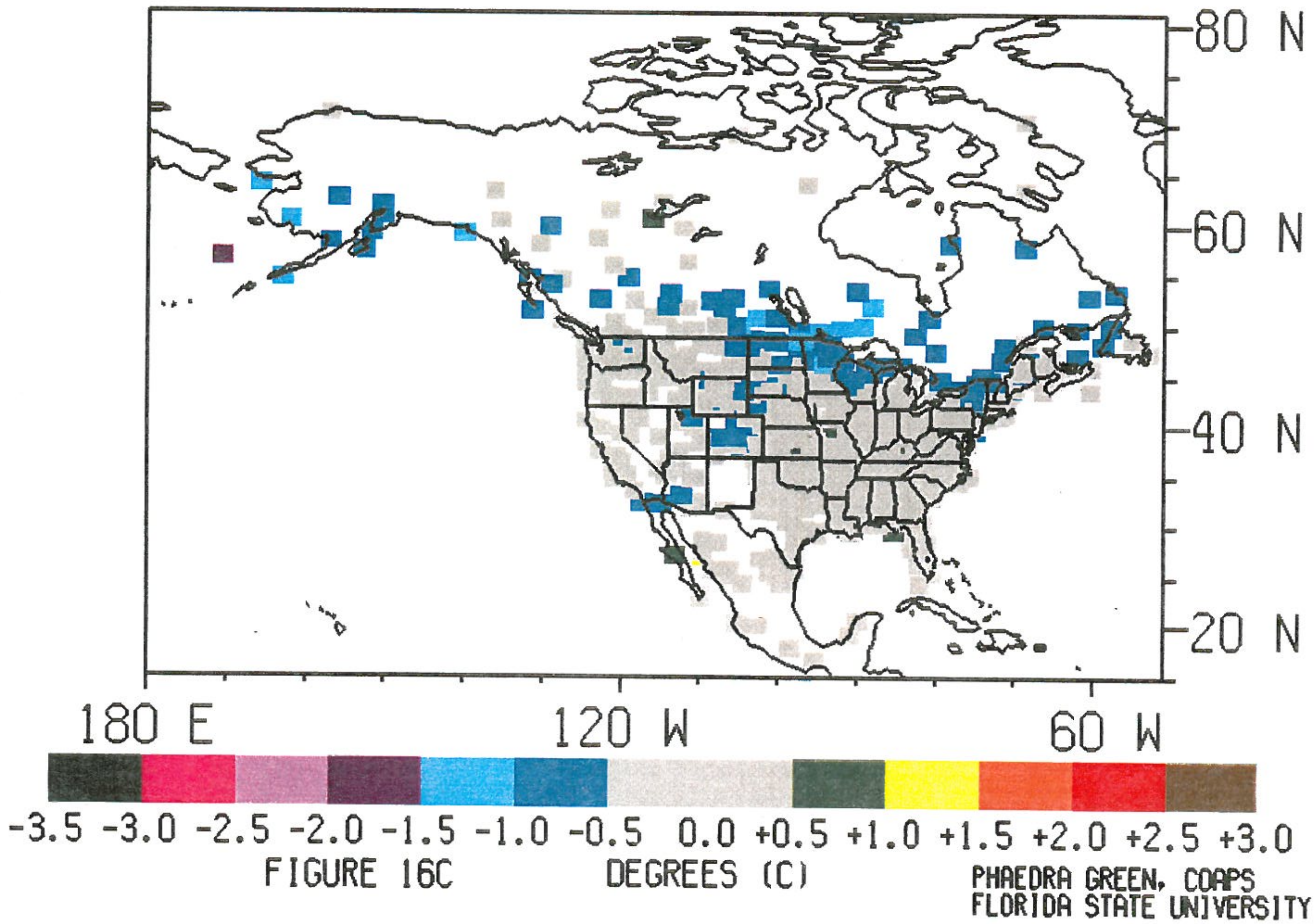


FIGURE 16C

COLD EVENT MINUS NEUTRAL EVENT

MEAN MONTHLY TEMPERATURE FOR ENSO MONTH JJA

