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DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL MODELING

INFLUENCE OF THE SEA SURFACE TEMPERATURE VARIABILITY ON FORMATION OF PLUVIAL CONDITIONS IN NORTH AMERICA

BACHELOR'S THESIS

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BACHELOR THESIS ASSIGNMENT

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Applied Ecology

Thesis title

Influence of the Sea Surface Temperature Variability on Formation of Pluvial Conditions in North America

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Objectives of thesis

The goal of this bachelor's thesis is to examine the sea surface temperature variability of Atlantic Multidecadal Oscillation and El Niño Southern Oscillation on formation of pluvial conditions in North America. The literature review of previous research will be provided as well as the results and conclusions of general circulation model analysis conducted on this topic.

Methodology

For the study the simulations of SST anomalies from the National Center for Atmospheric Research Community Atmospheric Model will be used to compare different effects of North Atlantic and tropical Pacific Ocean's SST anomalies on climate of North America. In order to analyze the significance of the influence standard statistical methods will be used and implemented in R/R Studio software.

The proposed extent of the thesis

ca 40 pages incl. illustrations

Keywords

Atlantic Multidecadal Oscillation, El Niño Southern Oscillation, wet spells, climate variability

Recommended information sources

Cook, B.I. et al., 2010. Forced and unforced variability of twentieth century North American droughts and pluvials. Climate Dynamics, 37, pp.1097–1110.

Cook, B.I., Seager, R. & Miller, R.L., 2011. On the Causes and Dynamics of the Early Twentieth-Century North American Pluvial. Journal of Climate, 24(19), pp.5043–5060.

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Oglesby, R.J. et al., 2011. The role of the Atlantic Multidecadal Oscillation on medieval drought in North America: Synthesizing results from proxy data and climate models. Global and Planetary Change, 85, pp.56–65.

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Declaration

I declare that I have written this bachelor's thesis by myself under the leadership of doc. Ing. Martin Hanel, Ph.D. The leaders of my research conducted in the United States of America were Dr. Robert Oglesby and Dr. Michael Veres, who also provided additional information. I stated all the literature resources that I have used in this thesis.

In Prague 12. 4. 2016 ……………………………………..

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I would like to thank the leader of my thesis doc. Ing. Martin Hanel, Ph.D for his leadership and help. Also to Dr. Robert Oglesby and Dr. Michael Veres for their help with the research part of my thesis. I am very grateful to the entire Robitschek Scholarship staff for giving me the opportunity to study in the United States where I conducted the research. I would also like to thank my family which supported me during my studies.

In Prague 12. 4 .2016

Abstrakt

Dlouhotrvající pluviálová období, která mohou vést k velkoplošným záplavám, jsou vážnou hrozbou pro ekonomii a lidskou společnost vůbec. Tyto extrémně vlhké podmínky jsou způsobeny kombinací různých faktorů. Dominantní vliv má variabilita teploty povrchové vody oceánů v kombinaci s variabilitou zemského povrchu. V současné době jsou období sucha lépe zmapovaná, než pluviály, ty jsou však v podstatě pouze opačným procesem, než sucha. Pokud budeme pozorovat opačné procesy k těm, co vytváří suché podmínky, pravděpodobně najdeme příčiny pluviálů. Porozumění klimatologickým procesům může zásadním způsobem zlepšit předpovědi v meziročních a mezidekadálních měřítkách S ohledem na probíhající klimatické změny je tudíž tato problematika pro lidskou společnost velmi aktuální a důležitá.

Předmětem této práce je zkoumání vlivu variability Atlantické multidekadální oscilace (AMO) a El Niño jižní oscilace (ENSO) na klimatické podmínky, specificky povrchovou teplotu, srážky a na integrovanou vlhkostní konvergenci, v oblasti Severní Ameriky. Data, získaná pomocí klimatického modelu, byla vytvořena v předchozí studii. Podle výsledků analýzy dat má teplá fáze ENSO zásadní vliv na vytvoření podmínek vhodných pro vznik pluviálu v centrální části Spojených Států Amerických. Studená fáze AMO v kombinaci s teplou fází ENSO má především vliv na rozložení srážek a velikost rozšíření areálu působení samostatné teplé fáze ENSO. Zajímavým zjištěním je také vliv studené fáze AMO na vznik pozitivní vlhkostní anomálie během zimní sezóny na západě Spojených Států. Nález této anomálie je důležitý především ve spojení s historickým pluviálem ze začátku dvacátého století, nicméně toto zjištění není podpořeno příznivými výsledky statistické analýzy.

Klíčová slova

Atlantická multidekadální oscilace, El Niño jižní oscilace, vlhká období, klimatická variabilita

Abstract

Long lasting pluvial periods leading to large scale flooding can be a serious threat for human economy and society in general. These extreme wet conditions are caused by a combination of different factors. The dominant influence seems to have SST variability in combination with land surface variability. Nowadays droughts are better mapped than pluvials, but pluvials are essentially just the opposite of droughts, so if we observe the opposite processes that are causing droughts, we can probably find causes of pluvials. Understanding processes determining climate variability can improve predictions at interannual-decadal time scales which can be, with ongoing climate changes, very important for human society.

In this paper the influence of Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO) variability on climate conditions, specifically surface temperature, precipitation and integrated moisture convergence, over North America is discussed. Climate model data were obtained from previous study. The results show that the formation of pluvial conditions over central part of the U.S is strongly influenced by warm phase of ENSO. Cold phase of AMO combined with warm ENSO has mostly effect on spatial extent of the pluvial conditions created by ESNO forcing. Coincidence of moisture surplus anomaly with cold AMO forcing during winter season is also important finding especially in connection to twentieth century pluvial, however it is not supported by statistical analysis.

Key words

Atlantic Multidecadal Oscillation, El Niño Southern Oscillation, wet spells, climate variability

List of Acronyms

AMO	Atlantic Multidecadal Oscillation
CAM2	Community Atmospheric Models version 2
CAM3.1	Community Atmospheric Model version 3.1
ENSO	El Niño Southern Oscillation
GCM	Global Climate Mode
NADA	North American Drought Atlas
NASH	North Atlantic subtropical high-pressure system
NCAR	National Center for Atmospheric Research
NCL	NCAR Command Language
NOAA	National Oceanic and Atmospheric Administration
PDSI	Palmer Drought Severity Index
SST	Sea Surface Temperature
U.S.	The United States of America

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1. Introduction

During the last millennium, there have been several long lasting dry periods (droughts) and persistent widespread wet periods (pluvials) (e.g. Fye et al. 2003; Woodhouse et al. 2005). Both types of these extreme events can have a large impact on human society. In the last 15 years there were several of these anomalistic fluctuations in North America such as consecutive droughts in 2000-2005 in the central and western United States (Hu et al. 2011), an ongoing exceptional drought in western United States (NDMC 2016), Ohio River valley summer flooding in 2008, and central and southern U.S. flooding in 2010 (Hu et al. 2011). This is the main reason why studying, understanding and predicting droughts and pluvials is so important (Fye et al. 2003). With ongoing and future climate changes, the global water cycle and precipitation patterns are very likely to be affected (Zhou et al. 2012). According to the 5th Assessment Report on climate change from the Intergovernmental Panel on Climate Change (IPCC 2014) there are likely more land regions where the number of heavy precipitation events has increased than where it has decreased. Recent detection of increasing trends in extreme precipitation and discharges in some catchments implies greater risks of flooding on a regional scale. It is crucial to determine how to predict the precipitation patterns. Once this is understood, it then becomes possible to apply this information in disaster risk management, spatial or land-use planning and others (IPCC 2014). Modeling of past climate events can help to better assess future climate changes.

2. Thesis goals

The goal of this bachelor's thesis is to examine sea surface temperature (SST) variability influence of Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO) on the formation of pluvial conditions in North America. The extensive literature review of previous research will be provided as well as the results and conclusions of research conducted by myself on this topic. Significant questions to ask are: How do different anomalies in SSTs create wet conditions in central and western North America? Are there any interactions between individual SST patterns that combine to create wet conditions in central and western North America?

Examination of SST variability will be made using the National Center for Atmospheric Research Command language (NCL) under the supervision of Dr. Robert Oglesby and Dr. Michael Veres. The output of this experiment will be plots of surface temperature, precipitation and moisture flux over North America under diverse conditions of SSTs with specific focus on seasonal variability. Additional statistical analysis will be conducted by using the program R/R Studio.

Questions for future research include: How does land surface variability interact with SST variability creating the pluvial conditions? Does any pattern exist connecting pluvial occurrence between central and western North America and western and central Europe?

3. Literature Review

3.1 Methods of Studying Pluvials

Instrumental records only extend about 100-150 years into the past and necessitates the need for other ways to reconstruct past climate data (Cook et al. 2014). This includes proxy records, historical literature and climate models.

Proxy data incorporate, for example, thickness of rivers, lakes or offshore sediment layers, salinity and chemical analysis of lake and marine sediments (e.g. Guiot et al. 1993; Schimmelmann et al. 1998; Kallel et al. 2000) isotopic and biotic analysis of marine sediments (Andrews & Giraudeau 2003) ice core and coral data or tree ring data (Moberg et al. 2005), fossil pollen data (Peyron et al. 1998). Tree-rings serve as one of the most widespread and important proxy records. They are used for reconstructing past values of the Palmer Drought Severity Index (PDSI; Palmer 1965), which incorporates moisture supply (via precipitation) and evaporative demand (as a function of temperature). Since drought can be understood as a moisture deficit event and pluvial as a moisture surplus event, reconstructions of PDSI values for past events are important for tracking variabilities in climate (Cook et al. 2011). Fye et al. (2003) state a high correlation between regionally averaged instrumental data and reconstructed summer PDSI data, and note that PDSI data can be used for similar moisture anomalies during the last 500 years. Tree-ring data also have some limitations. They provide information solely about subpolar terrestrial regions, mostly from warm seasons, for reconstruction of cold seasons the data are available only from semiarid and Mediterranean species (Mann 2002).

Historical data (e.g., chronicles of European towns, agriculture yields reports, city governmental records, etc.) are useful for past climate reconstruction especially in Europe and Asia, where pluvials have also occurred (Vašků 1997). The Colorado River Compact from 1922 in North America can serve as an example of a historical record about pluvials. In the Colorado River Compact, which was made during an era of the twentieth century pluvial, an overly generous amount of water (in perspective to present river flows) was allocated between states in the Colorado River Basin (Christensen et al. 2004).

General circulation models (GCM) and regional climate models play a critical role in the understanding of hydroclimatic variability (Cook et al. 2010). The first coupled ocean-atmospheric GCM was made by the Geophysical Fluid Dynamics Laboratory at the beginning of the 1960s. Long-term climate predictions depend on the Earth's energy balance between four main climate components which are atmosphere, land surface, ocean and sea ice. GCMs are representing a complex mathematical image of these components. These elements interact with each other, they exchange heat, moisture and momentum. The atmospheric component is important carrier of heat and water, the ocean component plays a big role in climate being a reservoir of heat and carbon. Surface characteristics (e.g. snow cover, vegetation, soil water…) are simulated in the land surface component. Solar radiation absorption and exchanges of heat and water between air and sea are modulated by the sea ice component (GDFL 2016).

Changes in local effects, such as land surface feedbacks due to soil moisture or snow cover, are known to influence the length and severity of climate anomalies (Oglesby & Erickson 1989; Oglesby et al. 2002). SST variability can also have a crucial effect on the development of North American climate (eg. Seager et al. 2005; Mo et al. 2009; Kushnir et al. 2010; Cook et al. 2011). Some of the most important SST influences on precipitation patterns in North America on interannual time scales are the Atlantic Multidecadal Oscillation (Oglesby et al. 2011), El Niño Southern Oscillation (Ropelewski & Halpert 1986) and the Pacific Decadal Oscillation (Zhang et al. 1997).

3.2 Sea Surface Temperature Variability and its effects on North America

Sea surface temperature is a crucial feature in climate observations. Since the ocean covers most of the Earth's surface, the temperature of its surface is a dominant element of global average temperature and hence is implied in atmospheric global circulation model as a boundary condition. SSTs are obtained either by in-situ measurements using temperature sensors attached to various objects occurring in sea (ships, ocean reference stations, surface drifting buoys) or by space-based measurements. Satellites collect temperature data by inferring it from microwave and infrared radiation emitted by the ocean. Combination of these two techniques provide precise and widespread picture of SSTs (NOAA OCOP 2016). As an important climate component SST variability has a significant influence on precipitation patterns over North America with a particular effect of AMO (e.g. Hu & Feng 2008; Mo et al. 2009; Hu et al. 2011) and ENSO (e.g. Ropelewski & Halpert 1986; Hu & Feng 2001).

3.2.1 Atlantic Multidecadal Oscillation

Atlantic multidecadal oscillation can be explained as climate swings occurring most evidently around the North Atlantic with a period of oscillation from 50 to 70 years. It was first noticed by Jacob Bjerkens, who was primarily studying El Niño, in 1964 (Kerr 2000). Schlesinger and Ramankutty (1994) used singular spectrum analysis on global surface temperature records and diagnosed an oscillation with a 65-70 year period, suggesting its origin in the internal variability of the ocean-atmosphere system. In another research study, the variability was observed by proxy based reconstruction of multi-century surface temperatures as well as an instrumental record, however the short history of the instrumental record and long oscillatory time makes this topic difficult to assess. Multi proxy data confirm this oscillation to be present in the climate system over the last 300 years (Delworth & Mann 2000)

When studying pluvials it is important to understand how the AMO is related to rainfall in the continental United States. A study by Enfield et al. (2001) uses three data sets to determine the effects of AMO: monthly reanalysis of global SST anomalies, monthly rainfall over the United States and the records of Mississippi River outflow and Florida's Lake Okeechobee inflow. When AMO is in a warm or cold phase, SSTs over the entire North Atlantic show positive or negative anomalies, respectively. According to the results, AMO cool phases occurred during 1905-1925 and 1970-1990, and warm phases during 1860-1880 and 1940-1960. During warm phases most of the United States receives less than the normal amount of precipitation, which coincides with Midwestern droughts in the 1930s and 1950s (Enfield et al. 2001). Hu et al. (2011) use GCM simulations to understand processes lying between AMO and summertime precipitation over North America. Because the model anomalies are closely matching the observed anomalies it is suggested that AMO is responsible for summertime precipitation over North America at decadal time scales (Hu et al. 2011). AMO has a considerable impact on regional circulation regimes over North America when anomalies of persistent pressure and prevailing winds affect specific rainfall anomalies. The cold phase of AMO is connected with a precipitation surplus in the central United States. The main reason for this is that the monsoon rainfall is constrained to the south of the south-western region of United States by more northwesterly wind anomalies over the monsoon region (Hu & Feng 2008). Concurrently, the precipitation surplus in the central United States is supported by circulation anomalies and enhanced moisture transport which in turn is caused by substantial southerly low-level flow from the Gulf of Mexico. This flow is commonly associated with SST anomalies in the western tropical Atlantic Ocean (Wang et al. 2006; Hu & Feng 2008; Hu & Feng 2010). Oppositely during the warm phase of AMO most of North America receives below-average precipitation because the previously explained anomaly pattern changes (Hu & Feng 2008).

During different phases of AMO, different circulation anomalies occur. SST anomalies can, by differential heating, affect the atmosphere (specifically atmospheric pressure) with the largest disparity in the North Atlantic subtropical high-pressure system (NASH). Comparing the cold phase of AMO with the control run (monthly global climatological SST field averaged over the period from 1871-2008) NASH enhances and shifts its center towards the west by roughly 20°. During this process, the western part of the NASH is protracted in the meridional direction. This means the whole of North America is under the impact of the western part of this high pressure system. Enhanced NASH creates two anomalous anticyclones, one in the eastern subtropical Pacific and one in the western subtropical North Atlantic. Along the eastern rim of the Rocky Mountain region, a relatively low pressure area occurs due to elevated terrain causing a southerly wind anomaly to develop. This wind helps to carry the moisture from the Gulf of Mexico (as mentioned above) to the central and northern United States and the convergence supports storm development and above average precipitation anomalies. When AMO is in the cold phase there appears to be a horizontal shear across North America. The air mass on the north of this shear has a continental character while the southern mass has an oceanic origin. They interact with each other resulting in above-normal precipitation (Hu et al. 2011; Oglesby et al. 2011).

AMO is not responsible for all of the precipitation variability over North America by itself but operates mostly in conjunction with ENSO (Oglesby et al. 2011).

3.2.2 El Niño Southern Oscillation

El Niño is a periodic fluctuation of SSTs in the tropical Pacific Ocean and is strongly related to the Southern Oscillation. Fluctuations in sea level barometric pressure are described with the Southern Oscillation and quantified by the Southern Oscillation Index. Pressure is measured between Darwin, Australia and Tahiti observation stations. In normal conditions there is lower pressure over Darwin and higher pressure over Tahiti. These conditions lead to westward air circulation which is followed by warm surface oceanic water resulting in rainfall over Australia and the western Pacific. During an El Niño phase, which is connected with a smaller difference between barometric pressure in Darwin and Tahiti, the easterly winds are weaker and therefore the warm oceanic water layer is not drawn as far westwards as under normal conditions. This shifts the thermocline deeper under the water surface and slows the upwelling flow of cold nutrient-rich deep ocean water, normally occurring near the western coast of North America. Under El Niño conditions, which peak at the end of the year, equatorial South America receives above normal precipitation. Early Christian inhabitants connected this phenomenon with their celebration of the birth of Jesus, El Niño in Spanish, hence the name (NOAA 2016).

In a study conducted by Ropelewski and Halpert (1986), the connection between ENSO activity and North American precipitation and temperature anomalies was investigated using idealized two-year ENSO episodes. Above average precipitation correlated with ENSO occurs in 81% of cases for an area of North America including the southeastern region and north Mexico from October through March and also in the Great Basin of the western United States from April through October. Negative temperature anomalies occurred in 80% of simulated ENSO episodes in the southeastern region near the Gulf of Mexico from October through March (Ropelewski & Halpert 1986). In research obtained by Hu and Feng (2001), teleconnections between precipitation patterns in the central United States and ENSO activity were investigated. This region shows interannual summer rainfall in a 3-6 year period which is not in persistent correlation with ENSO cycle. Results showed that ENSO teleconnections were active in two time periods in the last 125 years, 1871-1916 and 1948-1978. In the time of an active teleconnection warm phase, ENSO circulation supported a deformation in the lower troposphere which caused wet summers, the opposite process appeared during the cold phase of ENSO. These results partially explain the interannual rainfall summer patterns in central North America. (Hu & Feng 2001). Wet conditions in the High Plains region are related to an El Niño–like SST anomaly pattern with a warm equatorial Pacific, warm Indian Ocean, cool waters in the central North and South Pacific, and warm waters along the coasts of the Americas (Seager et al. 2005). Also the drier conditions were observed during La Niña phase and medieval droughts in North America were related to cool conditions in the tropical Pacific (Oglesby et al. 2011).

3.2.3 Interrelationship between AMO and ENSO

AMO is the originator of the atmospheric circulation anomalies and ENSO seems to be able to strongly modify them (Hu & Feng 2012). A study conducted by the U.S. Climate Variability and Predictability Drought Working Group shows that AMO's effect on annual precipitation in North America is much weaker than the effect of ENSO because AMO primarily affects summertime precipitation and when averaged over the whole year it has a weaker effect (Hu & Feng 2008; Feng et al. 2011). ENSO affects North America mostly in seasons other than summer, with the strongest force during boreal winter therefore the annual effect is stronger. According to these results, either ENSO has a different impact on rainfall during different AMO phases, or AMO influences variations in the effect of ENSO (Hu & Feng 2012). The influence of the SST anomalies seems to be large when they differ in their phases (EL Niño and the cold phase of AMO, La Niña and the warm phase of AMO) (Mo et al. 2009).

3.3 Historical Pluvials

The best way of approaching my thesis topic is to look into the history of the occurrence of pluvials. Pluvials seem to appear all over the northern hemisphere within the last millennium.

From the Asia region it is worth mentioning the Mongolian pluvial which occurred at the beginning of 13th century. This above average moisture era (1211 to 1225 CE) does not include the wettest years on the record of reconstructed PDSI values in this area, but is the longest period of persistent wetness in the last 1,112 years. Abnormal wetness and a warm but not exceptionally hot climate also matches with the rise of Chinggis Khan's empire and the expansion of the Mongols (Pederson et al. 2014). Another mention about persistent wet spells in Asia is in tree-ring based research from Quilian Mountains where eight wet periods were observed during the last millennium (Fang et al. 2009).

Vašků (1997) distinguishes four "little" pluvial eras during the last millennium in the Czech lands. He collects information about historical climate from abundant historical records such as chronicles of towns, records of water allocations, old rural calendars and even poems. The pluvials occurred in 1078–1118, 1310–1350, 1560–1600 and 1763–1804. They are mostly characterized by extreme floods, extreme soil erosion, crop failure and consecutive famines that were so severe they were compared to medieval plague epidemics (Vašků 1997). Another reference to European pluvials comes from the Fennoscandia region. Hydroclimate variability was described using tree-ring proxy data to observe five pluvial events (moisture surplus in five or more consecutive years) over the last millennium in the thirteenth, sixteenth and seventeenth centuries (Seftigen et al. 2014). Another tree-ring climate reconstruction from south-eastern Finland talks about prolonged periods of wet spells during 1081–1095, 1433–1447 and 1752–1765 (Helama & Lindholm 2003).

According to Cook (2014) North American multidecadal pluvials are apparent during ca. 1090–1120, 1260–1350, and 1440–1475 CE (Figure 1 and 2). For this reconstruction they used spatially averaged NADA (North American Drought Atlas) data over four regions (Southwestern, Central Plains, Northwestern, and Southeastern) to derive regional time series of PDSI (1000–2005 CE).

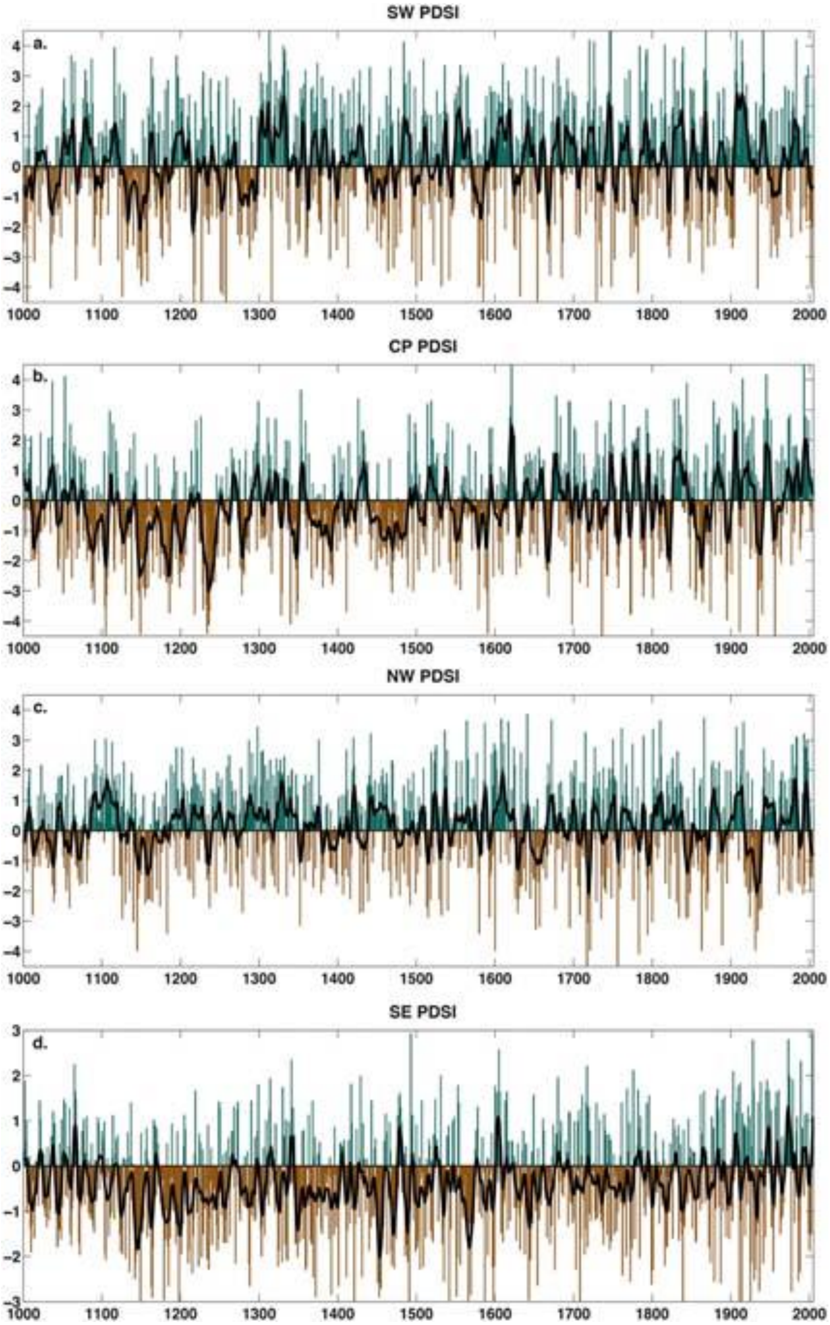


Figure 1: "Area averaged PDSI from the North American Drought Atlas for the (a) Southwestern, (b) Central Plains, (c) Northwestern, (d) Southeastern region. Green and brown bars are the original data, and dark black lines are a smoothed version of the time series using a 10-yr LOWESS spline" (Cook et al. 2014)

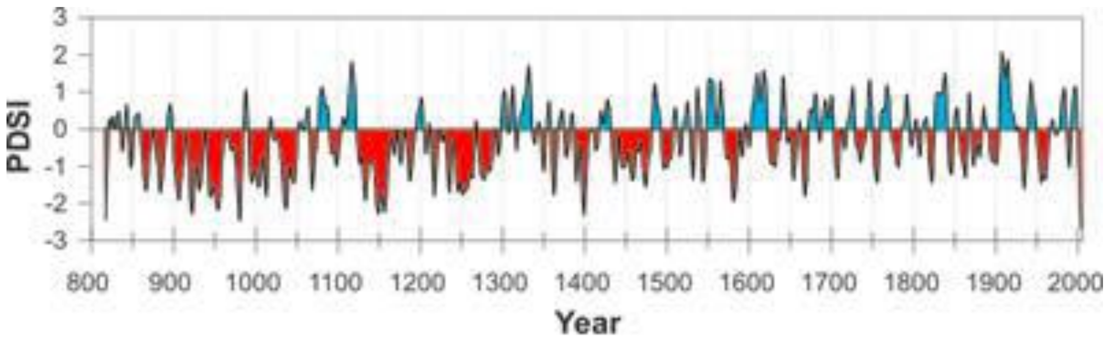


Figure 2: "Regional reconstruction of the PDSI, AD 818–2003, smoothed with a 10-year spline. Red shading indicates negative values and dry years, and blue indicates positive values and wet years" (Woodhouse et al. 2005)

Also Fye et al. (2003) mention that the 20th century pluvial had three potential analogs in the sixteenth century from 1549 to 1548, in the seventeenth century from 1602 to 1622 and in the nineteenth century from 1825 to 1840 described by mean reconstructed summer PDSI (Figure 3).

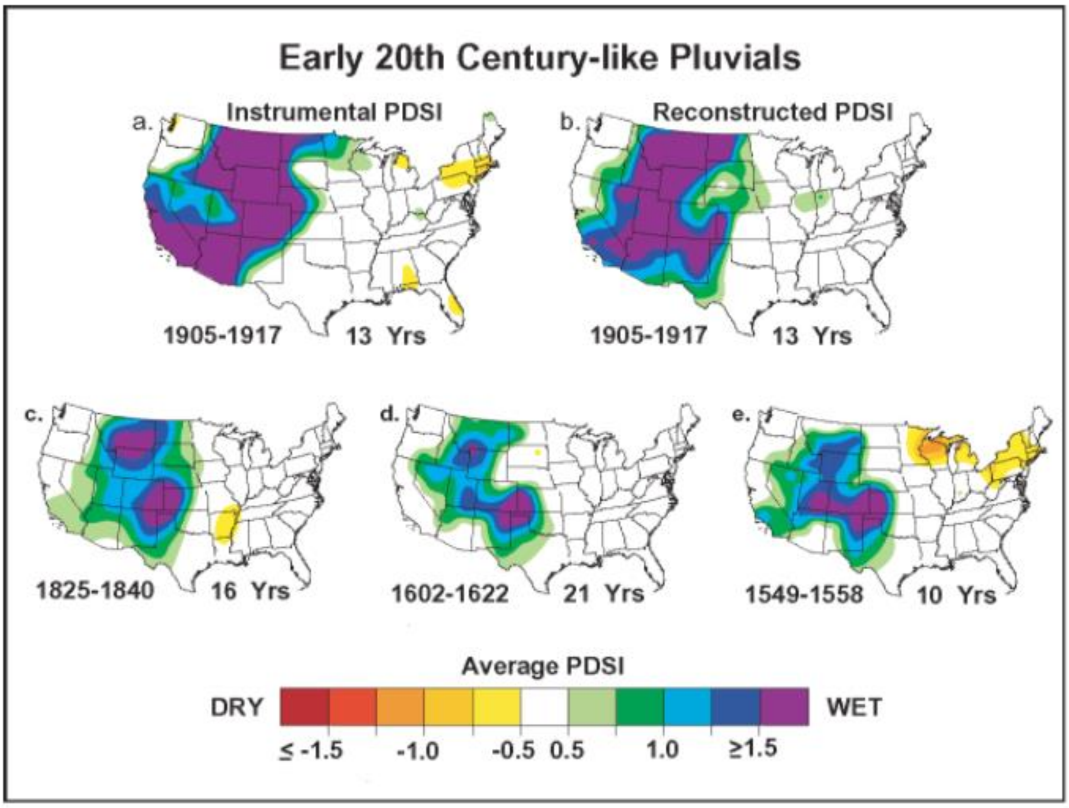


Figure 3: "The early twentieth-century pluvial and its analogs. (a) and (b)Mean instrumental and reconstructed summer PDSI for the period 1905–17; (c)–(e) Mean reconstructed summer PDSI averaged and mapped over the United States for the time periods indicated" (Fye et al., 2003).