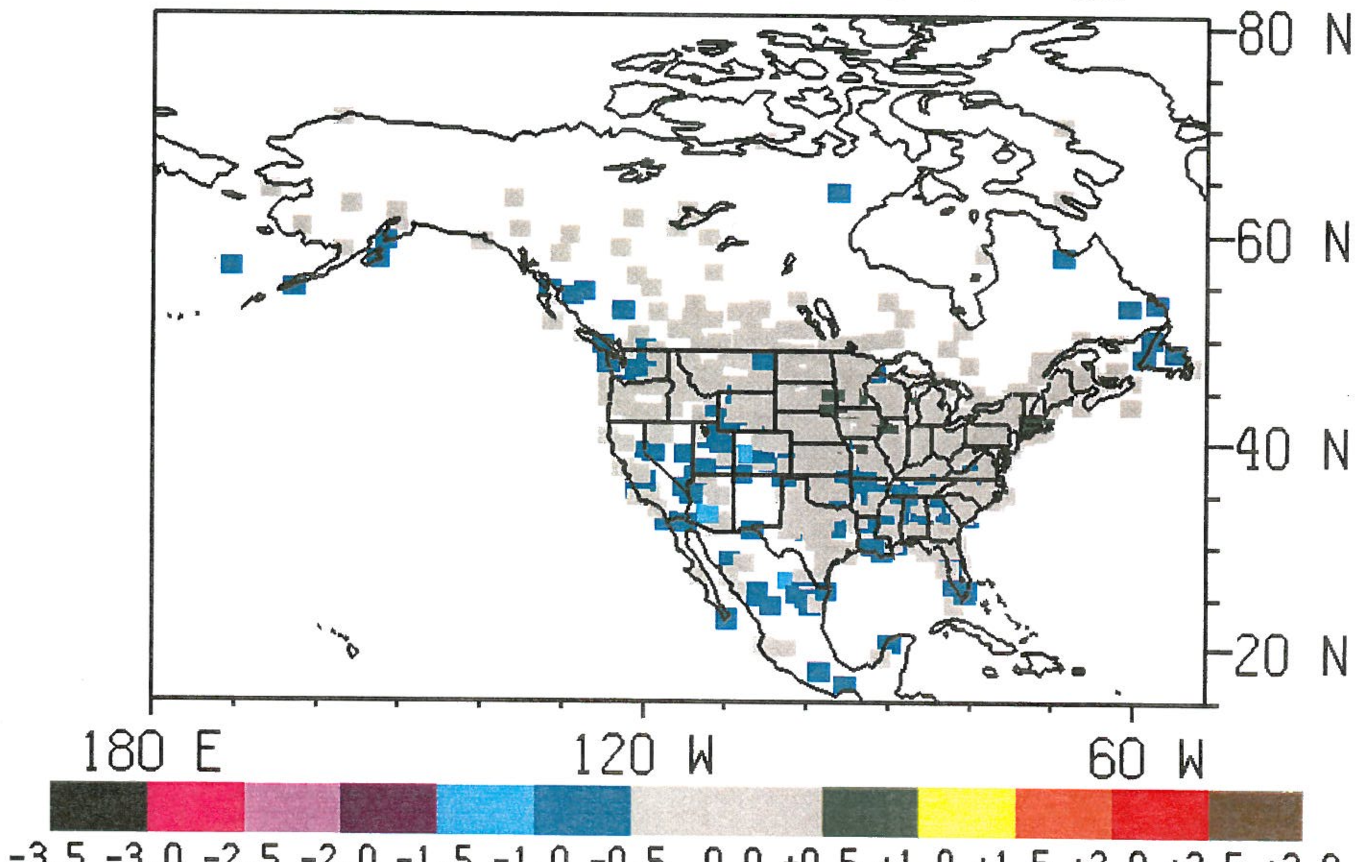
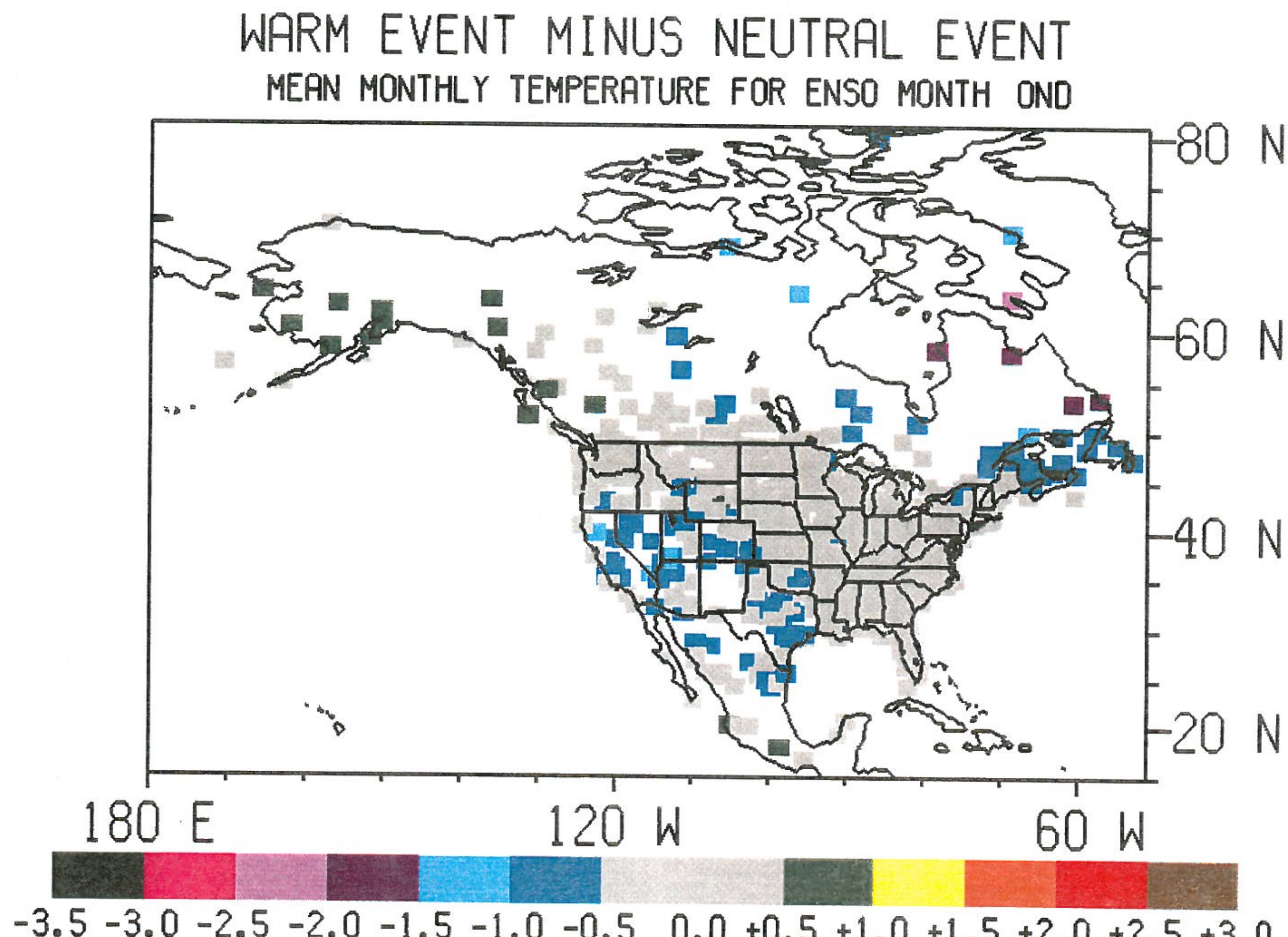
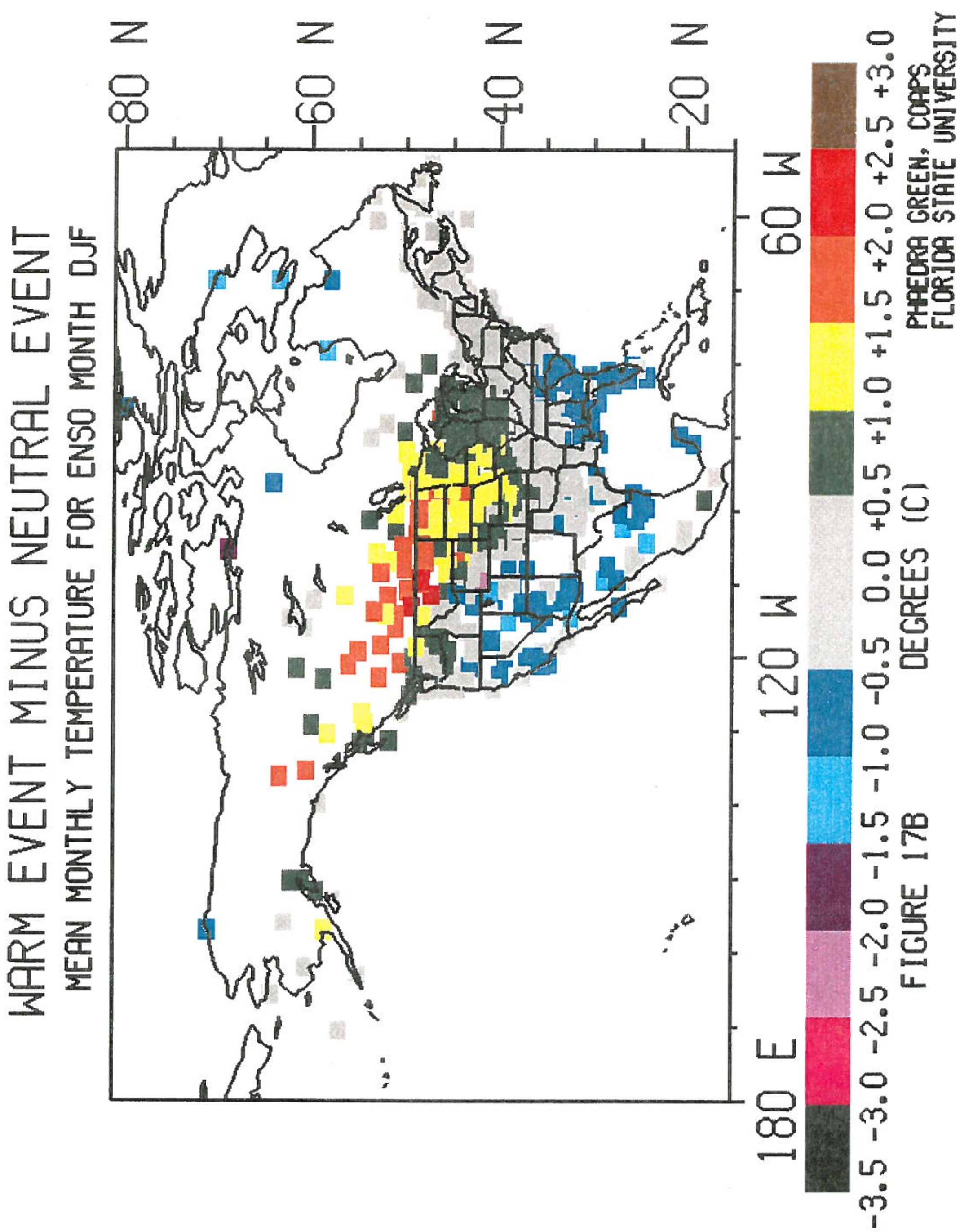


FIGURE 16D DEGREES (C)

PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY


WARM EVENT MINUS NEUTRAL EVENT
MEAN MONTHLY TEMPERATURE FOR ENSO MONTH OND
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 +0.5 +1.0 +1.5 +2.0 +2.5 +3.0
DEGREES (C)
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY
FIGURE 17A


WARM EVENT MINUS NEUTRAL EVENT
MEAN MONTHLY TEMPERATURE FOR ENSO MONTH DJF
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 +0.5 +1.0 +1.5 +2.0 +2.5 +3.0
DEGREES (C)
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY
FIGURE 17B

WARM EVENT MINUS NEUTRAL EVENT

MEAN MONTHLY TEMPERATURE FOR ENSO MONTH MAM

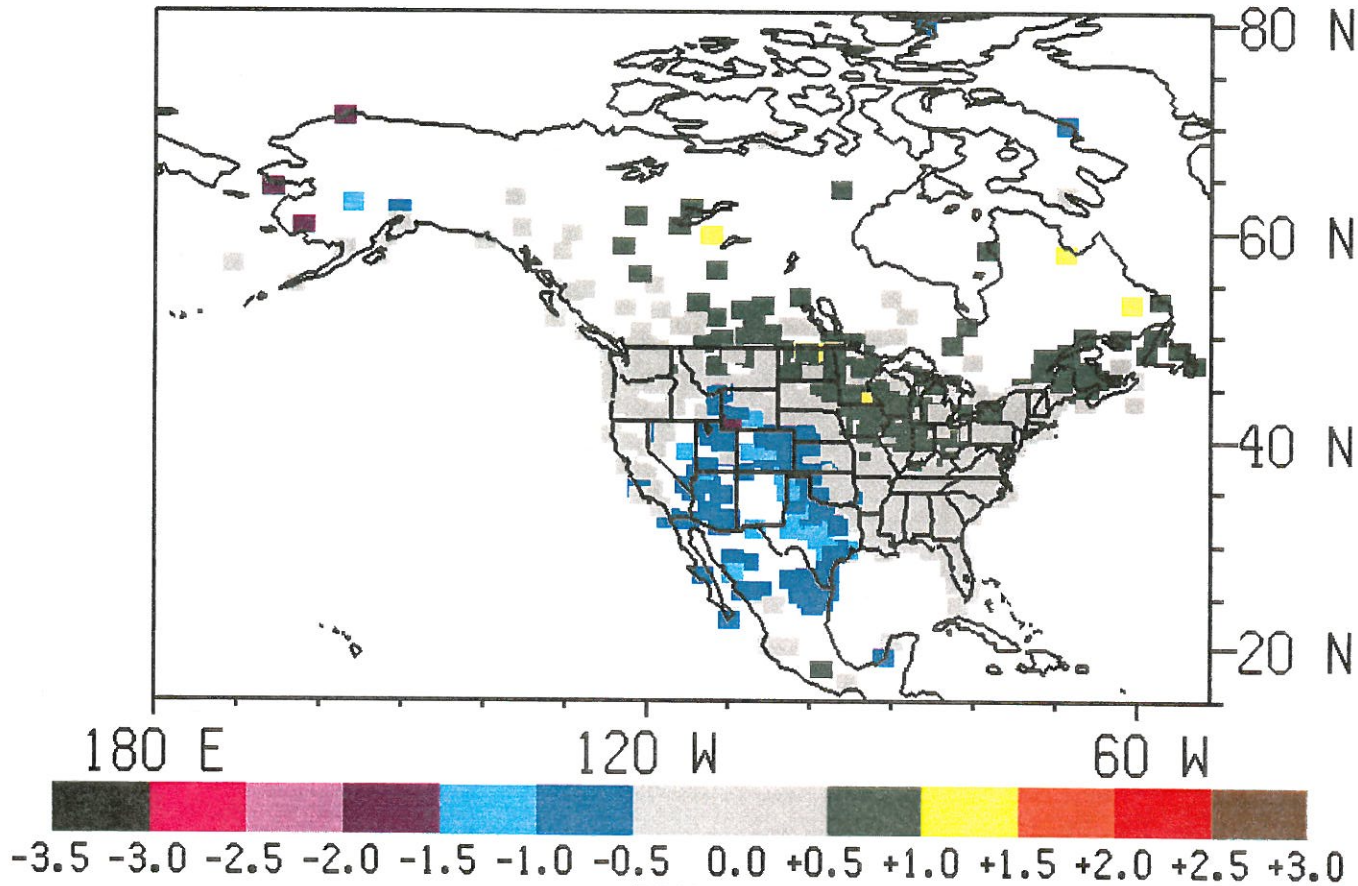
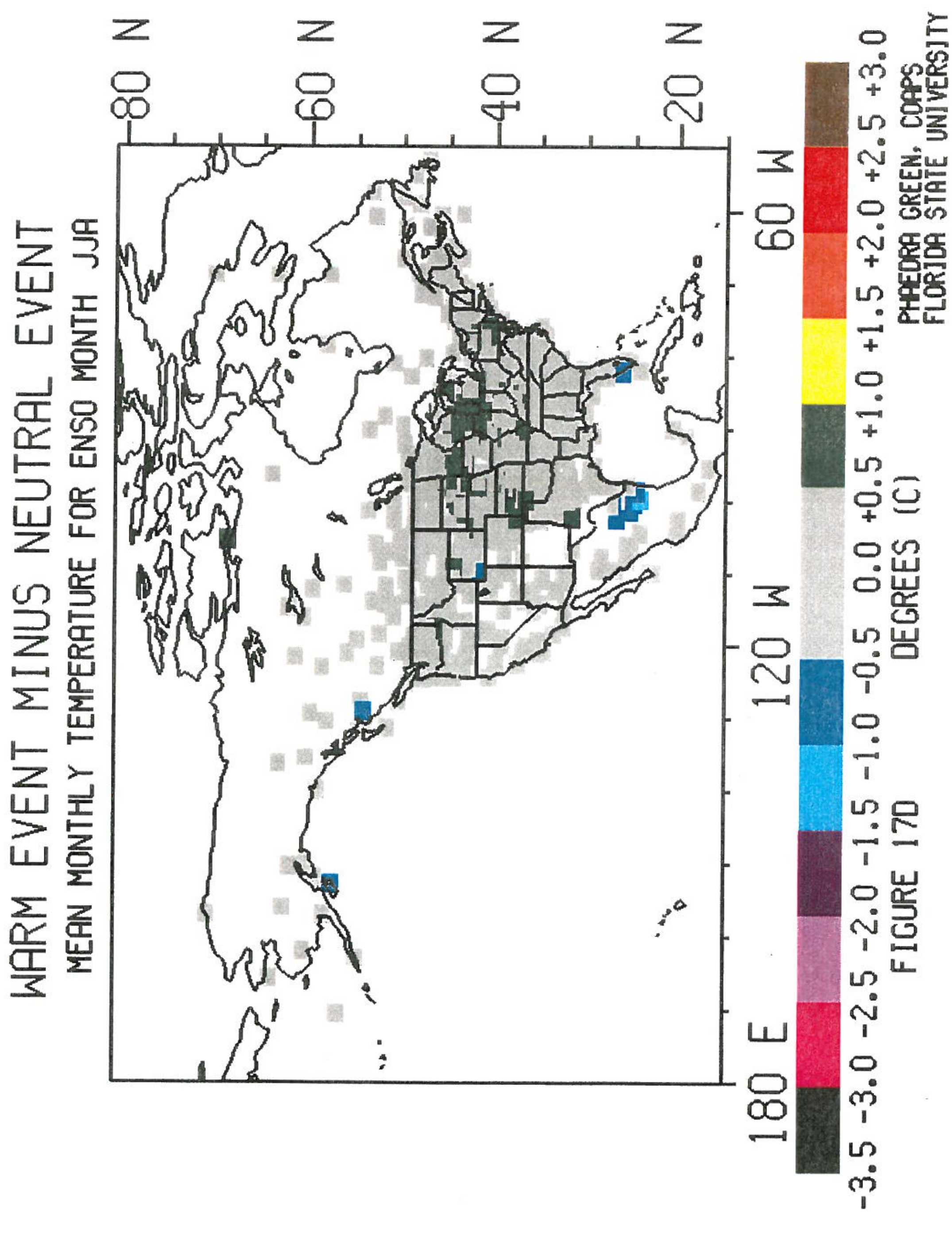