Van der Schrier and Barkmeijer (2007) study atmospheric circulation in North America and its connections to the 1818-1824 drought and the 1825-1840 pluvial. They compare tree-ring PDSI reconstructions to results of an ocean-atmosphere coupled climate model of intermediate complexity. The simulations show that wet conditions are maintained from the winter or early spring to summer by reorganized atmospheric circulation over the United States. The new circulation pattern allows subtropical moisture from the Gulf of Mexico to flow northwards into the region of the Great Plains (van der Schrier & Barkmeijer 2007).

3.3.1 The Twentieth-Century Pluvial in the Western United States

An inappropriate allocation of water resources between Upper and Lower Colorado River basin states decided by The Colorado River Compact in 1922 can serve as a good example of how the pluvials may affect human society, decision making, and water management. This allotment was based on measuring the discharge of the Colorado river during abnormally wet conditions at the beginning of the twentieth century (Christensen et al. 2004). This wet anomaly is considered to be a part of a period referred to as the twentieth-century pluvial which took place in western America, covering a nine-state area (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Utah and Wyoming), in approximately 1905-1917. The spatial and time extension of this particular pluvial event was determined using observed and reconstructed PDSI data (Fye et al. 2003). It is further confirmed by observations from 136 climate stations from the National Weather Service. Its high intensity, long time and wide spatial span make it a unique event within the past 12 centuries (Woodhouse et al. 2005).The development of this pluvial occurred in two wet phases with a short break in 1910 of dry or near-normal conditions which coincided with La Niña phase of ENSO. La Niña is typically connected with precipitation suppression in the southwest of North America and the southern Great Plains (Cook et al. 2011). According to observed and reconstructed data analysis, the occurrence of the twentieth-century pluvial was primarily a winter season phenomenon. High winter precipitation and wet summers clustered in consecutive years were probably the most important driving forces of this climate anomaly. A big contributor to this moisture anomaly seems to be moderately heavy and heavy 5-day periods of precipitation (Woodhouse et al. 2005). But almost all regions also experienced precipitation deficits, the southwest during summer and autumn, the northwest during winter and the Central Plains during spring (Cook et al. 2011). This supports the theory that cooler temperatures also strengthen the extensive appearance of the pluvial with an effect of less evaporation and slower melting of accumulated snowpack (Woodhouse et al. 2005). Temperatures during this particular pluvial were cooler not just compared to nowadays but also relatively to temperatures at the end of nineteenth century. Different regions were affected by a mixture of higher precipitation rates and evaporative demand effects creating pluvial conditions. Moisture surplus in the Southwest originated from increased precipitation, in the Central Plains a decreased evaporative demand was important, and in the Northwest the pluvial was a result of the combination of these two moisture anomalies. SST variability was also examined. During this pluvial event, El Niño occurred five times (in 1905, 1906, 1912, 1914 and 1915). The effect of this seems to be mostly observed in the Southwest by increased precipitation and moisture convergence. During the pluvial, the North Atlantic was cooler than normal (Cook et al. 2011). This state is usually connected with an increase of precipitation in central North America predominantly during the warm season (Enfield et al. 2001). The cold phase of AMO is linked with ten winters during the twelve year period, reflecting especially winter circulation, precipitation and temperature anomalies (Cook et al. 2011).

4. Methodology

Previously made GCM simulations of SST anomalies from CAM3.1 developed by the NCAR (Collins et al. 2006), originally discussed in Hu et al. (2011) and Hu and Feng (2012), were used in this thesis to compare different effects of the North Atlantic and tropical Pacific Ocean's SST anomalies. Using model simulations, distinct effects of AMO and ENSO anomalies were separated. One weakness of this method is that it does not provide an entirely complete picture of the present-day climate, because of its simplification of the real climate system.

4.1 NCAR Community Atmospheric Model version 3.1

NCAR CAM3 is an atmospheric GCM that includes Community Land Model version 3, thermodynamic sea ice model, and an optional slab ocean model. It is designed to be modular and flexible so it can be used by the general scientific community in various climate studies. The model was changed compared to its previous version (CAM2) mostly in the parameterization of moisture processes, radiation processes, and aerosols. This led to a more precise and realistic simulation of tropical tropopause temperatures, boreal winter land surface temperatures, surface insolation, and clear-sky surface radiation in polar regions. Importantly for my research, the variation of cloud radiative forcing during ENSO events shows a much better correlation with satellite observations (Collins et al. 2006). The model simulations are in agreement with simulations made using different models (Mo et al. 2009; Feng et al. 2011).

This study uses the same configuration of this model as Hu et al. (2011) and Hu and Feng (2012) which has 26 levels in vertical and 42-wave triangular spectral truncation that is equivalent to a 2.8-degree resolution in longitude and latitude. During the model runs, the solar constant, concentration of greenhouse gases, and land surface vegetation parameters/distributions remain at the current conditions. The change that has been made to the model by Hu et al. (2011) is the addition of specific anomalies to the observed climatological SST in order to create the model experiments. The merged monthly mean U.K. Hadley Centre sea ice and SST dataset version 1 and 2 of the U.S. NOAA weekly optimum interpolation SST analysis were used to derive the observed SST data (Hurrell et al. 2008). This SST product has a spatial resolution of 1.0° x 1.0° in latitude and longitude. (Hu et al. 2011)

4.2 Model Experiments

This research focuses on examining how anomalies in different phases of the AMO and ENSO differ from a control simulation. The monthly global climatological SST field, averaged for 1871–2008, was used for every year of the 40-year control run. The control run served as a reference for comparison with SST experimental runs of different phases of the Pacific and North Atlantic Ocean's SST anomalies and was denoted as Ctrl.

The anomalies were simulated in different experimental runs. The AMO forcing experiments were conducted by Hu et al. (2011). For developing the SST anomalies, they identified the years (for the period 1871–2008) that had the annual AMO index in the warmest (coldest) quartile. The driving SST anomalies for the experimental runs were based on the average SST anomalies during the periods with AMO index in the warmest (coldest) quartile. To amplify signal to noise ratios and hence allow for a clearer dissection of causal mechanisms the magnitudes of these SST anomalies were then inflated by a factor of 2. (Hu et al. 2011). The ENSO forcing experiments were conducted by Hu and Feng (2012). In order to develop the SST anomalies, they identified the years (for the period 1871–2008) that had the annual El Niño-3.4 SST in the warmest (coldest) quartile. Again to amplify signal to noise ratios and allow for a clearer dissection of causal mechanisms the magnitudes of these SST anomalies were then inflated by a factor of 2 (Hu & Feng 2012). For experiments of AMO and ENSO forcing, the SST anomalies in the Pacific and North Atlantic Ocean were established for every month and year, and the CAM3.1 was integrated for 25 years. During anomaly simulations climatological SSTs were imposed elsewhere in the oceans (Hu et al. 2011; Hu & Feng 2012).

Since the particular interest of this research is in pluvials, moisture surpluses, the primary concentration was on the simulation of the cold phase of AMO and the warm phase of ENSO and their interaction. These phases of SSTs are commonly connected with enhanced moisture regimes above North America (described in the literature review chapter). However, simulations for the warm phase of AMO and the cold phase of ENSO were made as well. These oscillation phases are usually associated with a lack of precipitation and consecutive droughts (e.g. Feng et al. 2011; Oglesby et al. 2011; Hu & Feng 2012) The AMO driven experiments were denoted as Ac for the cold phase, Aw for the warm phase, and An for climatologically neutral SSTs in the Atlantic Ocean. The ENSO driven experiments were labeled Pc for La Niña conditions, Pw for El Niño phase, and Pn for climatologically neutral SSTs in the tropical Pacific Ocean. The analysis included examining the differences in averages (monthly, seasonal, annual, 25-year) between the experimental runs and the control run. Variables examined included temperature, precipitation, evaporation and vertically integrated moisture convergence (calculated as precipitation minus evaporation). Precipitation rate was also plotted as relative precipitation for better visualization of the anomaly. Relative precipitation was calculated as experimental anomaly divided by the control run and multiplied by 100, in order to derive the relative precipitation increase or decrease compare to the control run. For each variable and time average, a control plot and experimental plots were made, in which the anomaly from the control run was depicted (experimental run minus control run). Experimental plots contained different phases of AMO and ENSO – AnPw, AcPn for single SST forcing and AcPw for interaction. The same was constructed for the opposite phases of AMO and ENSO, which means a combination of AnPc, AwPn and AwPc.

4.3 Statistical analysis

The data described above were also statistically analyzed in the program R, specifically R Studio (RStudio Team, 2015). The focus was on determining if there is a statistically significant difference between the control and experimental runs for each grid point and each variable. The tested hypothesis was H0: Variables of experimental runs AnPw, AcPn, and AcPw are not significantly different from variables of control run in seasonal time perspective.

The data were organized in a data table where the values for AnPw, AcPn, and AcPw were compared with values for the control simulation.

H0 was examined with a two sample t-test for unpaired data. It was processed with a formula for test statistics:

$$T = \frac{\overline{X} - \overline{Y} - \delta}{\sqrt{(n-1)S_x^2 + (m-1)S_y^2}} \sqrt{\frac{nm(n+m-2)}{n+m}}$$

where $\acute{X}$is the sample mean for control data with a sample size of n and $\acute{Y}$ is the sample mean for experimental data with a sample size of m. The value of T was then compared to the two-tailed test critical value for Student's t-test distribution for infinite degrees of freedom for confidence level of 95% which is 1.9600. The grid points, where the difference between experimental data and the control run was statistically significant, were plotted on a map of North America. These plots were made for each tested variable and each season.

5. Results

5.1 Temperature

In the 25-year average run, the surface temperature anomalies for North America, especially for the central and southeastern regions, are colder in El Niño phase and the cold phase of AMO (Figure 4) than in La Niña and the warm AMO phase (Figure 5).

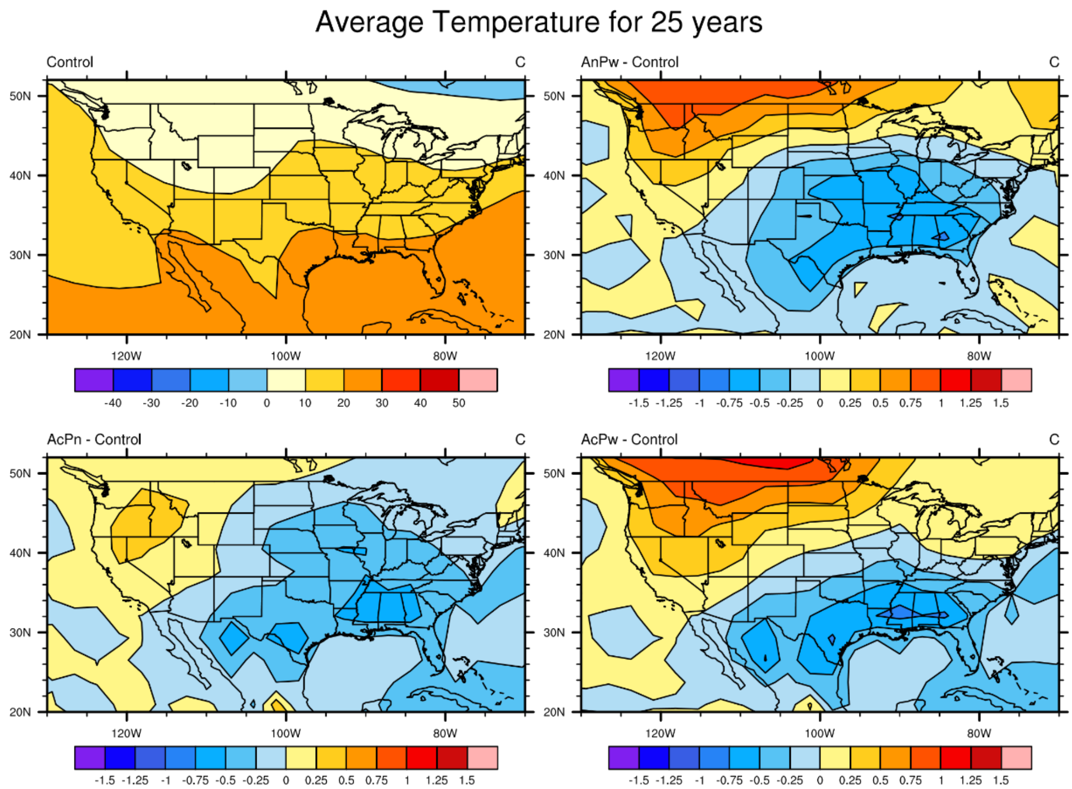


Figure 4: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged over 25 years for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

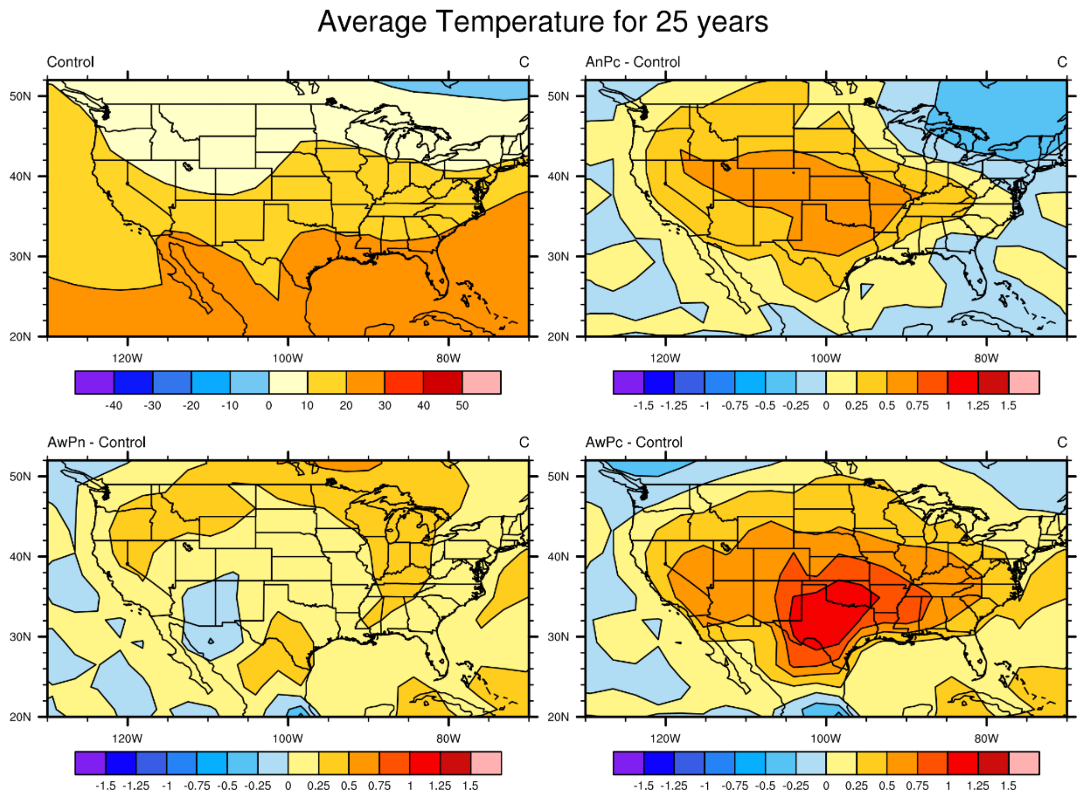


Figure 5: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged over 25 years for North America. Control run and anomalies (cold phase of ENSO, warm phase of AMO and their interaction) are shown.