FIGURE 17C

PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY


WARM EVENT MINUS NEUTRAL EVENT
MEAN MONTHLY TEMPERATURE FOR ENSO MONTH JJA
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-3.5 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 0.0 +0.5 +1.0 +1.5 +2.0 +2.5 +3.0
FIGURE 17D
DEGREES (C)
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY

COLD EVENT MINUS NEUTRAL EVENT

TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH OND

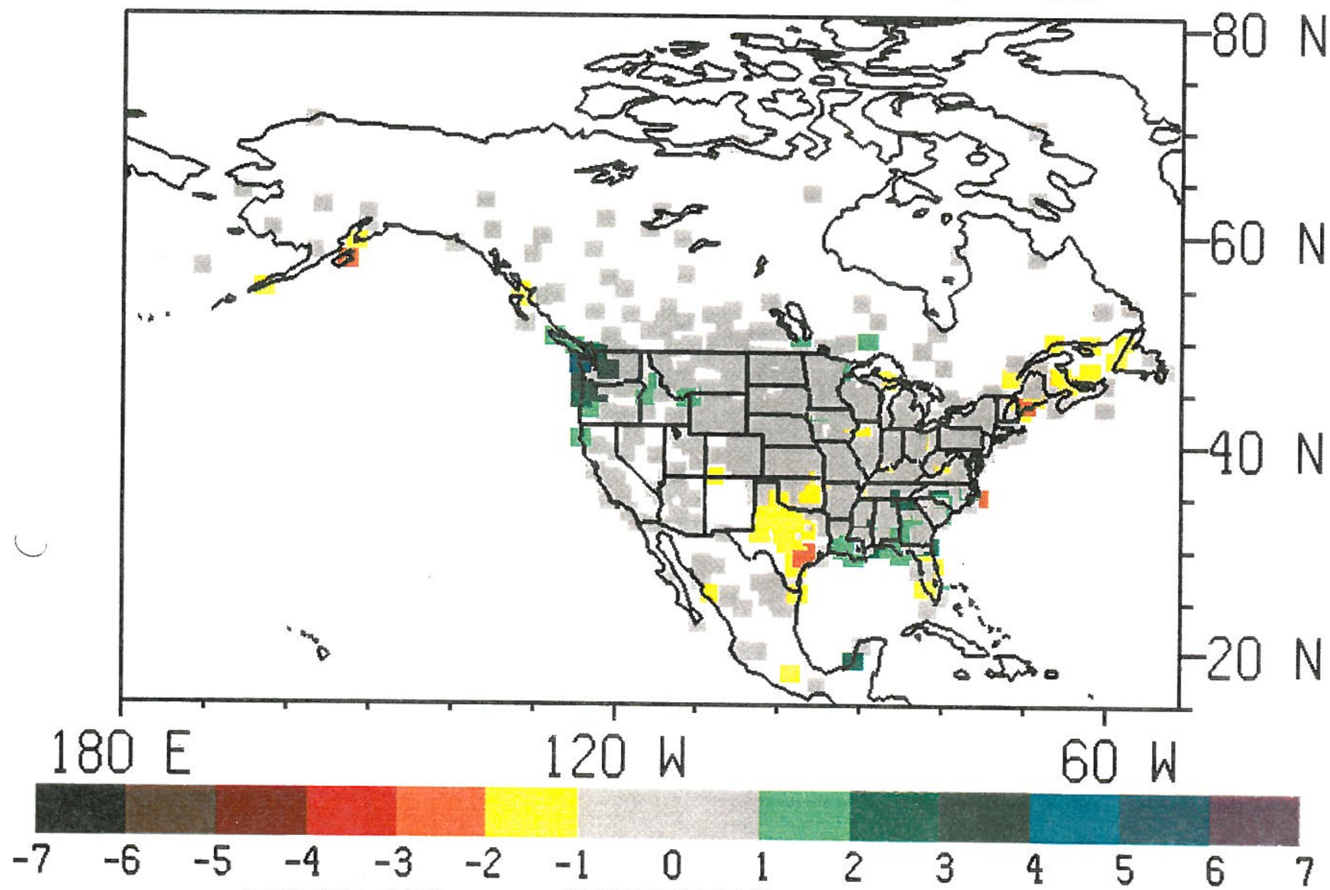


FIGURE 18A

PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY

COLD EVENT MINUS NEUTRAL EVENT

TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH DJF

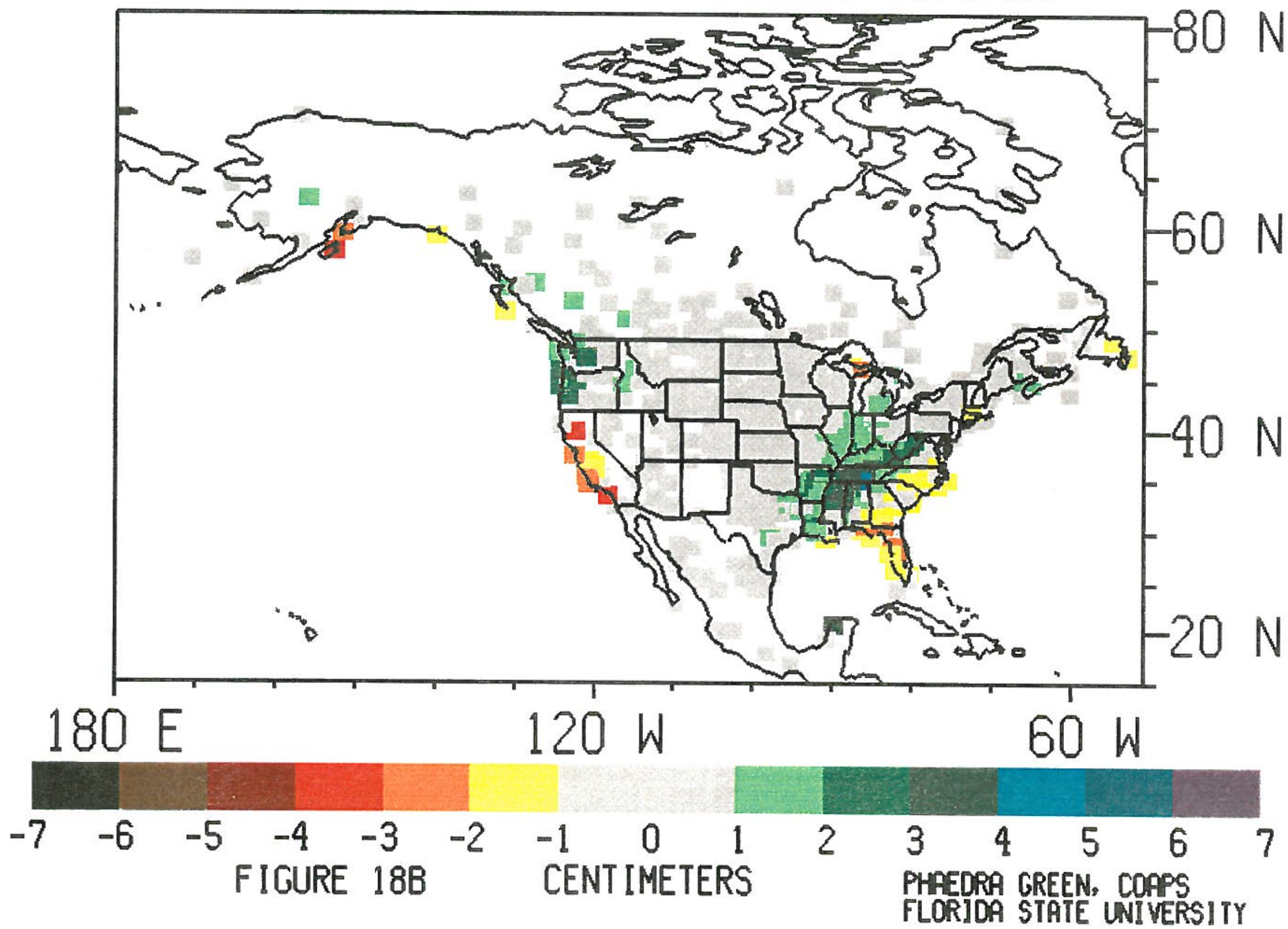
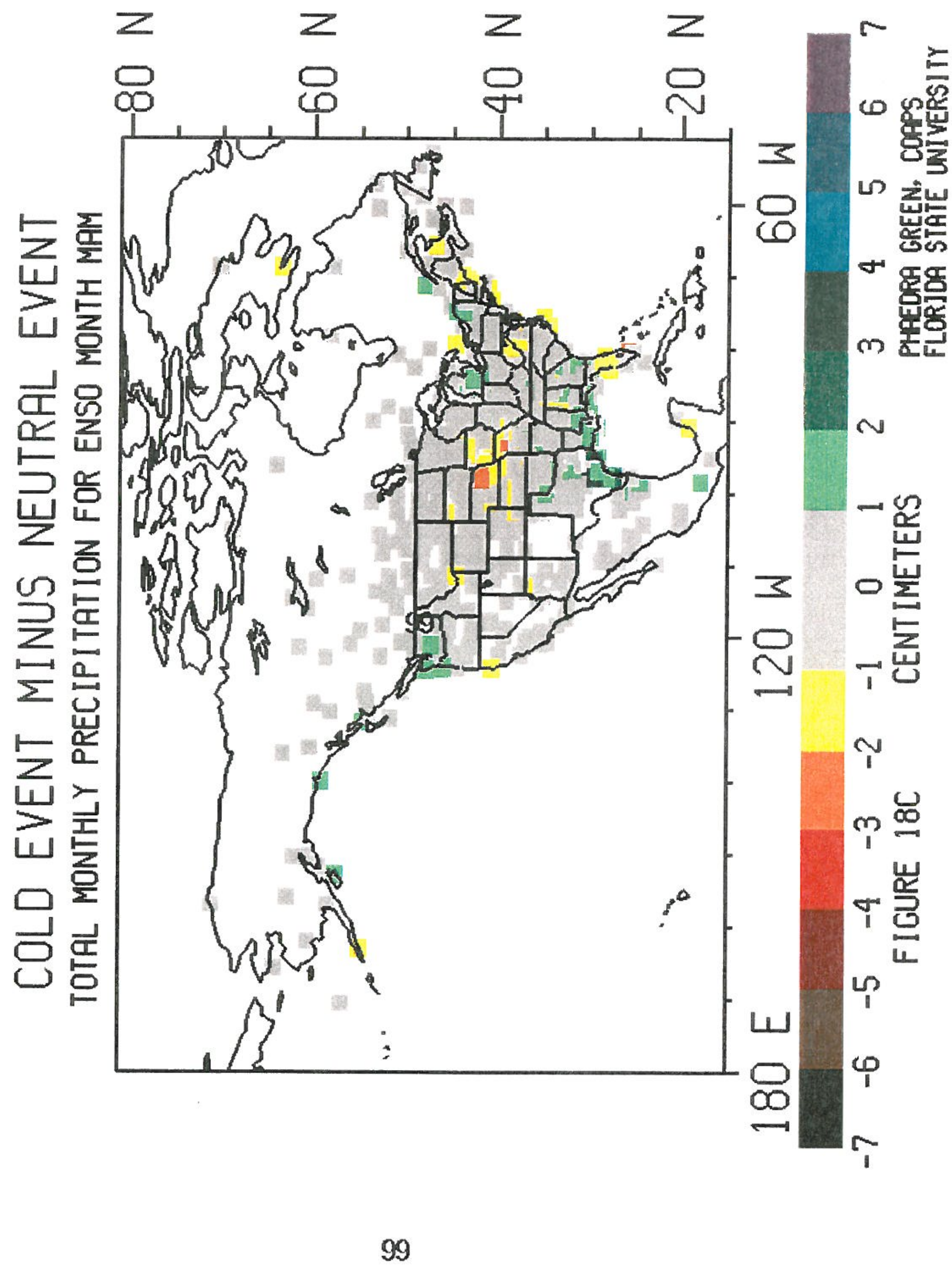


FIGURE 18B


COLD EVENT MINUS NEUTRAL EVENT
TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH MAM
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
CENTIMETERS
FIGURE 18C
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY

COLD EVENT MINUS NEUTRAL EVENT

TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH JJA

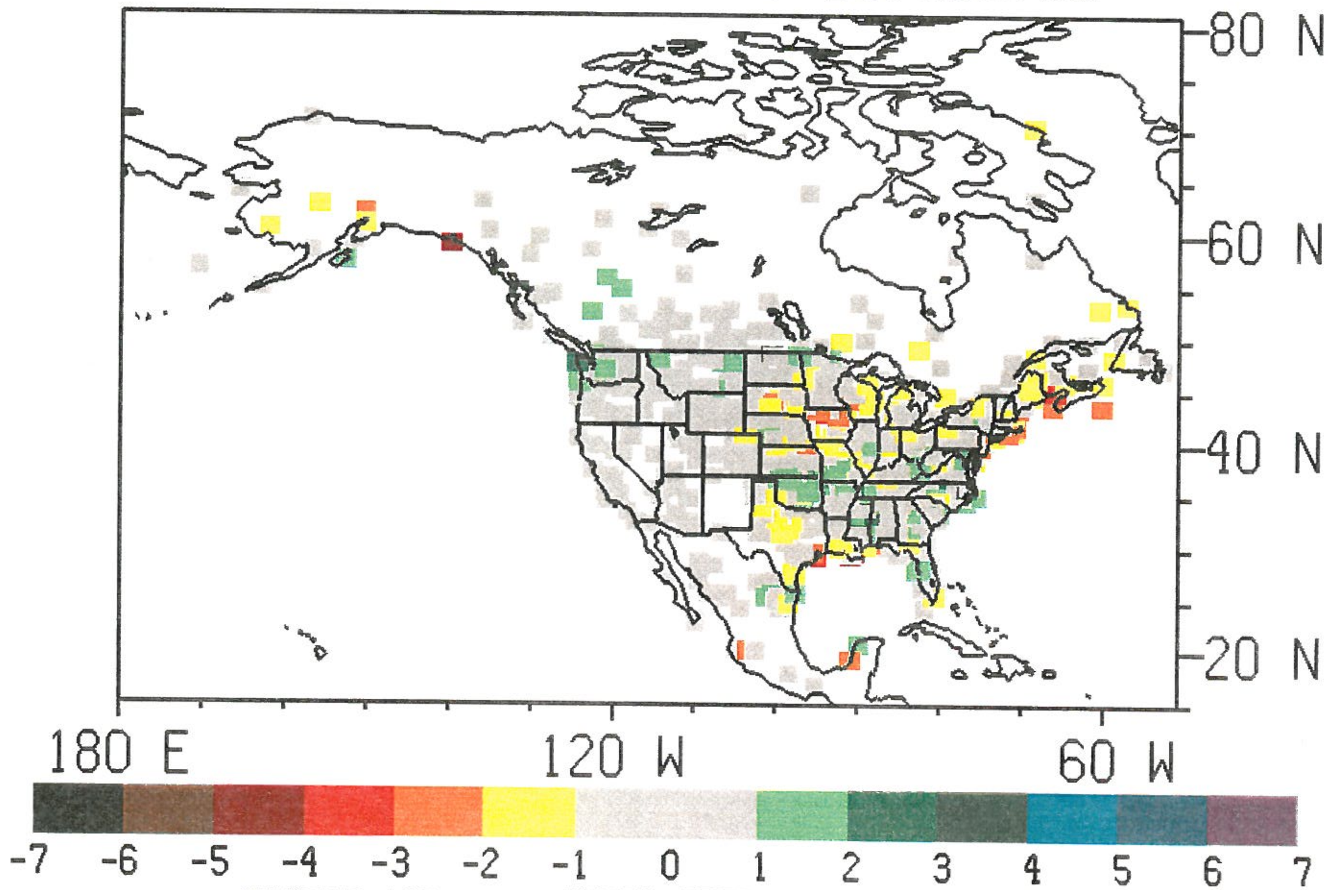


FIGURE 18D