For annual averaged surface temperatures, the cold anomalies of the AnPw experimental run occur for the central part of North America in 19 out of 25 years. For yearly averaged surface temperatures, the cold anomalies of the AcPw experimental run occur for northern Mexico and the U.S. states along the coastline of the Gulf of Mexico in 21 out of 25 years. For monthly averaged (averages of each month in a 25-year experimental run compared to averages of each month in the 40-year control run) surface temperatures, the cold anomalies are evident in spring months March, April and May (MAM) for most of North America (Figure 6) with all experimental combinations (AnPw, AcPn, AcPw) and for June and July mostly for the AnPw anomaly and the central part of North America (Figure 7).

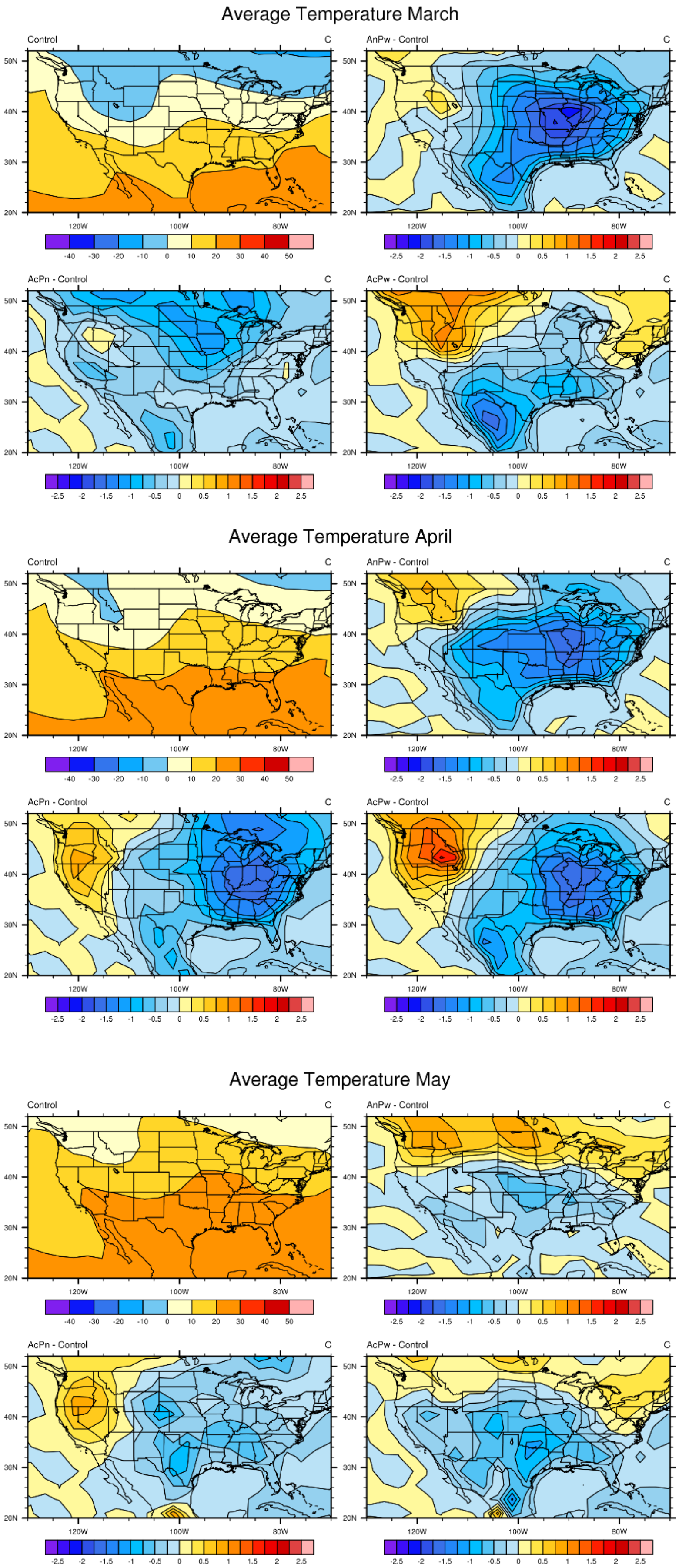


Figure 6: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged for each month over 40 years for control run and 25 years for experimental runs for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown for March, April, and May, the spring season.

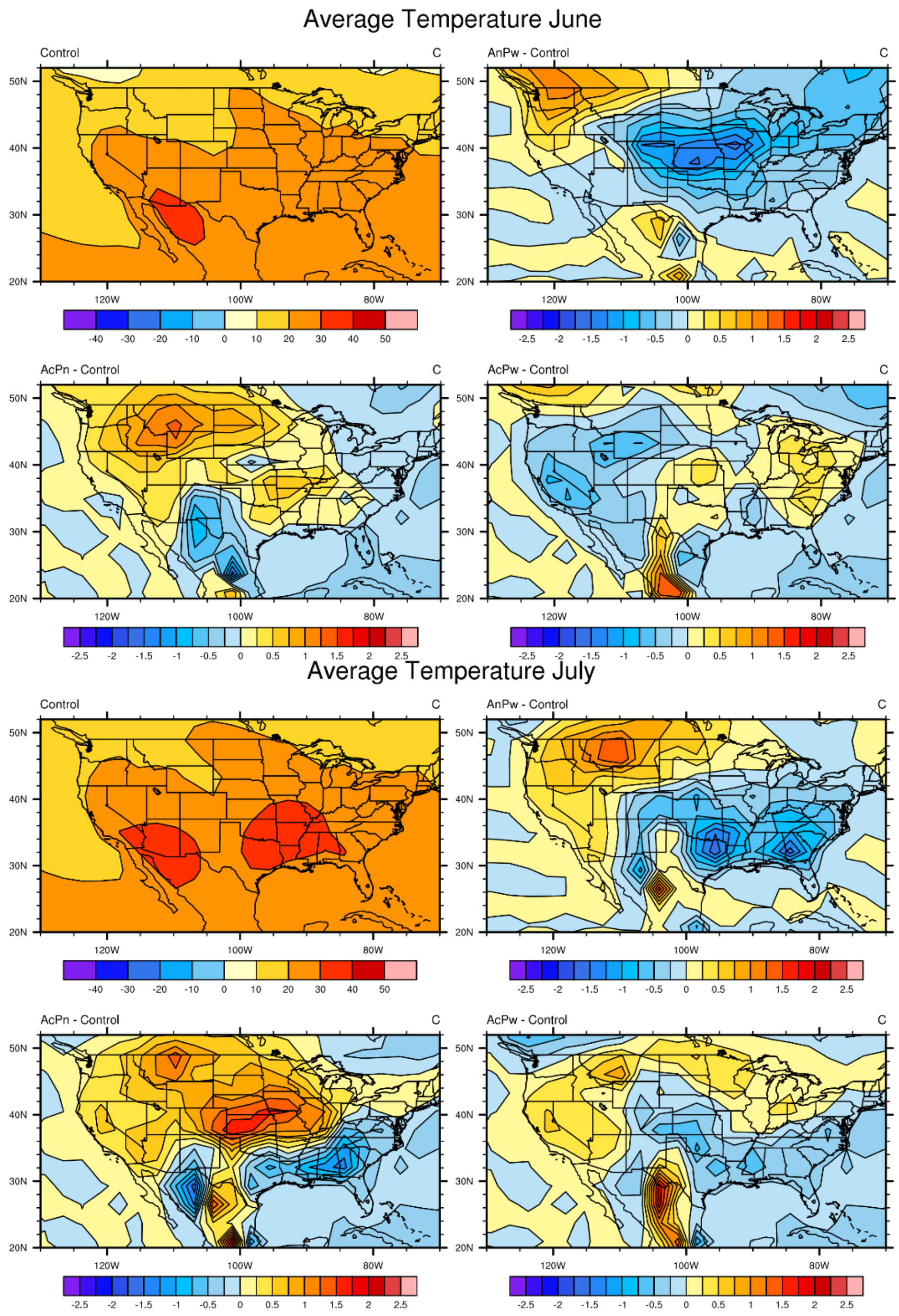


Figure 7: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged for each month over 40 years for control run and 25 years for experimental runs for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown for June and July.

The seasonal averages show the same results (Figure 8 and 9) where for the summer season AnPw experimental run seems to have the biggest influence on the development of cold anomalies in central America.

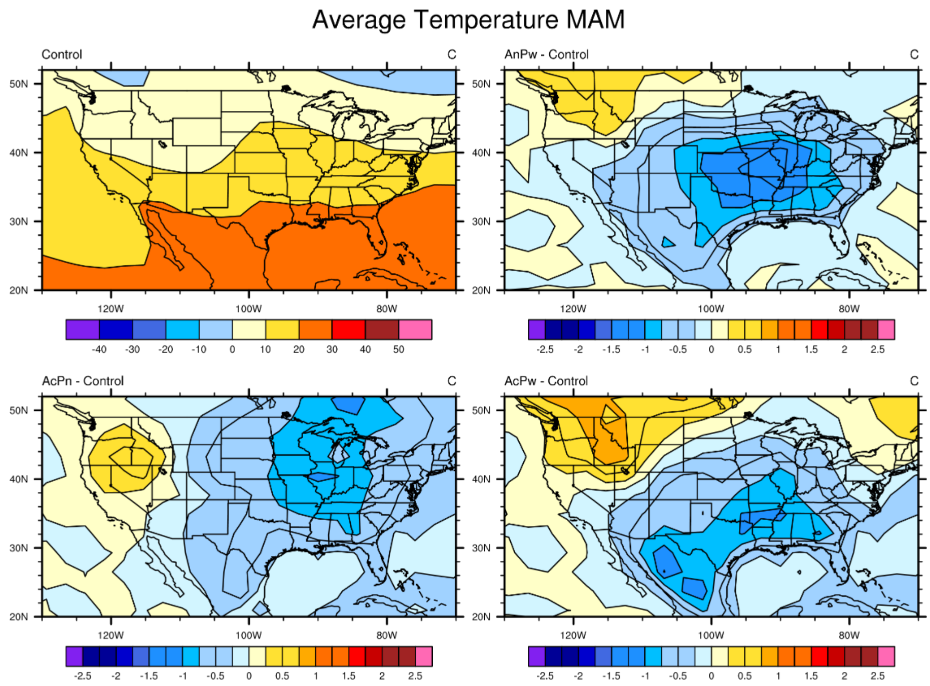


Figure 8: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged for each March, April and May together over 40 years for control run and 25 years for experimental runs for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

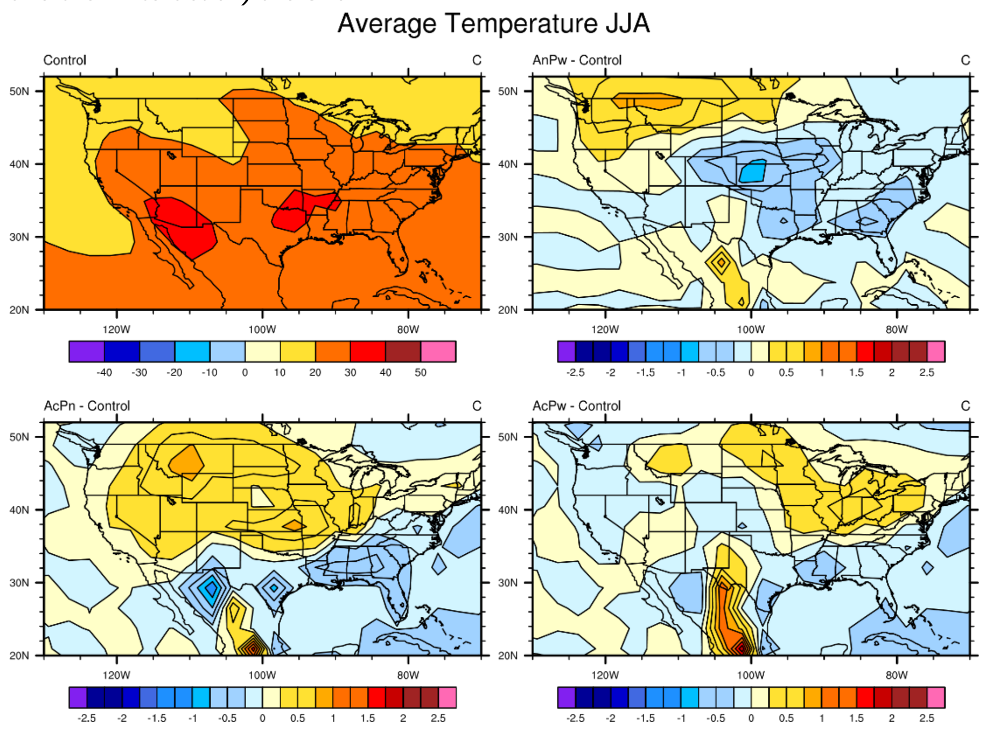


Figure 9: Simulated impact of ENSO and AMO on surface temperatures (°C) averaged for each June, July and August together over 40 years for control run and 25 years for experimental runs for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

The temperatures for fall and winter seasons are not presented, because from the perspective of pluvial formation, they are not important, the evaporation influenced by temperatures is negligible during fall and winter, especially for regions within temperate climate zone (Figure 10).

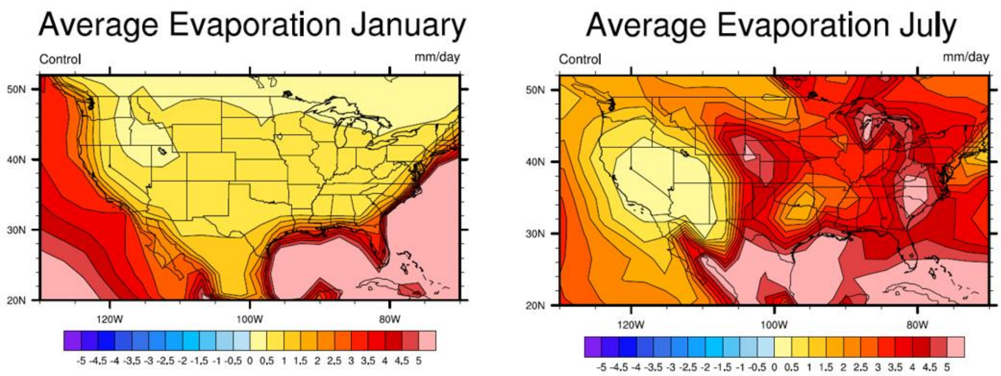


Figure 10: Comparison of evaporation (mm/day) simulated and averaged for January and July for 40 years of control run.

The statistical analysis did not show a statistically significant decrease in temperature anomalies within experimental runs over the U.S. The plots presented in Figure 11 are showing a significant temperature increase for the AcPw experimental run over the northwest U.S. in the spring and winter seasons and for AnPw over the northwest U.S. for the winter season.

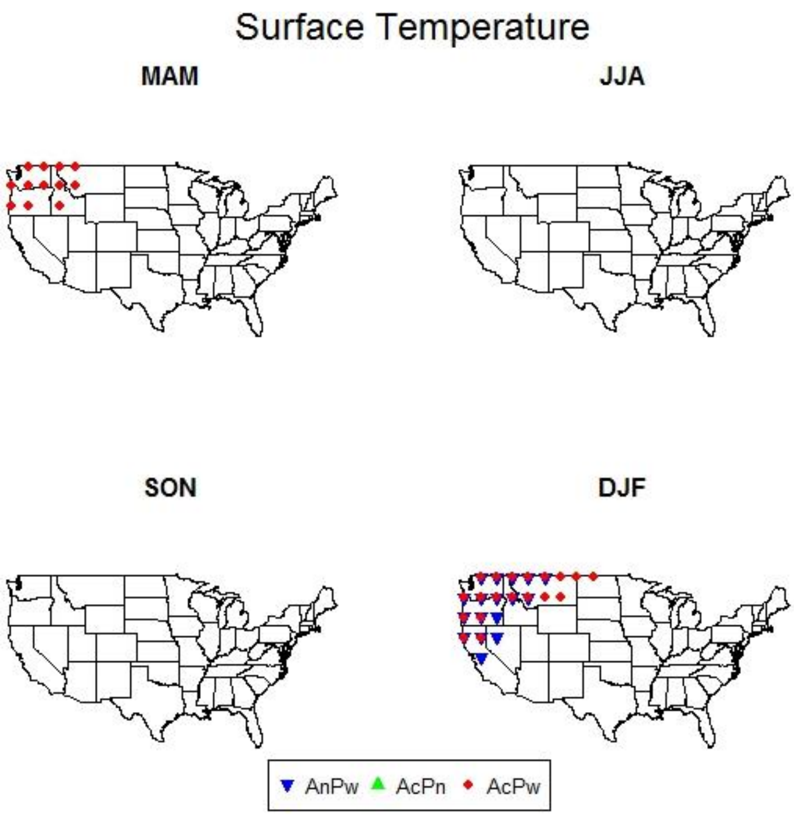


Figure 11: Statistical analysis of surface temperatures for distinct experimental simulations (AnPw – blue points, AcPn – green points and AcPw – red points) plotted over the United States region for spring, summer, fall and winter seasons. In the plots grid points show where temperature of experimental run is significantly higher (95% significance level) than temperature of control run.

5.2 Precipitation

For annual relative precipitation, the AnPw as well as AcPw anomaly causes an increase of precipitation in 16 out of 25 cases for the central part of North America. For the west coast region, no trends were observed within annual averages of relative precipitation. Monthly averaged relative precipitation for spring season (MAM), shown in Figure 12, reveal precipitation surplus for the AnPw and AcPw experiments over most of North America with exceptionally increased relative precipitation in May over the southwest region.

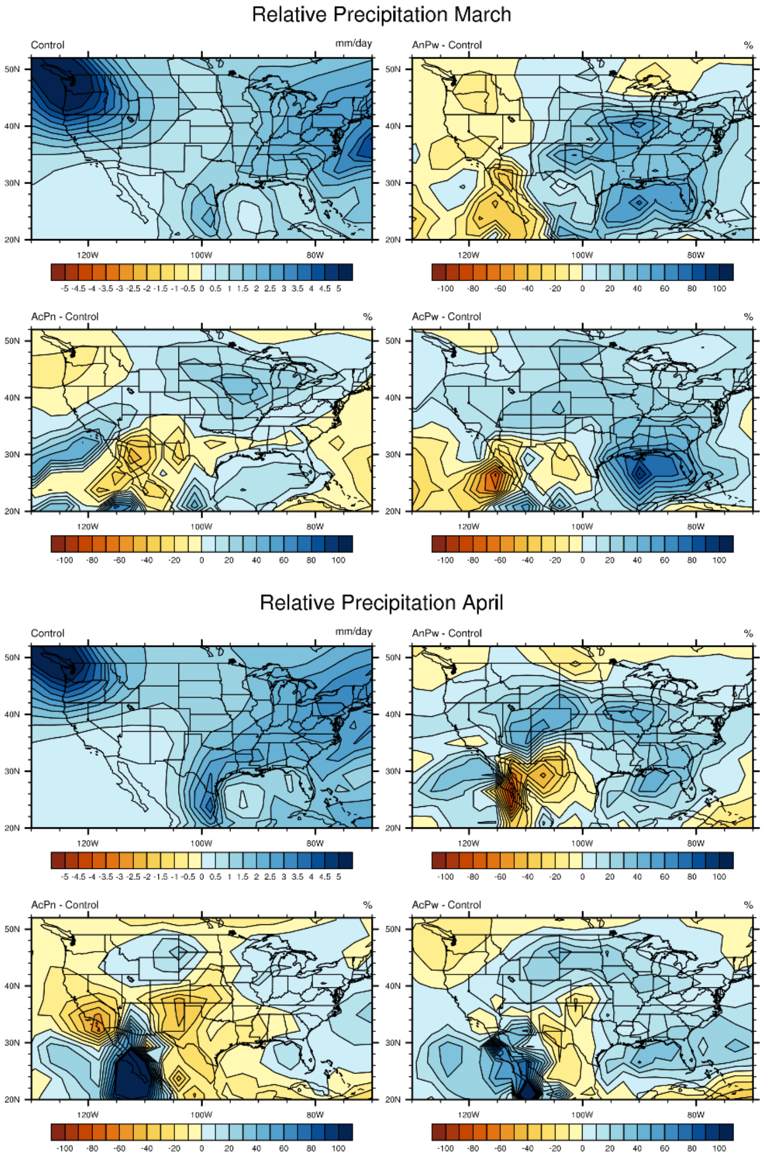
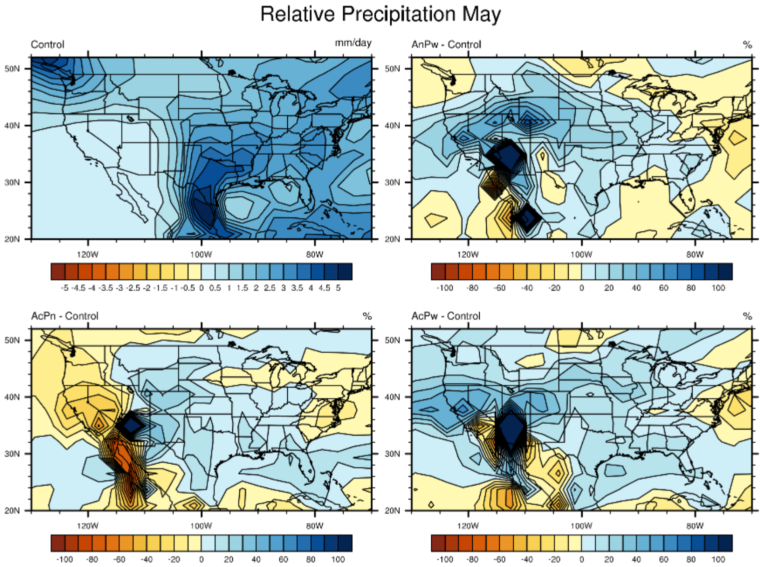


Figure 12: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each month over 40 years for control run (mm/day) and relative precipitation for 25 years of experimental run (%). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown for March, April, and May, the spring season.



The AcPn experimental relative precipitation run for the spring season shows more diversified conditions over North America with exceptional relative precipitation over Arizona in May. A similar trend for AnPw and AcPW can be seen in seasonal averages although for AcPn the anomalies are negligible (Figure 13).

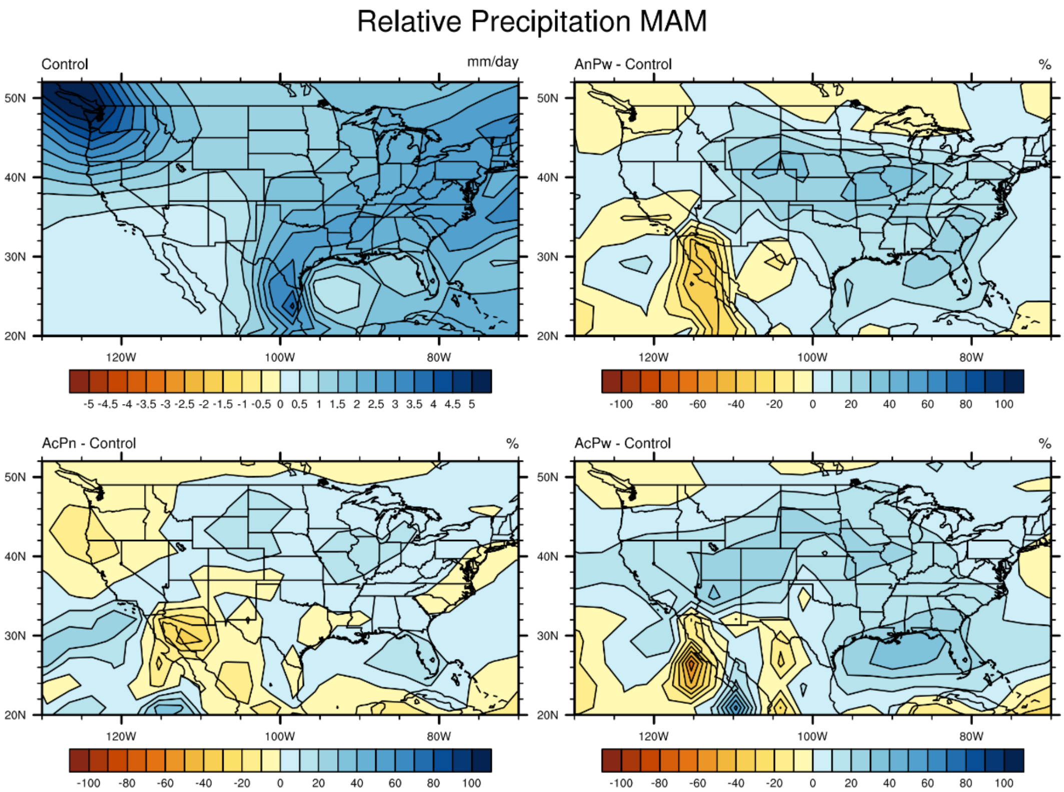


Figure 13: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each March, April and May over 40 years for control run (mm/day) and relative precipitation for 25 years of experimental run (%). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

Monthly averaged relative precipitation for the summer season (JJA) within all anomalies (AnPw, AcPn, AcPw) display high relative precipitation increase over the southwest region (Figure 14) identically to the seasonal averages (Figure 15).