WARM EVENT MINUS NEUTRAL EVENT

TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH OND

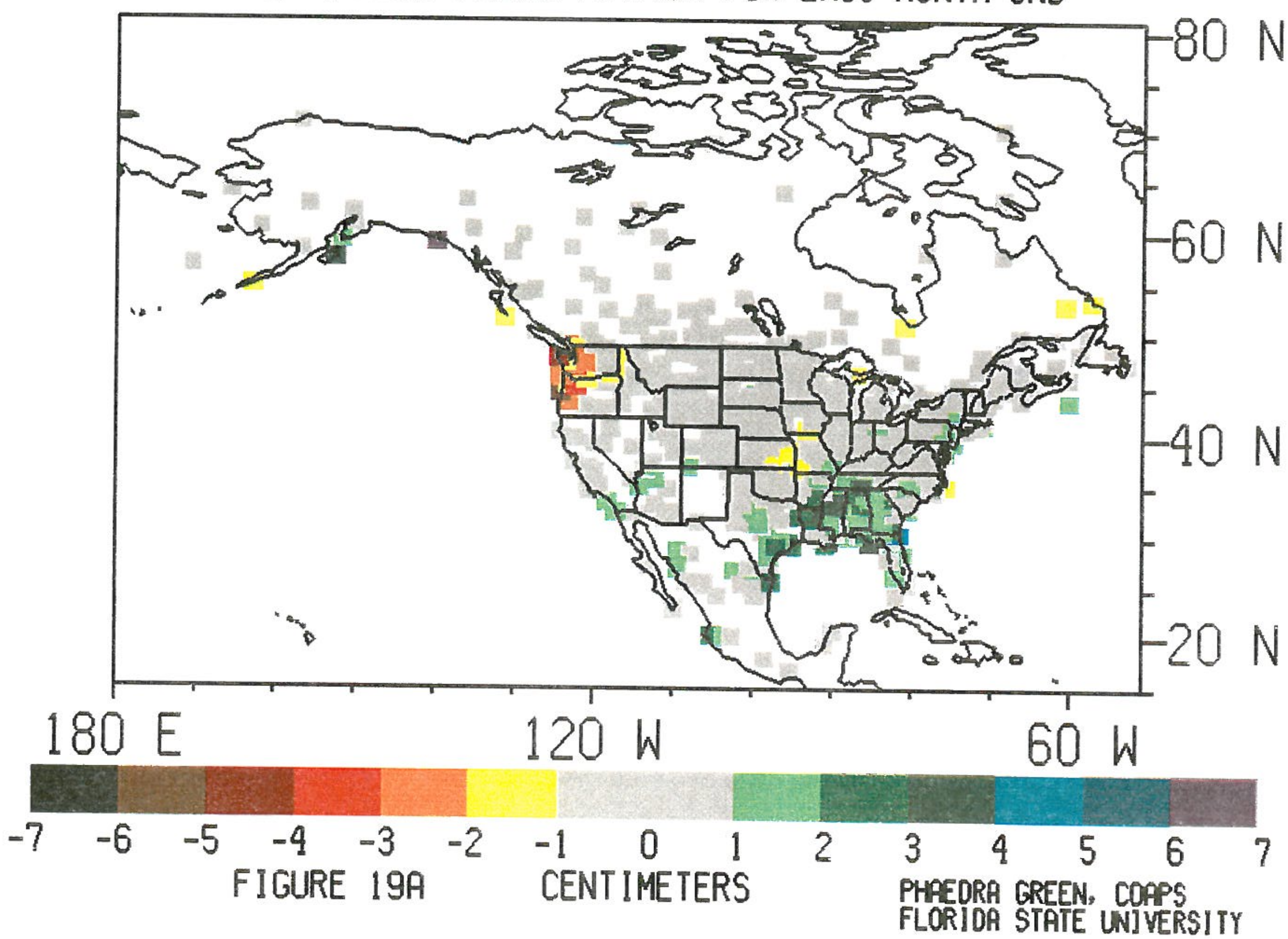
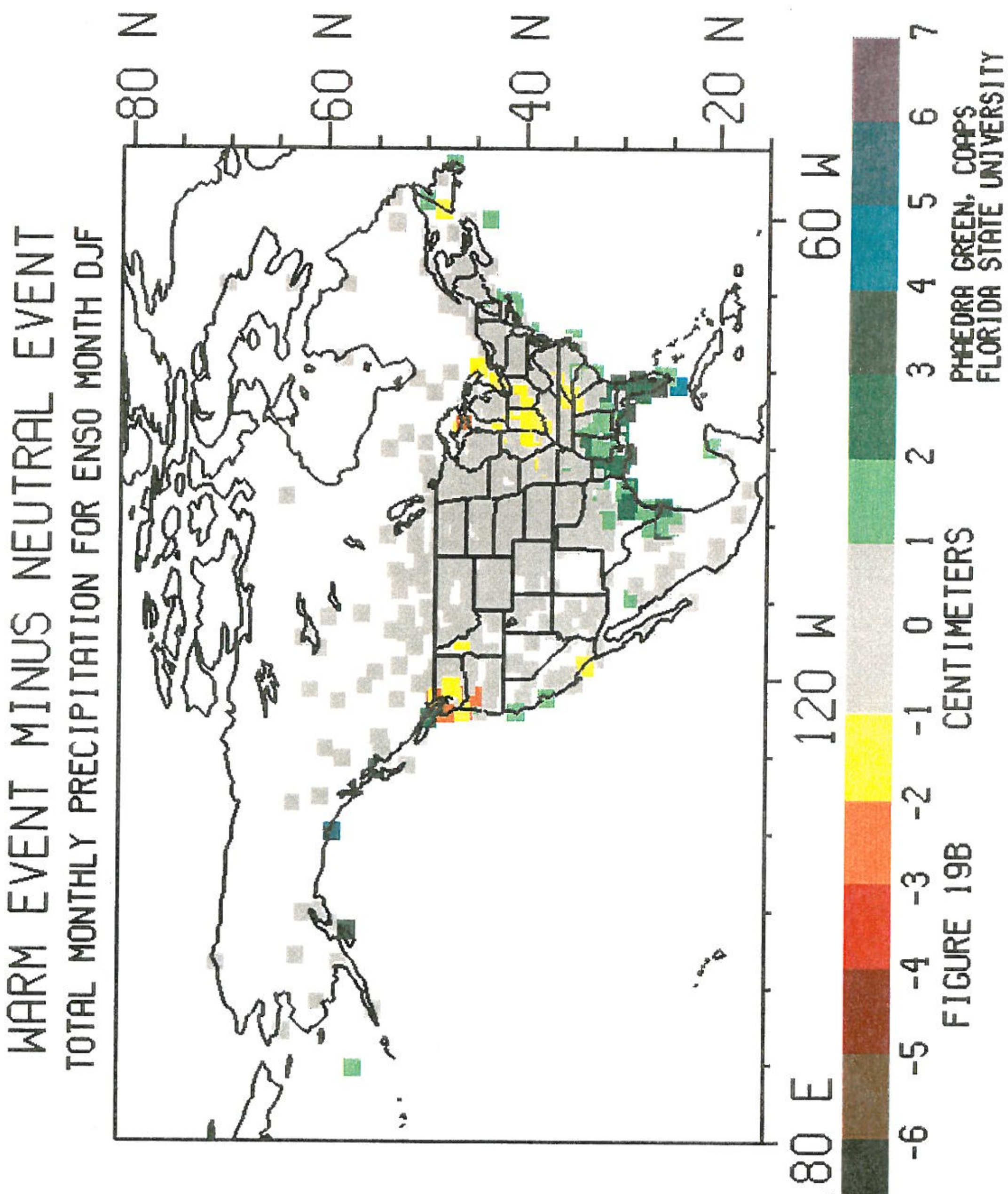


FIGURE 19A


WARM EVENT MINUS NEUTRAL EVENT
TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH DJF
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
CENTIMETERS
FIGURE 19B
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY