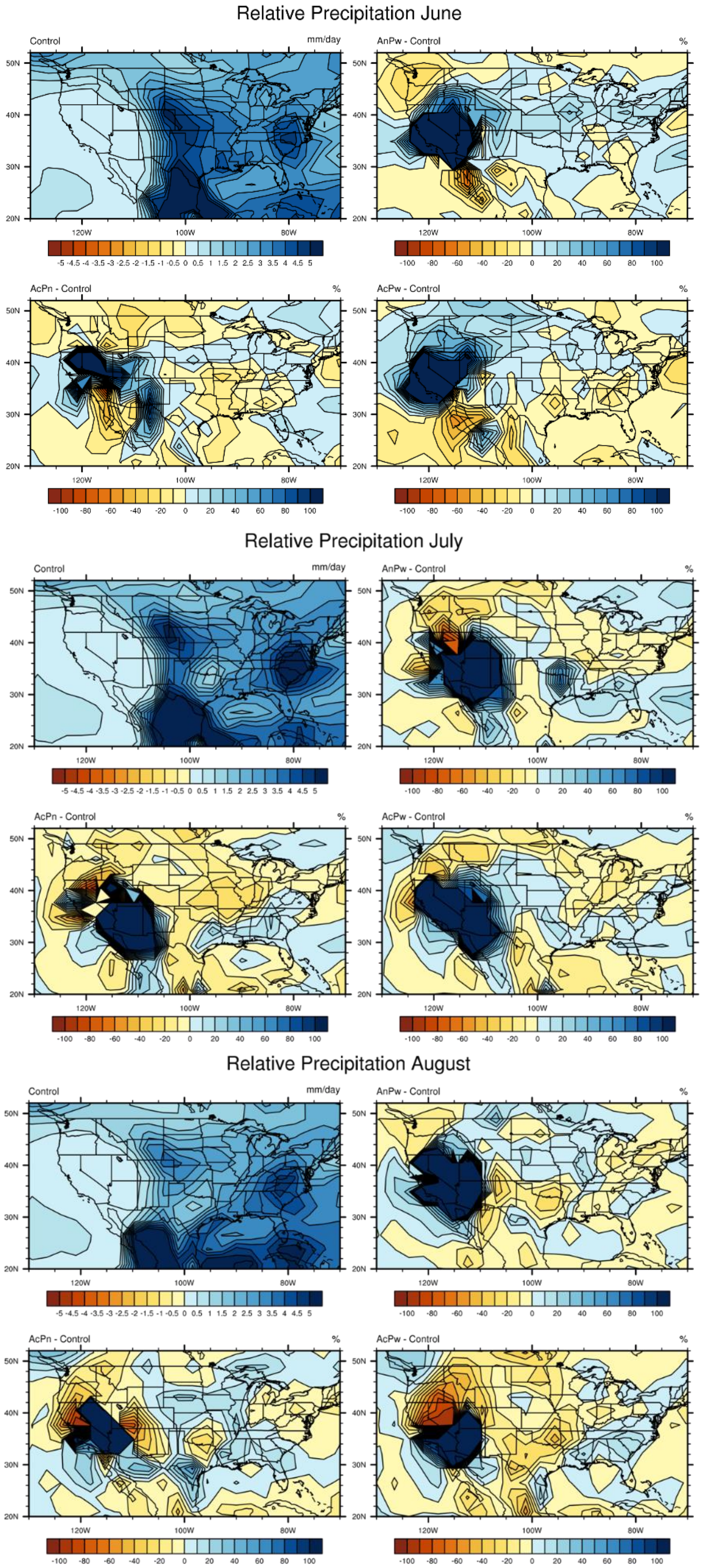


Figure 14: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each month over 40 years for control run (mm/day) and relative precipitation for 25 years of experimental run (%). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown for June, July, and August, the summer season.

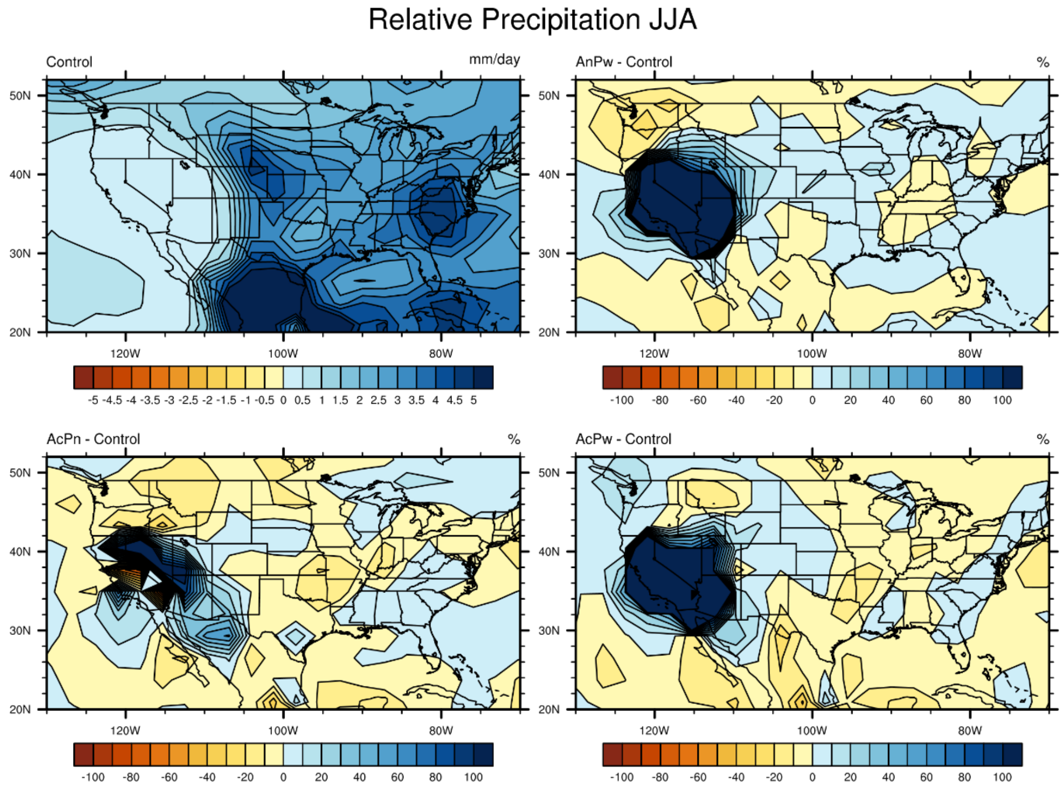


Figure 15: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each June, July and August over 40 years for control run (mm/day) and relative precipitation for 25 years of experimental run (%). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

To have a better understanding of the precipitation patterns over North America, regular precipitation seasonal anomalies plots for all the seasons (Figure 16, 17, 18 and 19) are also presented. The spring season precipitation surplus is present within all experimental runs (AnPw, AcPn and AcPw) over North America with a larger surplus for AnPw and AcPw in the eastern and central parts of the U.S. (Figure 16). For the summer season, AnPw has a large impact on North America, especially for the central region, and AcPw for the central and western regions (Figure 17).

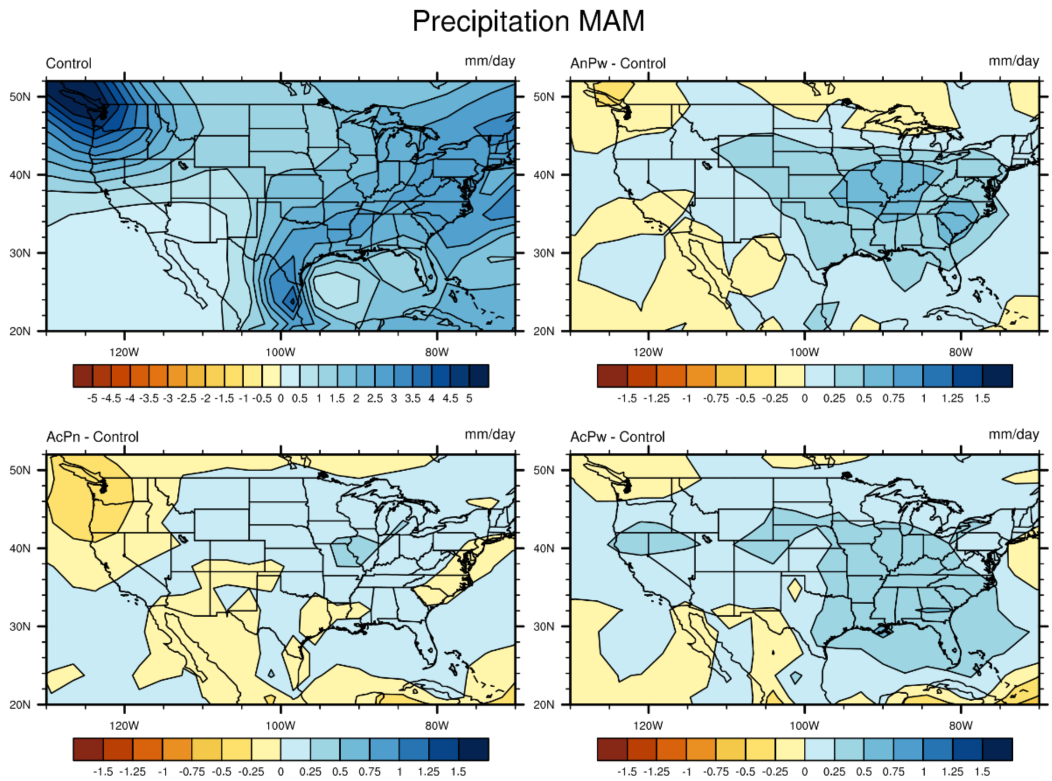


Figure 16: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each March, April and May over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

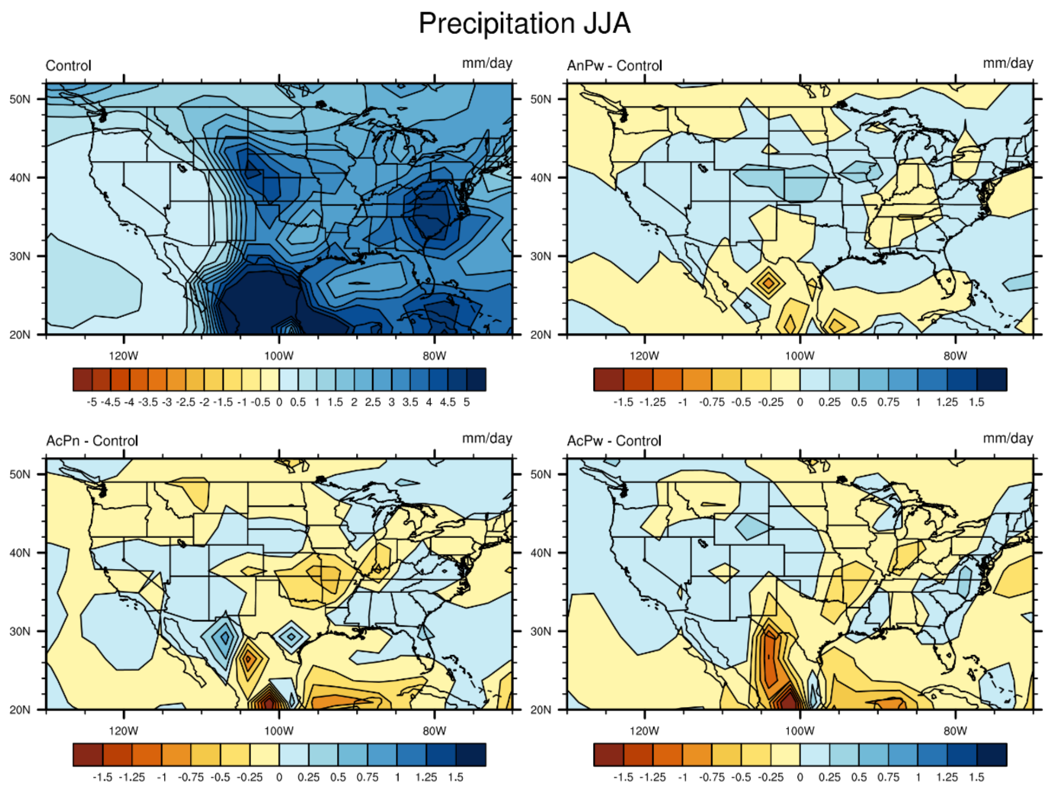


Figure 17: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each June, July and August over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

Fall precipitation positive anomalies occur over most of the U.S. for the AcPn and AcPw experimental runs, for the AnPw experimental run, the positive anomaly is located over the eastern and northwestern parts of the U.S. (Figure 18).

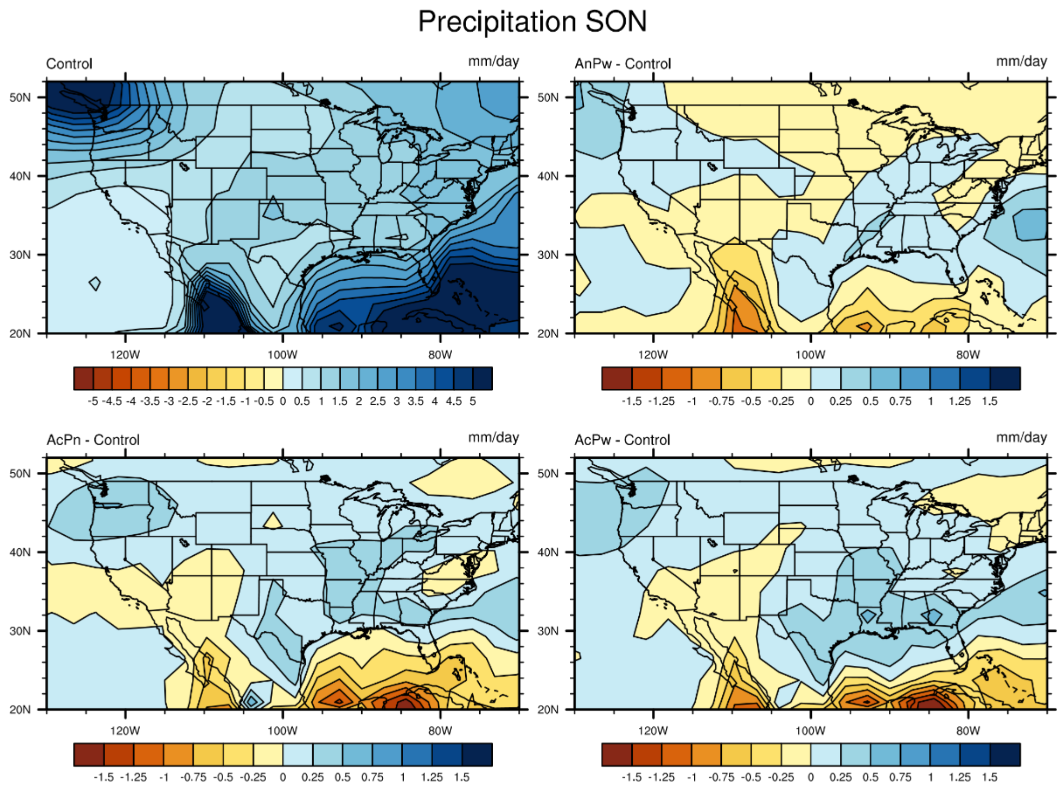


Figure 18: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each September, October and November over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

The winter precipitation surplus dominates over most of the U.S. with AcPn forcing and over the eastern and northern parts of the central region for AnPw forcing (Figure 19).

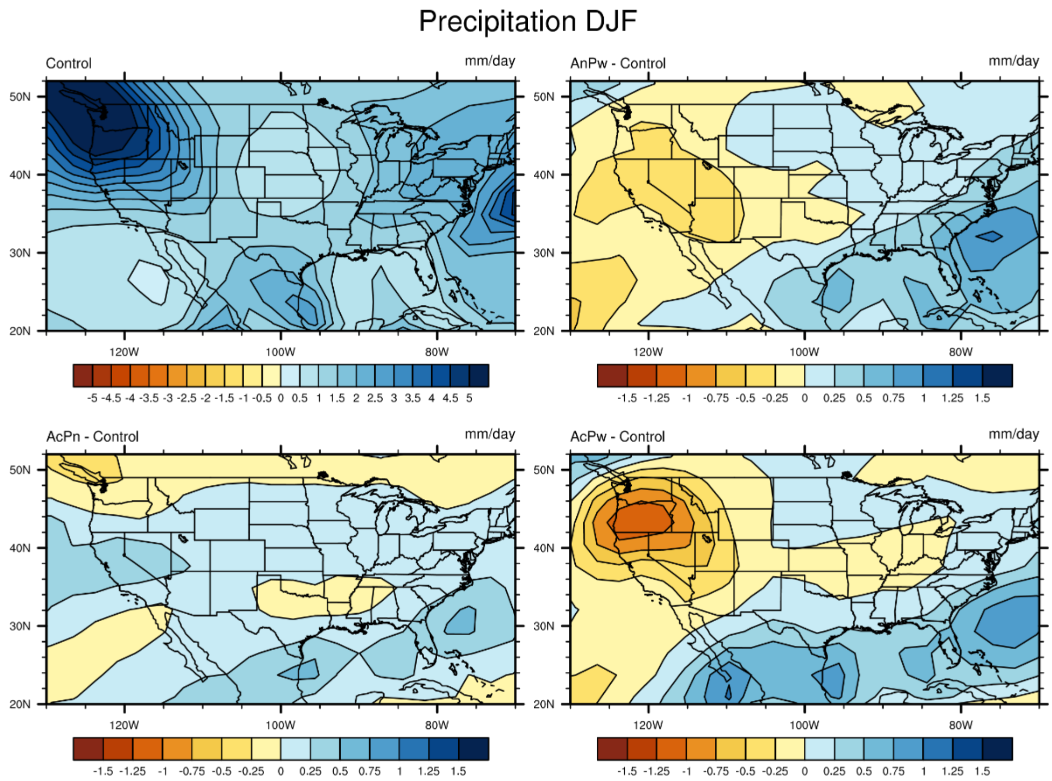


Figure 19: Simulated impact of ENSO and AMO on precipitation patterns over North America. Precipitation averaged for each December, January and February over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

Statistical analysis of seasonal precipitation revealed significantly higher precipitation rates during the AnPw experimental run over the central and eastern regions of the U.S. in the spring season, over portions of the central and western regions for the summer and over part of the southeast region in the winter. During the AcPn experimental run the seasonal precipitations were substantially larger in southern Montana, Wisconsin and Michigan during spring, in New Mexico during summer, in California, southern Oregon, southern Nebraska and the southeast region along the Gulf of Mexico for fall, and the Iowa-Missouri-Illinois region for winter. The AcPw experimental run shows significantly bigger precipitation for the central northern region, the east of the Southwest and the southeast region for spring, for parts of Idaho, Wyoming, Utah and California in summer, for the coastal region around the Gulf of Mexico in fall and for Florida in winter (Figure 20).

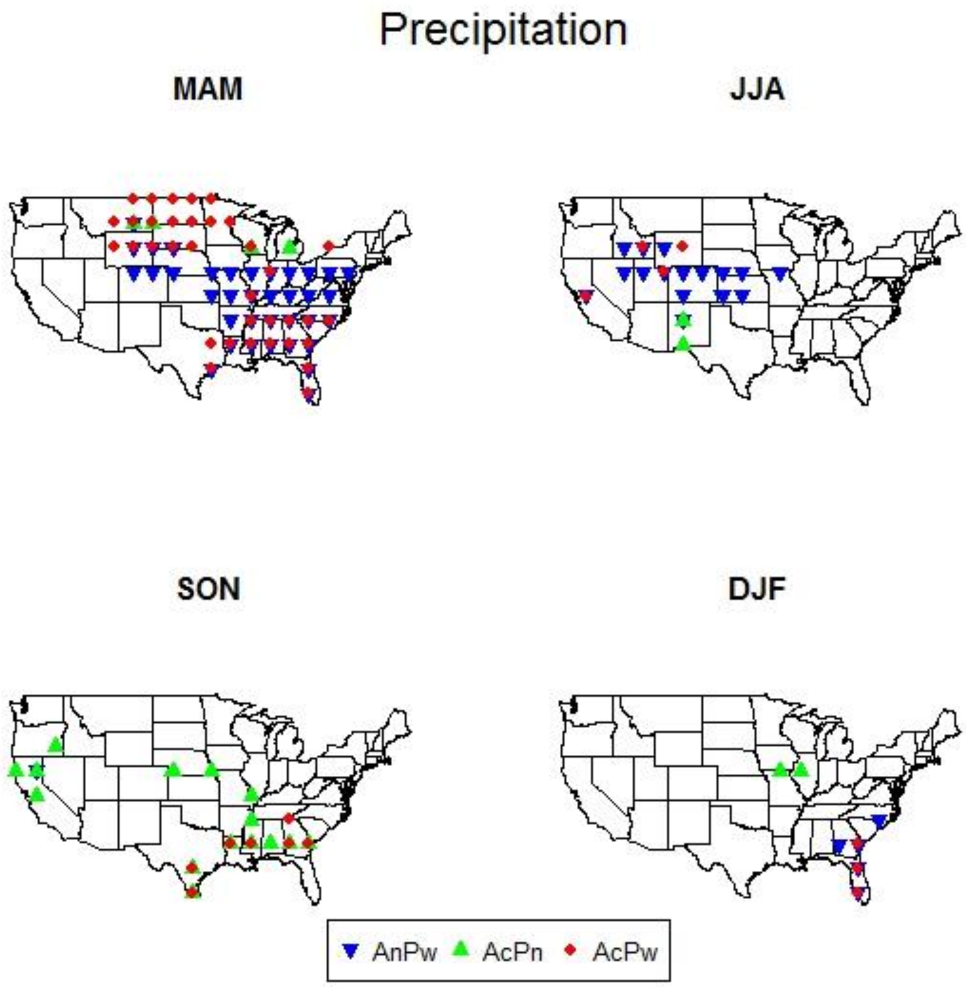


Figure 20: Statistical analysis of rainfall for distinct experimental simulations (AnPw – blue points, AcPn – green points and AcPw – red points) plotted over the United States region for spring, summer, fall and winter seasons. In the plots are pictured grid points where precipitation of experimental run is significantly higher (95% significance level) than precipitation of control run.

5.3 Integrated moisture convergence

The 25-year average of moisture convergence plots show the influence of El Niño single forcing and a combination of the cold phase of AMO and El Niño forcing on positive anomaly over the central and eastern parts of the region (Figure 21).

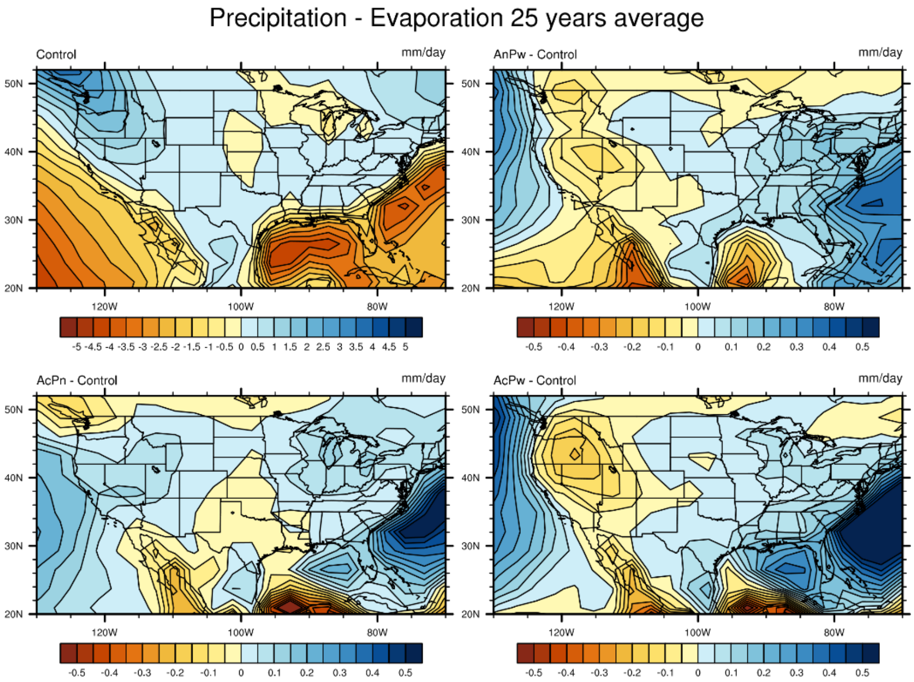


Figure 21: Simulated impact of ENSO and AMO on integrated moisture convergence averaged over 25 years for North America. Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

AcPn is the most noteworthy influence on annual averages of moisture fluxes over North America, from a pluvial formation perspective, where in the western region the positive anomaly occurs in 14 of the 25 cases. Seasonal plots of moisture flux show a positive precipitation effect of AnPw and AcPw over most of the U.S., the effect of AcPn is apparent across the central and eastern regions (Figure 22).

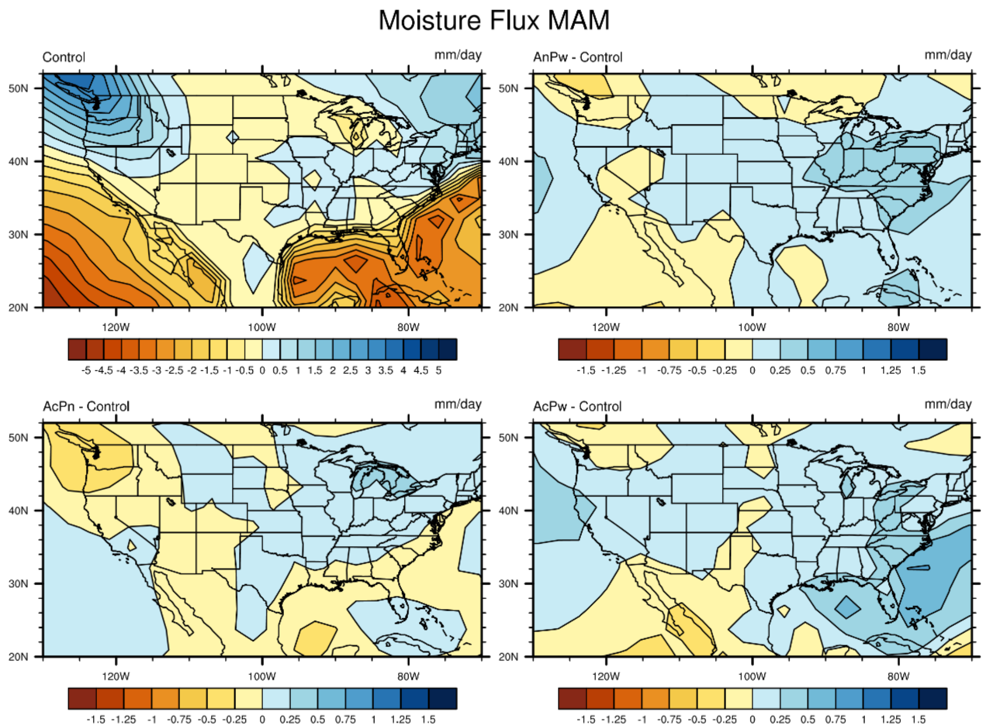


Figure 22: Simulated impact of ENSO and AMO on moisture flux patterns over North America. Integrated moisture convergence averaged for each March, April and May over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

Looking closely at the spring months separately (Figure 23), in March a moisture surplus is visible for the entire U.S. in the AcPw experimental run, for the central and eastern regions in the AnPw run and for the eastern and parts of the central and western regions in the AcPn run. For April the most expansive moisture surplus anomaly is observed for the AnPw experimental run, for AcPn and AcPw the anomaly is located mostly above the eastern part of the country. In May the moisture anomalies seem to be less spatially continuous but all of the experimental runs positively affect the moisture surplus over the central U.S.

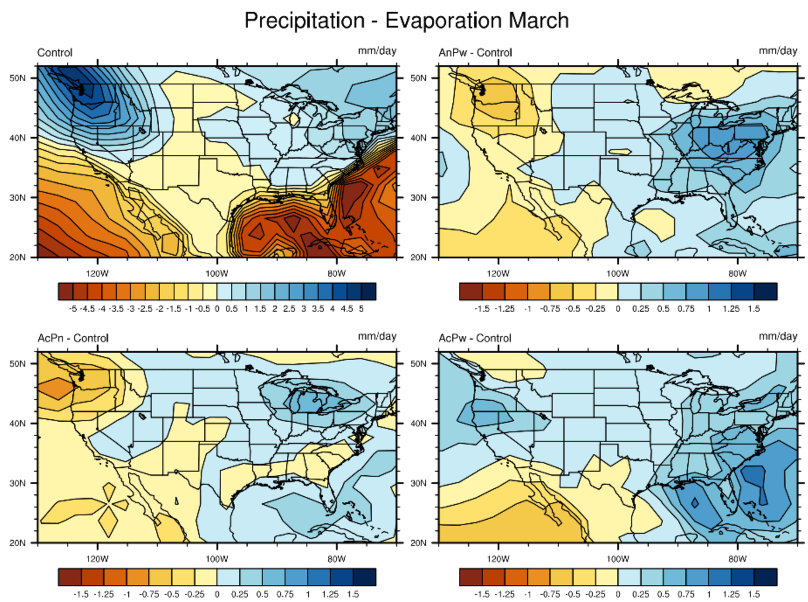
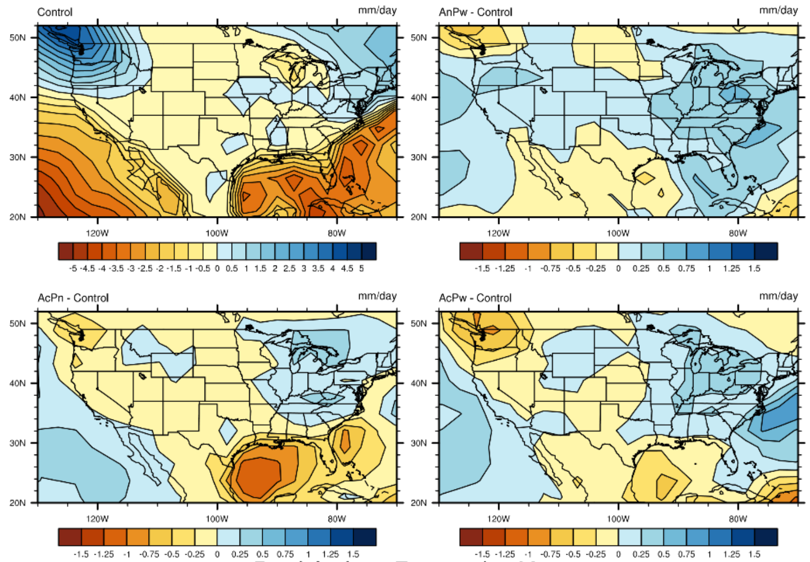
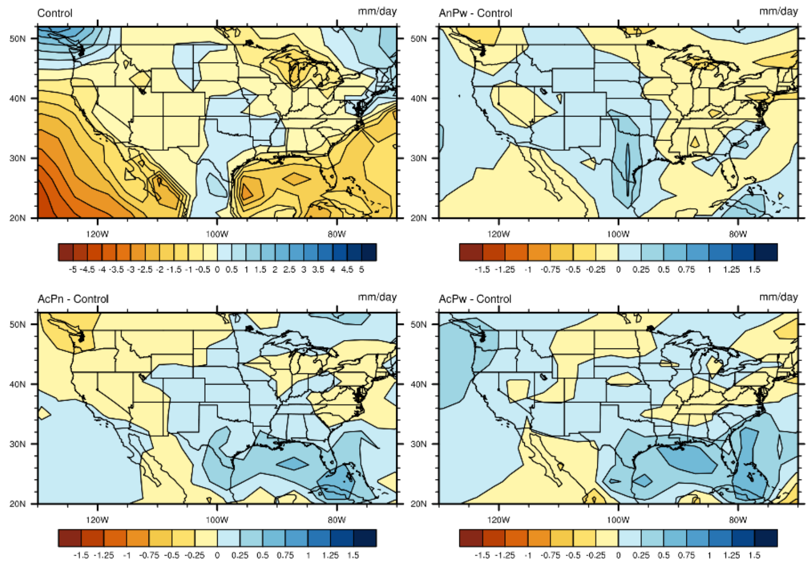


Figure 23: Simulated impact of ENSO and AMO on moisture flux patterns over North America. Integrated moisture convergence averaged for each month over 40 years for control run and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown for March, April, and May, the spring season.