WARM EVENT MINUS NEUTRAL EVENT

TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH MAM

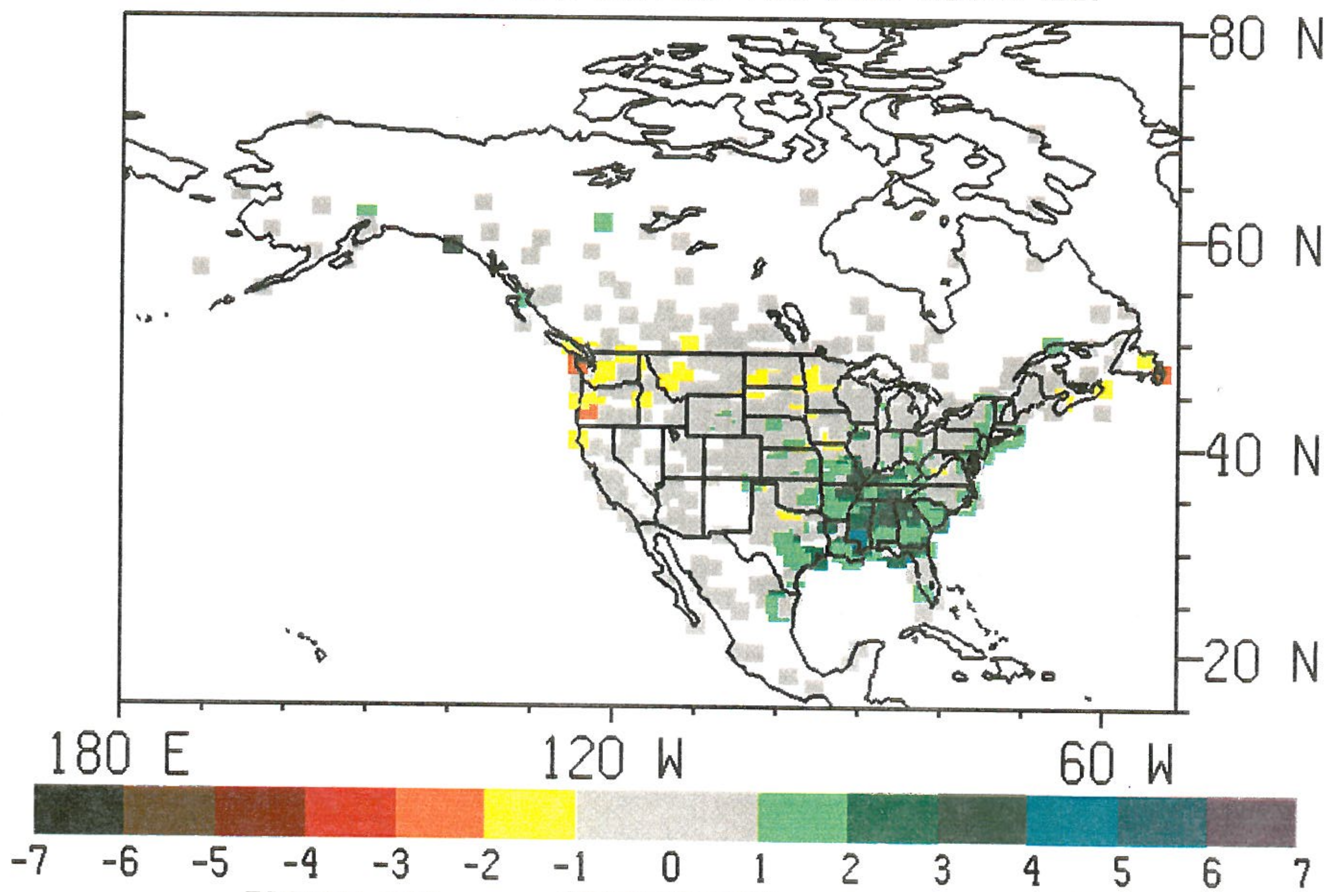
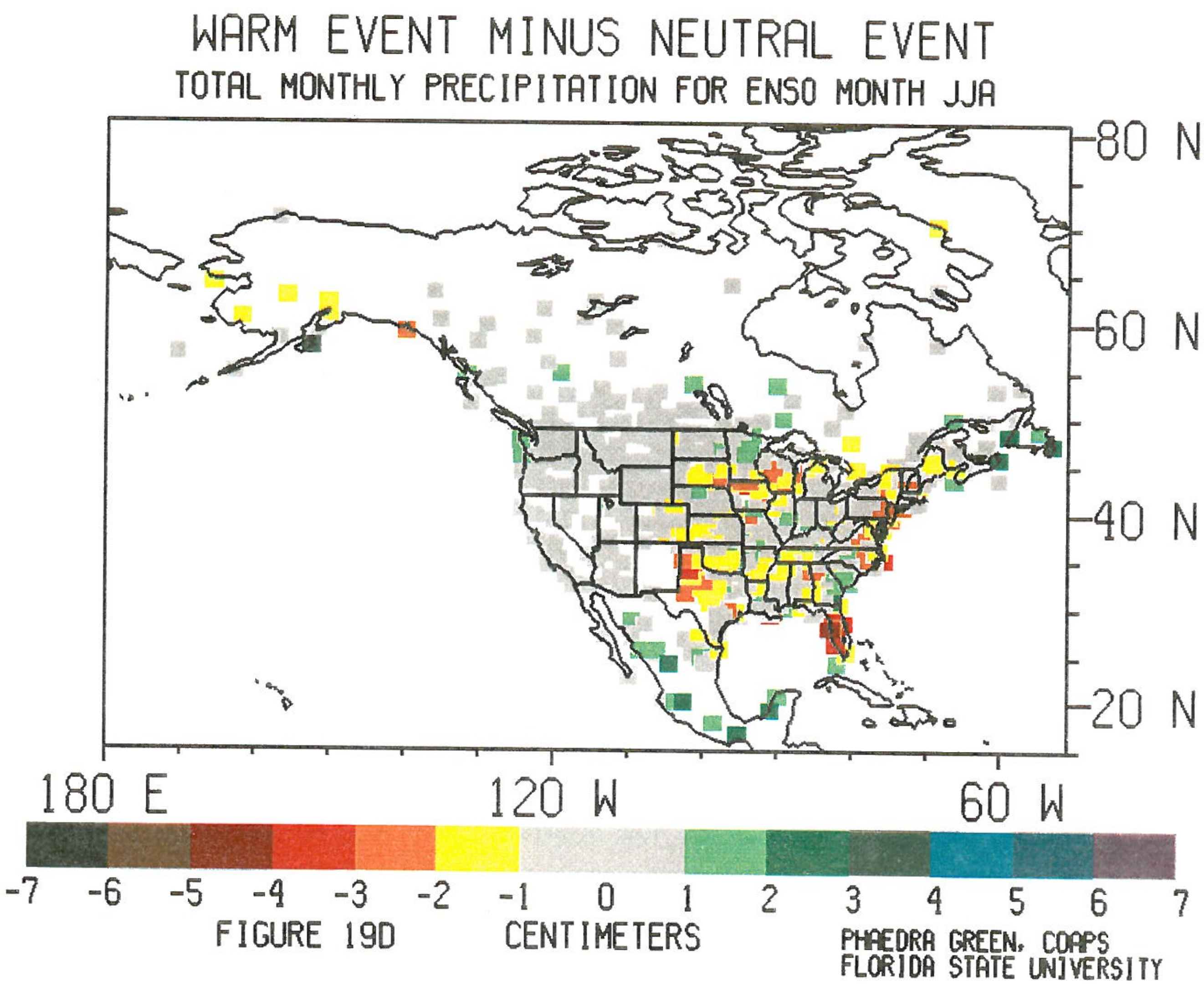


FIGURE 19C


WARM EVENT MINUS NEUTRAL EVENT
TOTAL MONTHLY PRECIPITATION FOR ENSO MONTH JJA
80 N
60 N
40 N
20 N
180 E
120 W
60 W
-7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
FIGURE 19D
CENTIMETERS
PHAEDRA GREEN, COAPS
FLORIDA STATE UNIVERSITY