Precipitation - Evaporation April



Precipitation - Evaporation May



The summer season doesn't have any positive values of moisture flux anomalies. In the fall season the moisture convergence plots show positive anomalies for all experimental runs over the eastern and northwestern parts of the U.S. and for the central region in the AcPw experiment (Figure 24).

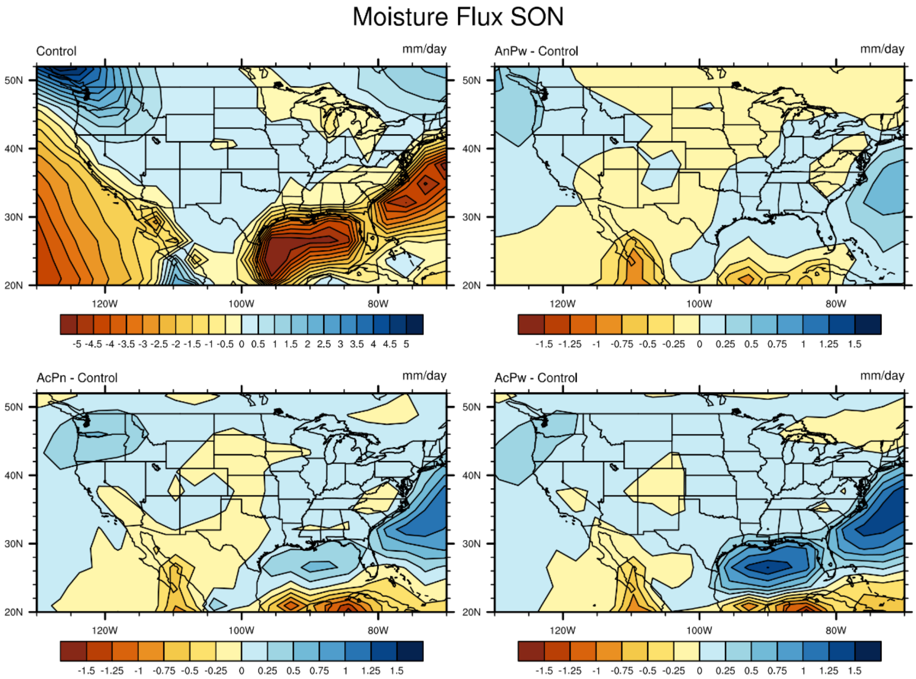


FIgure 24: Simulated impact of ENSO and AMO on moisture flux patterns over North America. Integrated moisture convergence averaged for each September, October and November over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown

For the winter season all of the experimental plots show positive anomalies of moisture flux over the central and eastern regions, and the AcPn experimental run displays a moisture surplus over the western region as well (Figure 25).

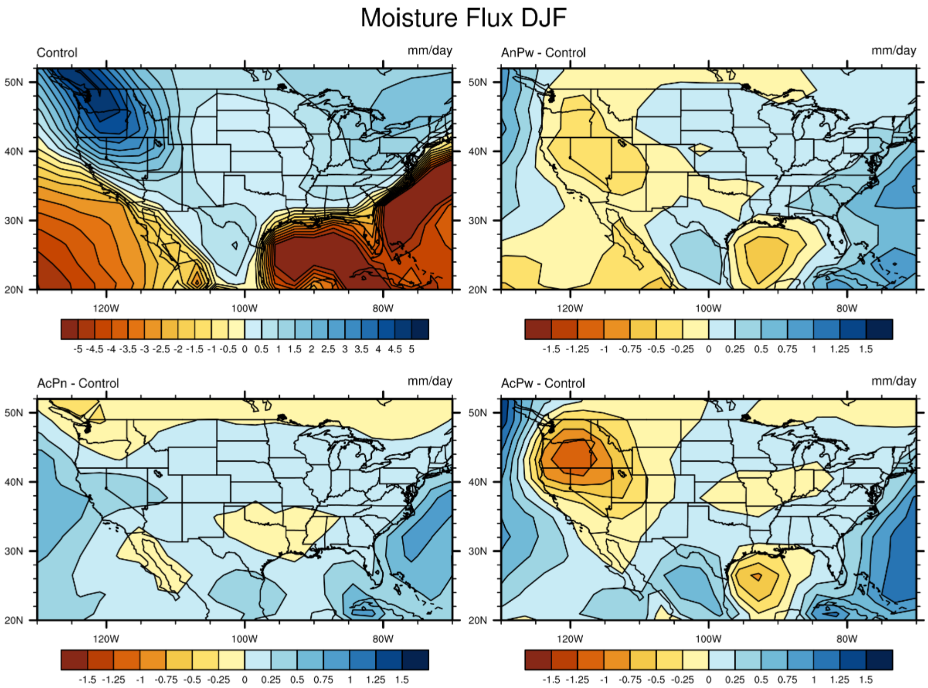


Figure 25: Simulated impact of ENSO and AMO on moisture flux patterns over North America. Integrated moisture convergence averaged for each December, January and February over 40 years for control run (mm/day) and for 25 years of experimental run (mm/day). Control run and anomalies (warm phase of ENSO, cold phase of AMO and their interaction) are shown.

Statistical analysis of moisture flux convergence has similar results to precipitation analysis and the results are presented in Figure 26. During the AnPw experimental run, the moisture flux is significantly bigger over the central and eastern regions of the U.S. in the spring season, over portions of the central and western regions for summer and over part of the southeast region in winter. The AcPn experimental run shows substantially positive moisture flux over southern Montana, Wisconsin and Michigan during spring, over New Mexico during summer, northern California, Texas and the coast of the Gulf of Mexico during fall, and over Wyoming and parts of the Southwest during winter. For the AcPw experimental run, values of moisture flux are significantly bigger for the central northern region, the east of the Southwest and the southeast region for spring, for parts of Idaho, Utah and California in summer, for the coastal region around the Gulf of Mexico in fall and for Florida in winter.

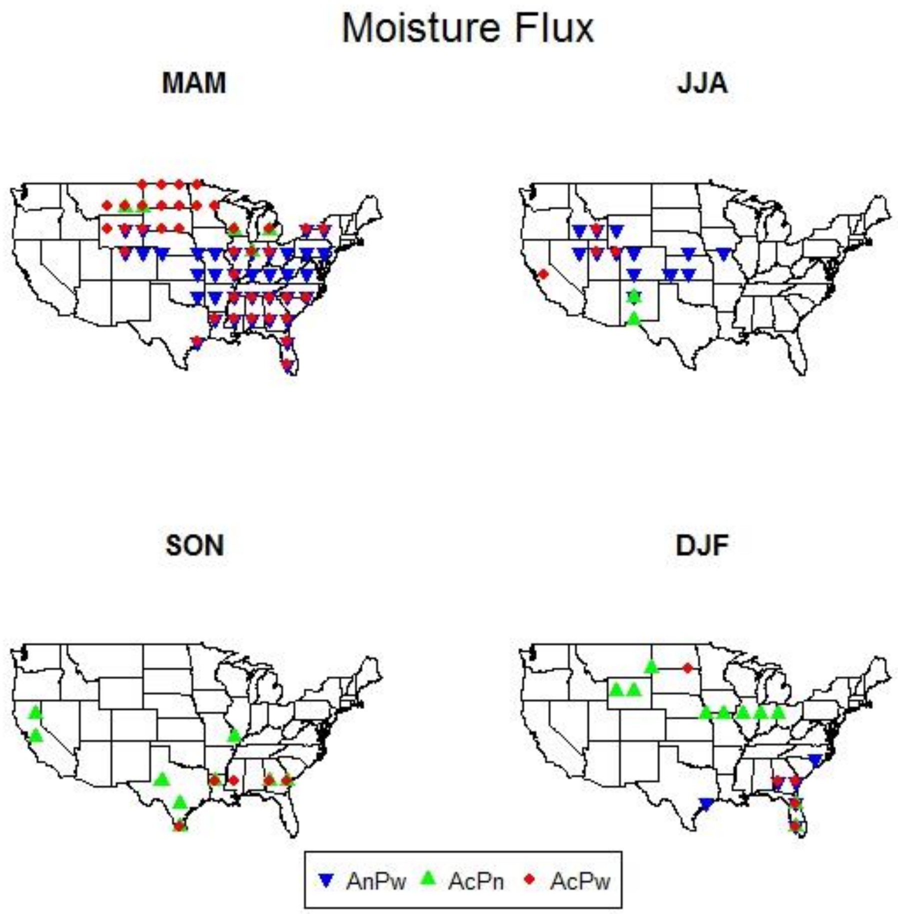


Figure 26: Statistical analysis of integrated moisture convergence for distinct experimental simulations (AnPw – blue points, AcPn – green points and AcPw – red points) plotted over the United States region for spring, summer, fall and winter seasons. In the plots are pictured grid points where moisture flux of experimental run is significantly higher (95% significance level) than moisture flux of control run.

6. Summary and discussion

According to the results of the CAM3.1 simulation, the cold phase of AMO and warm phase of ENSO have an effect on long term temperatures over North America, especially in comparison to opposite phases of these oscillations (warm AMO, cold ENSO). These results are consistent with previous research findings like in Feng et al. 2008 or Hu et al. 2011. From an annual perspective, the warm ENSO forcing seems to have an influence on lower temperature development over the central U.S. and a combination of cold AMO and warm ENSO has an influence on the south of North America. Seasonal temperature trends show an improvement of cold temperatures over the entire studied region for spring and summer, during summer the effect of El Niño on colder temperatures in central U.S is notable. However, statistical analysis reveals that none of these results are statistically significant at 95% confidence level.

Precipitation seems to be mostly enhanced during the spring season, which is also confirmed by the conducted statistical analysis. The warm phase of ENSO by itself has a large contribution, in interaction with AMO precipitation anomalies has slightly different spatial distribution and larger spatial extent. Plots of relative precipitation anomalies show an exceptional increase of precipitation in the western region during summer, however the plots of absolute precipitation in mm/day do not display such an enormous increase. It can be explained by a comparison of precipitation in the experimental run to a very low amount of precipitation in the control run, therefore plots show an exceptional increase even though the amount of absolute rainfall is not significantly above average. The summer precipitation over the central U.S. region seems to be influenced mostly by the warm phase of ENSO. The teleconnection between El Niño and precipitation surplus over the central United States has been mentioned in a few previous studies (Enfield et al. 2001; Hu & Feng 2001; Seager et al. 2005) and another study suggested AMO to be the most important driver of summer rainfall over North America (Hu & Feng 2012).

The moisture flux NCL plots show the most evident increase during spring, this is also supported by the statistical analysis. The results are very similar to the precipitation results. During El Niño a positive moisture flux is observed over the central and eastern regions. The interaction of warm ENSO and cold AMO in the spring season shifts the positive moisture flux northwards from the central region and positive moisture flux anomalies over the southeastern part of the country have a bigger spatial extent compared to the conditions under the influence of only ENSO.

The positive winter anomaly (also seen within precipitation plots) over the west coast that coincides with the same anomaly in the 25-year averaged moisture flux anomaly is also noteworthy. According to the statistical analysis, these anomalies are not significantly different from the control run conditions. However they still correspond with causes of the twentieth century pluvial (Woodhouse et al. 2005). Results of the moisture flux analysis are not compared to any other studies because similar research was not found.

Understanding of SST variability and its influences on climate is still a fervid topic in climate science. Data used for research presented in this study are made by a single GCM and further research on this topic should consider data from multiple climate models as was done, for example, by Oglesby et al. (2011). Focus should be also put on the interaction of the warm phase of AMO and the warm phase of ENSO, because under these conditions a suitable positive low-level pressure anomaly exists over the central U.S which can enhance moisture transport and precipitation development (Hu & Feng 2012).

7. Conclusions

Goals of this thesis, summarized in the thesis assignments, were accomplished. An extensive literature review was provided in a separate chapter, although most of the authors studying SST variability and its effects pay their attention to drought, the opposite process of pluvial. In this study I focused on the particular phases of AMO and ENSO described in the literature as variability that positively affects precipitation over North America. Plots, made using NCL and statistical analysis conducted in program R/R Studio, are explained in the results section and presented in the figures chapter.

The most important results, answering the research questions set in the goals of this thesis, are: The warm phase of ENSO has a significant effect on precipitation and moisture flux in the central United States region. Significantly higher precipitation and moisture flux are observed mostly during the spring season. The cold phase of AMO in interaction with the warm ENSO has an impact on the precipitation distribution and spatial extent of moisture surplus anomalies in comparison with those caused solely by ENSO. Singular cold phase AMO forcing seems to have an impact on winter precipitation over the Californian region which is consistent with the findings about the well understood early twentieth century pluvial.

Focus of future investigation of this particular research should be on evaluating data from different GCM models with the same technique as used in this study. More attention should also be given to understanding the interaction between the warm phase of ENSO and the warm phase of AMO. Similar research should be conducted for Europe searching for teleconnections between AMO and pluvial occurrence. Another topic to study is the interaction between climate and land surface variability.

8. References

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